

the INDUSTRIAL ENVIRONMENT — its EVALUATION & CONTROL

**U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
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FOREWORD

In 1958 the Public Health Service's Occupational Health Program introduced the Syllabus, a compilation of training aids, in conjunction with courses presented by the Service to industrial hygiene personnel.

Training people in the profession of industrial hygiene was not a new concept in 1958. The Occupational Health Activity of the Public Health Service was established in 1914 to protect and preserve the health of the American worker. From the very beginning, one of the tenets of our organization was the promotion and improvement of industrial hygiene and industrial medicine.

In 1970 Congress passed the Occupational Safety and Health Act. This Act specifically instructed the National Institute for Occupational Safety and Health (NIOSH) to ". . . 1) develop and establish recommended occupational safety and health standards, and 2) perform all functions of the Secretary of Health, Education and Welfare under Sections 20 (Research and Related Activities) and 21 (Training and Employee Education) of this Act."

This third edition, which has become an industrial hygiene textbook rather than a syllabus, is the most comprehensive to date. The subject matter is extremely broad, covering topics from mathematics to medicine. The first few chapters, in addition to providing historical information, cover such areas as mathematics, chemistry, biochemistry, physiology and toxicology. Other chapters deal

with specific areas of interest to those concerned with evaluating the potentially harmful effects of physical and chemical air contaminants. New chapters have been added on safety, solid waste, and control of water pollution. It is not possible to provide sufficient information in any of the chapters to make the reader an authority; rather, the book is to be used in conjunction with other training aids. References are included at the end of each chapter for further study.

Authors of chapters in this edition were selected for their expertise in the particular subject covered. In reviewing the affiliations of the authors, it is interesting to note that there are 15 representatives from universities, 19 from industry, and 12 from the consulting field, as well as several representatives from State agencies and technical societies.

The appreciation of the National Institute for Occupational Safety and Health is extended to the contractor, George D. Clayton & Associates, Southfield, Michigan, and the contributing authors. They have shared their expertise at a time when overwhelming demands are being made upon them.

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CHAPTER I

INTRODUCTION

George D. Clayton

HISTORY OF INDUSTRIAL HYGIENE

Industrial hygiene is the science of protecting man's health through the control of the work environment. Man and his environment are indivisible. They react upon each other in the form of a "give-and-take" relationship. Frequently it is assumed that man moves through his environment and molds it to his desires; however, it may be more productive to think of the environment and man as moving through and changing each other simultaneously.

Historically, there was very little concern for protecting the health of the worker prior to 1900. Man's life, at the dawn of civilization, was a struggle for existence, and the mere job of survival was an occupational disease. As stratification of social classes progressed, slaves performed the common labor; and this continued until relatively recent times. The propensity of man towards war provided a fluid and steady slave supply. So disdainful was the idea of manual labor, that at one period in their culture Egyptians were prohibited by law from performing it. With this attitude of society in regard to the working man, it is no wonder there were no efforts made to control the working environment and to provide a healthful, comfortable place in which to work.

As early as the fourth century, B. C., lead toxicity in the mining industry was recognized and recorded by Hippocrates, although no concern was demonstrated for the subsequent protection of the worker. Approximately 500 years later, Pliny the Elder, a Roman scholar, made reference to the dangers inherent in dealing with zinc and sulfur, and described a bladder-derived protective mask to be used by laborers subjected to large amounts of dust or lead fumes. For the most part, however, the Romans were much more concerned with engineering and military achievements than with any type of occupational medicine.

In the second century, Galen, a Greek physician who resided in Rome, wrote voluminous theories on anatomy and pathology. Dogmatic in his writing, Galen recognized the dangers of acid mists to copper miners, but he gave no impetus to the solution of the problem.

The advent of feudalism in the Middle Ages did little to improve work standards; possibly the sole advancement of the age was the provision of assistance to ill members and their families by the feudal "guilds." Observation and experimentation flourished in the great universities of the 12th and 13th centuries, but the study of occupational diseases was virtually ignored.

Further achievements in the field of industrial hygiene were sadly lacking until the publication,

in 1473, of Ulrich Ellenbog's pamphlet on occupational diseases and his notable hygiene instruction. Hazards associated with the mining industry were effectively described in 1556 by Georgius Agricola, a German scholar. His "De Re Metallica" was translated into English in 1912 by Herbert and Lou Henry Hoover. Agricola's 12-sectioned treatise included suggestions for mine ventilation and protective masks for miners, a discussion of mining accidents and descriptions of what we refer to today as "trench foot" (effects on the extremities due to lengthy exposure to the cold water of damp mines) and silicosis (a disease of the lungs caused by inhalation of silica or quartz dust).

As late as the 16th century industrial hygiene was fraught with mysticism. For example, it was believed that demons inhabited the mines and could be controlled by fasting and prayer. Typical of the Renaissance was the alchemist, Paracelsus. For five years this Swiss doctor's son worked in a smelting plant and subsequently published his observations on the hazards of that industry. The book was laden with erroneous conclusions, such as the attribution of miners' "lung sickness" to a vapor comprised of mercury, sulfur and salt; nevertheless, his warnings about the toxicity of certain metals and outline of mercury poisoning were quite advanced.

Generally accepted as the first inclusive treatise on occupational diseases was "De Morbis Artificum" by Bernardo Ramazzini, an Italian physician. Published in 1700, this book described silicosis in pathological terms, unrefined as they were, as observed by autopsies on miners' bodies. Ramazzini outlined "cautions" which he felt would alleviate many industrial hazards, but these were for the most part ignored for centuries. "De Morbis," however, had a gargantuan effect on the future of public hygiene. The question asked by Ramazzini, which was later to be included in almost every physician's case history of a patient, was "Of what trade are you?"

The 18th century saw many notable physicians scratching the surface of the industrial hygiene problem. Sir George Baker correctly attributed "Devonshire Colic" to lead in the cider industry and was instrumental in its removal. Percival Pott, in recognizing soot as one of the causes of scrotal cancer, was a major force in the passage of the "Chimney-Sweepers Act of 1788." Both a political and medical influence, Charles Thackrah wrote a 200-page treatise dealing with occupational medicine. A farsighted scientist, Thackrah asserted that "Each master . . . has in great measure the health and happiness of his workpeople

in his power . . . let benevolence be directed to the prevention, rather than to the relief of the evils." Thomas Beddoes and Sir Humphry Davy collaborated in describing occupations which were prone to cause "phthisis" (tuberculosis). Davy also aided in the development of the miner's safety lamp.

In spite of these numerous advances, the 18th century developed few *true* safeguards for workers. It was not until the English Factory Acts of 1833 were passed that government first showed its interest in the health of the working man. These are considered the first effective legislative acts in the field of industry and required that some concern be given to the working population. However, this concern was in practice directed more toward providing compensation for accidents than controlling the causes of these accidents. Various European nations followed England's lead and developed Workmen's Compensation Acts. These laws stimulated the adoption of increased factory safety precautions and inauguration of medical service in industrial plants. A sense of "community responsibility" was evolving, epitomized by the interest of newspapers and magazines in the control of the environment. For example, the London Illustrated News, one of the most popular publications of the 19th century, affixed the blame in a mine explosion to negligence in proper gas-testing methods. The same article made a point of the fact that no safety lamps had been provided. In 1878, the last of the English "factory acts" centralized the inspection of factories by creating a post for this purpose in London.

The United States had an early 20th century champion of the cause of social responsibility for workers' health and welfare in the person of Alice Hamilton, a physician. She presented substantiated evidence of a relationship between illness and exposure to toxins; she went further by proposing concrete solutions to the problems. This was the start of an "Occupational Medicine Renaissance." Public awareness was becoming acute and legislation was being passed. In 1908 the federal government passed a compensation act for certain civil employees, and in 1911 the first state compensation laws were passed; by 1948 all the states had passed such legislation.

These Workmen's Compensation Laws were important factors in the development of industrial hygiene in the United States, as it became more profitable to control the environment than to pay for the compensation.

The U. S. Public Health Service has been a world leader in evaluating diseases of the working man and development of controls, as well as fostering an interest in occupational diseases by various state agencies, universities, management and unions. The U. S. Public Health Service and the U. S. Bureau of Mines were the first federal agencies to conduct exploratory studies in the mining and steel industries, and these were undertaken as early as 1910. The first state industrial hygiene programs were established in 1913 in the New York Department of Labor and by the Ohio Department of Health (see Chapter 49).

One of the earliest attempts made to link the

industrial environment with a specific disease was the exploration of the high incidence of tuberculosis among garment workers. Given needed authority in 1912 by Presidential action, the Public Health Service embarked upon investigations in many industries and backed up their findings with concrete, workable solutions.

By 1933 federal employee health service was offered by the Tennessee Valley Authority, followed by the Army, Navy, Air Force and Atomic Energy Commission less than ten years later. The great depression of the 1930's had gone far to convince the federal government of a real need for intervention in the economy and welfare of American life. On an even larger scale, the creation of international bodies, such as the International Labor Organization and the World Health Organization, has given the world common goals for which to strive. Through studies and consulting services these organizations share the magnitude of the problem. They realize that technical advances necessarily have disadvantages as well as advantages, particularly in the field of industrial hygiene. For example, as the development of atomic energy progresses, a radiation hazard exists which was heretofore unknown.

RECENT DEVELOPMENTS

Today we view occupational medicine in an entirely new light. A tenet of our modern society is that every worker has the right to the fulfillment of his spiritual and material needs, while at the same time enjoying freedom from fear of trauma and disease. Our emphasis has shifted from correctional to preventive industrial hygiene, and occupational medicine has now become an integral part of medical education. The rapid advancement in automation provides a tremendous challenge in the field of environmental control.

Although the United States has moved more rapidly than any other nation in the world in ferreting out diseases of the work force and developing control measures, the ever increasing desire of our society for an acceleration in elimination of diseases caused by the environment, and specifically the work environment, has demanded a far greater effort than what has been shown in the past. Congress has reacted to these social demands by passing three major pieces of legislation:

1. The Metal and Nonmetallic Mine Safety Act of 1966. Health and safety standards for metal and nonmetallic mines are spelled out in this Act. A Review Board (The Federal Metal and Nonmetallic Mine Safety Board of Review) is created, consisting of five members, appointed by the President, with the advice and consent of the Senate. Groundwork is laid for the creation of advisory committees to assist the Secretary of the Interior; these committees are expected to include an equal number of persons qualified by experience and affiliation to present the viewpoint of operators of such mines, and of persons similarly qualified to present the viewpoint of workers in these mines, as well as one or more representatives of mine inspection or

safety agencies of the state. The Act also provides for mandatory reporting (at least annually) of all accidents, injuries and occupational diseases of the mines; and expanded programs are developed for the education of personnel in the recognition, avoidance and prevention of accidents or unsafe or unhealthful working conditions. Finally, this Act promotes sound and effective coordination between federal and state governments in mine inspection procedures. Major deficiencies of this Act included the fact that no health representatives were provided on Advisory Committees, nor was there a provision for research in mine safety or miner health.

2. The Federal Coal Mine Health and Safety Act of 1969. This Act attempts to attain the highest degree of health protection for the miner. It delineates mandatory health standards and provides for the creation of an Advisory Committee to study mine problems. Additional authority is given, through this Act, to the federal government to withdraw miners from any mine which is found to be in danger, and prohibits re-entry into any such mine. The Act itself reads, to "provide, to the greatest extent possible, that the working conditions in each underground coal mine are sufficiently free of respirable dust concentrations in the mine atmosphere to permit each miner the opportunity to work underground during the period of his entire adult working life without incurring any disability from pneumoconiosis or any other occupation-related disease during or at the end of such period." This is accomplished by the control of dust standards and respiratory equipment; the development of rules for roof support, proper ventilation, grounding of trailing cables, distribution of underground high-voltage and a provision for mandatory medical examinations for the miners at fixed intervals.
3. Occupational Safety and Health Act of 1970. The declared Congressional purpose of the Occupational Safety and Health Act of 1970 is to "assure so far as possible every working man and woman in the nation safe and healthful working conditions and to preserve our human resources." Under its terms, the federal government is authorized to develop and set mandatory occupational safety and health standards applicable to any business affecting interstate commerce. The responsibility for promulgating and enforcing occupational safety and health standards rests with the Department of Labor; the Department of Health, Education and Welfare is responsible for conducting research on which new standards can be based and for implementing education and training programs for producing an adequate supply of manpower to carry out the purposes of the Act.

The latter's responsibilities are carried out by the National Institute for Occupational Safety and Health. Among the functions which may be carried out by the Institute is the one which calls for prescribing of regulations requiring employers to measure, record and make reports on the exposure of employees to potentially toxic substances or harmful physical agents which might endanger their safety and health. Employers required to do so may receive full financial or other assistance for the purpose of defraying any additional expense to be incurred. Also authorized are programs for medical examinations and tests as may be necessary to determine, for the purposes of research, the incidence of occupational illness and the susceptibility of employees to such illnesses. These examinations may also be at government expense. Another HEW function is annual publication of a list of all known toxic substances and the concentration at which toxicity is known to occur. There will also be published industrywide studies on chronic or low-level exposure to a broad variety of industrial materials, processes and stresses on the potential for illness, disease or loss of functional capacity in aging adults; also authorized at the written request of any employer or authorized representatives of employees, is determination by HEW as to whether any substance normally found in the place of employment has potentially toxic effects. Such determinations shall be submitted to both the employer and the affected employee as soon as possible. Information obtained by the Department of Health, Education and Welfare and the Department of Labor under the research provisions of the Act is to be disseminated to employers, employees and organizations thereof.

Space does not permit a detailed discussion of each of these pieces of legislation, but they are required reading for any student interested in industrial hygiene.

SCOPE & FUNCTION OF INDUSTRIAL HYGIENE

Definition of the Profession

Industrial hygiene is both a science and an art. It encompasses the total realm of control, including recognition and evaluation of those factors of environment emanating from the place of work which may cause illness, lack of well being or discomfort either among workers or among the community as a whole.

Definition of the Professional

The industrial hygienist is a competent, qualified individual educated in engineering, chemistry, physics, medicine or a related biological science. His abilities may encompass three major areas: (1) recognition of the interrelation of environment and industry; (2) evaluation of the impair-

ment of health and well-being by work and the work operations; and (3) the formulation of recommendations for alleviation of such problems.

Scope

The scope of industrial hygiene is threefold. It begins with the recognition of health problems created within the industrial atmosphere. Some of the more frequently encountered causes of these problems are: chemical causes (liquid, dust, fume, mist, vapor or gas); physical energy (electromagnetic and ionizing radiations); noise, vibration and exceedingly great temperature and pressure extremes; biological (in the form of insects, mites, molds, yeasts, fungi, bacteria and viruses) and ergonomic (monotony, repetitive motion, anxiety and fatigue, etc.). These stresses must all be evaluated in terms of their danger to life and health as well as their influence on the natural bodily functions.

The second heading encompassed within the scope of industrial hygiene is that of *evaluation*. The "work atmosphere" must be evaluated in terms of long-range as well as short-range effects on health. This can be accomplished by a compilation of knowledge, experience and quantitative data.

Finally, industrial hygiene includes the *development of corrective measures* in order to eliminate existing problems. Many times these control procedures will include: a reduction of the number of persons exposed to a problem; the replacement of harmful or toxic materials with less dangerous ones; changing of work processes to eliminate or minimize worker exposure; adoption of new ventilation procedures; increasing distance and time between exposures to radiation; introduction of water in order to reduce dust emissions in such fields as mining; "good housekeeping," including clean toilet facilities and adequate methods of disposing of wastes; and the provision of proper protective working attire.

Function

A unique field, industrial hygiene employs the chemist, physicist, engineer, mathematician and physician in order to adequately fulfill the responsibilities inherent in the profession, which include:

1. Examination of the industrial environment;
2. Interpretation of the gathered data from studies made in the industrial environment;
3. Preparation of control measures and proper implementation of these control measures;
4. Creation of regulatory standards for work conditions;
5. Presentation of competent, meaningful testimony, when called upon to do so by boards, commissions, agencies, courts or investigative bodies;
6. Preparation of adequate warnings and precautions where dangers exist;
7. Education of the working community in the field of industrial hygiene; and
8. Conduct of epidemiologic studies to uncover the presence of occupation-related illness.

WHERE ARE THE NEEDS?

There are approximately 4,000 industrial hygienists in the United States. These dedicated scientists often undergo periods of deep frustration as they attempt to coordinate facts and arrive at workable solutions. The realization that time is of the essence in dealing with potential health hazards makes the industrial hygienist keenly aware of his great responsibilities. An alert response by an astute industrial hygienist could save the lives and health of many workers. A true statesman, the good industrial hygienist learns to temper his findings and conclusions with patience; for he knows that oftentimes employers will not be receptive to the tremendous cash outlays necessary to implement a good industrial hygiene program.

Currently, industrial hygienists are employed by industry, federal, state and local governments, universities, insurance companies and unions. Many large industries have staffs of ten or more people. Other industries, depending upon their organization, will have only one industrial hygienist at the corporate office and trained technicians in each of the company's plants. Small industries (less than 5000 employees) unless they have highly specialized problems, have not found the need to employ a full-time industrial hygienist. These companies either use the services available to them from government agencies or retain industrial hygiene consultants.

A number of excellent universities offer a Master's degree in industrial hygiene. Harvard, the first university to confer this degree, started their program in 1918. Since they pioneered such a program 55 years ago, there are at least eight more universities offering graduate programs in industrial hygiene leading to a Master's or Doctorate degree. Their names, as well as information on grants and scholarships can be obtained from the National Institute of Occupational Safety and Health, Rockville, Maryland. With the advent of new federal laws protecting the health of the worker, the need for professional industrial hygienists and technicians will increase dramatically in the 1970's. Those companies which currently do not have need for an industrial hygienist will hire at least one as a result of the recently enacted legislation. Companies which had a small staff will find it to their advantage to increase their capabilities and provide more comprehensive service than they did in the past.

There are only two or three cities in the United States which currently have comprehensive industrial hygiene programs. Other cities will find that protecting the health of the worker is a solid investment and consequently will develop programs. There are not more than ten states in the United States providing comprehensive industrial hygiene programs. Just as with industries, the states will need a large number of industrial hygienists in the 1970's to fulfill the requirements of the Occupational Safety and Health Act. Additional funding by the federal government will spur the development of such programs. Unions have begun to realize the benefits of employing a full-time

professional industrial hygienist on their staffs. Presently at least three industrial hygienists are employed by unions. This trend will continue with increased awareness of the union officials of the benefits accruing to the workers through sound industrial hygiene programs.

CONTENTS AND OBJECTIVES OF THE SYLLABUS

The chapters which follow are written by persons of outstanding reputation in the particular field covered by his (her) chapter. A group of distinguished professionals has been selected from various types of industries, from universities, consulting groups and government, from the east to the west coast, all having the desire of providing a manuscript sufficiently comprehensive that it will encompass the entire environmental field, including subjects not commonly considered part of industrial hygiene; i.e., water pollution, safety and solid waste.

Our objectives have been:

1. To compile into one source the diversity of expertise needed to attain competency in the recognition, evaluation and prescription of methods of control of environmental problems.

2. For the use of persons having a basic science degree who are entering the field of industrial hygiene and environmental control, provide a manual which will furnish them with the broad scope of knowledge required for an intelligent approach to the diversity of problems encountered in this field.
3. To make available a tool which may be used as a text in training courses or in universities to introduce graduate students to the field of industrial hygiene and environmental health.
4. To introduce persons having a specialty in one of the facets of industrial hygiene or environmental health to all *other* facets of this profession.

It is our aim to reach the beginners in the profession, whether in government, industry, research or universities; the graduate students entering the profession from cognate fields and persons having a specialty who need a "refresher" in the related fields.

The world in which we live is so complex, we believe that any individual truly interested in one facet of the environment should be, at the least, somewhat knowledgeable in the various categories of environmental control methods.

CHAPTER 2

THE SIGNIFICANCE OF THE OCCUPATIONAL ENVIRONMENT AS A PART OF THE TOTAL ECOLOGICAL SYSTEM

Don D. Irish, Ph.D.

OCCUPATIONAL AREA IS PART OF THE WHOLE

The occupational ecological system is a significant part of the total ecological system. Since it can be measured, we can exert some control over it and make contributions to the health and well-being of the people in the occupational ecological system. These contributions can favorably affect the impact of the total system on our population since a worker may spend one-fourth of his time in the occupational area, and workers are a significant part of the total population.

The purpose of this chapter is to examine the relation of the occupational environment to the total ecological system, to observe the significance of this relationship to the work of the industrial hygienist, and to recognize the favorable effect that his work in the occupational environment could have on the total system.

Nonoccupational exposure is an exceedingly complex and variable factor. Recognition of such exposure is necessary to an understanding of the overall environmental impact on man. The man who drove to work in heavy traffic or walked down a busy street received much greater exposure to carbon monoxide from automobile exhaust than he would have in an acceptable work area. Similarly, a worker who smokes one pack or more of cigarettes per day will be exposed to many times the amount of carbon monoxide that he would be exposed to in an acceptable work environment. This smoker would also be exposed to many times the amount of particulate matter from his smoking than he would contact in an acceptable work area.

There are many other nonoccupational exposures but these examples serve to illustrate two obvious areas of excessive exposure in the non-occupational area. Such exposures cannot be ignored by those responsible for the health and well-being of people even if their responsibility is primarily in the occupational area.

OCCUPATIONAL INTERACTION WITH NONOCCUPATIONAL

In considering the occupational area one must recognize the interaction with the nonoccupational area and the significance of this interaction to the health and well-being of the individual.

We learned a long time ago that a man who drinks a lot of alcoholic beverages is much more susceptible to injury from exposure to carbon tetrachloride; also, that a man with excessive exposure to silica dust is more susceptible to

tuberculosis. Such possible interactions should be kept in mind.

The following illustration demonstrates a different kind of interaction. We were studying the blood bromide concentration of men exposed to low concentrations of methyl bromide in their work. The environmental exposure in their operating area was carefully measured. The exposure was well within acceptable limits. Clinical studies verified this fact. It was valuable to establish a relationship between exposure and blood bromide at exposures within acceptable limits, as this would be useful in the future as a clinical check on the workmen.

One day a workman from this group was found to have a blood bromide concentration sufficiently high to be of concern if it had come from exposure to methyl bromide. Investigation revealed that he had been taking inorganic bromide medication which accounted for the high blood bromide.

Workmen may be brought to the clinic for regular preventive checkups. Biochemical measurements on these workmen may be exceedingly valuable to verify acceptable exposure, also to catch any indication of fluctuations in operating conditions and allow correction before significant exposure can occur. This is a very useful system, but we must be sure we have all the facts before we conclude what caused any observable biochemical changes.

THE INDIVIDUAL AS PART OF THE ECOLOGICAL SYSTEM

Ecology is defined in Webster's dictionary (1971) as "The science of the totality or pattern of relations between organisms and their environment." I prefer to call ecology the science of the interaction of *everything* with *everything else*. The ecological system is the system within which these interactions take place.

The ecological system is not exactly synonymous with the environment. My environment includes everything around me. The ecological system *includes* me. The individual person is a highly significant factor in the control of the environment in the interest of the health and well-being of the person.

A freight elevator was installed with all the usual safety devices. It was approved by state inspectors. A switch on the door made it necessary to close the door before the hand switch would operate the elevator. A tall lanky lad found that he could get his toe to operate the switch closed by the elevator door, and with contortion he could

still reach the operating switch. It would have been easier to close the front door, but it was a challenge. He was that rarity, a man with the reach to do it. No one knows how many times he operated the elevator this way, but one day he left his other foot over the edge of the elevator and seriously injured that foot when the elevator passed the next floor. Yes, fools can be very ingenious in overcoming "foolproof" engineering.

Misoperational problems are not limited to mechanical injury. There was the individual who liked a window wide open. Under certain wind conditions the air from the window blew across the face of a hood so as to allow volatile chemicals to escape from the face of the hood into the work area around the hood.

There was also the man who liked to "sniff" perchloroethylene. He arranged his work so that he could be "high" on perchloroethylene a large part of his work day.

The individual is a significant part of the occupational ecological system. His understanding and cooperation are essential to attaining a healthful work environment. We hope this understanding will carry over to some degree to the non-occupational ecological system.

PEOPLE IN THE ENVIRONMENT

An important factor in the environment of an individual is "people." People in both the occupational and the nonoccupational environments are of significance to the health and well-being of that individual.

One day the psychologist in our personnel department asked me if we were having any complaints of noise from a certain operation. I told him we were, but we could find no justification for the complaints based on noise measurements made in the area. He commented, "You won't; the workers just don't like the foreman."

In another instance we found it desirable to coordinate a careful study of the environment with a concurrent clinical study of the workmen in the area. One group of older, experienced workmen refused to cooperate. They liked the foreman and their work and were afraid we might make some changes. With friendly understanding, the purpose was explained and they were reassured. You are always dealing with people in the occupational environment.

Another illustration introduces a different problem. Joe came into the clinic with a mashed thumb. The physician tried to get an understanding of the reason for the accident. He asked, "What happened, Joe?" "Oh, I got my thumb in between a couple of drums." "You have a good record, Joe, why did this occur?" "I was thinkin'." "What were you thinking about, Joe?" "Oh, I was thinkin' about my wife's sister." Knowing that health or financial problems in the family may worry people, the physician asked, "What's wrong with your wife's sister?" Joe answered with ecstatic fervor, "Doc, there just *ain't nothin' wrong* with my wife's sister."

We should recognize that people in the *non-occupational* environment may have an effect which may result in misoperation. Such misopera-

tion can lead to exposure to chemical substances, physical energies, or mechanical injury. This can occur either on or off the job.

The problem of people in the environment is not measured by any analytical instrument, though the instrument may measure a misoperation caused by people. The problem of people is not controlled by preventive engineering alone, though it can help. Effective operation requires a good understanding of people and the ability to get their understanding and cooperation. This is an obligation of the industrial hygienist, the physician and other persons responsible for control of the environment in the interest of the health and well-being of the workmen.

CHEMICALS, ENERGIES AND ORGANISMS

The usual considerations in the occupational environment are more measurable than people. Chemical substances are a concern of the industrial hygienist. Physical energies include: ionizing radiation, a concern of the health physicist; heat, light and noise, a concern of the industrial hygienist; and mechanical injury, a concern of the safety engineer. Then there are biological organisms (other than man) which are a concern of the sanitary engineer.

These are part of the environment both on and off the job. These can be controlled in the occupational environment by good engineering and good operating procedures attained with the understanding and cooperation of the employees. Yes, people are also very important here.

We observed that men from a specific operation were reporting to the clinic with mild complaints which seemed similar to complaints that would be expected from an over-exposure to a solvent used in the operation. Careful analysis by the industrial hygienist, in many locations and at many different times, did not show enough solvent in the air to cause the trouble. A continuous recording analytical instrument was devised in the research laboratory and installed in the operating area. Through its use we found that when either the supervisor or the industrial hygienist was not around, the operator was inclined to leave a leak or spill to be cleaned up by the next shift operator. The men named this instrument the "Squealer" as it was telling us of their misoperation. They began to work with an eye on the recorder. They realized that when the "Squealer" did not squeal they felt better. They changed the name of the instrument to the "Stink clock." The supervisor told us he saved the price of the instrument by reduced solvent loss, and that the overall operation by the men greatly improved. We had their understanding and their cooperation. They realized that we were interested in their health and well-being.

During regular preventive observation of the men in the clinic, lack of adverse effects may show that exposures to chemical substances in the environment have not been excessive. It should not be taken to mean that excessive exposures are impossible or unlikely under other circumstances of use.

For example, a supplier assured his customer that there was no hazard from skin contact asso-

ciated with a particular material because there had been frequent skin contacts with the material in their own operations with no adverse effects. They neglected to indicate how they handled the material, or that contacts were always followed by immediate decontamination of the skin. In use by the customer, the material was spilled on a man's skin. He was several miles out in the "bush" in northern Canada in the winter with the temperature below zero Fahrenheit, and with no water available for decontamination. The man died from poisoning due to skin absorption of the material. Simple experiments on animals in the toxicological laboratory showed that the material was very toxic when absorbed through the skin. When a supplier indicates that no problems have been encountered in handling a particular material, ask how they handle it. Ask them what toxicological information they have on the material.

In controlling the occupational environment in the interest of health and well-being, established acceptable exposure limits for a healthful environment are very useful. These acceptable exposures are expressed as "acceptable concentrations" by the American National Standards Institute and as "threshold limit values" by the American Conference of Governmental Hygienists (such standards are discussed in detail in Chapter 8). These limits are not exacting scientific thresholds of response. They are the judgments of people with knowledge and experience. The intelligent use of these limits depends on the understanding and judgment of the man who must control the occupational environment.

We must recognize that the industrial hygienist usually deals with a variable exposure. Enough analyses are needed to clearly define the probable fluctuations and to establish a significant time weighted average. Maximum concentrations must be determined as well as duration and frequency of peaks of exposure. The summation of this information to define the exposure situation requires the good judgment of a knowledgeable industrial hygienist. The application of the established acceptable limits for a healthful environment also requires the good judgment of a knowledgeable industrial hygienist. Acceptable limits cannot be used effectively as just a routine check point.

Those people responsible for suggesting acceptable limits or for using acceptable limits are part of the ecological system — the industrial hygienist, the physician, the toxicologist and all the other environmental control people. The effectiveness of their operation can have a very significant effect on the occupational ecological system.

When an injury does occur, clinical observation of the victim can provide very valuable information and should be reported in the literature. As was discussed in the previous section, the exposure can be variable. Most important, be sure you know all of the chemical substances or physical energies to which the victim was exposed and, hopefully, quantitation of exposure.

During the early development of 2,4 dichlorophenoxy acetic acid (2,4 D), careful toxicological studies were made on animals in the toxicological laboratory. It was concluded that the material at

the high dilution used in the field as a weedkiller was not a significant hazard. After years of use there was a report of a death in Canada from 2,4 D. The man drank a glass full of the diluted solution from the spray tank with suicidal intent. The physician who observed the man in the clinic and the manager of the contract spray company where the solution had been mixed, both confirmed that it was, in fact, 2,4 D. Calculating from the toxicological information, I did not think this was possible. An agricultural scientist was going to visit the area where this death occurred so I asked him to investigate. He asked the foreman of the spray crew, "What did you use as a weed-killer before you used 2,4 D?" "Oh, we used sodium arsenite." "Then you stopped using sodium arsenite?" "No, we just added 2,4 D to the sodium arsenite."

The man who died had drunk enough sodium arsenite to have killed ten people. When you draw a conclusion from that first clinical case, be sure you know all of the materials to which the victim was exposed. This serves as a reminder that people are involved, people between you and the actual circumstances of the incident.

As previously stated valuable information on the nature and amount of exposure can be obtained by biochemical measurements on a person suspected of exposure. This depends on the absorption, transport, metabolism and excretion of the material. Blood, urine or exhaled air analysis can give valuable clues to the nature of certain of the materials to which the person was exposed. The analysis used depends on the way the body handles the material in question. Many volatile organic materials are exhaled in the breath. Infrared analysis can give an indication of the nature of the material and some indication of the amount of exposure.

To illustrate, a man came into the clinic and reported that he had been exposed to a certain volatile solvent. Infrared analysis of his exhaled air showed that he had not been exposed to the solvent he indicated but to a very different solvent. Had the clinic proceeded on the basis of his report of exposure, the handling of the case would have been in error. Some biochemical measurements can be very useful when wisely used.

COMPLEXITY OF THE WHOLE

The ecological picture as a whole is too complex to understand or to control when considered in its entirety (both occupational and nonoccupational). Yet, those who are responsible for the health and well-being of people in the system must keep the total picture in mind.

That total picture includes the chemical substances, physical energies and biological organisms in the occupational area which we can measure and over which we can have some control. As previously discussed, the exposures can be variable. Levels of concentration alone are not enough. One must know the frequency and duration of exposures. There is no simple mathematical procedure which will give a specific numerical answer. One can determine the time weighted average and the maximum concentration, duration and fre-

quency of peak concentrations. These are meaningful if one has sufficient analytical data which represent the actual exposure conditions. These exposure conditions can then be related to the acceptable limits proposed by various organizations. This comparison gives some understanding of the significance of possible exposures in the area studied. In addition, however, one must keep in mind the complexity of the whole. The final decision requires judgment of the whole based on available knowledge and experience.

Comparable factors are in the nonoccupational area where we have little control. Hopefully, we may have some effect by carry-over of experience from the occupational area. In both the occupational and nonoccupational area the individual is an important factor. The people in the environment of the individual both on and off the job have a significant effect.

OBTAINING UNDERSTANDING AND COOPERATION

Obtaining the understanding and cooperation of people in the environment of concern is critical to effective control of that environment. This statement has been made several times in this chapter. It was a significant factor in many of the illustrations used. This is such an important part of effective control that it justifies summation here for emphasis. Without understanding and cooperation all the most careful measurements and careful engineering of an operation may be ineffective. We repeat — fools are most ingenious in overcoming “foolproof” engineering.

It is simple to state “Get their understanding and cooperation.” *Getting* it is not always that simple. How does one get it? The method will vary with the industrial hygienist and with the people in the operation of concern. The following methods are suggested as having been successful under many circumstances. What you will do depends on your judgment of the particular circumstances with which you are concerned at a particular time and the people with whom you are concerned.

Previous mention was made of the value of a careful environmental survey and concurrent clinical study of the men involved as a preventive control. Before such a study is made, it is valuable to get all the men in the operation together. A regular safety meeting can be used; it should include all the people — supervisors as well as laborers. Explain what is intended and why. Invite questions from the group. Answers and explanations should be in simple, direct language which they can understand.

During the survey of the environment, the workers' interest and understanding may be helpful. You can obtain a lot of information on the operation from the individual workmen. When the survey is complete, it should be reported to the whole group. Tell them basically what was found, in language they can understand. Indicate what should be done, if anything, to assure a good work

environment. When they understand that you have a sincere interest in the workers' health and well-being, it increases their cooperation in effectively controlling the operation.

When you are checking the environment of an operation, talk with the individual workmen. Ask them for information and suggestions. Including them in control efforts will result in more effective cooperation. Take every opportunity to inform all the people who may be concerned with your area of operation. Discussion at safety meetings is useful in getting information to a group. Also look for a chance for discussion with individuals, — all individuals — executives, supervisors, engineers, operators, janitors.

You should also be concerned with the design of a new production unit. Your cooperation with the engineers in design and construction can aid in giving consideration to control of the environment. Inclusion of good environmental control principles in the design and in the construction of a new production unit is essential. It can save a lot of reconstruction later. It also can make the control of the environment in the interest of health and well-being a much more effective operation.

When talking with groups at a safety meeting or with individual workmen, take every opportunity to discuss also the application of their understanding of healthful working conditions to their off-the-job activities. Through the understanding and cooperation of the employees, we may also have a significantly favorable effect on the nonoccupational ecological system as well as the occupational; hopefully, some of the “understanding” will be carried over by the workmen to their off-the-job activities.

PRACTICAL CONTROL

Yes, the total picture is complex, yet there are a lot of practical things that can be done. We can measure the chemical substances, physical energies and biological organisms in the occupational environment. We can control them through good engineering and good operation. We can and must obtain the understanding and cooperation of the employee in order that our environmental control may be effective. We can compare our findings with the acceptable limits suggested by various groups. With an understanding of the basis of these limits and the significance of our findings, we can judge the effectiveness of our control. We must recognize the possible impact of both occupational and nonoccupational factors.

The most effective use of our present knowledge should be made. We need to make an effort to increase that knowledge through toxicological, environmental and clinical research. We should recognize the complexity of the whole ecological system. This complexity should not discourage us from the effective application of the good practical knowledge which is available. With the practical application of all the factors discussed and the understanding and cooperation of the workers, our efforts can have a very favorable effect on health and well-being.

CHAPTER 3
REVIEW OF MATHEMATICS

Janet L. Patteeuw

INTRODUCTION

The mathematics required in the practice of industrial hygiene is that usually included in mathematics courses which precede the calculus and includes an introduction to statistics. It assumes, as a minimum, a previous acquaintance with elementary algebra and plane geometry at the high school level.

COMPUTATION

Laws of Exponents

Exponents provide a shorthand method of writing the product of several like factors. If b is any number and n is a positive integer, the product of n of the quantities b is denoted by b^n . Symbolically,

$$b \cdot b \cdots b = b^n,$$

where n is the exponent, b is the base, and b^n is read "b to the nth power." This definition can be extended to include exponents other than positive integers. If n and m are positive integers, the following properties hold:

$$b^0 = 1 \quad \text{if } b \neq 0$$

$$b^{-n} = \frac{1}{b^n}$$

$$b^{n \cdot m} = \sqrt[m]{b^n} = \left(\sqrt[n]{b}\right)^m.$$

The theorems on exponents follow easily from the preceding definitions:

(1) $b^m \cdot b^n = b^{m+n}$

(2) $\frac{b^m}{b^n} = b^{m-n}$

(3) $(b^m)^n = b^{m \cdot n}$

(4) $(ab)^n = a^n \cdot b^n$

(5) $\left(\frac{a}{b}\right)^n = \frac{a^n}{b^n}$

Scientific Notation

Very large and very small numbers can be expressed and calculated efficiently by means of scientific notation, a method which depends primarily on the use of exponents.

A number is said to be expressed in scientific notation when it is written as the product of an integral power of 10 and a rational number between 1 and 10. For example,
 $253 = 2.53 \times 10^2$

$$0.0253 = 2.53 \times \frac{1}{100} = 2.53 \times \frac{1}{10^2} = 2.53 \times 10^{-2}.$$

The procedure illustrated by these examples may be stated as follows:

- (1) Place the decimal point to the right of the

first non-zero digit, thus obtaining a number between 1 and 10.

(2) Multiply this number by a power of 10 whose exponent is equal to the number of places the decimal point was moved. The exponent is positive if the decimal point was moved to the left and negative if it was moved to the right.

By use of the laws of exponents and scientific notation, computations involving very large or very small numbers are simplified. For example,
 $\frac{378,000,000,000 \times 0.000004}{2000}$

$$\begin{aligned} &= \frac{3.78 \times 10^{11} \times 4 \times 10^{-6}}{2 \times 10^3} \\ &= \frac{3.78 \times 4 \times 10^{11-6}}{2 \times 10^3} \\ &= 3.78 \times 2 \times 10^{11-6-3} \\ &= 7.56 \times 10^2 \\ &= 756. \end{aligned}$$

Significant Digits

Measurements, in contrast to discrete counts, often result in what are called approximate numbers. For example, the dimensions of a table are reported as 29.6" by 50.2". This implies that the measurement is accurate to the nearest tenth of an inch and that the table is less than 50.25" and more than 50.15" in length. Similarly, using symbolic notation,

$$29.55'' < \text{width} < 29.65''.$$

Thus the area of the table is not $29.6 \times 50.2 = 1485.92$ square inches. Instead the exact area is between $29.55 \times 50.15 = 1481.9325$ square inches and $29.65 \times 50.25 = 1489.9125$ square inches; it is clearly nonsense to report the area as 1485.92 with six non-zero digits when even the fourth digit is in doubt. It thus becomes important to indicate the digits which are "significant."

In making measurements the number of significant digits that can be recorded is determined by the precision of the instruments used. It is possible to indicate the accuracy of a measurement by actually giving the tolerance or possible error. For example, the length of the table could have been recorded as 50.21 ± 0.02 inches, indicating that the actual length lies between 50.19 and 50.23 inches.

Another method of indicating accuracy is to express all measurements in scientific notation. The digits in the rational number are then called significant digits. For example, 124.6 can be written as 1.246×10^2 where 1, 2, 4 and 6 are the significant digits. This method clarifies measurements such as 24,000 by indicating whether they

are accurate to the nearest thousand, hundred or ten units.

Summarizing the preceding, the significant digits in a number are:

- (1) Non-zero digits
- (2) All zeros which are not used to place the decimal, i.e., zeros only if they are:
 - (a) between non-zero digits
 - (b) at the right of non-zero digits and are, in some way, indicated as significant
 - (c) at the right of non-zero digits which occur after a decimal point.

For example,

<i>Number</i>	<i>Significant Digits</i>
24,000 = 2.4×10^4	2, 4
24,000 = 2.400×10^4	2, 4, 0, 0
1087 = 1.087×10^3	1, 0, 8, 7
0.0015 = 1.5×10^{-3}	1, 5
0.0003 = 3×10^{-4}	3

Computational Accuracy

In any computation involving sums and differences, the number with the least number of digits following the decimal point determines the number of decimal places to be used in the answer. For example,

$$\begin{array}{r} 2883 \\ 43.46 \\ 0.1376 \\ \hline 2926.5976 \end{array} \text{ should be } 2927.$$

Since 2883 has no digits following the decimal place the answer must be expressed as 2927.

With products or quotients the accuracy of the result depends on the number of significant digits in the component measurements. Thus the number of significant digits to be retained in the result is the least number of significant digits in any of the factors. For example,

$$8.216 \times 3.71 = 30.48136 \text{ should be } 30.5.$$

Since 3.71 has only three significant digits, only three should be retained in the result.

Note that in the use of a formula involving absolute constants, these constants may be assumed to have as many significant digits as desired; in other words, they may be ignored in any determination of the number of significant digits to be retained in the result of the computation.

Table 3-1

N	0	1	2	3	4	5	6	7	8	9
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396

Note that the decimal points are omitted in such a table. Hence

$$\log 5.34 = 0.7275.$$

In order to find common logarithms of numbers larger than 10 or less than 1, the method of scientific notation is used. The logarithm of such a number can be written as the sum of an integer,

Rounding

In performing computations, it is recommended that rounding be accomplished after the calculation has been performed in order to incur the least possible error. The rules of rounding state that in rounding off a digit:

- (1) Add 1 if the succeeding digit is more than 5
- (2) Leave it unchanged if the succeeding digit is less than 5
- (3) If the succeeding digit is exactly 5 round off the number so that the final digit is even.

In each of the following examples the number is rounded to three digits:

- (1) 45273 is rounded to 45300
- (2) 45243 is rounded to 45200
- (3) 45250 is rounded to 45200
- (4) 45350 is rounded to 45400
- (5) 45250.03 is rounded to 45300.

Logarithms

Lengthy computations can often be greatly simplified by the use of logarithms. The formal definition states that if b is any positive number different from 1, and $b^y = x$, then the exponent y is called the logarithm of x to the base b . In symbols, $y = \log_b x$. For example, $\log_3 9 = 2$ since $3^2 = 9$.

It is important to note that a logarithm is an exponent. Since this is true the same properties that hold for exponents also hold for logarithms. They can be restated in the following manner:

- (1) $\log_b (x \cdot y) = \log_b x + \log_b y$
- (2) $\log_b \left(\frac{x}{y}\right) = \log_b x - \log_b y$
- (3) $\log_b (x^n) = n \log_b x$.

Common Logarithms. Logarithms which use 10 as a base are called common or Briggsian logarithms. Usually these are written simply as $\log x$, without any base indicated, meaning $\log_{10} x$.

In order to find the common logarithm of a number note first that $\log 1 = 0$ and $\log 10 = 1$ since $10^0 = 1$ and $10^1 = 10$. Thus the logarithm of any number between 1 and 10 will be a value between 0 and 1. The values have been calculated and are available in tabular form. A portion of such a table is shown below.

called the characteristic, and a positive decimal fraction between 0 and 1, called the mantissa. For example,

$$534 = 5.34 \times 10^2 = 10^{0.7275} \times 10^2 = 10^{2.7275}.$$

$$\text{Thus } \log 534 = 2.7275.$$

More simply, in finding the logarithm of a number written in scientific notation, the characteristic is

the exponent of the power of 10 and the mantissa is the entry in the table corresponding to the first part. For example,

$$\log 52 = 1.7160.$$

This same rule applies to numbers less than 1, although the result can be written in many different ways. For example,

$$\begin{aligned} 0.00534 &= 5.34 \times 10^{-3} \\ \log 0.00534 &= -3 + 0.7275 \\ &= 10 - 3 + 0.7275 - 10 \\ &= 7.7275 - 10 \\ &= 3.7275 \\ &= -2.2725. \end{aligned}$$

The final form, -2.2725 , is the most inconvenient since it does not contain a characteristic and mantissa.

When the logarithm of a number is known, it is a simple process of using the tables and working backwards in order to find the original value, called the antilogarithm.

Natural Logarithms. The natural or Napierian system of logarithms employs as its base the irrational number e whose decimal expansion is $2.71828 \dots$. Natural logarithms are usually denoted by $\ln x$ or $\log_e x$.

Tables also exist for the natural logarithms of numbers between 1 and 10. To obtain the natural logarithms of other numbers the number must again be written in scientific notation. Then the properties of logarithms are applied. For example,

$$\begin{aligned} 642 &= 6.42 \times 10^2 \\ \ln 642 &= \ln 6.42 + 2 \ln 10 \\ &= 1.85942 + 2(2.30259) \\ &= 6.46460. \end{aligned}$$

Note that the number to the left of the decimal point in a natural logarithm does not indicate the location of the decimal point in the antilogarithm.

Logarithmic Conversions. In order to change logarithms with a base b into logarithms with any other base a it is only necessary to multiply by the constant factor $\log_a b$. That is, $\log_a x = \log_b x \cdot \log_a b$.

Specifically, for conversions between natural and common logarithms,

$$\begin{aligned} \log x &= 0.4343 \cdot \ln x \\ \ln x &= 2.3026 \cdot \log x. \end{aligned}$$

Computation with Logarithms. Simplification in computation is obtained by the use of the three basic properties of logarithms stated above. Consider, for example, the heat stress equation

$$E_{\max} = (10.3)(V)^{0.4}(42 - VP_a).$$

This computation can be greatly simplified by writing it in the form

$$\log E_{\max} = \log 10.3 + 0.4 \log V + \log (42 - VP_a).$$

GRAPHING

A graph is a pictorial representation of the relationship between two or more quantities. By this means a union is formed between the two elementary streams of mathematical knowledge — algebra and geometry.

Cartesian (Rectangular) Coordinate System

The most common two-dimensional graph makes use of linear scales for each of the quantities

being considered. Two perpendicular lines and a unit of length are chosen. Customarily the horizontal line is called the x -axis and the vertical line the y -axis. By this means a one-to-one correspondence can be established between the points in a plane and all ordered pairs of real numbers. This is demonstrated in Figure 3-1.

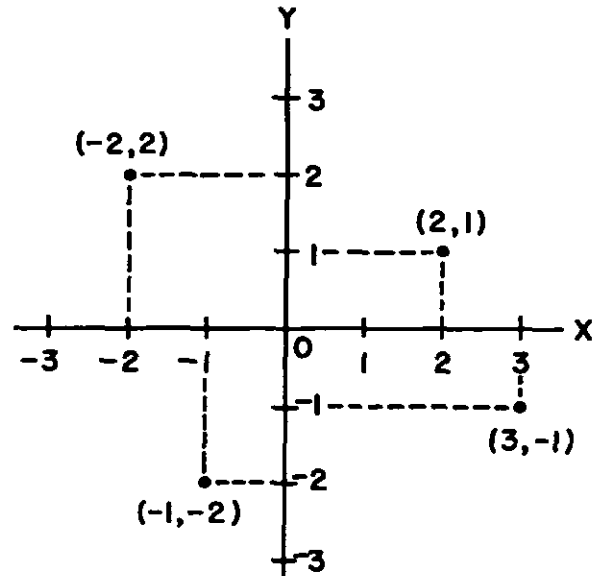


Figure 3-1

Linear Functions

An equation in which none of the variables is raised to a power is called a linear or first-degree equation. The graph of such a function is always a straight line. A linear equation often appears in what is known as slope-intercept form: $y = mx + b$, where x is the independent variable; y is the dependent variable; b is the y -intercept, the value for y when $x = 0$; and m is the slope, the change in y divided by the change in x .

As an example consider the graph of the equation $y = -\frac{3}{2}x + 2$ shown in Figure 3-2.

Since the y -intercept is 2, the line passes through the point $(0, 2)$. Since the slope is $-3/2$, the line falls three units vertically for every two units that it runs horizontally.

Second and Higher Degree Equations

There are many forms of second and higher degree equations, but few will be encountered in industrial hygiene. One exception may be the parabola which has the general form $y = Ax^2 + Bx + C$. As an example, consider the equation $y = 4x - \frac{x^2}{2}$. The simplest method of graphing

such a function is to form a table of values that satisfy the equation.

Table 3-2

y	-1	0	1	2	3	4	5	6	7	8
x	-4.5	0	3.5	6	7.5	8	7.5	6	3.5	0

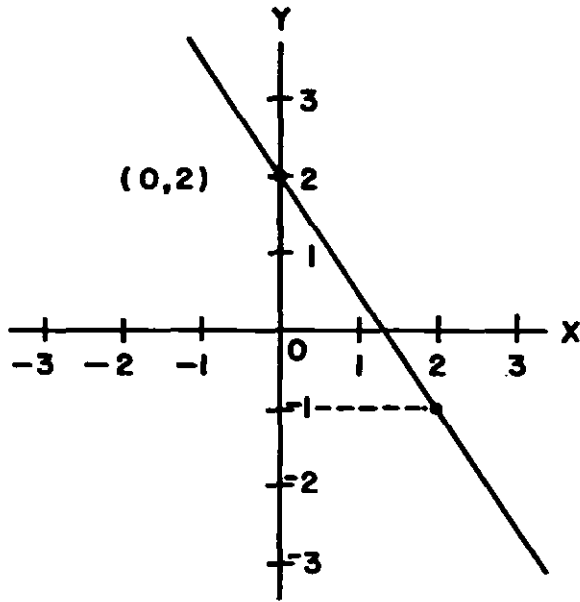


Figure 3-2

The graph of this function is illustrated in Figure 3-3.

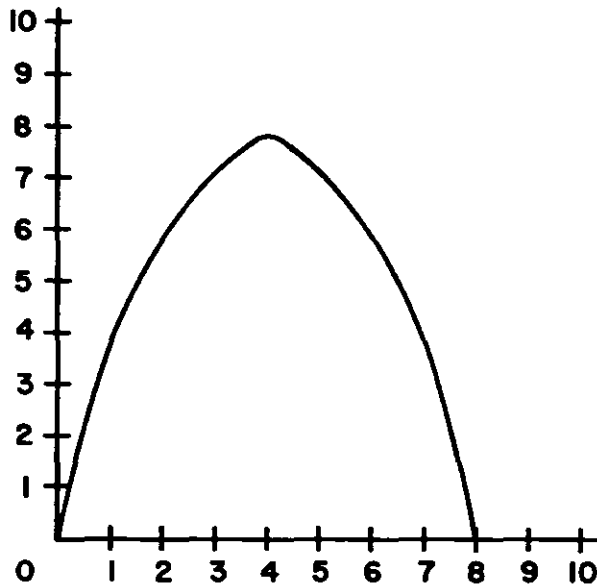


Figure 3-3

Exponential Functions

An exponential function is any function in which a constant is raised to a variable power and has the general form $y = a(c^{bx})$. A number of ventilation, dilution and noise level equations are of this type. Should such a function be graphed on rectangular coordinate paper when, for example, $c > 1$ and b is positive, the result is a curve of the type shown in Figure 3-4.

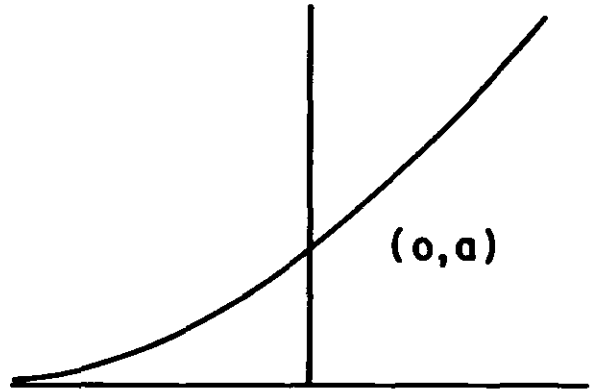


Figure 3-4

If the logarithm of both sides of the equation $y = a(c^{bx})$ is taken the result is $\log y = \log a + bx \cdot \log c$. If x and $\log y$ are taken as the variables, this equation has the slope-intercept form of the equation of a straight line, $y = mx + b$. This equation may then be plotted as a straight line on semi-logarithmic paper, which has a linear scale on the horizontal axis and a logarithmic scale on the vertical one. As shown in Figure 3-5, the y-intercept becomes $\log a$ while the slope is $b \log c$.

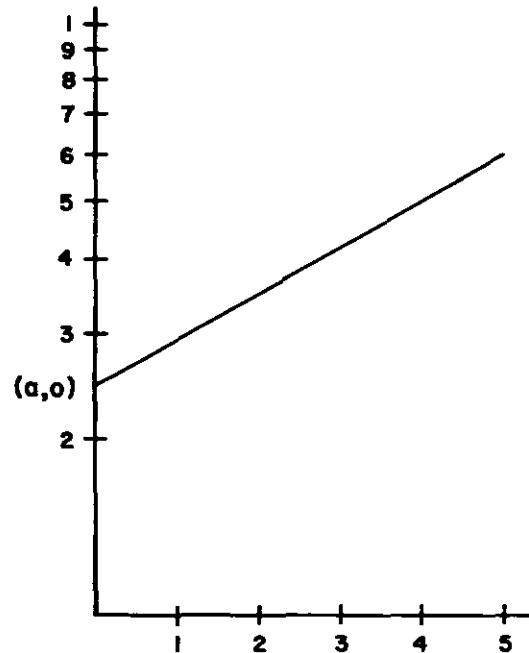


Figure 3-5

Power Functions

A power function has the general form $y = ax^b$. Graphing such a function on rectangular coordinate paper often requires the finding of a

great number of points. However, if the logarithm of both sides of the equation is taken the result is $\log y = \log a + b \log x$. If $\log x$ and $\log y$ are the independent and dependent variables respectively, the form of this equation is again the slope-intercept form of a straight line, $y = mx + b$. This equation may then be plotted on logarithmic paper, which has a logarithmic scale on both axes. The plot will be a straight line with slope b and y -intercept $\log a$ as shown in Figure 3-6.

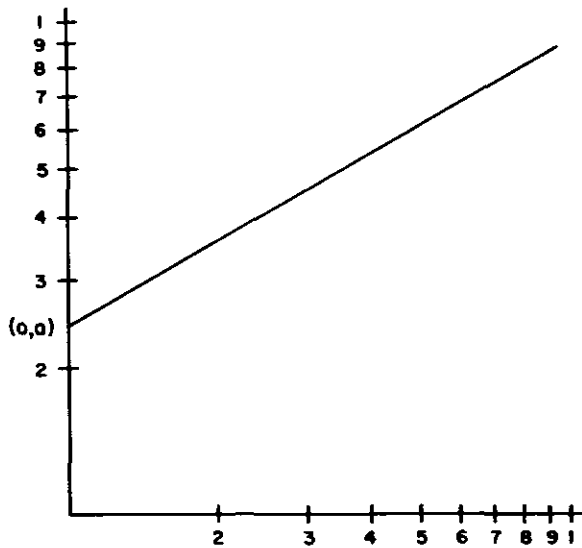


Figure 3-6

STATISTICS

Frequency Distributions

In any study of statistics the main concern, either in fact or in theory, is with sets of numerical data. The entire set is usually called the population while some subset of it which is being considered is called a sample. One of the first steps in analyzing a population is to arrange the members of the sample in an array, thus exhibiting the frequency distribution of the population.

The frequency distribution that occurs most often in both industry and nature is the normal

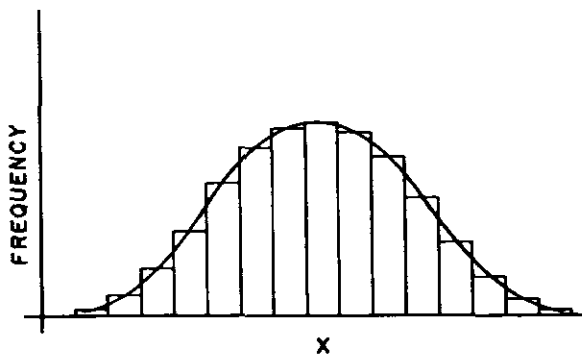


Figure 3-7

distribution. This distribution can be represented by a bell-shaped curve; that is, a symmetrical curve with most of the values falling somewhere near the middle of the range of values, as shown in Figure 3-7.

Many other distributions have also been characterized. In fact, studies of the distribution of measurements of particulate air pollutants and particle sizes indicate that a suitable frequency function is that of the log-normal distribution. In this distribution, the logarithms of the actual measurements are approximately normally distributed. A special type of logarithmic paper, called log-probability paper, is used to plot this distribution.

Measures of Central Tendency

In addition to the general information provided by a frequency distribution, there are quantitative characterizations of a population called parameters. The first of these is a measure of central tendency, a number about which the data tend to concentrate.

If the distribution of a set of numbers is approximately normal, three measures of central tendency are frequently used. The most important of these is the arithmetic mean, the sum of all the values divided by the number of values. Symbolically,

$$\bar{x} = \frac{x_1 + x_2 + \dots + x_n}{n} = \frac{\sum_{i=1}^n x_i}{n}$$

If one or more of the values appears more than once, the calculation may be simplified by multiplying each of the values by the number of times it appears. Then

$$\bar{x} = \frac{\sum_{i=1}^n (x_i \cdot f_i)}{N}$$

where f_i is the frequency with which x_i appears and N is the total number of values being considered. This is the method used to calculate a time-weighted average, such as that used in referring to threshold limit values.

The second common measure is the median, the middle observation when the numbers are arranged in order of magnitude. If there are an odd number of values, the median is uniquely defined; if there are an even number, the average of the two middle values is used. For example, the median of the numbers

$$7, 11, 21, 24, 31, 92 \text{ is } \frac{21 + 24}{2} \text{ or } 22.5.$$

Another measure of central tendency is the mode, the number in a collection which occurs most frequently, if such a number exists. This value is often not uniquely defined, or, if it is, may not be representative of the sample.

If the frequency distribution is approximately log-normal rather than normal, the most appropriate measure of central tendency is the geometric mean. This is defined as the n th root of the product of the n values. Symbolically,

$$\bar{x}_g = \sqrt[n]{x_1 \cdot x_2 \cdot \dots \cdot x_n}$$

This calculation can be greatly simplified by the use of logarithms.

$$\begin{aligned} \text{Since } \bar{x}_g &= (x_1 \cdot x_2 \cdots x_n)^{\frac{1}{n}}, \\ \log \bar{x}_g &= \frac{1}{n} (\log x_1 + \log x_2 + \cdots + \log x_n) \\ &= \frac{1}{n} \left(\sum_{i=1}^n \log x_i \right) \\ \text{and } \bar{x}_g &= \text{antilog} \left[\frac{1}{n} \left(\sum_{i=1}^n \log x_i \right) \right]. \end{aligned}$$

Again, if some of the values should appear more than once, as in a particle size distribution, the formula becomes

$$\bar{x}_g = \text{antilog} \left[\frac{1}{N} \left(\sum_{i=1}^n f_i \cdot \log x_i \right) \right].$$

This computation may be carried out by the use of either common or natural logarithms.

Measures of Dispersion

A second numerical characterization of a population is provided by a measure of dispersion, a number describing how the values of the collection deviate from some central value.

If the distribution is approximately normal, the appropriate measure of dispersion is the standard deviation. The difference between any value in a set of data and the mean is called the deviation from the mean. If these deviations are squared, summed, and divided by $n-1$, the resulting number is the variance of the distribution. The positive square root of the variance is the standard deviation. Symbolically,

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}}.$$

To simplify calculations, this may also be written as,

$$s = \sqrt{\frac{n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i \right)^2}{n(n-1)}}.$$

Again, if some of the values should appear more than once, this frequency of appearance, f_i , is introduced into the equation. In that case

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2 f_i}{N-1}}.$$

As a computational aid the standard deviation may also be written as

$$s = \sqrt{\frac{N \sum_{i=1}^n f_i x_i^2 - \left(\sum_{i=1}^n f_i x_i \right)^2}{N(N-1)}}.$$

The significance of the standard deviation lies in the fact that if a distribution is approximately normal, 68.3% of the observations will lie within one standard deviation of the mean, 95.4% will lie within two standard deviations of the mean, and

99.7% will lie within three standard deviations of the mean. A graphic presentation of this is shown in Figure 3-8.

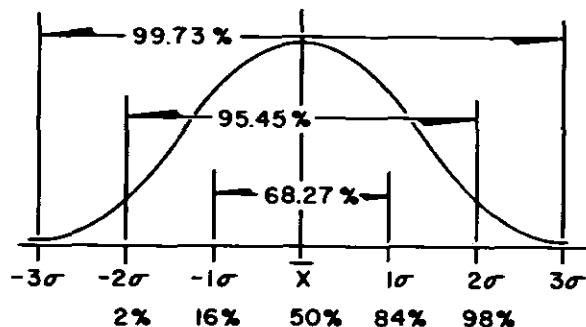


Figure 3-8

When the distribution is approximately log-normal, the standard geometric deviation is the appropriate measure of dispersion. The equation for this measure is

$$s_g = \text{antilog} \sqrt{\frac{n \sum_{i=1}^n \log^2 x_i - \left(\sum_{i=1}^n \log x_i \right)^2}{n(n-1)}}.$$

Again, when some of the values appear more than once the frequency, f_i , is introduced. Then,

$$s_g = \text{antilog} \sqrt{\frac{N \sum_{i=1}^n f_i \log^2 x_i - \left(\sum_{i=1}^n f_i \log x_i \right)^2}{N(N-1)}}.$$

The significance of the standard geometric deviation is analogous to that of the standard deviation if we recall that in a log-normal distribution the logarithms of the values are approximately normally distributed. Thus, 68.3% of the values lie between \bar{x}_g/s_g and $\bar{x}_g \cdot s_g$, 95.4% lie between $\bar{x}_g/2s_g$ and $\bar{x}_g \cdot 2s_g$, and 99.7% lie between $\bar{x}_g/3s_g$ and $\bar{x}_g \cdot 3s_g$. It should be noted that these are the principles which govern the use of log-probability graph paper.

Testing Hypotheses

Frequently an investigator has in mind a particular hypothesis or assumption about the population being sampled. This usually consists of assigning a specific value to one or more of the parameters of the population, such an assignment depending on past experience. Then a test must be devised whereby the hypothesis is either accepted or rejected once the sample has been taken. The determination of this test depends on certain characteristics of the population which will not be discussed here. A good statistical reference such as those cited at the end of this chapter will provide a detailed method for selection of a test statistic. It should be understood, though, that the failure to reject a hypothesis does not imply that it is true; it simply means that the information is such that we are not in a position to reject the hypothesis.

Curve Fitting

In addition to characterizing a population, the methods of statistics are often used in making predictions. This involves the consideration of relationships between two or more variables. Such a study usually begins with the plotting of the points on a rectangular coordinate system, giving a visual image of the relationship between the variables. In the case where the values of y are fairly well approximated by a linear function of x , linear correlation is said to exist. A measure of the closeness of this correlation is given by the linear correlation coefficient

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \cdot \sum_{i=1}^n (y_i - \bar{y})^2}}$$

If this value is close to 0, there is little linear relationship between the variables; while if it is near +1 or -1, the linear relationship may be greater. However, the extent of such a relationship depends strongly on the sample size. Also, there may be a high degree of correlation that is not of the linear type and thus not indicated by the linear correlation coefficient.

When a relationship is seen to exist between two variables, it is often desirable to approximate the function in order to predict the value of one variable from the other. This is often accomplished simply by joining the data points by a curve that appears to best approximate the relationship, as shown in Figure 3-9.

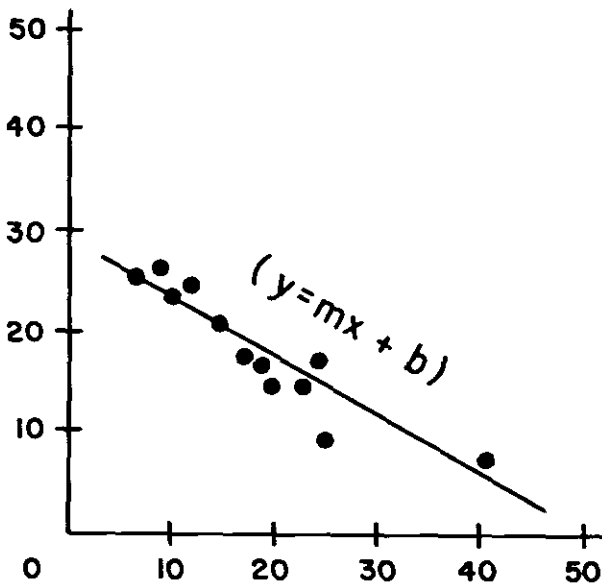


Figure 3-9

An equation of this curve can then be found by substituting points on the curve into the general equation of the curve and solving the resulting

equations simultaneously. A more precise method of determining the equation is given by the method of least squares, a procedure which minimizes the error committed in fitting a curve of a definite type to a set of data. A detailed description of this method can be found in most of the references cited at the end of this chapter.

Dimensional Analysis

Expressions of concentrations of atmospheric contaminants in industrial hygiene are usually corrected to 25°C and 760 mm Hg pressure, but the actual conditions are frequently not sufficiently removed from this standard to require temperature and pressure corrections. When calculating concentrations, recall that one gram-mole is the amount of material in grams equal to the molecular weight of the material. Also, at standard temperature and pressure (0°C and 760 mm Hg), one gram-mole of any compound in the gaseous state occupies 22.4 liters.

Terms Peculiar to Industrial Hygiene

The concentration of gases and vapors is usually expressed as parts per million parts of air, ppm, on a volumetric basis.

$$\begin{aligned} \text{ppm} &= \frac{\text{parts}}{10^6 \text{ parts (air)}} \\ &= \frac{\text{micro-liter}}{\text{liter (air)}} \\ &= \frac{\text{cubic meters}}{10^6 \text{ cubic meters (air)}} \\ &= \frac{\text{cubic feet}}{10^6 \text{ cubic feet (air)}} \end{aligned}$$

This is similar to the concept of percent,

$$\% = \frac{\text{parts}}{100 \text{ parts}}$$

The concentration of fumes, mists, dusts, and of gases and vapors on occasion, is expressed as milligrams of material per cubic meter of air, mg M³.

Examples

- (1) Given the concentration of a contaminant in ppm, convert to mg M³.

$$\text{Since } 1 \text{ ppm} = \frac{1 \text{ liter}}{10^6 \text{ liters}}$$

$$\begin{aligned} \text{Concentration} &= \left(\frac{1 \text{ liter}}{10^6 \text{ liters}} \right) \times \left(\frac{1 \text{ gram-mole}}{22.4 \text{ liters}} \right) \\ &\times \left(\frac{\text{MW Grams}}{\text{gram-mole}} \right) \times \left(\frac{10^3 \text{ liters}}{\text{M}^3} \right) \\ &= \frac{\text{grams}}{10^3 \text{ M}^3} \\ &= \frac{\text{mg}}{\text{M}^3} \end{aligned}$$

At 25°C and 760 mm Hg, one gram-mole of a perfect gas or vapor occupies 24.45 liters. Therefore, under these conditions,

$$\frac{\text{mg}}{\text{M}^3} = \text{ppm} \times \frac{\text{Molecular Weight}}{24.45}$$

- (2) Derive an equation for the preparation of

a known concentration of a volatile liquid given the following:

V_T = Chamber volume in liters

MW = Molecular weight of a substance

T = Absolute temperature

P = Pressure in mm Hg

ρ = Density in grams per milliliter

v = Volume of material to be used in milliliters

C = Concentration in ppm

$$C \text{ (ppm)} = \frac{(v \text{ ml}) \rho \frac{\text{gm}}{\text{ml}} \frac{22.4 \text{ liters}}{\text{gm-mole}} \frac{\text{gm-mole}}{\text{MW gms}} \frac{T}{273} \frac{760}{P}}{V_T \text{ Liters}} \times \frac{10^6 \text{ parts}}{10^6 \text{ parts}}$$

$$= \frac{(v) (\rho) \frac{22.4}{\text{MW}} \frac{T}{273} \frac{760}{P}}{V_T} \times 10^6.$$

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REVIEW OF CHEMISTRY

Fred I. Grunder

INTRODUCTION

Chemistry is that branch of the physical sciences which plays an extremely important role in the characterization and quantitative measurement of the toxic substances of interest in the field of occupational health. A proper understanding of the several phases of chemistry permits the occupational health specialist to use this tool effectively in solving the environmental problems in this field. A proper understanding of inorganic chemistry is required for the appreciation of the properties of the mineral and inorganic chemical substances which are of concern to the health and well-being of the worker exposed to these materials as airborne particulates, fumes, or mists in the workplace. A basic grasp of organic chemistry is important because of the great variety of toxic organic solvent vapors and particulate compounds encountered in industrial operations. Analytical chemistry is a major tool used in occupational studies in the evaluation of chemical hazards, including the levels of airborne contaminants in the working environment and the concentrations of toxic substances, intermediates, and metabolites in the human or animal body tissues and fluids.

GENERAL INORGANIC CHEMISTRY

It can be observed readily that the world is composed of a tremendous variety of material substances. Superficial inspection reveals many of these to be composed of two or more identifiable components. Often more deliberate study will show the components to be made up of still other distinguishable substances. If the examination process is continued with ever-increasing sophistication, there will come a point where further subdivision will no longer be possible. The materials which cannot be divided into simpler chemical entities are called *elements*. The smallest unit which can be recognized as a particular element is known as an *atom*. Each atom of an element is chemically identical to every other atom of the same element, while uniquely different from those of other elements. There are presently 105 known elements, from which the material of the universe is made.

Atoms are composed principally of positively-charged *protons*, negatively-charged *electrons* and uncharged *neutrons*. The protons are situated at the center of the atom along with uncharged neutrons in the *nucleus*. The electrons are oriented at some distance from the nucleus and impart size and electrical balance to the atom. Each atom has the same number of protons as electrons to maintain electrical neutrality. The number of protons in the nucleus is the *atomic number* which

uniquely defines the elemental identity of the atom. The number of protons combined with the number of neutrons approximates the *atomic weight*. The atomic weight of an atom is proportional to its true, physical mass. Hence, 12.0 grams of carbon (atomic weight = 12) contain 6.023×10^{23} carbon atoms. The mass in grams of any element which is equal to that element's atomic weight is called one gram-molecular weight, or one *mole*, which always contains 6.023×10^{23} (Avogadro's Number) atoms of that element. Each of the elements has a name and a symbol assigned to it. For example, the eleventh element (atomic number 11) is called sodium which has the chemical symbol Na.

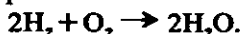
Elements combine with one or more other elements in definite ratios to form *compounds*. The smallest unit of a compound is called a *molecule*. Molecules are held together by the sharing of pairs of electrons between the atoms to form chemical bonds. Bonds are classified according to the extent of the sharing involved. A *covalent* bond is one in which the pair of electrons is shared equally by two atoms. An example of a covalent bond is the hydrogen molecule in which the two identical atoms share the lone electron pair. If the atoms involved are not from the same chemical element, the chances of equal sharing are diminished. In extreme cases, the bond is known as *ionic*. Sodium chloride (NaCl) is a good example of an ionic bond, the sodium existing essentially as the positively-charged ion and the chlorine as the negative chloride ion. Sharing of more than one electron pair leads to double and triple bonding. The nitrogen molecule is an example of a higher-order bond. In this case, the two atoms share three pairs of electrons to form a triple bond.

The chemical symbol for a compound is merely a composite of its constituent atoms along with numerical indications of the ratios of the combining elements to one another. For instance, the symbol for water, H_2O , represents a molecule which contains two atoms of hydrogen and one of oxygen. The *molecular weight* of a compound is equal to the sum of the atomic weights of all the atoms making up the molecule of that compound. Similarly to the case for individual atoms, the mass in grams of any compound which is equal to that compound's molecular weight is called one mole which contains 6.023×10^{23} molecules of that compound.

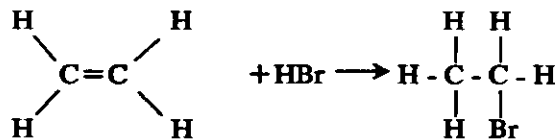
Often it is convenient and useful to express a molecular symbol or *formula* as more than just an accounting of the atoms present. It is known, for example, that certain groupings of atoms appear regularly in chemistry. They are called

"groups" or "functional groups" or "radicals" and they are treated as separate elemental forms when writing the formula. In organic chemistry the methyl (CH₃-) and ethyl (C₂H₅-) groups are common functional substituents in class compounds. Confusion is avoided in organic chemistry by using constitutional or structural formulas. For example, the formula for ethyl alcohol, is written as CH₃CH₂OH or C₂H₅OH rather than C₂H₆O (a molecular formula) to emphasize the constitutional arrangement of the atoms within the molecule and to distinguish it from methyl ether (CH₃OCH₃) which has the same molecular formula.

Chemistry uses the element symbols to abbreviate complex descriptions of chemical reactions. For instance, if a reaction is initiated between hydrogen and oxygen in a mixture, water will be produced. The whole reaction can be written as the symbolic expression:



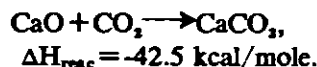
The exact way in which a chemical reaction is written expresses certain essential aspects of the reaction. This equation identifies the reactants as hydrogen and oxygen and shows that they combine in a ratio of two molecules of H₂ to one of O₂ to yield two molecules of H₂O. A complete description of the above reaction would include a description of the pertinent reaction conditions. It is significant that the equation is balanced with respect to both the numbers and the kinds of atoms in the reactants and the products. In correct chemical equations, atoms cannot be created, destroyed, or transmuted. In organic chemistry (see discussion of bonds in section on Organic Chemistry) where the structure of molecule is especially important reactants and products are written structurally:



Chemical reactions occur because the final products are energetically more stable than the initial reactants under the conditions of the reaction. The difference in energy between reactants and products can commonly be observed as heat liberated, as in the burning of wood. Consideration of the amounts of liberated heat of reaction is important in thermodynamics where this is shown quantitatively as part of the chemical equation:

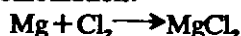


The value of 42.5 kcal/mole is the amount of energy released as heat in the reaction. It is given the symbol ΔH and is defined as the *heat of reaction*. In tabular form, positive values for heats of reaction represent *endothermic* reactions which absorb heat from the surroundings. The reaction of CaO and CO₂ releases heat energy, indicating that it is *exothermic* and that the heat of reaction is negative ($\Delta H = -42.5$ kcal/mole). It appears positive in the preceding equation because it is a positive product of the reaction. Another expression for the same reaction is:

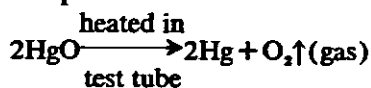


Basically, chemists are concerned with four types of chemical reactions, i.e. combination, decomposition, displacement, and double decomposition. Examples of these are as follows:

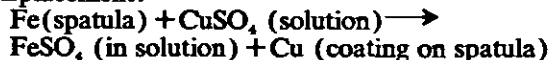
Combination:



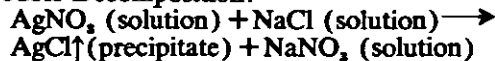
Decomposition:



Displacement:

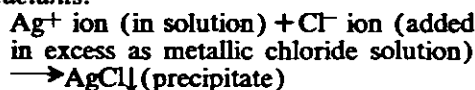


Double Decomposition:



Chemical reactions go to completion when one of these four conditions is met:

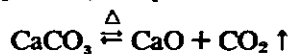
- 1) *Increasing the concentration of one of the reactants:*



Silver chloride has a very low solubility product which means that the product (Ag^+) \times (Cl^-) cannot exceed its value of 1.56×10^{-10} moles per liter*;

*One gram mole is the number of grams equal to the molecular weight of a substance.

- 2) *Removing one of the products as a gas:*



The escape of the gaseous product, carbon dioxide, allows quicklime to be formed from limestone in a kiln.

- 3) *Removing one of the products as a precipitate:*



When hydrogen sulfide is passed into a weakly acid solution of a soluble lead salt, the lead is converted completely to highly insoluble lead sulfide.

- 4) *Removing one of the products as a slightly ionized substance:*



The addition of sodium hydroxide to ammonium chloride produces slightly ionized ammonium hydroxide which dissociates into ammonia and water. As a result the reaction shifts almost entirely to the right.

In the examples of chemical reactions given above there are two additional basic classifications: first, reactions involving an electron transfer and a resulting change in the oxidation state of a substance and, secondly, reactions where there is no oxidation-reduction process. Thus, in the burning of magnesium in chlorine gas, magnesium is oxidized from the elemental to the divalent (+2)

state while chlorine is reduced from the elemental to the negative (-1) state whereas in the double decomposition reactions there is no oxidation-reduction process occurring, but only an exchange of elements whose reactions go to completion for the reasons stated previously. The following discussion treats further the matter of oxidation-reduction, an extremely important aspect of analytical chemistry processes.

In the water molecule, H_2O , the hydrogen atoms are essentially ionized by the oxygen's strong affinity for electrons. The resulting charge and oxidation state for hydrogen is then $+1$ and that for oxygen is -2 . In the elemental form (H_2 & O_2) hydrogen and oxygen display no net charge and they have an oxidation state of 0. The reaction of hydrogen and oxygen to form water however, involves a transfer of electrons. The hydrogen atoms' loss of their electrons to the oxygen atom is called *oxidation*; the gain of these electrons by the oxygen is called *reduction*. Reactions of this type are called oxidation-reduction reactions or *redox* reactions. In any redox reaction, the total number of electrons lost by an oxidized species must exactly equal the number of electrons gained by the reduced species. This relationship enables redox reactions to be used in quantitative analysis. The amount of a substance in a redox reaction which will give up or receive one mole of electrons (6.023×10^{23} electrons) is called an *equivalent*.

Naturally occurring materials, irrespective of their elemental make-up, assume three different descriptions or states: *solids*, *gases* and *liquids*. Solids have a definite shape and volume and are held together by strong inter-molecular and inter-atomic forces. For many substances, the forces are strong enough to maintain the atoms in definite, ordered arrays called *crystals*. Solids having little or no crystalline character are called *amorphous*.

Gases, on the other hand, have weaker attractive forces between individual molecules. As a result, gases diffuse rapidly and assume the shape of their container; their volumes are easily affected by changes in temperature and pressure. Because true gases (the fixed gases) are relatively free of interactions between individual molecules, the behavior of a gas is dependent on only a few general laws based upon the properties of volume, pressure, and temperature. Under normal conditions, for instance, the pressure exerted by a gas multiplied by its volume is a constant at a fixed temperature and a given number of molecules:

$$PV = \text{constant.}$$

A temperature rise will produce a corresponding increase in pressure at constant volume and fixed number of molecules. A temperature rise will also produce a corresponding increase in volume at constant pressure and number of molecules:

$$T_2/T_1 = P_2/P_1 \text{ or } T_2/T_1 = V_2/V_1$$

where T_1 = absolute temperature (degrees Kelvin or Rankin) of a gas whose volume is V_1 and T_2 = absolute temperature of a gas whose volume is V_2 .

At constant temperature and pressure, equal

volumes of gases contain equal numbers of molecules regardless of the nature of the gas. A volume of 22.4 liters will contain one mole or 6.02×10^{23} molecules (or atoms of a monatomic gas) at sea-level pressure and $0^\circ C$ or $32^\circ F$. An equation for relating the four properties of gases (P , V , number of moles, T) which is applicable over a fairly wide range of conditions is called the *ideal gas law*;

$$PV = nRT, \text{ where } P = \text{pressure}$$

V = volume

n = number of moles

T = temperature in degrees absolute

R = gas constant (determined by the units used for the other four).

When dealing with gases, it is customary to express volumes in terms of standard conditions of temperature and pressure. Thus, if data are obtained at conditions other than standard it is necessary to correct the volumes. For this purpose, an adaptation of the ideal gas law is used:

$$V_s = (P/P_s) (T_s/T) V$$

where V_s = volume at standard temperature and pressure

P_s = standard pressure

T_s = standard temperature in degrees absolute

V = volume observed

P = pressure observed

T = temperature observed in degrees absolute

The molecules of the liquid state of matter are separated by relatively small distances such that the attractive forces between molecules tend to hold the molecules within a definite volume at a fixed temperature. The repulsive forces between molecules also exert a sufficiently strong influence, however, that volume changes caused by increases in pressure may be neglected.

One of the most useful properties of liquids is their ability to *dissolve* gases, other liquids, and solids. Solvents are covalent compounds in which the molecules are much closer together than a gas; therefore, the intermolecular forces are relatively strong. When the molecules of a certain covalent solute are physically and chemically similar to those of a liquid solvent, the intermolecular forces of each are of the same magnitude and the solute and solvent will usually mix readily with each other.

The amounts of dissolved solutes are commonly expressed in terms of *concentrations* in solvents. The *molarity* of a solution is the number of moles of solute per liter of solution, designated by "M". The *molality* is the number of moles of solute per 1000 grams of solvent, designated by "m". The *normality*, "N", of a solute is the number of gram-equivalent weights of solute per liter of solution. The expression "parts per million" represents one part by weight of solute per one million parts by weight of solvent in liquid systems. One "ppm" is equivalent to one microgram

per milliliter or to one milligram per liter of solution.

In aqueous solutions the concepts of acidity and basicity are important. For most purposes an acid can be described as a hydrogen ion (proton) donor. Hydrochloric acid is an excellent example of a strong acid. Similarly, a base is described as a hydrogen ion acceptor. Sodium hydroxide is an example of a strong base. For aprotic compounds which have no ionizable hydrogen, an acid can be defined as a substance (such as aluminum chloride) which accepts an electron pair from a base, and any substance, (such as NH_3) that can behave as an electron pair donor is a base.

In aqueous systems, the acidity or basicity of a solution is measured by pH which is defined as the negative logarithm of the hydrogen ion concentration (expressed in moles per liter). It ranges from 1 to 14, pH 14 being extremely basic (the hydroxide ion, OH^- , greatly predominating), pH 1 being extremely acidic (the hydrogen ion, H^+ , greatly predominating), and pH 7 being neutral (the hydrogen ion and hydroxide ion concentrations equal).

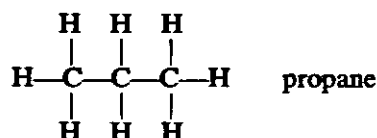
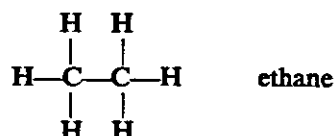
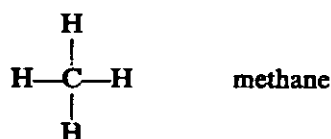
The basic concepts of general chemistry presented in this section are designed to provide the non-chemist members of the industrial hygiene profession with a general understanding of the principles of chemistry as they relate to the application of analytical chemistry to occupational health. The reference texts cited at the end of this chapter should be consulted periodically, as the needs of work situations require, to obtain the more detailed information on the aspects of individual problem areas.

ORGANIC CHEMISTRY

Organic chemistry is the study of carbon compounds, excluding the limited number of those inorganic substances which contain carbon such as carbon monoxide, carbon dioxide, carbonates and metal carbonyls. The common elements found in the thousands of organic compounds include carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, chlorine, bromine, and iodine, in the order of their relative occurrence. Organic chemistry is involved in most activities of modern life. The basic principles of organic chemistry are applied to the study of drugs, rubber, clothing, plastics, explosives, fuels, paints, solvents and numerous other essential commodities.

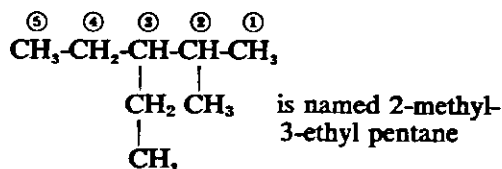
The carbon atom forms four covalent bonds. These bonds may be to other carbon atoms, to hydrogen, oxygen, one of the halogens (chlorine, bromine, iodine, fluorine), nitrogen, sulfur or to other atoms. The bonds may involve single electron-pairs which form single bonds, two electron-pairs giving double bonds ($>\text{C}=\text{C}<$), or three electron-pairs forming triple bonds ($-\text{C}\equiv\text{C}-$).

More than one million organic compounds are known. Their existence is due to the unique capacity of carbon atoms to join together forming chains or rings. Compounds formed from hydrogen and carbon only are called *hydrocarbons*. The aliphatic series of saturated hydrocarbons provides the simplest example of this property.

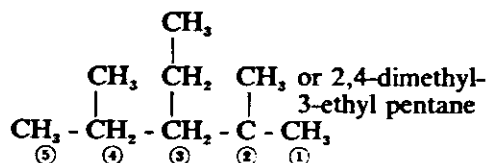


Homologous series of compounds are named according to the number of carbon atoms in the longest chain. The standard (International Union of Pure and Applied Chemistry) rules for naming carbon compounds are summarized below:

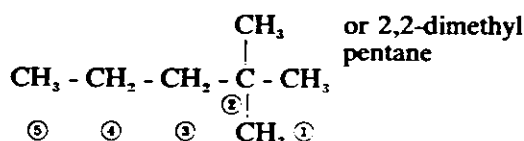
- 1) The longest continuous chain of carbon atoms is named as the parent compound.
- 2) The carbon atoms in this chain are given numbers starting at one end, and substitute groups are given numbers corresponding to their position on the chain. The direction of the numbering is chosen to give the smallest sum for the numbers of the side chain constituents:



- 3) If the same group appears more than once, the prefix di-, tri-, or tetra- is used to indicate how many groups there are:



- 4) With two identical side chain groups at one position, numbers are given for each:



- 5) If several different substituent groups are present, they are assigned according to the alphabetical arrangement of substituents or in order of increasing size of the side chain.

Branched chains often have names of their own.

Thus, $\begin{matrix} \text{CH}_3 \\ | \\ \text{CH} \\ | \\ \text{CH}_3 \end{matrix}$ is an isopropyl group. For example,

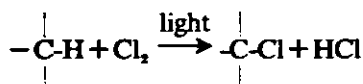
$\begin{matrix} \text{CH}_3 \\ | \\ \text{CHOH} \\ | \\ \text{CH}_3 \end{matrix}$ is called isopropanol

$\begin{matrix} \text{CH}_3 \\ | \\ \text{CHCH}_2\text{CH}_3 \\ | \\ \text{CH}_3 \end{matrix}$ is called isopentane.

The field of organic chemistry is generally divided into two broad classes of organic compounds, aliphatic compounds and aromatic compounds.

Aliphatic Hydrocarbons

The saturated hydrocarbons, which contain only single bonds, are also known as alkanes or paraffinic hydrocarbons. The general formula for these compounds is $\text{C}_n\text{H}_{2n+2}$ where n is an integer. They are less reactive than the unsaturated hydrocarbons and are insoluble in water, sodium hydroxide and sulfuric acid. They do, however, undergo reaction under certain vigorous conditions. When treated with either chlorine or bromine and light or a catalyst, a halogen atom can substitute for a hydrogen atom:



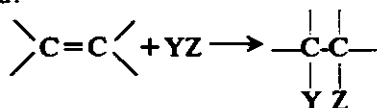
They can be heated from 400° to 600°C to promote thermal decomposition, a process called cracking, and yield simpler alkanes, alkenes and hydrogen.

Alkenes are unsaturated, olefinic hydrocarbons. They contain at least one carbon-carbon double bond. The suffix -ene is substituted for -ane in naming them. The parent hydrocarbon chain is chosen as the longest chain containing the double bond. The position of the double bond is designated by the number of the first carbon atom involved in the double bond. Thus, $\text{CH}_3\text{CH}=\text{CHCH}_3$ is 2-butene, and $\text{CH}_2=\text{CHCH}_2\text{CH}_3$ is 1-butene. The double bond is given the lowest number, so the compound $\text{CH}_3-\text{CH}-\text{CH}=\text{CH}-\text{CH}_2$



is 4-methyl-2-pentene rather than 2-methyl-3-pentene.

Characteristic reactions of this group occur at the carbon-carbon double bond. The most characteristic reaction of the alkenes is the addition reaction. Generalized, this reaction can be represented:



Many substitution groups can be represented by Y and Z (examples are H_2 , HX , X_2 , H_2SO_4 , H_2O and others where $-\text{X}$ is used to indicate a halogen such as chlorine or bromine).

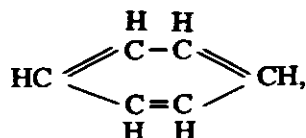
The paraffin-base oils contain mainly saturated open-chain hydrocarbons, whereas asphalt-base

oils contain appreciable amounts of naphthenes such as cyclopentane, cyclohexane and their alkyl derivatives. The major fractions separated from crude petroleum are shown in the following table:

Fraction	Boiling Point Range, $^\circ\text{C}$	Composition (Approximate)
Gas	<20	C_1-C_4
Petroleum Ether	20-60	C_5-C_6
Ligroin (Light Naphtha)	60-100	C_6-C_7
Natural Gasoline	40-205	C_5-C_9 + Cycloalkanes
Kerosene	175-325	C_9-C_{16} + Aromatics
Fuel Oil	300-375	$\text{C}_{15}-\text{C}_{20}$
Lubricating Oil	>300	$\text{C}_{20}-\text{C}_{25}$
Asphalt or Petroleum Coke	>300	> C_{25}

Aromatic Hydrocarbons

Benzene is the simplest of the aromatic compounds; it has the formula C_6H_6 and its structure is:



although experimental evidence indicates that all the carbon-carbon bonds are equivalent.

The correct structure is often shown as:



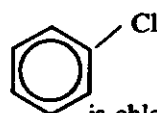
Where the circle indicates that the multiple bonding is shared equally among all six carbon atoms.

Benzene readily undergoes substitution reactions, such as halogenation:

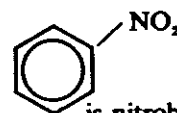


Benzene is very stable and resists addition reactions which would destroy the ring system.

In naming monosubstituted derivatives of benzene, the substituent's name is prefixed to "benzene." Thus:



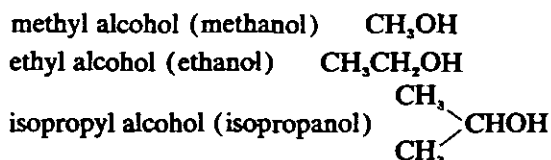
is chlorobenzene



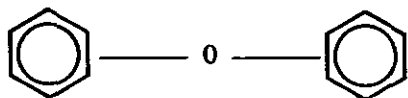
is nitrobenzene

Some aromatic compounds are better known by such common names as:

Some of the common alcohols are:

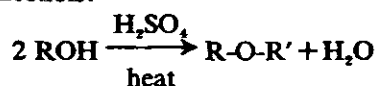


Ethers have the general formula $\text{R-O-R}'$. Their names are derived from those of "R" groups followed by the word "ether." Thus, $\text{CH}_3\text{OC}_2\text{H}_5$ is methyl ethyl ether and



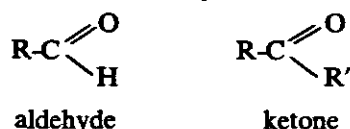
is diphenyl ether.

Diethyl ether is the most common member of this class of compounds. It is used as a solvent and an anesthetic. Ethers are often prepared by dehydration of alcohols:



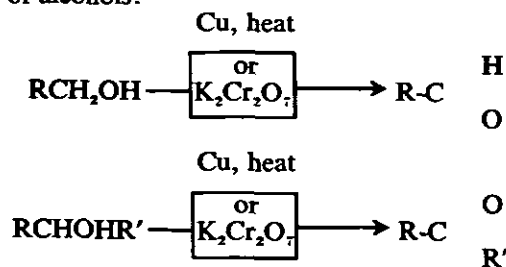
Ethers, as compared with alcohols are fairly inert.

Aldehydes and ketones are carbonyl compounds having one and two alkyl groups respectively joined to the carbonyl function:

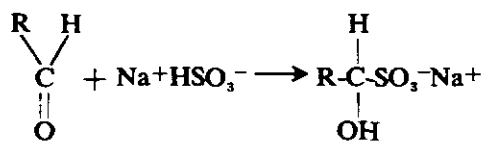


(R and R' may be either aromatic or aliphatic)

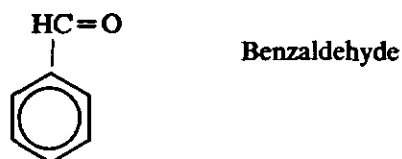
These compounds can be prepared by oxidation of alcohols:



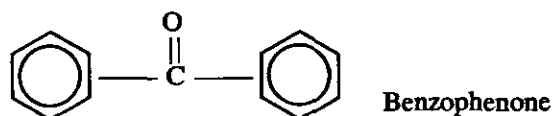
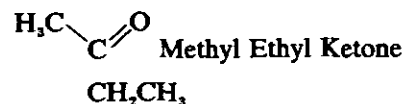
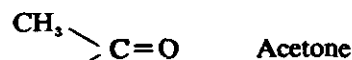
The carbonyl group ($-\overset{\text{O}}{\text{C}}-$) is primarily responsible for the characteristic reactions of these compounds which can be oxidized to carboxylic acids or reduced to alcohols. They also undergo addition reactions involving the carbon-oxygen bond such as the analytically important one with sodium bisulfite:



Some common aldehydes are:

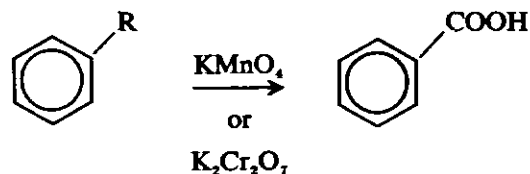


A few common ketones are:

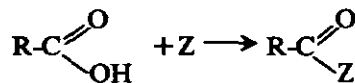


Carboxylic acids contain a carboxyl group ($-\overset{\text{O}}{\text{C}}-\text{OH}$) and are acidic in nature. The general

formula for monocarboxylic acids is RCOOH where R may be aromatic or aliphatic. These acids can be obtained by the oxidation of primary alcohols, aldehydes or alkyl benzenes.

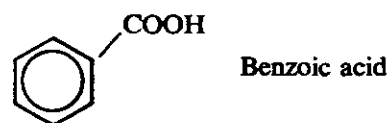
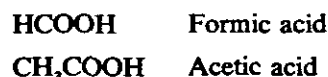


In the reactions that occur, the hydroxyl is usually the reacted group. A typical reaction is one of the type:

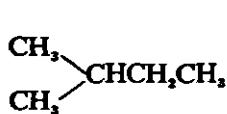
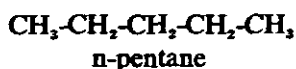


where Z may be Cl, OR', NH_2 , etc.

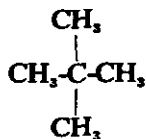
Some of the common acids are:



Isomers are defined as compounds having the same molecular formula but a different structure. There are essentially two major types of isomerism: structural isomerism and optical isomerism. Examples of structural isomers include the pentanes, all of which have the empirical formula C_5H_{12} , but different physical and chemical properties:



iso-pentane



neopentane

A more striking example of structural isomerism is the compound C_2H_6O . This can be the molecular formula for methyl ether CH_3OCH_3 , or ethyl alcohol CH_3CH_2OH , two compounds showing marked differences in physical and chemical properties.

Optical isomers involve a central atom to which a number of different groups are attached. Two optical isomers are molecules which are identical except for the spatial orientation of the groups attached to the central, asymmetric atom. They are mirror-images of one another. The most readily observed difference between the two is the difference in the rotation of the plane of polarization if a beam of plane-polarized light is allowed to pass through a solution of the compound. This type of isomerism is useful in identifying certain biochemical reaction products.

ANALYTICAL CHEMISTRY

The analytical methods used in industrial hygiene may be divided into classical chemical methods and instrumental methods. Such a distinction is based more on the historical development of analytical chemistry than on any clear differences between the two methods, as both the strictly chemical and the instrumental methods usually are completed with a physical measurement, such as spectrophotometry. It is possible to further separate the classical chemical methods as volumetric or gravimetric.

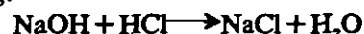
Classical Chemical Methods of Analysis

A *volumetric analysis* is one which is completed by measuring the volume of a liquid reagent of known concentration required to react completely with a substance whose concentration is being determined. The chemical reaction must be such that the amount of the known reactant can be related exactly to the amount of the analysis substance present. A reaction, to be useful for volumetric analysis, must be rapid, complete and have a sharp endpoint. Two basic types of reactions may be considered as representative of volumetric analyses.

Acidimetry and *alkalinity* reactions involve the neutralization of acids and bases. A titrimetric procedure is used to determine the amount of a standard solution of a reagent (i.e., one of precisely-known concentration) required to react

completely with a specific chemical substance in a prepared solution of a sample.

Titrimetric reactions dependent upon neutralization reactions must be complete at a definite endpoint based on an abrupt change in pH which occurs at the equivalence point. An example of a neutralization reaction in an aqueous system is the following:



When the hydrogen ion (H^+) and hydroxide ion (OH^-) concentrations are equal, the solution is said to be neutral (pH 7.0 aqueous solution). However, the actual pH at the equivalence point of an acid-base titration is not necessarily equal to 7.0, since it depends on the degree of ionization and hydrolysis of the products of the reaction.

The majority of titrimetric procedures use an indicator to determine the endpoint accurately. An indicator is generally a complex organic compound having a weakly acidic or basic character capable of a sharp transformation in color over a definite, but narrow, pH range. Several factors play a role in determining the pH interval over which a given indicator exhibits a color change:

- 1) Temperature,
- 2) Electrolyte concentration (total ionic strength),
- 3) Effect of organic solvent systems.

Two sources of error that may occur when determining the end-point of a titration using visual indicators are:

- 1) The indicator does not change color at or near the hydrogen ion concentration that prevails at the equivalence point;
- 2) Very weak acids (or bases) cannot be titrated with satisfactory results.

The first of these sources of error can easily be corrected by using a blank. The second, however, cannot be remedied because of the difficulty in deciding exactly where the color change occurs.

The other type of chemical reaction suitable for titrimetry is called *oxidation-reduction* or "*redox*." The ions of a large number of elements can exist in different oxidation states. Suitable oxidizing or reducing agents can cause a redox reaction with such ions. Many of these reactions satisfy the requirements of volumetric analysis.

One of the most widely used oxidizing agents is potassium permanganate ($KMnO_4$). It has an intense purple color which can serve as its own indicator for the endpoint. The reagent will oxidize metallic ions from low to high oxidation states and negative ions such as chloride to chlorine at the zero or ground state. Its use in some reactions is restricted due to the multiplicity of possible reactions that may occur in the presence of more than one oxidizable substance.

Potassium dichromate ($K_2Cr_2O_7$) is another important oxidant. It is not as powerful as potassium permanganate and some of its reactions proceed slowly. However, the solid reagent can be obtained in high purity and stable, reliable solutions may be prepared conveniently. Dichromate solutions are most useful for titrations carried out in 1 to 2 normal acid or alkaline solutions.

A substance which is useful both as an oxidizing and as a reducing agent is iodine, generally used in the form of the triiodide ion, I_3^- , which is formed by the reaction of iodine, I_2 , with the iodide ion I^- . The indirect or iodometric methods involve the treatment of a solution with an excess of iodine and then measuring the amount of iodine used. Starch is an indicator for iodimetry and iodometry. Iodometry is used regularly for the determination of aldehydes and hydrogen sulfide collected in sampling reagents of sodium bisulfite or ammoniacal cadmium sulfate, respectively.

Gravimetric analyses constitute another important group of analytical methods for determining substances quantitatively. A gravimetric method is one in which the analysis is completed by making a weight determination. A gravimetric procedure requires that the analytical substance must be separated quantitatively from other chemical entities in the sample. Numerous techniques are available for this separation. These include precipitation, solvent extraction, volatilization, complexation and electrochemical separations.

Precipitation methods are the most common gravimetric procedures. However, all precipitates are not suitable for gravimetric analysis. The precipitate must have a sufficiently low solubility to insure that the solubility losses do not affect the results of the analysis seriously. Further, it must be possible to isolate the precipitate quantitatively from the liquid by simple, rapid filtration and to free it readily of contaminants by a simple treatment. The exact chemical composition of the precipitate must be definite to allow calculation of the component of interest. Ideally, the precipitate should not be hygroscopic and should have a large molecular weight relative to the analytical constituent contained therein.

Solid-liquid solvent extractions involve both simple removal of impurities by dissolving them from the desired precipitate and the reaction of the solvent with a component to make it either soluble or insoluble. Soxhlet extractions are good examples of the latter technique. Organic solvents find considerable application to this type of extraction.

Liquid-liquid extractions make use of two mutually immiscible liquids to redistribute the desired solute on the basis of differences in solubility. The extraction of a metallic salt from an acid solution into an organic solvent is one example.

Solid-gas extractions are used to remove a desired gas from a mixture of gases. Adsorption of volatile organic compounds from the air by activated carbon is an example of solid-gas extraction.

Another useful technique in gravimetric analysis involves the use of *volatilization* methods. Simple examples include the determination of water by loss on ignition and the decomposition, evolution and subsequent weighing of carbon dioxide. Volatilization methods can be classified either as evaporation and/or sublimation or as distillation and aeration procedures. The drying of a sample to remove water and the separation of aluminum chloride are accomplished by evaporation and sublimation techniques, respectively.

In the case of liquid mixtures of organic substances, the individual components may be separated effectively by distillation at atmospheric pressure or under vacuum. The determination of carbonate by the generation and removal of carbon dioxide followed by subsequent weighing is an example of a gravimetric aeration technique.

Elemental substances may be separated from other substances and metallic constituents deposited quantitatively by electro-chemical separations. In electrolytic methods, a pure deposit that adheres firmly to the electrode is required. Temperature, the presence of complexes and the evolution of hydrogen affect the quality of a deposit. Deposits obtained from complex ions in solution tend to be dense and adherent. Heating and stirring the solution during electrolysis speeds up deposition as a result of higher current densities. When the material has been completely deposited, it may be dried and weighed.

Instrumental Methods of Analysis

The final measurement in an analytical determination has been greatly facilitated in recent years by the use of highly sophisticated instrumentation. The industrial hygienist should never lose sight, however, of the preparatory work necessary before the final measurement can be made. Instrumentation is available for the qualitative and quantitative analysis of both inorganic and organic compounds.

The basic feature of *ultraviolet and visible spectrophotometry* is the selective absorption by aqueous and other solutions of definite wavelengths of light in the ultraviolet and visible regions of the electromagnetic spectrum. The fundamental law governing ultraviolet-visible absorption photometry is Beer's Law which relates the absorption of light linearly to concentration:

$$A = kC$$

"A" is the absorbance of the solution, "C" is the concentration and "k" is a constant whose value depends upon the wavelength of the radiation, the nature of the absorbing system, and the optical path length or cell thickness. Absorption data for spectra are usually recorded in terms of absorption versus wavelength. Wavelengths used for analysis are those at which the substance absorbs strongly. Ultraviolet and visible spectrophotometry is used in occupational health laboratories for the determination of inorganic substances and numerous organic contaminants of air, urinary metabolites and such blood components as carboxyhemoglobin and circulating heavy metals.

Infrared spectrophotometry makes analytical use of the molecular vibrations and rotations in chemical substances exposed to radiation from the infrared region of the spectrum. The atoms within a molecule vibrate and rotate at definite frequencies which are characteristic of that molecule. A sample placed in a beam of radiation in a dispersive infrared spectrophotometer absorbs energy at certain definite frequencies characteristic of the molecular components in the sample cell and will transmit the other frequencies. The absorption (or transmittance) within a specific frequency

range may be correlated with the specific motions of the functional chemical groups of a molecule to identify their presence or absence.

No two compounds with different molecular structures can have identical infrared spectra. Hence, the infrared absorption spectrum is a characteristic physical property (it is often termed a "fingerprint") of a compound, and it is a powerful tool in both qualitative and quantitative analyses, particularly for organic compounds as well as for certain inorganic structures, notably CO, SiO₂, and NO bonds. Quantitative analysis may be performed on a sample by selection of a specific absorption band whose response varies directly with the concentration of a given chemical species.

X-ray diffraction and fluorescent methods are based upon physical properties related to the atomic numbers of the constituent atoms in chemical compounds and not on any chemical properties of these substances.

When monochromatic x radiation strikes a crystalline material, the planes of the atoms in the material diffract the x ray beam at angles which depend upon the interplanar spacings in the crystal lattice. An appropriate x-ray spectrometer is used to scan and measure the wavelength and intensity of the diffracted rays. The resulting *x-ray diffraction* pattern is characteristic of the components of a sample, and crystalline materials, such as quartz (a form of free silica) or asbestos can be identified readily in mixtures of compounds. The sample patterns are compared with those of standards to identify and measure quantitatively the crystalline components of a sample.

X ray fluorescence is produced by an element which is irradiated by an intense beam of x rays. This fluorescence is observed as secondary x rays whose wavelengths are characteristic of that element. An x-ray spectrometer can be used to disperse the emitted secondary x rays and elements identified in the resulting spectrogram. Analytical curves are prepared from standard series of the pure compounds and the elemental constituents determined quantitatively. Errors of less than five percent are common with this method. The sensitivity (limit of detection) will vary from a few parts per million by weight to one percent depending on the element and the matrix material.

Emission spectroscopy and *atomic absorption spectrophotometry* are complementary techniques for the determination of atoms, ions, and a few molecular substances. The region of the electromagnetic spectrum involved includes the near infrared, the visible and the ultraviolet. The methods for analysis make practical use of this radiation for both qualitative and quantitative determinations.

Flame emission and emission spectrographic techniques are based upon the excitation of atomic and ionic species to higher energy levels from which states they emit characteristic wavelengths of light as they return to their individual ground states. In flame emission, the sample solution is aspirated into a flame and certain wavelengths are monitored to detect characteristic emissions. An emission spectrograph uses electrical energy to excite the atomic (or molecular) species in a solid or liquid sample. The complete emission spectrum

is dispersed with a diffraction grating or a prism. The spectra are detected by phototubes or are recorded on a photographic emulsion supported on a plate or film. The recorded spectrograms are examined in a comparator-densitometer using qualitative and quantitative standards of reference. Flame emission spectroscopy is also used for quantitative analysis since the amount of light emitted at a characteristic wavelength is proportional to the concentration of element.

Atomic absorption spectrophotometry makes use of the property that the atomic vapors of an element will absorb that element's characteristic radiation in proportion to its concentration in a flame. The sample is aspirated in solution form into a flame as in flame emission spectroscopy. The operating principle is based upon the decrease in the intensity of a monochromatic beam of light from a hollow cathode lamp or other source consisting of the same elemental substance. Atomic absorption is used mostly for quantitative analyses and, as with flame emission and arc and spark emission spectroscopy, it is valuable for the determination of metallic and metal-like elements in any type of sample which can be solubilized.

The term *gas or vapor phase chromatography* includes all chromatographic separation techniques using a gas as the mobile phase. Gas-liquid chromatography (GLC) makes use of a liquid distributed over the surface of a solid support as the stationary phase in the form of a column and a gas (helium, argon, nitrogen or hydrogen) as the mobile phase. The injected sample is vaporized and transported onto the column with one of the common carrier gases. The stationary phase adsorbs the sample components but not the carrier gas. Different compounds in the sample are retained to varied degrees by the stationary phase; hence, they pass through the column at different rates. The mobile carrier gas phase, which flows continually through the column, carries the different sample components through the column to appear in turn at a detecting device used in establishing the retention times of the individual compounds and in providing a signal for amplification to a recorder or integrator for a quantitative analysis. The output is recorded as a series of peaks on a strip chart recorder or fed to an electronic integrator for direct readout. The elution time is a function of the component, the particular stationary phase and the column temperature.

When the separate sample components have been identified, standardization of the GLC method is performed with a series of gas or vapor standards under identical chromatographic conditions. Measurement of peak areas, preferably by electronic integrators, provides the basis of quantitative analysis. This instrumental technique is extremely useful for the determination of organic contaminants in ambient and industrial atmospheres.

A wide variety of *electrochemical methods* depend on the phenomena that occur within an electrochemical cell. One electrochemical method that is used for specific analyses is polarography or voltametry in which the current passing through

a solution is measured as a function of the applied voltage. Essentially every element and many organic functional groups may be responsive to polarographic analysis. The polarographic behavior of any substance is unique for a given set of experimental conditions. If an unknown substance can undergo either cathodic reduction or anodic oxidation, qualitative and quantitative analysis is possible. Polarographic recordings, called polarograms, are obtained by measuring the current and the applied voltage between a special type of polarized microelectrode and a non-polarized reference cell. Typical applications of polarography include the analysis of samples for lead, cadmium, zinc or mercaptans.

A second electrochemical technique useful in many applications is based upon the use of ion-selective electrodes. These electrodes are used for the measurement of several cations (positive ions) and anions (negative ions) in solution including K^+ , Na^+ , Ag^+ , H_3O^+ , Cl^- , F^- and NO_2^- .

Three types of electrodes in common use are glass, liquid and solid state membrane electrodes. Glass membrane electrodes depend on the presence of certain compounds in glass to render them useful for the determination of certain ions. One of the properties of the glass electrode is its highly selective response to hydrogen ions when used as a pH electrode. Other glass membrane electrodes are available for the determination of ions such as sodium, potassium and calcium. Liquid membrane electrodes respond to a potential established across the interface between the solution to be analyzed and an immiscible liquid that bonds selectively with the specific ion. This type of electrode has been developed for the perchlorate and nitrate ions. Solid state membrane electrodes have the opposite property of glass (i.e., useful for measuring anions); have been developed recently and their operation depends upon the principle of selective precipitation. Thus, the fluoride ion electrode consists of a single crystal membrane of lanthanum fluoride supported between a reference solution and the sample solution. Specific ion electrodes are so closely related to pH electrodes that they tend to be affected by acidity or basicity changes; however, these effects can be overcome by buffering an unknown sample to a pH near the neutral point. The sensitivity of these electrodes depends upon each particular type.

Only a few of the analytical methods available to occupational health have been discussed. Subsequent chapters will elaborate on analytical principles and techniques in greater detail, particularly with regard to applications in occupational health. In addition, the list of recommended texts for additional reading should be consulted regularly.

Suggested Further Reading

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CHAPTER 5

REVIEW OF BIOCHEMISTRY

Martin Rubin, Ph.D.

and

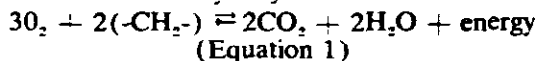
John T. Mountain

INTRODUCTION

In some respects the life process resembles a gyroscope. It is in metastable equilibrium requiring a continuous energy input to function in a structure carefully designed and built to accommodate the system. Yet, despite the intrinsic delicacy of its operation, it is remarkably able to cope with and recover from stresses that would cause alterations in its equilibrium. Living systems are incredibly complex and require an exquisite integration of processes to fulfill the requirements of energy production, structural formation and maintenance and homeostasis — the maintenance of the status quo. Biochemistry provides the scientific discipline to accommodate much of our present knowledge of life. It is convenient to review the subject from the viewpoint of the divisions that have been enumerated. To show how normal biochemical processes may be affected by chemical agents, examples of biochemical pathology will be cited, as well as clinical applications of biochemistry in the detection of occupational disease.

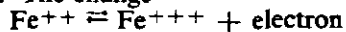
Energy Production

The fundamental reaction by which energy is produced in the body may be written:



This is an oxidative process by which oxygen has been added to the fuel source, $(-CH_2-)$ to produce the waste materials carbon dioxide, water and energy. As in other energy transformations, the total amount of energy available is independent of the path by which the change occurs. It depends only upon the difference between the free energy of formation of the reactants on the left and the products on the right.

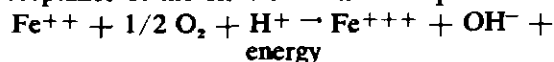
Although the chemical change in the energy-producing system can be written as depicted, the actual source of the available energy originates in the relative positions of electrons in the orbital structures of the atoms involved in the reactions. At one end of the spectrum of electron movement we recognize that an atom may release an electron altogether. The change



represents such an oxidation of Fe^{++} to Fe^{+++} with release of an electron. Since such a process can occur only with the simultaneous acceptance of the electron by another moiety, an oxidation is coupled by a reduction. In biological systems, for example, the oxidative loss of the electron from the Fe^{++} structure is frequently coupled with acceptance by oxygen according to the reaction

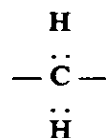


In this case the oxygen atom has been reduced by acceptance of the electron. The total process

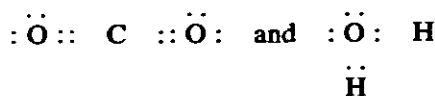


represents a transformation from reactants on the left to products on the right at a lower energy level.

The statement of the reaction involved in the major biological source of energy (equation 1) represents a less extreme movement of electrons than that described for the iron atom. In essence the formulation suggests that the movement of an electron pair from its essentially equidistant point between the carbon and hydrogen atoms in the structure



closer to the oxygen atoms in the product structures



involves a decrease in the energy levels of the reactants and products. The available liberated energy can be usefully trapped by the organism. The energy-trapping mechanism must be one which provides the potential for the conversion of the chemical-bond energy of oxidation to heat, electrical, mechanical or new formulations of chemical bond energy by means of specialized transducers.

To fulfill its function in living systems the overall reaction of energy production implies the availability of oxygen, the fuel substrate $(-CH_2-)$, the removal of waste products (CO_2 , H_2O , and other materials) and a system for control of energy made available by oxidation. These conditions may not prevail due to injuries related to the industrial environment. Silicosis may impair oxygen transport from lung to blood; carbon monoxide may combine with hemoglobin to prevent it from carrying oxygen. The cells may not have access to substrate when the cell membrane is poisoned: thus glucose cannot move into the cell due to inactivation of the phosphorylating enzymes. Waste products cannot be removed when kidney function is damaged by toxic agents such as mercury, uranium, and phenolic substances.

Oxygen Metabolism

Life ceases within minutes when the continuous supply of oxygen is interrupted. A responsive integrated physical, mechanical, hydraulic and

chemical system provides this essential element. The diffusion of oxygen from the air inspired in the lungs to the tissues, where it is utilized, is facilitated by a sequential decrease in its partial pressure. The pO_2 of approximately 158 mm in the inspired air decreases to about 103 mm in the alveolar spaces of the lung, 100 mm in the arterial blood, and 37 mm in the peripheral venous blood subsequent to tissue utilization. The mechanical system of the muscle-controlled collapsible lung provides for the volume flow of oxygen containing air. The hydraulic arrangement of the heart pump and blood vessels allows for the fluid movement of the blood which serves as the oxygen transport medium. In the blood the biconcave doughnut-shaped erythrocyte (red cell) serves as a package for the oxygen transporting protein hemoglobin. This cellular bundle has manifest advantages in protecting and controlling the delivery system.

Hemoglobin

From the viewpoint of the biochemist, the protein hemoglobin provides an intriguing example of the evolution of a molecular structure adapted to a specific function.

The total molecule, with a molecular weight of approximately 64,000 is made up of four subunits of about 16,000. Each subunit has two essential components. One is a polypeptide chain of somewhat more than 140 linearly condensed amino acids. Associated with each polypeptide chain is a planar iron-porphyrin complex, heme, which serves as the oxygen binding moiety. The heme structure fits into a cavity of the polypeptide. In simplified diagrammatic outline, the hemoglobin structure can be visualized as illustrated in Figure 5-1. In order to most effectively fulfill its biological oxygen transport function within the red cell package, the molecule of hemo-

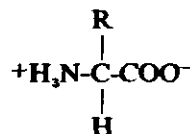


Perutz MF: The hemoglobin molecule, Scientific American, Nov. 1964.

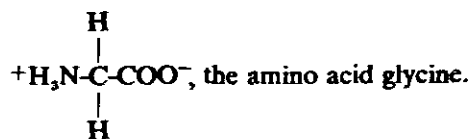
Figure 5-1. Hemoglobin Structure

globin has been carefully designed. It is globular in shape so that it provides maximum volume in the least space. High solubility of the protein is maintained by a large number of charged groups on the surface of the molecule. These tend to attract and hold polar water molecules close to the protein. The hydrophilic shell helps to keep hemoglobin in the aqueous phase.

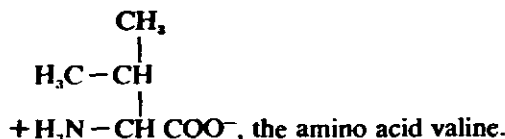
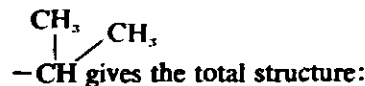
During a normal lifetime, a human will produce five different types of polypeptides which will pair to form four different kinds of hemoglobin. Alpha and epsilon polypeptides appear first in embryonic life followed by alpha and gamma chains in the foetus. With birth, the gamma chain production ceases, to be replaced by the combination of alpha and beta chains of hemoglobin A₁, the major component of adult hemoglobin. Starting with birth, small quantities of a second hemoglobin, A₂, made up of alpha and delta chains are to be found in the erythrocyte. The ultimate arrangement in space of the polypeptide chains is dependent upon the sequence of the polymerization of the alpha amino acids of which they are composed. In the typical amino acid structure:



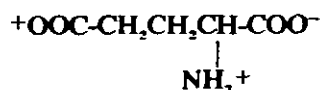
the R group can represent a variety of possible substituent groups. When it is a hydrogen atom, the total structure would be



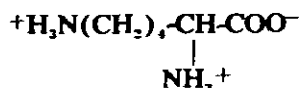
An uncharged hydrophobic lipid group such as:



When the substituent groups are ionizable, as in glutamic acid:



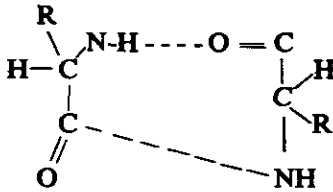
+H₃NC lysine.



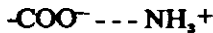
The polymer resulting from linkage of the amino acids through alpha amino and carboxyl ends will have points of charge extending from the chain of this primary backbone structure:



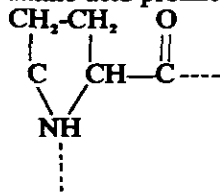
The subsequent arrangement in space of the peptide chain depends upon interactions between groupings. The bonding of a hydrogen atom of the peptide linkage between nitrogen and a reactive peptide oxygen atom, (a "hydrogen bond"):



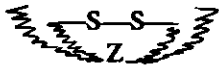
can lead to coiling of the chain in the shape of an alpha helix. This has the overall appearance of a straight cylinder with the peptide backbone wound in a spiral. In addition to the hydrogen bonds, the availability of appropriately placed oppositely charged, "R", side chain groupings can assist in the maintenance of a specific three-dimensional conformation of the structure.



Sharp bends in the chain are made possible by the linkage of the cyclic amino acid proline



More definite intrachain linkage is achieved, for example, by covalent bonding of sulfur atoms from reactive cysteine amino acids:



In the case of the hemoglobin polypeptides made up of approximately 140 amino acid residues, a significant contribution to the structure arises from the interaction of the uncharged hydrophobic R side groupings. These interact by Van der Waals surface forces to provide an essentially uncharged internal cavity from which water molecules are excluded and into which a "heme" oxygen binding structure carefully fits.

Hemoglobin is packaged in the erythrocyte with a variety of enzymes and other substances which play a supporting role in its function and survival. The red blood cell, in humans, has lost its original nucleus; has no mitochondria — those "powerhouses" of the tissue cells—yet uses energy. It has a limited capacity for synthesis, and wear and tear will limit its life span. The term "the rancid red cell," applied to aging cells, seems appropriate; although it functions in oxygen transport, too much oxygen can injure the cell. The anti-oxidant, Vitamin E, is one of its safeguards. Normally, alpha tocopherol, the principal E Vitamin is adequate as supplied in the usual

diet, but special conditions such as high oxygen pressure warrant supplementation. Hence the astronauts' diet includes a proprietary orange drink with a high content of this vitamin.

Oxides of nitrogen as well as more complicated nitrogen compounds — amines, nitro compounds, the sulfa drugs — either directly or through their metabolites can oxidize the iron of hemoglobin to the ferric state. In most people, fortunately, the enzymes of the cell can regenerate hemoglobin by reducing the ferric iron. However, there exists a substantial population in which this process functions poorly. Infants do not have fully developed methemoglobin reducing systems. Drinking water standards for nitrate nitrogen take cognizance of this. There are persons who by reason of genetic defects are inordinately susceptible to methemoglobinemia from contact with a variety of common drugs and chemicals such as naphthalene, sulfas, anti-malarials, nitro and amino compounds. The frequency of such individuals is relatively high (ca. 10%) among American Negroes). Its significance in industrial hygiene and its relation to glucose-6-phosphate dehydrogenase deficiency has been noted in the literature. A smaller frequency of the population are known to exhibit hemoglobin variants — sickle cell, type M, Portland, etc. These variants arise from substitution of different amino acids in the molecule. The variant hemoglobins lack durability. Chemical stress may cause irreparable damage, with anemia resulting. Lists of substances known to induce methemoglobinemia and hemolytic anemia appear in the references.

Other Proteins

As in the case of hemoglobin, the three-dimensional structure of the vast array of proteins found in the body is determined by the sequence of the amino acids of their primary structure. The extent of their helical structure, charge interaction, cross-linking and other secondary and tertiary structural characteristics flow from this factor. In general, the proteins dissolved in the body fluids are globular in shape. A notable exception is the plasma protein fibrinogen which is long and narrow. As in the case of hemoglobin, its structure is in keeping with its function in blood clotting. The straw-shaped fibrinogen molecule readily forms a mat to trap the formed elements of the blood to form a clot at the bleeding point.

Other proteins of the blood plasma include albumin, the major constituent of the plasma proteins. Albumin provides a regulatory influence on the fluid balance of the blood through its osmotic effect. The globulin proteins of the plasma in general provide the potential for immunologic defenses. Upon exposure of the organism to antigenic foreign proteins or small molecules linked to protein (haptens) the immune defenses of the body produce a protective protein antibody able to react and neutralize the antigen. The globulin fraction of plasma proteins, especially the gamma globulins, provide this defensive capability. Structural proteins, such as collagen in connective tissue, are generally long and linear. Collagen is a triple-stranded counter-twisted triple helix. Keratin of skin, hair and nails is constructed of single peptide chains of alpha helices counter-twisted

into bundles of triple chains. This structure provides both strength and flexibility.

A deficiency of the serum protein, α -1 antitrypsin, has been found in some persons with chronic respiratory disease. The deficiency has been correlated with emphysema and a genetic dependence established. Experimental evidence indicates proteolytic enzymes released from injured cells may exacerbate the damage unless suppressed by antitrypsin. Studies of coal miners have yielded controversial conclusions. The frequency of antitrypsin deficiency, which is highest among persons of North European ancestry, makes it a factor to consider in investigations of emphysema and respiratory diseases. The measurement of serum antitrypsin is routinely carried out in many clinical laboratories, although usually in relation to other diseases.

Enzymes

Enzymes, the catalysts of the body, are also proteins. As for other proteins their three dimensional structure or conformation is the consequence of the sequence of the amino acids in their primary structure. The ordered geometry of the enzymes in space provides specific sites at which the substrate molecules upon which they act may become fixed. As a consequence of the localization of the substrate at the active site of the enzyme the energy required to initiate a subsequent reaction is decreased. This decrease in activation energy means that a larger fraction of the molecules will have sufficient energy for reaction even at body temperature, as compared to relatively extreme conditions of pH and temperature required for similar reactions in vitro. The reaction rate will consequently increase. Enzymes thus increase the speed of the reaction. Nearly any influence which changes the shape of the enzyme molecule will influence its ability to function as a catalyst. Modifications in the *hydrogen ion concentration (pH)* of the environment will influence the charge distribution of the enzyme surface and may thus alter the shape of the enzyme or modify the ability of charged substrates to approach and be affixed to the active site. Characteristically enzymes are found to be most effective at an optimal pH. Other influences such as the concentration of charged particles in the medium may also influence the enzyme surfaces. Thus the *ionic strength* of the solution is significant. The *ambient temperature* is important because with increasing temperature the substrate molecules have increasing energy. More of the molecules are capable of reacting and the rate of the reaction increases. On the other hand the enzyme protein also is susceptible to the influence of an increase in temperature and may be inactivated (denatured) with loss of catalytic capacity. The positive and negative effects balance at a point of optimal temperature. For many enzymes this is body temperature.

The catalytic role of enzymes is critical in the performance of metabolism. Factors which influence their rate of reactivity markedly alter body function. The *availability of substrate molecules* is clearly a limiting consideration. When substrate molecules are present in such high concentration

that they continuously occupy all the active catalytic sites of the enzyme the reactions may proceed at *maximal velocity* (V_{max}). On the other hand, the removal of substrate by alternative competitive pathways of reaction, or the presence of molecules in the medium which compete for the active catalytic site may slow a given enzymatic reaction in a sequence of reactions to the point at which it becomes the rate limiting step in an overall metabolic process. Other forms of inhibition are known. When, for example, a component of the medium other than the substrate can attach to the enzyme surface in such a way as to alter the configuration of the active site, it may simultaneously decrease the catalytic activity of the enzyme. This "*allosteric inhibition*" provides a mechanism for the control of enzyme activity and with it a method of process control in the cell. An additional control mechanism involves the accumulation of the products of a given reaction or sequence of enzymatic reactions. Since many systems operate at initial and final energy levels which are not widely separated, the pileup of product may be sufficient to slow or halt the progress of the reaction. This *feedback inhibition* can be exerted at a single enzymatic step or in a chain of reactions.

The structure of an enzyme and hence its catalytic activity may be modified by other influences. In the body these proteins are subjected to a continuous process of breakdown. This may occur by oxidation and hydrolytic scission (proteolysis) of the peptide chains.

External influences such as the presence of toxic metals in the body can interact with active catalytic enzyme sites or react elsewhere with the molecule to render it ineffective. Interruption of the function of a critical enzyme can have overwhelming toxic effects for the organism.

A classic example of this, and of so-called "lethal synthesis," occurs when fluoracetate is metabolized in the citric acid cycle (Figure 5-2): fluocitrate is formed, which bonds irreversibly to the enzyme aconitase, rendering the system inoperable.

While many enzymes function as a single protein entity, a number require the presence of other co-factors and activators. The vitamins, especially those of the B-vitamin group, are in this category. Thiamine, biotin and lipoic acid are co-enzymes frequently associated with enzymes required for the addition and removal of carbon dioxide from substrates. Nicotinamide, riboflavin, and ascorbic acid have roles in energy transfer associated with oxidation/reduction reactions. Pantothenic acid is an essential component of the enzyme complex, coenzyme A, involved in the metabolism of acetyl groups. Vitamin B-12, cyanocobalamin, has the trace metal cobalt as an integral portion of its structure and is a component of the enzyme system which is concerned with the metabolic handling of a one-carbon unit. Folic acid, another member of the B-vitamin family, has a related function.

In the absence of an adequate nutritional supply of the vitamins, the function of the enzymes of which they are components is severely compromised. The resulting metabolic malfunction

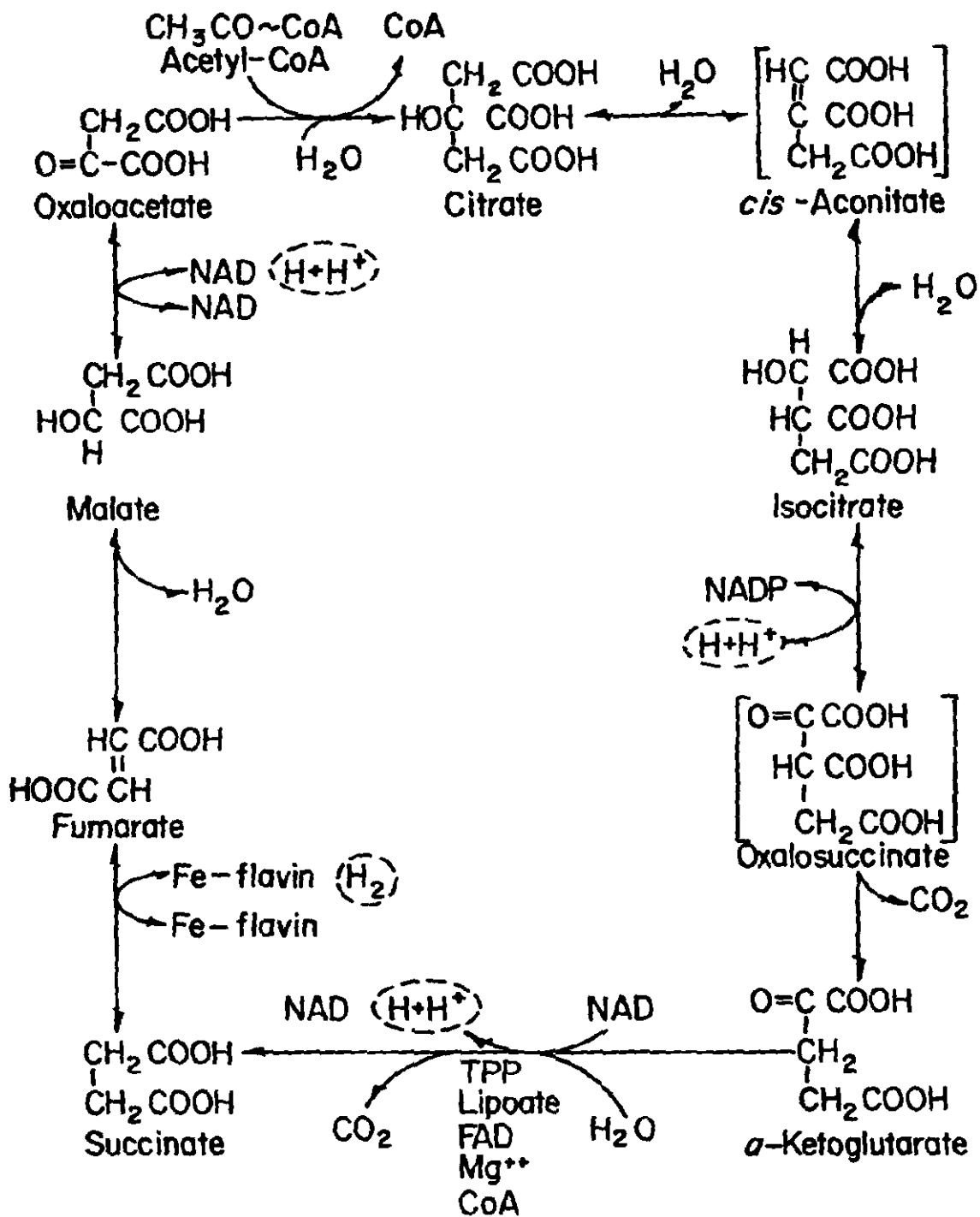


Figure 5-2. Steps in the Tricarboxylic Acid Cycle

finds expression many ways. Tiredness, lack of energy, anemia, loss of weight, loss of appetite and a host of subclinical and, in the acute stages, overt clinical manifestations can occur.

Cobalt has been mentioned as a component of the total enzyme systems involved in the metabolism of single carbon units. Other metals fulfill related functions as enzyme co-factors. Calcium and magnesium have prominent roles in hydrolytic reactions. Copper, iron and molybdenum serve for the purposes of oxidation/reduction systems. Zinc occurs in hydrogen transport enzyme systems, in the hydration of carbon dioxide to form carbonic acid and, as does manganese, in enzymes involved in the cleavage of peptide bonds. With the exception of calcium and iron, nutritional deficiencies are rare for these trace elements. It is generally the fact that the intestine provides a barrier to the excess accumulation of the metals. On the other hand the nutritional intake of iron and calcium may be marginal for some portions of the population. Women during the childbearing years are subjected to continuous iron loss in menstrual bleeding. Their nutritional replacement of this loss is frequently insufficient to maintain homeostasis. At times of rapid skeletal growth in children, during periods of lactation and in older age for both women and men the usual intake of calcium may also be marginal or insufficient.

Types of Enzymes. In the course of the previous discussion some examples have been cited of the types of reactions catalyzed by enzymes. A systematic grouping on this basis would include the 1) *oxidoreductases*, enzymes concerned in oxidation/reduction reactions 2) *the transferases*, enzymes which bring about the movement of a molecular grouping from a substrate to a recipient 3) *the hydrolases*, which are involved in cleavage of bonds by the addition of the elements of water 4) *the lyases*, a group of enzymes whose function is the cleavage of a segment of a molecule 5) *the isomerases*, which catalyze the rearrangement of the molecular framework and 6) *the ligases*, which bring about the combination of molecular structures by covalent linkage.

The isolation of enzymes of distinctive structure but which perform the same catalytic function is a subject of considerable interest. These *iso-enzymes* by virtue of their variable cellular distribution and modified responsiveness to controlling mechanisms, are able to provide enhanced modulation of the complex integration of the reactions which occur in metabolism. The fact that organs of the body and consequently the tissues and cells of which they are composed may have specialized functions is a matter of considerable import for the diagnosis of disease. When liver tissue is destroyed as in acute hepatitis, the breakdown of the liver cells releases cellular enzymes to the plasma. By measuring the plasma enzyme activity of the liver transferases such as glutamic-pyruvic transaminase and the liver dehydrogenases such as lactic dehydrogenase, it becomes possible for the physician to obtain a biochemical index of the cellular destruction. Muscle tissue damage, as in acute myocardial infarction or in the wasting diseases of muscular dystrophy can be monitored

by the activity level of the phosphate group transfer enzyme, creatine phosphokinase. Differentiation between damage to the liver or the heart can be made by the identification in plasma of the respective lactic dehydrogenase isoenzyme.

Because of their essential functions the enzymes are vulnerable points of attack by external influences. Toxic agents from the environment as well as drugs used for diagnosis and therapy can induce marked changes in the entire organism by alteration of the rates of enzyme reactivity.

Measurement of the activity of the enzyme cholinesterase has been very useful in surveillance of exposure to anti-cholinesterase insecticides. The enzymes in the blood, like that in the nervous tissue, split acetyl choline into acetic acid and the base, choline, but other substrates may be used in following the reaction. Depression of enzyme activity below normal is an indicator of response to the agent.

In other cases serum enzymes may be increased, rather than depressed, as a result of toxic injury to cells or organs. There are five isoenzymes of lactic dehydrogenase occurring in serum. These may be separated by electrophoresis, using standard clinical laboratory equipment. They are designated by number according to their rate of migration, and their proportions reflect, in large degree, their tissue of origin. The heart contributes much of LDH isoenzyme No. 1, the liver mostly LDH isoenzyme No. 5. Recent work on animals, and a few cases of mercury exposure of workmen suggests that an increase of LDH isoenzyme No. 5 over normal proportions may serve as an indicator of liver injury from exposure to inorganic mercury.

Protein Synthesis

Under normal conditions the continuous breakdown of protein is matched by protein biosynthesis. The individual stays in nitrogen balance in that nitrogen constituents provided in the diet are matched by nitrogen excretion in feces and urine. During periods of growth the increase in cell mass requires that protein synthesis be accelerated. More nitrogen is retained than is excreted. The individual is in a state of positive nitrogen balance.

Whether for replacement or for growth the continuous need for protein synthesis is met by an exquisitely coordinated mechanism in the cell. The problems to be solved are formidable. The flow of requisite structural components, the amino acids, must be maintained and controlled in the cell environment. The transfer of the amino acids from the plasma across the cell wall requires a specific transport mechanism and a supply of energy. Once within the cell the amino acids need to be selected and arranged in the proper sequence so that when final linkage takes place between their adjacent amino and carboxyl groups, the resulting polypeptide chain will have the exact sequence requisite for its biologic and biochemical function. To provide an inkling as to the dimensions of the problem, consider that thousands of proteins of specific structure may be required, that variation in sequence of amino acids may result in uncountable structural modification, and that

the initiation and termination of the synthetic events must be completely controlled if the cell is to avoid death by atrophy or by the uncontrolled overgrowth of cancer.

The somewhat more than two dozen individual amino acids required for protein synthesis have their original source in the dietary intake. When ingested in the form of food proteins, they are cleaved in the intestine by the proteolytic enzymes of the pancreas, (trypsin, chymotrypsin and an array of peptidases) to the constituent amino acids which are then actively absorbed across the intestinal wall into the plasma. While the processes of metabolic transformation can convert most of the amino acids from one structural form to another, a number can be provided only from food sources. These "essential amino acids" include valine, methionine, threonine, leucine, isoleucine, phenylalanine, tryptophan and lysine. For adequate nutrition a protein intake of between 1 to 2.5 g/kg/day from a variety of foods including meat, eggs, milk and plant sources is considered requisite. The lower value provides for normal tissue replacement in the adult while the higher value is needed for the rapidly growing infant.

Following absorption from the intestine, the amino acids circulate in the plasma for utilization directly in cellular protein synthesis or metabolic conversion. The uptake of amino acids by the cell involves their specific "active transport," an energy requiring process, across the cell membrane. While the detailed mechanism of membrane transport is not clarified, it is established that in some instances the process is controlled by an initial attachment of hormones to specific receptor sites on the cell membrane. This triggers the subsequent events which bring about the cellular synthesis of proteins.

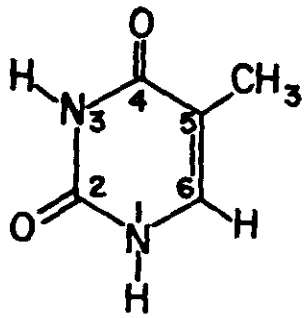
Blueprints for Proteins

Protein synthesis starts with the stimulation of the cell nucleus to read an appropriate portion of its stored genetic information in its macromolecular double-stranded desoxyribonucleic acid (DNA) and produce from this template a messenger ribonucleic acid (mRNA) which will serve as the information source for protein synthesis in the cell cytoplasm. The mRNA moves from the nucleus to the cytoplasm and affixes to the ribosomes located in the fine structure of the cell sap. At this point the amino acids of the cytoplasm are selectively activated using available energy from the "high energy" chemical bond of adenosine triphosphate (ATP) to attach to a carrier transfer ribonucleic acid (tRNA). The activated amino acid is then delivered to the ribosome where it is attached to the template of the messenger RNA. Depending upon the nature of the code of the RNA the various activated amino acids are tied to the ends of the growing peptide chain to form the linear peptide. The tRNA, having delivered its specific amino acid, returns to the cytoplasm for reloading of an amino acid. The processes which signal the start of protein synthesis and its completion at the end of the peptide chain are not clearly understood as yet for mammalian cell systems. It appears though that a regulatory code provides for the start and stop signal of protein biosynthesis.

The remarkable capability of living things to transmit hereditary information resides in the unique structure of the nucleic acids. Their building blocks are the nucleotides composed of the sequence: base-sugar-phosphate. The bases are derived from the purine and pyrimidine classes of compound by minor functional group modifications (Figure 5-3). The sugars in the nucleotides are either of the ribose or 2-desoxyribose structure with the nucleotide assembly linked by way of a phosphate ester. Not only does the nucleotide serve as a common structural unit in the nucleic acid but also in an isolated unit as a co-factor of many enzyme systems to be later discussed. The linkage of nucleotides to form a strand of nucleic acid is through the combination of a phosphate of one nucleotide to the sugar of a second. In this way the nucleotide bases extend horizontally from the linear chain in the same way that the rungs of a ladder are tied to the frame. In actuality two chains of nucleotides associate with the bases in apposition and are linked through hydrogen bonds. The total system would be approximated by visualizing the rungs of the ladder to be cut in the center of each but held together so that they still had a ladder appearance. A further complication is that the ladder instead of being in one plane is twisted in a right-handed helix. In order for this structure to serve as an information mechanism it unfolds so that a single strand of nucleotides is exposed to the environment. Synthesis of a new strand now takes place by the linear alignment of complementary bases to those of the original strand. The lineup of bases in the newly formed nucleic acid (mRNA and tRNA) provides for the specific ability of the new structure to selectively pick a given amino acid from the environment for protein synthesis on the ribosomal surface. Protein synthesis can be influenced by environmental factors. Inhalation of vanadium pentoxide alters the content of the amino acid cystine in the hair of rats and the fingernails of workmen. The lungs of coal miners with emphysema contain more of the fibrous tissue protein, collagen, than do normal lungs or abnormal, but not emphysematous, lungs. Protein synthesis can be altered or stopped by exposure of man to environmental factors and this can result in enzyme induction or repression, misdirected or uncontrolled protein synthesis. These changes then manifest themselves as clinical changes, lesions or death.

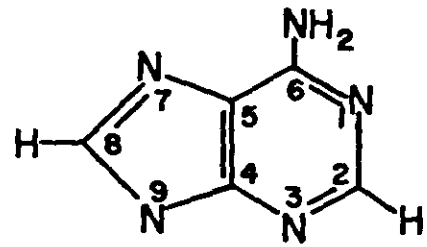
Hormones

Hormones are defined as a class of endogenous compound effective in low concentration in controlling or modifying metabolic processes at a distant receptor. Their activity may be exerted on a target cell to induce metabolic change directly, or they may serve to cause the production of a second hormone which in turn controls cellular function, or a given hormone may have both types of end result. The hormones originating in the pituitary gland in response to "releasing factors" have generally been divided into two groups depending upon their anatomical source. Hormones of the anterior lobe include the gonadal active follicle stimulating hormone (F.S.H.), the luteinizing hor-



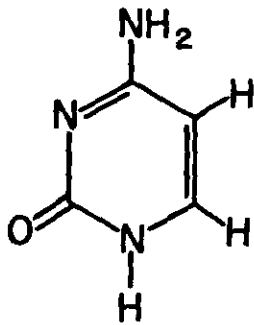
Thymine

PYRIMIDINES

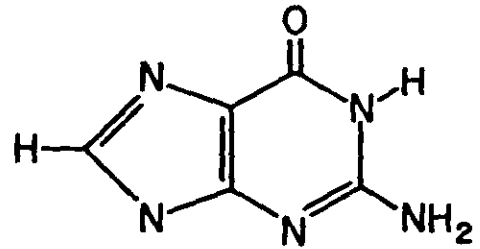


Adenine

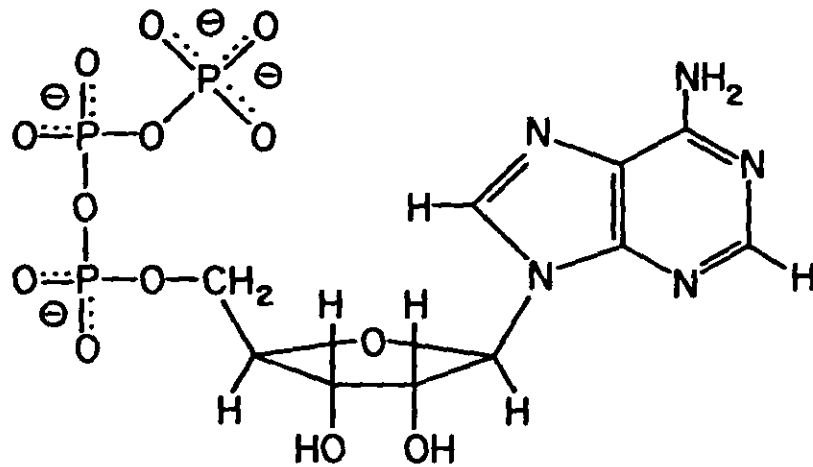
PURINES



Cytosine



Guanine



Adenosine Triphosphate

Figure 5-3. Typical Pyrimidine, Purine and Nucleotide Fragment

mone (L.H.), and prolactin whose major effects act directly upon their specific target cells. In addition, the anterior pituitary also produces other protein hormones which may also have more general metabolic effects. *Thyroid stimulating hormone* acts directly upon the thyroid gland to induce the capture of plasma iodide by the gland, its incorporation into a protein thyroglobulin, scission of the protein to yield a second amino acid hormone *thyroxine* which circulates in the plasma partly bound to a carrier protein, thyroid binding hormone. Thyroxine acts as a potent regulator of cellular metabolism inducing a marked increase in the rate of oxygen utilization simultaneously with a sharp increase in cellular metabolism. The *growth hormone* of the anterior pituitary is especially effective in inducing protein synthesis in early development. Increase in cell mass, development of the long bones and accelerated utilization of carbohydrate are among its noteworthy effects. The primary effect of the *adrenocorticotrophic stimulating hormone* (ACTH) is to induce the synthesis of the steroid hormones of the adrenal cortex. Two hormones of the posterior pituitary have regulatory functions. *Oxytocin* and *vasopressin* are peptides of eight amino acids each. The major effect of the former is to cause contraction of smooth muscles. Vasopressin has a significant action on the kidney inducing salt and water retention.

Although several dozen intermediates and steroid metabolites have been isolated from the adrenal cortex, two compounds represent the major hormonal products of the gland. *Cortisol* (*hydrocortisone*) is elaborated upon the stimulus of ACTH by a biosynthetic pathway which starts with the two-carbon acetate unit. Successive combinations of three such units lead to a six-carbon intermediate which is then degraded to the five-carbon isoprenoid structure. Condensation of three five-carbon units leads to the C-15 farnesol moiety which in turn doubles to form the 30-carbon linear squalene structure. It is of interest that these intermediates in the pathway of mammalian biosynthesis also occur in the plant world and lead to the familiar essential oils. Cyclization of squalene produces the condensed four-ring structure of the steroid nucleus and degradation of the side chain produces the C-27 sterol, cholesterol. When the nutritional circumstances of the individual provide a greater supply of C-2 acetate units than can be utilized for energy or biosynthetic turnover the excess is converted into fats, including cholesterol. The combination of excessive lipid intake, especially saturated fats, and a sedentary and stressful life style is associated with high concentrations of cholesterol in the plasma and with atherosclerotic plaque deposition in the vascular system. Individuals in this category are high risk possibilities for coronary disease.

Although not universally accepted, some evidence suggests that carbon monoxide and carbon disulfide may elevate cholesterol and promote plaque formation. Vanadium compounds have been found to inhibit cholesterol synthesis in animals and man; however, after some time the orig-

inal effectiveness disappears. The additional metabolic degradation of cholesterol in the adrenal gland produces *cortisol*. This steroid hormone provides the stimulus for a biochemical response to stress. It induces conversion of amino acids to glucose and stimulates the adipose storage areas of lipids to release fatty acid for transport to the liver for utilization as an energy source. The second major steroid hormone of the adrenal cortex is *aldosterone*. The role of this hormone is to assist in the control of the excretion of salt and water. When the adrenal is destroyed as in Addison's disease, the accelerated loss of salt and water can have rapidly fatal consequences. Other steroid hormones include *progesterone* produced by the corpus luteum and the placenta in pregnancy to maintain the uterine cellular structure, *estradiol* formed in the ovary and responsible for the development of secondary female sexual characteristics and *testosterone*, the sex hormone in the testes responsible for analogous processes in the male. Mention should be made of the important hormone *epinephrine* of the adrenal medulla. It is another means for biologic response to stress in that its production and distribution in response to a neural signal causes constriction of the blood vessels with increase in blood flow, release of glucose from the liver to the plasma and fatty acid from the lipid stores. All these responses provide an added capability to meet emergency contingencies. Several other glands provide significant factors for metabolic control. The pancreas is the source of the protein hormones, *insulin* and *glucagon*, which exert a direct control over the glucose level of the blood. Insulin is released from the pancreas upon elevation of blood sugar after a meal or for other reasons. By incompletely understood mechanisms the hormone accelerates the transfer of the sugar from the circulation to the cells where it may be stored as the polymer glycogen until required. Glucagon on the other hand, is elaborated when blood sugar levels fall below the normal range. Its major biochemical effect is to cause breakdown of glycogen and release of glucose to the circulation. *Parathyroid hormone* formed in the parathyroid gland and *thyrocalcitonin* a product of the thyroid gland are involved in the maintenance of calcium homeostasis. In response to a decrease in the normal circulating level of calcium, the released parathyroid hormone produces a sequence of biochemical responses whose net result is to elevate the concentration of plasma calcium. Hormone induced breakdown of bone cells provides calcium and simultaneously phosphate which is cleared by the kidney by hormone induced phosphaturia. Secondary conservation of calcium occurs at the kidney simultaneously with increased absorption at the intestine. An elevation of plasma calcium is followed by increased secretion of thyrocalcitonin producing enhanced deposition of the element on the skeletal surface and fall in circulating calcium levels. The biochemical balancing of the two hormones provides a fine adjustment for homeostasis of plasma calcium which is basically maintained by interaction of plasma calcium with the mineral reserves of the bone. For these hor-

mones and most others described above recent investigations have established a common sequence of events leading to their biochemical consequences. At the target cell hormone specific receptor sites on the cell membrane are stimulated to activate the membrane enzyme adenylyl cyclase. In turn the enzyme converts adenosine triphosphate (ATP) to cyclic adenosine monophosphate (cAMP) which in the intercellular milieu initiates the cellular events characteristic of the hormonal response. The formulation of this "second messenger" concept has provided a framework for further study of the intriguing question of the mechanism of the profound effects of trace amounts of hormonal substances. In essence the overall picture is one of an amplification system in which a trigger mechanism provokes a significantly enhanced response. An interesting correlative change that occurs with the membrane fixation of most hormones is the release and cellular uptake of calcium ion. This event has been invoked to explain the electrical changes observed in the membrane upon hormonal stimulus.

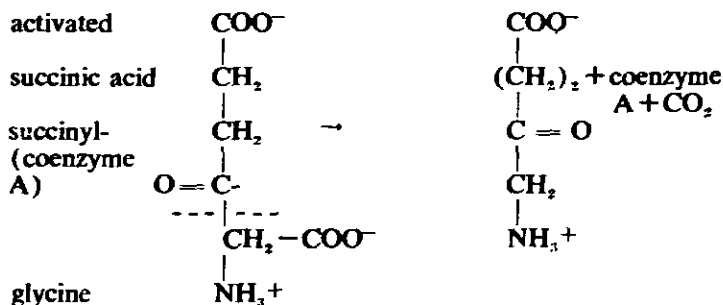
Hormone production or function is known to be altered by some metals and organic compounds.

Lead interferes with thyroid hormone production; the synthesis of epinephrines depends on adequacy of copper for an amine oxidase. It has been reported that a deficiency of norepinephrine was associated with treatment for alcoholism with antabuse; this compound is known to bind to copper. Chromium has been found to be an essential element, notably for its role in glucose metabolism. It is apparently an adjunct to insulin. Some elderly diabetics have been benefited by administration of chromium.

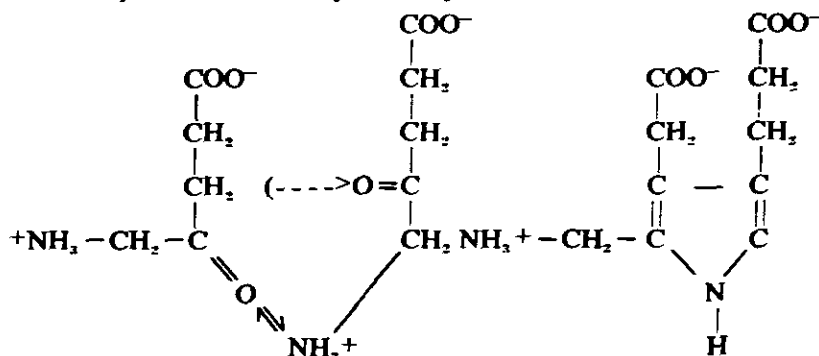
The Heme Porphyrin Structure

While the globin protein serves as the structural framework, it is the iron-porphyrin combination which is responsible for the molecular transport of oxygen. At the time of synthesis of hemoglobin in the young red cell all components, the globin protein, the porphyrin structure and the iron atom must be at the right place at the right time.

The biosynthesis of the porphyrin molecule starts with the amino acid glycine which couples with activated succinic acid in the presence of an enzyme catalyst to yield, after elimination of CO₂, delta aminolevulinic acid:



Two molecules of delta aminolevulinic acid join asymmetrically to form porphobilinogen in the presence of an enzyme catalyst:



and four molecules of porphobilinogen link in linear fashion and then ring close to form the important intermediate structure uroporphyrinogen. By selective loss of carbon dioxide and hydrogen atoms, this is converted to the essential structure protoporphyrin IX (Figure 5-4).

Insertion of the iron atom completes the assembly of the heme structure for junction with the globin to form hemoglobin.

Porphyrin Chemistry

Certain aspects of the heme structure are of special significance to its oxygen transport func-

tion. The planar structure of the molecule permits it to slip readily into the cavity of the globin protein. It is held there by several forces. The anionic charges of the porphyrin carboxyl side chains are linked to points of positive charge in the globin protein. The conjugated double bonds of the porphyrin confer aromatic character upon the structure with consequent availability of pi electrons. These interact with analogous aromatic structures strategically located in the cavity wall. The iron atom, linked by coordinate bonding to four nitrogen atoms of the porphyrin has two coordinating bonds available for additional linkage. One is

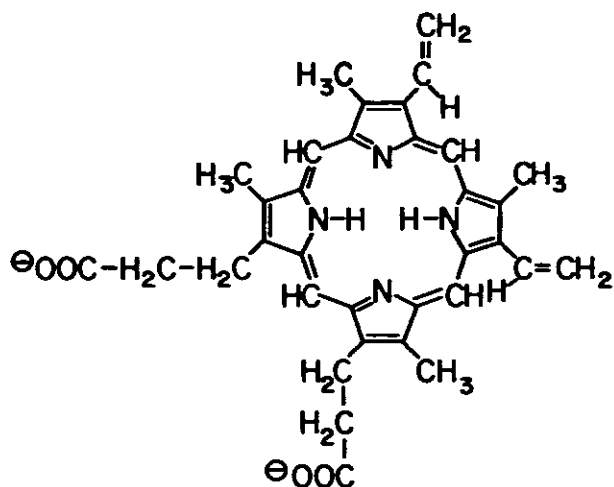
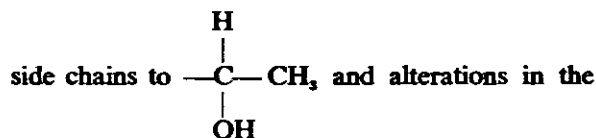


Figure 5-4. Structure of Protoporphyrin IX

utilized for linkage to a histidine amino acid of the globin structure and the sixth linkage is available for the reversible binding of oxygen.

In addition to the heme structure of hemoglobin, porphyrins are essential in the processes of energy production. In the cytochrome molecules, they perform the task of electron transport from one energy level to another. Subtle changes in the structure, as by conversion of the $-\text{CH}=\text{CH}_2$



structure of the combining protein serve to convert the molecule from its role of oxygen to electron transport.

Breakdown of the porphyrin structure involves cleavage of the ring to form a linear *tetrapyrrole* followed by scission of the tetrapyrrole to a dipyrrole structure. The accompanying color changes of the molecules provide the green pigment of bile and then the clay brown pigment of feces. When liver damage or obstruction inhibits the catabolism or excretion of the bile pigments, they appear in the blood and skin as the yellow color of jaundice.

Abnormalities of porphyrin metabolism are common to a number of industrial health problems. Delta aminolevulinic acid accumulates in



and the reduced flavin nucleotide. The latter compound feeds into the mitochondrial electron transport system for capture of the available energy in the form of the ATP high energy bond.



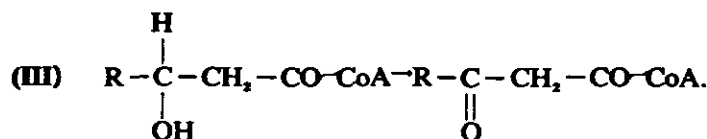
urine in lead poisoning and special chromatography columns are commercially available for assaying its urine content. Lead also increases the urinary coproporphyrin; this substance was once regarded as criterion for lead poisoning. As noted, accumulation of porphyrin waste products may cause porphyria or bilirubinemia unless the liver functions to convert them into less toxic, excretable compounds. The induction of liver enzymes, by DDT, to enhance bilirubin detoxication, has been noted.

Metabolism of Lipids

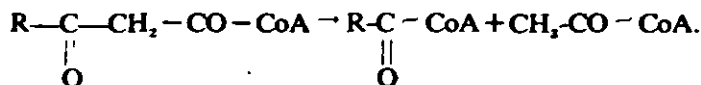
While carbohydrate and lipid can largely replace each other in the human diet some lipid appears essential to supply not only dietary palatability but also the highly unsaturated fatty acids that can not be produced by metabolic interconversions. The high caloric value of lipids also makes this class of nutrient a valuable energy storage reservoir. Upon ingestion the lipids along with other dietary nutrients are emulsified in the stomach and pass to the upper intestine where the bile acids, originating in the liver by catabolism of cholesterol, assist in the stabilization of the dispersed nutrients. The dietary lipids are then cleaved by the pancreatic lipases to yield fatty acids as well as mono and diglyceride scission products of the nutrient triglycerides. In the mucosal cells of the intestine a separation and re-shuffling of the lipid constituents takes place. Short chain fatty acids proceed by way of the portal circulation to the liver while the longer chain fatty acids are resynthesized into triglycerides. Dietary cholesterol is esterified to a great extent with unsaturated fatty acids during intestinal cellular transport. The lipids which move into the lymphatic circulation after absorption do so in the form of small droplets called chylomicrons. These are stabilized by a coating of protein which inhibits their tendency toward agglomeration. The lymphatic drainage is discharged into the circulation at the thoracic duct. Lipids are then picked up by adipose tissues or are metabolized by the liver. The course of lipid metabolism in the liver or peripheral tissues involves a process of sequential degradation by which the fatty acid chains are reduced two carbons at a time to yield acetyl coenzyme A. This common catabolic end point serves as the primary fuel source of the cell. The mechanism by which the catabolic sequence occurs is of some interest. In the first step the fatty acids are activated by the use of ATP bond energy to form their acyl thiol coenzyme A esters. In this form they are dehydrogenated to yield the alpha-beta unsaturated compounds (Reaction I).

In a second step a hydrolase enzyme adds a molecule of water across the double bond to produce a beta hydroxyl acyl derivative (Reaction II).

In the third step the hydroxyl group is oxidized by a dehydrogenase enzyme with a nicotinamide

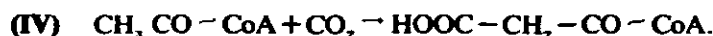


The reduced nicotinamide co-factor proceeds to surrender the hydrogen to mitochondrial oxidation for additional energy capture as the ATP bond.



The acetyl coenzyme A produced in this reaction feeds into the tricarboxylic acid (TCA) cycle. The residual fatty acid derivative is ready for further degradation by another two carbon units.

The reverse process of fatty acid synthesis



This in turn adds a second acetyl coenzyme A unit, loses carbon dioxide and ends as a C-4 keto acid, $\text{CH}_2-\text{CO}-\text{CH}_2-\text{CO}-\text{CoA}$. By reversal of previous reactions, essentially, the body produces a C-4 fatty acid, butyric acid, $\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CO}-\text{CoA}$. Repetition of the procedure results in chain elongation to form the longer chain acids. It is interesting to note that the process of fatty acid anabolism is not identical with the catabolic route. This difference provides the organism with the advantage of multiple points of metabolic control. The final step in the synthesis of triglyceride is the addition of the activated fatty acid to phosphorylated glyceride to form the final product. In addition to the storage of lipids in adipose tissue the materials of this category have an essential structural role in cell membranes. The generalized structure of these compounds consist of a diglyceride coupled through a phosphoric ester to a nitrogenous constituent. In the formula $\text{R}-\text{PO}_3-\text{CH}_2-\text{CH}_2-\text{NH}_3^+$ as for cephalin for example, the structure has a highly hydrophobic fatty diglyceride, R, head with a charged ionic polar nitrogenous tail. The net result is that the molecule orients itself in an aqueous medium with the polar group in the water phase and the lipid structure oriented in the opposite direction. When combined with cholesterol and proteins these phospholipids provide the structure of the cell membrane which allows for remarkable specificity and selectivity for the passage of small molecules. Modification in structure by substitution on the nitrogen atom provides for the multiplicity of the class of phosphatides. Attachment of the carbohydrate inositol yields the *inositides*.

Substitution of the glyceride fatty acid by aldehydes yields the family of plasmalogens.

The prostaglandins are an interesting family of lipid substances. Although fatty acids, chemically, they are tissue and cell hormones functionally.

co-factor to produce the corresponding keto acid (Reaction III).

In a final step of the process the fatty acid is cleaved to yield a molecule with two less carbon atoms with the simultaneous formation of an acetyl coenzyme A compound.

accounts for the fact that nutritional excesses can convert dietary constituents to fat. Acetyl coenzyme A by mediation of a biotin cofactor enzyme temporarily adds a molecule of carbon dioxide to form malonyl coenzyme A. (Reaction IV).

The analgesic effects of aspirin are ascribed to its inhibition of prostaglandin synthesis.

Metabolism of Carbohydrates

Dietary sugars and starches provide most of the carbohydrate in human nutrition. The starch macromolecule is hydrolyzed in the intestine by the pancreatic enzyme amylase. After cleavage to glucose this monosaccharide and others present in the food are absorbed across the mucosal surface of the intestine. For the most part the hexose sugars such as galactose and fructose are converted to glucose either during absorption or subsequently in the liver. After transport through the portal blood from intestine to liver the glucose is either utilized in the liver as an energy source, polymerized for storage as glycogen or proceeds through the peripheral circulation as part of the glucose supply to the tissues. Two major pathways characterize the catabolism of glucose. The first is the process of glycolysis by which glucose is converted anaerobically to pyruvic acid or further to lactic acid. The second alternative sequence, the pentose phosphate shunt, is an aerobic degradation of glucose which subserves certain specialized needs of the organism.

Glycolysis starts with the energy requiring phosphorylation of glucose to yield its 6-phosphate. Rearrangement of the molecule by enzymatic isomerization yields fructose 6-phosphate which is further phosphorylated to produce fructose-1, 6-diphosphate. This latter reaction is also endogenous in its requirement for an energy source. After phosphorylation at the ends of the molecule, scission takes place in the center to produce two phosphorylated C-3 units, phosphoglyceric aldehyde and phosphodihydroxyacetone. Enzymatic isomerization converts the latter to the former compound. In essence, then, one six-carbon sugar is converted to two three-carbon sugars. In the next stage of glycolysis the aldehyde group is converted to an acid with some of the

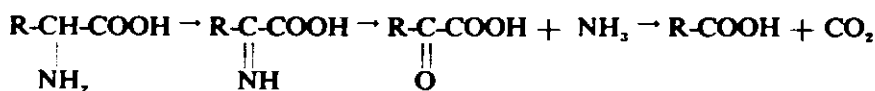
released energy trapped in the form of the reduced nicotinamide co-factor. In turn, the reduced co-factor feeds into mitochondrial oxidation to provide usable energy in the form of the high energy ATP bond. The glycolytic process continues with shift of the phosphate from its position at the end to the center of the molecule. The 2-phosphoglyceric acid loses a molecule of water to produce the enol phosphate which in turn relinquishes the phosphate to produce pyruvic acid. Under the usual conditions of oxygenation the pyruvic acid is oxidatively decarboxylated to yield carbon dioxide and acetyl coenzyme A. During vigorous muscular exercise the pyruvic acid is reduced to lactic acid which is released to the plasma for return to the liver. The glycolytic sequence thus starts with a six-carbon sugar, glucose, traps some of the decrease in free energy in the form of metabolically useful reduced co-factor or in the bond energy of ATP and provides four of its six carbons as acetyl coenzyme A for further metabolism.

The second major pathway for metabolism of glucose is oxidative, requiring oxygen for the first step. An enzyme, glucose-6-phosphate dehydrogenase, utilizing nicotinamide-adenine dinucleotide phosphate, (NADP), as a co-factor converts the glucose-6-phosphate substrate to the corresponding acid. The resulting decrease in free energy from the starting material to the reaction products is partly held in the form of the reduced nucleotide to be utilized elsewhere in the body for anabolic purposes, for example, the reductive steps involved in lipid biosynthesis depend on the availability of NADPH. Decarboxylation of the gluconic acid produces a five carbon pentose sugar. In an intricate series of recombinations and scissions the five-carbon pentose is eventually degraded to carbon dioxide. In contrast to muscle tissue which metabolizes glucose almost entirely by the Embden-Myerhof glycolytic path, the oxidative sequence of the pentose shunt occurs in other cells, especially liver and erythrocytes, as an alternative although less significant mode of carbohydrate

breakdown. The significance of this pathway is that it offers a means for the body to provide the pentoses needed for nucleic acids, yields NADPH needed for a number of anabolic tasks, and offers an alternate means for interconversion of carbohydrates as well as the breakdown of glucose. The reversal of carbohydrate breakdown can occur from any metabolite which is convertible to pyruvic acid. Such possible sources include the lipids and the proteins. Thus most foodstuffs can ultimately yield storage carbohydrate in the form of liver and muscle glycogen. At some points in the glycolytic and glycogen synthesizing pathways the reaction energetics is highly unfavorable for anabolism. At such points alternative steps circumvent this problem. For reversal of glycolysis one such step is the conversion of pyruvic acid to phosphoenolpyruvate. The problem has been solved by addition of carbon dioxide to pyruvate, to form oxalacetate followed by conversion of the ketoacid to phosphoenolpyruvate in a coupled reaction. While the breakdown of glycogen to glucose-1-phosphate is catalyzed by the complex group of phosphorylase enzymes the synthesis of the storage polymer follows an alternative pathway. Glucose-6-phosphate is coupled to the nucleotide uridine which serves as a carrier of the saccharide in the form of uridine diphosphate glucose (UDPG). In this form the glucose is available as well for interconversion to other sugars such as galactose and the amino sugars. The latter form a significant component of the mucopolysaccharides, a complex structural polymer especially of connective tissues.

Protein Metabolism

Amino acids derived from proteins can enter into the mainstream of energy production by elimination of the nitrogen of the amino group and oxidative conversion of the product to a fatty acid derivative. These reactions, which occur primarily in the liver, may be depicted in the following stages:



The ammonia produced in the sequence is combined with carbon dioxide to yield the excreted waste product urea, NH_2CONH_2 (Cf. Figure 5-5). For the adult on a usual mixed diet approximately 20-30 g/day of urea will be formed and excreted through the kidney into the urine. Uric acid is the end product of purine metabolism in man.

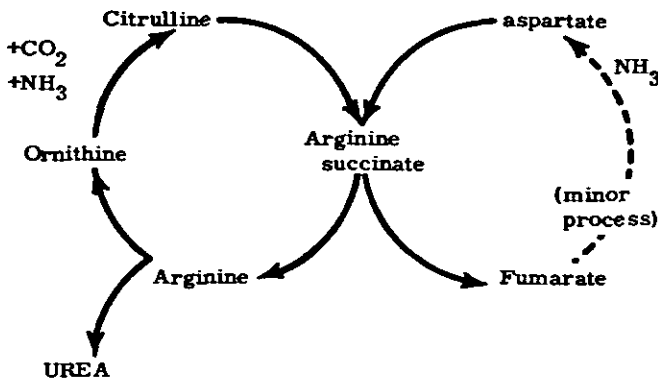
Metabolism of Acetyl Coenzyme A

The conversion of proteins, carbohydrates and lipids to the two-carbon acetyl unit in the form of its coenzyme A combination makes this a focal point of energy metabolism. By means of the tricarboxylic acid (TCA) cycle, the two carbons of the acetyl group are converted to carbon dioxide. The difference in the free energy levels of the acetyl group and its product carbon dioxide is held temporarily by the conversion of the oxidized form of the nicotinamide co-factor (NAD^+) to the reduced state, NADH. The steps involved

in the TCA cycle consist of a series of enzymatic condensations, redox reactions, and decarboxylations summarized in Figure 5-2. The net result of the total process is the elimination of the acetyl group in the form of CO_2 and the formation of reduced co-factors for energy trapping in mitochondrial oxidation.

Mitochondrial Oxidative Phosphorylation

Part of the energy released by catabolism is made available to the body in the form of heat. For all other purposes, however, it must be harnessed in a way which will permit its utilization in subsequent coupled energy requiring reactions. This is achieved in the process of mitochondrial oxidative phosphorylation. The oxidation process is controlled by subdivision of energy release into incremental steps. At appropriate points in the reaction chain, energy available from oxidative change is used to couple inorganic phos-



Dawkins MSR, Rees KR: A Biochemical Approach to Pathology. London, Arnold, 1959.

Figure 5-5. Urea Cycle

phate to adenosine diphosphate (ADP) to form the important energy storage form adenosine triphosphate (ATP). The reaction: $ADP + P_i \rightarrow ATP$ requires approximately 8000 Cal/mol to form the phosphate anhydride bond. Conversely when the ATP molecule is coupled in an appropriate enzyme system with an energy requiring reaction it is able to make available the 8000 Cal/mol of its "high energy" phosphate bond. In an appropriate system this energy can be utilized for new chemical bonding, electrical, or mechanical energy.

Steps in Mitochondrial Oxidative Phosphorylation

The free energy change ($-\Delta F'$) represented by the change from reactants to products, can be measured in calories or recalculated in terms of the change in electrode potentials, (E'_0), expressed in volts since the two terms are related by the expression: $\Delta F' = -\Delta E'_0 nF$ where n represents the number of electrons (or hydrogen atoms) involved and F is the Faraday (96,487 coulombs). From this relation it can be calculated that a difference of 1 volt between the E'_0 values when $n=2$ represents a change of 46,166 gram-calories. For mitochondrial oxidative phosphorylation the initial redox step at a value of $E'_0 = -0.32$ for the system $NAD^+/NADH + H^+$ ends with the reaction $1/2 O_2/H_2O$ at a value for E'_0 of $+0.82$. The difference between these E'_0 values provides a measure of the total potential energy available to the system. In order to capture and utilize this energy, mitochondrial oxidative phosphorylation takes place in discrete steps with a cascading change in the energetic levels of the system.

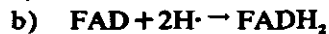
Step 1: $NAD^+/NADH + H^+$

In the previously described reactions of the TCA cycle the abstraction of a hydrogen atom to-

gether with its electron has been illustrated (Figure 5-2). The acceptance of the hydrogen atom and electron by NAD^+ represents the reduction of the co-factor coupled with the oxidation of the substrate. This change may be viewed in simplistic terms as a transfer of the potential energy of the donor to the recipient, $NADH$. The electrode potential of the $NAD^+/NADH + H^+$ system is about -0.32 volts as it operates in the cell.

Step 2:

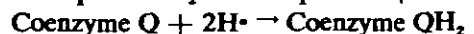
In the second step of mitochondrial oxidation the coupled reaction occurs by which the reduced nicotinamide co-factor, $NADH$, transfers its hydrogen and associated electron to a riboflavin co-factor, flavin adenine dinucleotide (FAD). The overall paired reactions may be written as follows:



Since the flavoprotein oxidized/reduced couple has an E'_0 value of -0.06 volts the reaction represents a difference of -0.26 volts. This change is more than sufficient to provide enough energy to convert adenosine diphosphate and inorganic phosphate to adenosine triphosphate, $ADP + P_i \rightarrow ATP$ since the energy requirement is about 8000 Cal, equivalent to 0.15 volts. Thus at this step of oxidative phosphorylation the respiratory chain is able to capture some of the released energy in the form of the reusable high energy bond of ATP.

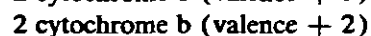
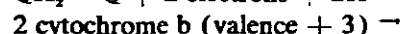
Step 3:

In the next step of electron transport the reduced flavin nucleotide transfers the hydrogens and associated electrons to the quinoid structure, coenzyme Q. The energy change implicit in the process is only 0.06 volts, insufficient for the formation of a high energy phosphate bond.



Step 4:

From reduced coenzyme Q the electrons are transferred to the iron porphyrin system cytochrome b while the released protons appear in the medium.



The change in E'_0 of approximately 0.26 volts is sufficient to allow for the formation of an additional high energy ATP bond.

Step 5:

Movement of the electrons from cytochrome b to the iron porphyrin cytochrome C_1 involves a change in energy level of only 0.03 volts, insufficient for the formation of an ATP molecule.

Step 6:

The final sequence of mitochondrial oxidation involving the electron transport from cytochrome c to cytochrome a, cytochrome a₃, and finally to oxygen with simultaneous uptake of protons from the medium to form water, is accompanied by a modification in E'_0 of a total of 0.73 volts. While this overall change would accommodate the formation of three ATP bonds in fact only one is formed.

The overall process of mitochondrial oxidative phosphorylation, starting with the substrate MH_2 , energy source and ending in the transfer of the hydrogen with its electron to form water, provides three ATP high energy bonds of a total seven that are theoretically possible. This is nonetheless a rather efficient mechanism for an energy transducer. One would compare this efficiency of about 43% with conventional systems such as the internal combustion engine or steam turbine and decide that it was rather good.

In summary, the process of energy formation starts with potential substrates from any of the major classes of nutrient proteins, carbohydrates, and lipids. By use of enzyme catalysts, a series of vitamin co-factors, and mineral elements in a synchronized interlocking organized chain, the potential energy implicit in the enzyme substrates is efficiently captured in the form of the chemical bond energy of the ATP molecule for use in energy requiring coupled reactions.

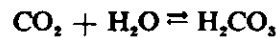
Uncoupling of Oxidative Phosphorylation

Some drugs and toxic agents have the capacity to interfere with the linkage of the energy capturing step of ATP bond formation and the process of electron transport in the mitochondrial electron transport system. As a result the engine continues to run, generates heat, but makes no progress. The transmission has been "uncoupled" from the wheels. As one may anticipate, substrates such as fats are consumed, but ATP bond energy for anabolic purposes is lacking. "Uncouplers" such as dinitrophenol were consequently used for weight reduction many years ago, but have been discarded because of their associated toxicity. Sweating may occur when the uncoupled energy is released, as observed in pentachlorophenol poisoning.

Removal of Wastes

The direct waste products of metabolism are water, carbon dioxide, nitrogen in the form of ammonia and a variety of minor specialized organic catabolites. The excretion of salts is partially regulatory and partially a waste disposal process. The continued processing of all these materials is essential for the functioning of the organism. Water, the major constituent of the body, requires continued input for replacement of the insensible loss of perspiration, in the moisture of the outgoing breath and as a solvent to remove solid wastes by solution in the urine. Control of fluid adjustment by the kidney is achieved by a feedback mechanism triggered by the osmotic pressure of the blood as it flows over the osmoreceptors of the kidney and by the sodium content of the blood as it flows through the adrenal cortex. The multiple controlling systems, especially the hormones (particularly aldosterone) of the adrenal cortex and the posterior pituitary hormone vasopressin, integrate the water balance at the kidney level.

The combustion of foods to yield carbon dioxide throws a continuous acid load upon the body. Carbon dioxide, a gas under ambient conditions, is in equilibrium with water to form carbonic acid by the reaction:



This reaction proceeds slowly under usual conditions but is tremendously speeded in the body by the zinc enzyme of the red cell, carbonic anhydrase. Since the acidity of the blood is carefully maintained at approximately a pH of 7.4, the carbonic acid generated by metabolism is rapidly neutralized to yield the bicarbonate anion, HCO_3^- , which returns to the plasma from the erythrocyte. The hydrogen ion from this reaction is neutralized by the buffers of the blood, notably oxyhemoglobin HbO_2^- , which simultaneously loses oxygen at the tissues and provides for the neutralization of the proton. The reaction $HbO_2^- + H^+ \rightarrow HHb + O_2$ thus simultaneously unloads oxygen at the tissues and provides for the neutralization of hydrogen ion arising from the carbonic acid of metabolism. The process is reversed at the lungs. The oxygenation of hemoglobin forms the stronger acid oxyhemoglobin which in turn liberates a proton for recombination with bicarbonate to form carbonic acid which in turn is converted to CO_2 by erythrocyte carbonic anhydrase to produce the CO_2 exhaled in the expired air. This mechanism for the elimination of carbon dioxide is one of rapid adjustment. The partial pressure (pCO_2) of the blood is constantly monitored by neural receptors which bring about changes in respiration to accommodate to the need for release of metabolic carbon dioxide. One is aware of the slowed breathing of sleep when metabolism is decreased. At such a time the demand for oxygen intake and carbon dioxide elimination is minimal compared to the accelerated breathing during vigorous exercise.

The rapid adjustment of the lungs to acid load is supported by the slower fine modulation at the kidney. One of the major excretory components of the urine is its phosphates. It will be recalled that phosphoric acid has three ionizable groups which function at various points in the acidity scale. The anion pair $H_2PO_4^-/HPO_4^{2-}$ is one which is operative in the maximal acidity range of urine which is roughly from about pH 4.6 to pH close to 8.0. Variations in acid load in the body can be compensated by a mechanism which results in the shift in the phosphate buffer pair by neutralization of the hydrogen ion of the acid. The reaction $HPO_4^{2-} + H^+ \rightleftharpoons H_2PO_4^-$ proceeds to the right and provides a means for the excretion of the acid load in the urine.

The elimination of the nitrogen load of metabolism is essentially by means of its conversion in the liver to urea and excretion of this product in the urine as has been previously discussed. It is clear that damage to the liver will inhibit the detoxification of ammonia through its conversion to urea. Not only does this detoxification mechanism fail with liver damage but so also are other metabolic detoxifications inhibited. Failure of kidney function by damage or disease is equally serious. The accumulation of nitrogenous waste products, azotemia, is usually monitored by measurement of the urea content of the blood. Continued elevation of blood urea offers a poor prognosis of recovery.

BIOCHEMICAL MONITORING

To this point, the authors have presented a body of factual information on the subject of biochemistry. Hopefully, the reader seeks to find how this may be applied to the problems for which he requires solutions.

The first fact that may be obvious from the material presented is that all men are created equal — but different! While genetic categories may be separated, within groups each individual has his own biochemical pattern. This suggests it might be desirable to have a biochemical profile of a worker available for comparison with his subsequent work and medical history. The development of automated procedures in clinical chemistry makes this feasible. An application of biochemical profiling to an industrial health problem is cited in the reading list. Researchers interested in finding sensitive indicators of injury to toxic agents may be intrigued by the pattern depicted in Figure 5-6. This combines data from serum, tissue from lung and adrenals, and leucocyte assays into one picture. Adrenal stress is evident from the elevation of adrenal succinic dehydrogenase: the leucocyte enzymes appear to respond opposite, and to a greater degree, than serum enzymes. One might be led to suspect that leucocyte enzymes may provide a better index of response to injurious exposure than do serum enzymes. Only adequate research will either corroborate or discredit such suspicions. The techniques of leucocyte separation and assays are described in the literature cited.

General monitoring by profiling such as these cases may be useful, but always requires interpretation; a worker may have an alcoholic weekend, or a current infection, and confuse the interpretation.

Monitoring of workers for exposure to metals has been facilitated by the development of the convenient and sensitive methods of atomic absorption spectroscopy.

Assay of cholinesterase activity of blood has been mentioned as useful in monitoring exposure to anti-cholinesterase insecticides. Another type of monitoring involves analysis of urine for the metabolite of the agent to be controlled: for example, measurement of urinary phenol content to evaluate degree of exposure to benzene.

With the prospect that regulatory agencies are aiming at setting biological standards for many organic, as well as inorganic substances, the subject of the next section becomes especially relevant.

DETOXIFICATION PROCESSES

The ability of the body to neutralize potentially damaging materials is remarkable. Heavy metals such as lead are shunted into the skeletal system where they are effectively buried in the bone. This protective process fails when the breakdown of bone, as in fever, may cause a release of the metal in quantity greater than can be handled by the normal slow and low level elimination in the urine and feces. In these circumstances, or when the incoming load is greater than can be effectively han-

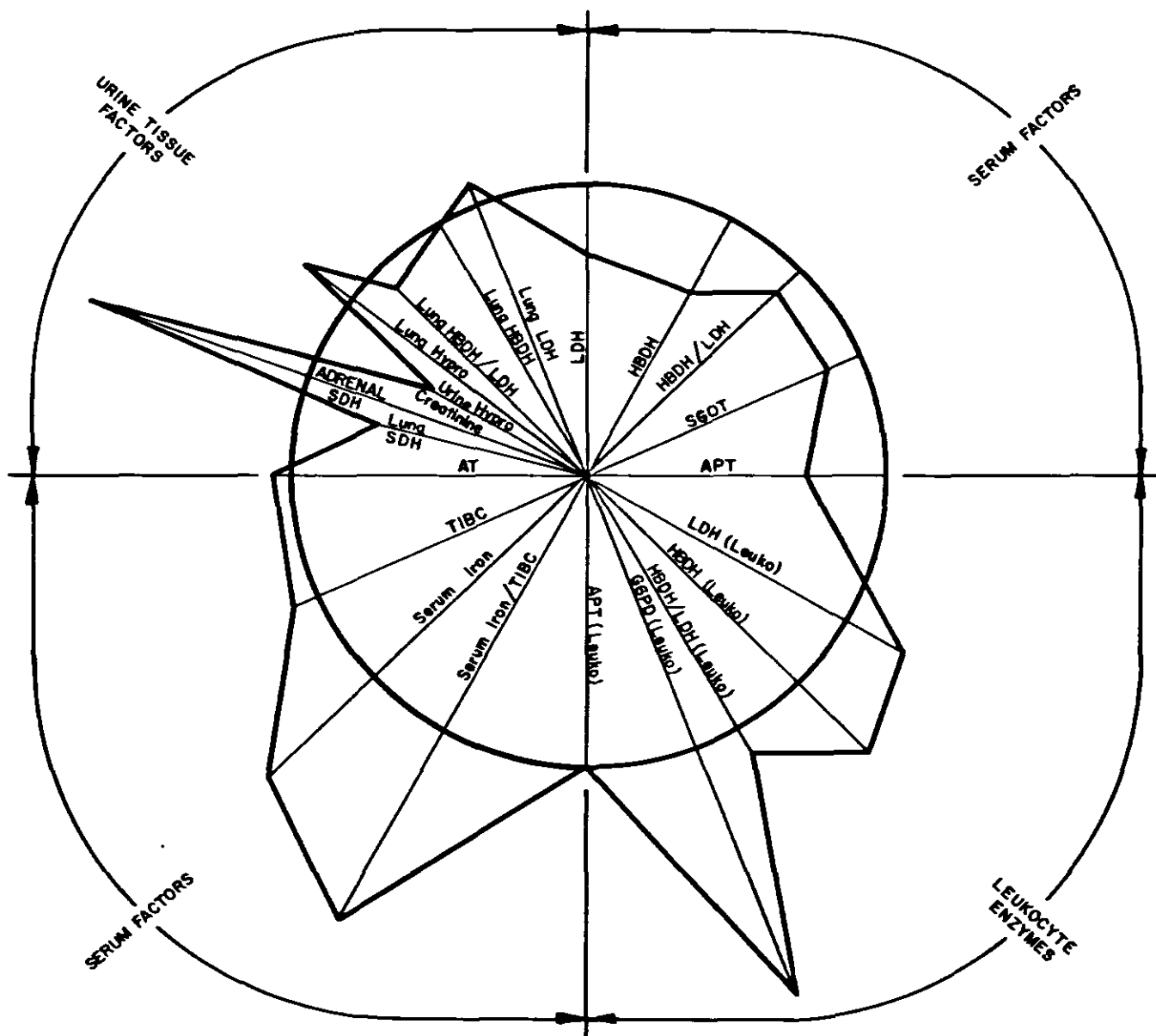
dled, the toxic symptoms of lead poisoning result. In his modification of the environment man has also introduced new factors in the problem. The radioisotopic elements uranium, strontium and plutonium also are buried in the bone for purposes of detoxication. These elements, however, retain their intrinsic toxicity associated with their continuing radiation. The net long term result is the radiation damage of the surrounding cells and the development of cancer.

Organic compounds are converted, if possible, to forms which can be excreted by the body or are non-toxic. The liver oxidases have a remarkable capability to add an -OH group to otherwise poorly reactive compounds. Aromatic materials such as benzene are converted to phenols. Aliphatic and heterocyclic compounds are hydroxylated to form alcohol derivatives. This mechanism provides a handle by which the organism is further able to convert the compounds to a water soluble product which can be excreted in the urine. Phenols, for example, can then be conjugated with sulfuric acid to form an ethereal sulfate, $ROSO_3H$, derivative. Sulfate derivatives of this kind are readily excreted in the urine. An alternative conjugation is by way of the sugar acids resulting in the formation of a soluble derivative of the form $RO(CHOH)_nCOOH$. Conjugation with amino acids, especially glycine or cysteine, also results in the formation of soluble products that can be cleared through the kidney and eliminated in the urine. Where the toxic agent is susceptible to hydrolytic cleavage, the appropriate enzymes may break them down to their non-toxic component structures. A variety of esterases and proteolytic enzymes are available for the cleavage of amide, peptide and ester bonds. One of the more serious groups of environmental and industrial toxicants is the family of amines, $R-NH_2$. The oxidation of these compounds to aldehydes and acids and their conjugation to more hydrophilic derivatives are frequent modes of their detoxication (Table 5-1). The converse process of reduction, especially of industrial nitro derivatives, $R-NO_2$, provides a mechanism for conversion to more tractable products for elimination.

Despite these ingenious metabolic mechanisms for detoxication, it is clear that the continued pollution of our environment is proceeding with materials in quality and quantity beyond our capacity to handle. Some evidence is available of some increased body burdens of lead and of an accumulation of organic insecticides in our tissues until the last several years. The remarkable biochemical homeostatic mechanisms need help from the technical, political and social efforts which are essential for solution of our critical environment problems.

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Biochemical Profile of Rats (Germ Free)
Exposed to Coal Dust. Control Values as
Reference.









Abbreviations:

- LDH — Lactic Dehydrogenase
- HBDH — Hydroxy Butyrate Dehydrogenase
- G-6 PD — Glucose-6-Phosphate Dehydrogenase
- APT — Alkaline Phosphatase
- SDH — Succinic Dehydrogenase
- AT — Serum Anti-trypsin
- TIBC — Total Iron Binding Capacity of Serum
- / — Slant Line Indicates Ratio Value

Courtesy Dr. Larry K. Lowry, Toxicology Section, NIOSH.

Figure 5-6. Profile, Germ Free, Coal Exposed, Control

TABLE 5-1 Major Types of Detoxication

Type	Foreign substance	Detoxication product examples
Methylation -CH ₃	Inorg. Compounds of As, Te Ring N compounds Certain complex aromatic phenols	(CH ₃) ₂ Se N-CH ₃  OH  OCH ₃ CHOH-CH ₂ NHCH ₃
Acetylation CH ₃ CO-	Aromatic Amines Amino Acids (Known exceptions: aromatic amine carcinogens, also aliphatic amines).	NHCOCH ₃  RCHCOOH NHCOCH ₃ e.g., Benzidene - hydroxylated aliphatic amines - aldehydes.
Ethereal sulfate -OSO ₃ H	Phenols (Cyclohexanol glucuronide)	OSO ₃ H 
Acetyl Mercapturic acid -SCH ₂ CHCOOH NHCOCH ₃	Aromatic Hydrocarbons Halogenated Aromatic HC's Polycyclic HC's Sulfonated esters C ₂ H ₅ SO ₃ -CH ₃ Nitroparaffins (C ₄ H ₉ NO ₂)	S-CH ₂ CHCOOH NHCOCH ₃  Br C ₂ H ₅ acetyl cysteysl- C ₄ H ₉ -acetyl cysteysl-
Thiocyanate	Cyanide, inorganic Organic Cyanides (Nitriles)	RCNS
Glycine -NHCH ₂ COOH	Aromatic Acids Aromatic-aliphatic acids Furane carboxylic acids Thiophene " " Polycyclic " " (Bile acids)	CONHCH ₂ COOH 
Glucuronate	Aliphatic (1°, 2°, 3°) and Aromatic Hydroxyl Aromatic Carboxyl	OC ₆ H ₉ O ₆  (Ether) C = O  OC ₆ H ₉ O ₆ (Ester)
Glucose Hydrazone	Hydrazine " derivatives?	NH ₂ N = CHC ₅ H ₈ O ₅

Courtesy Dr. H. E. Stokinger, Toxicology Section, NIOSH.

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CHAPTER 6

REVIEW OF PHYSIOLOGY

James L. Whittenberger, M.D.

INTRODUCTION

Physiology is the basic biomedical science which deals with function in living organisms. Since form and function cannot be studied apart from each other, anatomy and physiology were undoubtedly two of the earliest biomedical sciences to be developed. As rapid expansion of natural sciences occurred, particularly in the first half of the twentieth century, specialization and fragmentation has led to splitting off of several fields from the parent discipline of physiology — including biochemistry, biophysics, and more recently, molecular and cell biology. For the purposes of this Syllabus, we shall assume that physiology is concerned with the full range of function, from the activities of a living cell to the performance of the whole organism.

A major concern of physiology is the role of environmental factors in influencing function. A fundamental principle of mammalian physiology is that basic intracellular processes can proceed only if the fluid environment surrounding each cell is maintained in a nearly constant state with respect to temperature, oxygen supply, acidity and nutrients. A major role of most systems of the body — respiratory, circulatory, alimentary and excretory for example — is to maintain near-constancy of the so-called internal environment of the body. By contrast, the external environment is variable over wide limits — in temperature, humidity, ionizing and nonionizing radiation energy, barometric pressure, and presence of noxious gases and particles. Interaction between the organism and the external environment is continuous and calls upon various protective and adaptive responses of the organism. In ordinary life and in the usual working environment these adjustments are automatic and unconscious; they put no particular strain on the organism and are a part of healthy existence.

A primary objective of industrial hygiene engineering is to control the occupational environment so that workers will not be exposed to extremes of heat and noise, or to unsafe levels of noxious gases, dusts and fumes. The degree of control needed depends on the type and extent of biologic response that might be induced. Since it is not economical to control the environment completely, it is important to know the nature and extent of biologic response in order to make rational decisions about the extent of control needed in relation to other measures that can be used to protect the health of the workers. For example, it may not be feasible (too costly) to control the heat in the particular environment; however, a biological re-

sponse to heat (that is, a heat stress study curve) can be used to determine a safe level (using temperature and time) of exposure to heat and when the worker should be given a rest period.

The kinds of biologic response to occupational environmental stresses range from harmless physiologic responses (such as respiratory and circulatory adjustments to physical exercise) through a variety of toxicologic manifestations which may include acute diseases such as chemical pneumonias and chronic diseases such as silicosis, or cancer of various organ systems. Thus the responses to environment involve toxicology, pathology and other medical specialties besides physiology; but these sciences cannot be understood without a basic knowledge of physiology and biochemistry.

BASIC CELL FUNCTIONS

The basic unit of all living organisms is an individual cell. Certain principles are common to almost all cells and represent minimal requirements for maintaining the integrity of the cell. Thus a human liver cell and a free-living ameba do not differ much in their means of exchanging materials with the immediate environment, obtaining energy from nutrients, synthesizing proteins, and reproducing themselves.

The difference among cells in the different tissues of the body usually represents a specialization of some one function of the functions common to all cells. Thus the excitability of nerve cells represents a specialization of electrical phenomena common to the membranes of almost all cells; the transport of food molecules across intestinal cells is a specialization of transport mechanisms that are very similar in all cells.

Types of Molecules

Water forms the medium in which all living processes occur, and life as we know it is inconceivable in the absence of water. Sixty percent of the body weight is water, and 80% of the weight of a cell is water. Because so many different molecules can dissolve in water, it is an ideal medium for chemical reactions. Water participates in practically every process in the organism and without this medium we could not have a circulatory system.

Despite the importance of water, the chemistry of living systems is centered about the chemistry of carbon which makes up 45 percent of the dry weight of the body. Carbon atoms can form four separate bonds with other atoms, in particular with other carbon atoms, making possible the formation of large molecules with a variety of

structures. In combination with hydrogen, oxygen, nitrogen, and occasionally sulfur and phosphorus, carbon compounds make up the major classes of organic molecules in the body — proteins, lipids, carbohydrates and nucleic acids. Proteins constitute about 17% of the body weight — they make up much of the structure of the body as connective tissues and muscle. They catalyze most of the chemical reactions in cells and serve many specific functions, for example, as hormones, carriers of oxygen and carbon dioxide (hemoglobin), and as the principal mechanism of immunity (antibody formation).

Lipids make up about 15% of body weight and because of their relative insolubility in water perform a very important role in the permeability of cell membranes. One class of lipids includes the steroid hormones. Carbohydrates constitute only about 1% of body weight, but supply most of the energy needs of the body. Nucleic acids are even smaller in amount, but include the largest and most specialized molecules in the body — the deoxyribonucleic acid (DNA) molecules which are the blueprints of genetic information in the cell nucleus, and the ribonucleic acid (RNA) molecules which transcribe and carry the information in forms that can be used to synthesize proteins in the cytoplasm.

Energy and Cellular Metabolism

Metabolism refers to the sum of chemical reactions taking place in a living cell or organism; it includes both the process of fragmentation of large molecules into smaller ones and the synthesis of large molecules from raw materials in the cell. Both processes go on simultaneously in different parts of the cell, with hundreds of chemical reactions taking place in an orderly fashion.

That such reactions can take place at normal body temperature is due to the presence of special protein molecules which act as catalysts. Although enzymes are not destroyed by the reactions they catalyze, like all biologic molecules they are in a state of dynamic equilibrium between the rate of breakdown and the rate of synthesis. The cell's ability to control these rates is one mechanism for control of the rates of metabolism within cells. Some enzymes are highly specific, acting on only one type of substrate molecule; others interact with a range of substrate molecules which have a particular type of chemical bond or grouping which is specific for the enzyme. Over 900 different enzymes have been identified and there are undoubtedly many more to be discovered.

THE INTERNAL ENVIRONMENT

Like a free-living single-celled organism in the sea, every cell in the body is bathed in an aqueous medium — the extra-cellular fluid — which in salt composition is not dissimilar to that of the sea (at the salt concentrations which probably obtained when terrestrial life evolved from the sea). The extracellular fluid provides ready access to nutrients and oxygen, serves the needs for waste disposal and stabilizes conditions outside the cell membrane.

The extracellular fluid — the internal environment of the body — consists of two compart-

ments. Eighty percent of it surrounds the cells within tissues in all parts of the body; the remainder is within the vascular system — the liquid part of the blood — the plasma. Since the blood is pumped to all parts of the body, where cells are close to capillaries, there is rapid exchange between plasma and extracellular fluid. Consequently, the composition of the two fluid compartments is very similar, except for the presence of proteins in the plasma. The proteins do not normally pass through the capillary wall and they serve a very useful role in controlling fluid exchange in the capillaries.

Homeostasis

This important concept, first enunciated by Claude Bernard, refers to the relative fixity of the internal environment and the role of many organs and systems in stabilizing the internal environment. The temperature, the concentrations of oxygen, carbon dioxide, nutrients, and inorganic ions — all must remain relatively unchanged in the extracellular fluid. Virtually every system of the body contributes to this stability — the liver adds or subtracts molecules as needed, the lungs delicately adjust the oxygen and carbon dioxide in the blood, the kidneys excrete or absorb the right amount of water and salts, and so on. The activities of tissues and organs are regulated and integrated with each other so that any change in the internal environment automatically initiates a reaction to minimize the change. Thus stability is achieved in the presence of wide fluctuations in activity of the total organism and wide ranges of external environmental conditions.

NEURAL CONTROL MECHANISMS

The development of the human nervous system is one of the most remarkable of evolutionary achievements. The nervous system is a major interface between the organism and the environment; it serves in many of the mechanisms that maintain homeostasis; it controls posture and body movements; it is the seat of subjective experience, memory, language, and the thought processes that characterize human activity.

The fundamental unit of the nervous system is the neuron, which consists of cell body, dendrites, and the axone, which may be several feet in length. Only about 10% of the cells in the nervous system are neurons, the remainder serving mainly as supporting elements.

The connections between nerve cells, called synapses, play a key role in the transmission of impulses in the nervous system; one cell may be directly connected with as many as 15,000 other cells by means of synapses. The basic mechanism of impulse transmission is the action current which results from depolarization of the cell membrane under the influence of chemical or mechanical events. The threshold for depolarization differs in different parts of the neurons and is influenced by the local environment of the cell; this is also true of the synapse. Nerve stimulation or alteration of local ions may be excitatory (lowering threshold for depolarization and action potential generation), or inhibitory (raising the threshold).

Presumably the mechanism whereby impulses are transmitted through synapses involves the release of a chemical at a cell terminal, with rapid diffusion to a reactive site on the second cell. With few exceptions (acetyl choline in the parasympathetic system and norepinephrine in the sympathetic system), the identity of these transmitters is unknown.

There are three functional classes of neurons: 1) afferent neurons which frequently are connected to sensory receptors (touch, taste, smell, sight, etc.) and which transmit information in the form of coded action potentials from the peripheral to the central nervous system; 2) efferent neurons, which transmit action potentials from centers in the spinal cord and brain to skeletal muscle, smooth muscle, or secretory cells in the periphery; and 3) interneurons, which make up 97% of the total and which provide the vast number of interconnections in the central nervous system.

The sensory receptors are of special interest in environmental health for their responsiveness or lack of responsiveness to different kinds of energy in the environment. For example, extremely sensitive receptors in the eye respond to electromagnetic energy in the narrow visible spectrum, but the eye has no receptors which respond to long wave frequencies or to ionizing radiation. The auditory system is highly developed to translate sound energy into nerve action potentials, and smell receptors respond to as little as 4 to 8 molecules of a substance. Other receptors respond selectively to mechanical stresses and to changes in chemical energy. Although receptors in general are adapted to respond to a particular kind of energy, they usually can be activated by other forms applied in sufficient strength. For example, the visual receptors normally respond to light but they can be activated by intense mechanical stimuli, such as a blow on the eyeball.

The Reflex Arc

The reflex arc illustrates many of the components of nervous control. The five components are a receptor, an afferent nervous pathway to carry action potentials to the central nervous system, an integrating center in the spinal cord or brain, an efferent pathway to carry action potentials from the central nervous system, and the effector which is activated.

The receptor detects an environmental change (temperature, pressure, etc.), perhaps by a change of permeability, and alters its signals to the afferent nerve. The integrating center receives input from many receptors and from other parts of the nervous system. The net result of these inputs is an "order" which is transmitted by the efferent pathway to a muscle or gland. If the initial stimulus is cold exposure, the integrating center would be in the brain, and the effector response would be an increase in skeletal muscle tone and constriction of skin blood vessels which would conserve heat by diminishing blood flow. Such responses are automatic and usually not consciously perceived.

Divisions of the Nervous System

Overall the nervous system is divided into

central and peripheral portions, the central including both the brain in its several parts within the cranium, and the spinal cord within the vertebral column. Another way of dividing the system is into afferent and efferent components; the afferent includes the pathways from the specialized receptors and from other sensory nerve endings in tissue; the efferent system leaves the brain and spinal cord to transmit impulses to skeletal muscle, cardiac muscle, smooth muscle, and glands.

Autonomic Nervous System

The efferent system to skeletal muscle is the somatic nervous system; the other part of the efferent system is known as the autonomic nervous system. It deserves special attention because of its role in maintaining homeostasis. It provides dual innervation to the heart, the smooth muscle of lungs, blood vessels, intestinal tract, and other organs, and to secretory glands. The dual systems differ physiologically and anatomically and are called the sympathetic and parasympathetic systems. Whatever one division does to an effector organ, the other usually does the opposite; thus action potentials over the sympathetic nerves to the heart increase the heart rate, while action potentials over the parasympathetic fibers decrease it. Dual innervation with nerves inducing opposite effects provides a fine degree of control over an effector organ.

In general the sympathetic system helps the body cope with challenges from the outside environment (increasing flow to exercising muscles, constricting other vessels to sustain blood pressure, increasing metabolism, etc.) whereas the parasympathetic system is more active in digestion and other resting activities. Activation of the sympathetic system is likely to have widespread effects in the body, partly because the adrenal medulla is concurrently stimulated to secrete epinephrine (adrenalin) into the blood.

HORMONAL CONTROL MECHANISMS

A second communications and control system is provided by the glands of internal secretion, which secrete specific chemicals into the bloodstream which then circulates them throughout the body, where they may affect a small number of target cells or in some instances a large number of cells. An example of the former is the effect of thyrotropic hormone from the anterior pituitary, affecting only the cells of the thyroid gland. An example of widespread effect is that of insulin, which increases the entry of glucose into most cells of the body, except in the brain.

Except for maintenance of reproductive activities, the body is capable of functioning without the endocrine glands, including even the anterior pituitary — the so-called master gland. However, the level of function in the absence of hormones is very deficient. Metabolic activities are depressed and resistance to infection and other stresses is much below normal; in addition there are other abnormalities that relate to specific hormones.

A general principle pertaining to hormones is that they are always present in the blood, at concentrations that depend on 1) the rate of production in specific cells, 2) the amount of storage in

those cells, 3) the rate of release into the blood and 4) the rate of removal from the blood by absorption in a target organ, inactivation, or excretion. The control systems may act on one or more of these factors.

Until recent years, the endocrine systems were studied independent of the central nervous system, although it was recognized that the anterior pituitary was anatomically closely related to the base of the brain (the hypothalamus), and that emotional states could influence the function of the thyroid, the adrenal, and the reproductive glands of internal secretion. Now close functional, as well as anatomic, relationships between the two great communication systems of the body are well established.

In a sense the central nervous system "leads" the major components of the endocrine system by the secretion of "releasing factors" in the hypothalamus. These control the production and secretion of six separate hormones of the anterior pituitary:

1. The thyrotropic hormone regulates the production of thyroid hormone in the cells of the thyroid;
2. The adrenocorticotrophic hormone (ACTH) regulates the production of cortisol in the adrenal cortex;
3. The luteotropic hormone controls the production of progesterone;
4. The follicle-stimulating hormone controls the maturation and release of ova from the ovary;
5. The lactogenic hormone (prolactin) controls the production of milk by cells in the breast; and
6. The so-called growth hormone, which has multiple metabolic effects.

In addition to these effects mediated by the anterior pituitary, the hypothalamus secretes two other hormones formerly thought to be produced by the posterior pituitary — the anti-diuretic hormone which regulates the reabsorption of water in the kidney, and the hormone oxytocin, which stimulates contraction of the gravid uterus.

In addition to its central role in regulating the above hormones, the hypothalamus controls the autonomic nervous system, which in turn controls the secretion of epinephrine. There are a few hormones, such as insulin and aldosterone which are not regulated by the hypothalamus or pituitary.

Part of the control of hormone production is the negative feedback effect of the hormone produced by the target organ. Thus thyrotropic hormone from the pituitary stimulates the thyroid cells to produce thyroid hormone, but thyroid hormone, either produced by the organism or administered as a drug, depresses the output of "releasing factor" from the hypothalamus and in turn the output of thyrotropic hormone by the anterior pituitary.

Some of the mechanisms by which hormones act are known; others are not known. They do not create new functions of cells, but are usually found to alter rates at which existing processes proceed by increasing the activity of a critical enzyme (by increasing its production or by activating

a stored form) or by altering the rate of membrane transport. For example, one of the actions of insulin is to increase the rate of entry of glucose into cells. Actions of hormones on cells often involve interactions with other hormones; for example, epinephrine causes release of fatty acids from adipose cells only when thyroid hormone is present.

The role of hormones, especially those produced by the adrenal cortex, is important in the recognition of the responses of the body to any kind of stress, be it exposure to toxic chemicals, extremes of heat and cold, heavy exercise, and other stresses. Some effects of a toxic chemical may be direct effects on specific cells while the remaining effects are secondary to increased production of cortisol. Since adrenal cortical hormones play important roles in the inflammatory process, in immune responses, and in diverse metabolic processes, it is clear that a knowledge of hormones is essential to understanding the mechanisms of response to stress.

RESPIRATORY SYSTEM

In common understanding, the respiratory system includes only the lungs and conducting airways. Logically, the term should include the circulatory system as well, since the two systems are jointly responsible for meeting the respiratory needs of the body, providing as they do the mechanism whereby the countless billions of cells are kept in minute to minute contact with the external environment for access to oxygen and for elimination of carbon dioxide.

The basic role of the lungs and related components of the system is to provide the essential conditions under which rapid exchange of oxygen and carbon dioxide can take place between the atmosphere and the blood coming to the pulmonary capillaries. A large surface is needed and this is provided by the estimated area of 70 square meters for an adult male's alveolar surface, where pulmonary capillary blood is in close juxtaposition to the alveolar gas. The rate at which oxygen must be taken into the body (and proportional amounts of carbon dioxide released) varies from about 200 ml/min at rest to 30 times that amount during exhausting exercise. If this wide range of need is to be met without significant change in the internal environment, there must be corresponding changes in the rates at which pulmonary capillary blood is replaced and alveolar gas is exchanged with ambient air; these changes are accomplished by integrated responses of the cardiovascular system so that ventilation and perfusion of the alveolar surface is always closely matched in healthy individuals.

Airways

The conducting portion of the respiratory system appears well-designed as a low resistance pathway for uniform distribution of gases to the alveolar surface, with numerous characteristics which "condition" the air and protect the lungs from at least the largest of infectious or noxious particles in the atmosphere. Some of the protective aspects are as follows:

The convoluted, moist, and richly vascular

mucosa of the nose protects nose-breathers from inhaling particles larger than 5 or 10 microns in diameter; soluble gases are largely removed by absorption, and the inspired air is warmed and moistened (or cooled under hot, dry conditions). In addition, the sense of smell receptors in the upper reaches of the nose may serve a protective role.

The tracheobronchial system is lined with cilia which constantly force toward the larynx a "carpet" of mucus which is secreted by mucosal glands. The mucus carries with it the microorganisms and particles which have impinged upon it, as well as macrophages which move out of the alveoli, often with a burden of material scavenged from the alveolar surface. When the mucus reaches the pharynx it is usually swallowed, but may be expectorated. These "pulmonary clearance" mechanisms play an important role in preventing pulmonary effects from inhalation of dusts, fumes, and other materials of concern in occupational exposure. The cough mechanism is a coordinated pattern of mechanical events that tends to expel foreign materials from the tracheobronchial tree.

Other pulmonary responses occur in response to environmental exposures, but are less clearly protective. Most important of these is the bronchospasm which characterizes the response to many irritant gases. The partial or complete closure of bronchioles certainly impedes access to the alveoli, but it does so at the cost of greatly increased breathing effort and impeded gas exchange in severe cases. An asthma-like response is a normal reaction to many inhaled irritants; it also may represent hypersensitivity of such severity that further occupational exposure must be prevented.

Pulmonary Ventilation

Under precise nervous and chemical control, the respiratory muscles intermittently expand the thorax in such manner that the lungs are continually changing volume. The elastic properties of the lung tend always to empty the lung, but the thorax exerts an opposite effect, except when lung and thorax volumes are large. Consequently, the lung retains a substantial amount of gas even when all respiratory muscles are at rest. In quiet breathing inspiratory muscles contract to enlarge the thorax and lungs; expiration is largely passive. Both frequency of cycling and the volume cycled (tidal ventilation) are variable; respiratory movements can thereby alter the minute volume (tidal volume times frequency per minute) from about 6 liters at rest to over 100 liters during heavy exercise. The ventilation rate is adjusted to maintain the alveolar partial pressure of oxygen and carbon dioxide approximately constant. The increases of ventilation with increasing levels of physical activity are very important in maintaining the homeostasis of the body; such increases may be critical in determining the amount of exposure to noxious or potentially noxious gases or particles in the atmosphere.

Of each breath, at rest, approximately one-third does not exchange significantly with alveolar gas because about that amount of space is accounted for by the conducting airways and the volume of alveoli not perfused by blood. This

"dead-space" is normally about 180 ml in adult males and can be substantially increased in certain types of breathing appliances such as gas masks. Small increases in dead-space can be compensated by increased depth of breathing, but excessive dead-space can interfere with the adequacy of respiration.

Work of Breathing

Normally the work of respiratory muscles in ventilating the lungs accounts for a very small part of the total oxygen demand of the body — normally less than 3%. This is not the case when resistance to gas flow in the air passage is increased by bronchospasm or excess of secretions, or when the lung is diseased, as in pneumoconiosis, pulmonary fibrosis, and other occupational or non-occupational lung disease. In such conditions the increase of respiratory work may put a real burden on the whole cardiorespiratory system. Other conditions can also greatly increase the work of breathing, for example, the resistance of breathing through a gas mask, or having to breathe through a tracheostomy tube that is too small.

Ordinarily the respiratory muscles themselves are capable of performing the extra work required in the conditions mentioned above. This would not be the case when respiratory muscles are weakened by diseases such as myasthenia gravis or poliomyelitis, or by exposure to chemicals such as organophosphate pesticides.

Flow of Respiratory Gases

The ventilatory and gas exchange functions of the lungs are linked to the gas exchange needs of the body not only by the mass transport role of the circulatory system but by the peculiar respiratory functions of the blood. If oxygen could be transported only by physical solution in the blood, the kinds of organisms we know could not have evolved. The secret to efficient transport of oxygen (and to a large extent carbon dioxide also) is the red pigment hemoglobin, which combines loosely with oxygen, picking up a full load at the partial pressure of oxygen in the lungs and releasing a large part of the load at the partial pressures pertaining around the capillaries of tissues. Normal blood, by means of its hemoglobin-packed red cells, contains about 20 ml of oxygen per 100 ml blood at the alveolar oxygen pressure of approximately 100 mm Hg, compared to only 0.3 ml per 100 ml blood in physical solution. Under these conditions the hemoglobin is nearly saturated with oxygen. Since the hemoglobin is half-saturated at approximately 25 mm Hg, the blood can give up half its load of oxygen without lowering the pericapillary oxygen pressure to levels that would fail to provide adequate diffusion from interstitial tissue into cells.

Control of Respiration

The precise regulation of breathing to maintain alveolar oxygen and carbon dioxide levels essentially constant in the face of wide changes in body metabolism has always fascinated respiratory physiologists. Several factors are known, some closely interrelated (oxygen, carbon dioxide, and hydrogen ion concentration), but no theory fully explains the most remarkable adaptation of

respiration — the hyperventilation which occurs in proportion to the level of exercise.

Some of the control factors have special importance in certain occupational situations. Excess of carbon dioxide (as in contaminated atmospheres or rebreathing of expired air) is a powerful stimulant, causing 5- to 10-fold increase of ventilation at 5-7% CO₂ breathing. The mechanism may be a direct CO₂ effect on respiratory nerve cells or an indirect effect of increased hydrogen ion concentration in the cerebro-spinal fluid bathing the nerve cells.

In oxygen-deficient atmospheres the respiratory stimulation due to hypoxia is evident, the mechanism involving activation of specific receptor cells in the vicinity of the carotid arteries and the aortic arch. The strength of this stimulus was misjudged for a long time because of the interrelationships of O₂ and CO₂ effects. Just as high CO₂ is a powerful stimulant, the loss of CO₂ is a potent depressant. Thus the increase of ventilation due to hypoxia eliminates CO₂ out of proportion to metabolic production; the level of CO₂ pressure falls; blood becomes relatively alkaline; and the respiratory drive is inhibited. If there is time for acid-base adjustments to low CO₂, as in acclimatization to high altitude, the depressing effect of low CO₂ disappears and the stimulating effect of hypoxia becomes more evident, with beneficial consequences to the organism in terms of higher partial pressures of oxygen throughout the body.

THE CIRCULATORY SYSTEM

The heart and blood vessels, with the blood contained therein, are the efficient internal transportation system of the body. The system is dual, the right side of the heart pumping blood only to the lungs while the left side pumps the freshly aerated blood to the rest of the body. The normal adult has about five and a half liters of blood; each side of the heart pumps at a rate of about five liters per minute at rest and can increase the output about five-fold during heavy exercise.

Changes of cardiac output involve both frequency of contraction and volume expelled with each stroke. The automatic rhythmicity of the electrical generator of the heart is subject to both nervous and chemical influences. Efferent autonomic nerves from the cardiac control centers in the brainstem can strongly slow or speed up the cardiac beat; epinephrine and drugs can also affect the rate of firing or the speed of transmission through the conducting system.

The stroke output is affected by both intrinsic and extrinsic factors. A fundamental property of heart muscle is that the greater the stretch during relaxation, the greater the energy of the subsequent contraction; thus a speeding up of return of blood for the veins will tend to increase the diastolic filling (increasing the stretch of heart muscle fibers) and automatically increase the force propelling the increased quantity of blood into the arterial system. In addition, the "tone" and force of heart muscle contraction can be influenced by chemicals such as epinephrine and norepinephrine.

The Systemic Arterial System

The arterial system which connects the left cardiac ventricle with capillary beds throughout the body has two basic characteristics: 1) the thick elastic walls of the aorta and other large arteries which enable the system to accept pulses of blood from the contracting ventricles and hold the blood in a high pressure reservoir while it flows off more or less steadily through the peripheral arterioles, and 2) the arterioles themselves, which because of their overall high resistance to flow tend to keep arterial pressure up during cardiac diastole and which, equally importantly, are subject to local control, so that tissues and organs have perfusion rates adjusted to their metabolic needs.

The arterial system contains about 15% of the total blood volume, at pressures which range in a young adult from about 110 mm Hg at the end of cardiac systole to about 70 mm at the end of diastole. This pressure is normally adequate to serve the blood flow needs of all tissues, including the brain when the body is upright. This is not true when there are sudden losses of blood volume (hemorrhage), failures of cardiac output (functional or organic in nature), or when arteriolar tone is sufficiently diminished (as after prolonged bed rest, immobility from other causes, heat exhaustion, and fainting due to various causes).

The local control of arteriolar tone (determining resistance to flow) seems designed largely to protect the brain and heart. During muscular exercise the smooth muscle in arterioles supplying active muscles relaxes allowing greater flow to the muscles; simultaneously there is contraction of smooth muscle in arterioles of other tissues, virtually shutting off flow to organs whose function can be temporarily suspended, such as the digestive organs. Vasoconstriction of this sort never affects flow to the brain or the heart.

In addition to nervous control of local blood flow, other factors can markedly affect arteriolar resistance and hence flow; these include local metabolites such as CO₂, heat, and chemicals like histamine and epinephrine.

Capillary-Tissue Exchange

When blood passes through the arterioles of the systemic circulation, the relatively high resistance is associated with a fall in pressure to about 35 mm Hg at the arterial end of the capillary. The number of capillaries is vast, the aggregate cross-sectional area of capillaries being estimated at 600 times the cross-sectional area of the aorta. This "widening of the stream" into a so-called capillary lake is associated with a greatly decreased flowrate, down to about 0.07 cm/sec. The large capillary area, slow flow, and pressure gradient from capillary to tissue provide ideal conditions for movement of nutrients and oxygen into the extracellular space.

The system also evolved in a way to facilitate return of substances to the capillary lumen. One mechanism relates to net fluid movement at opposite ends of the capillary. Where pressure is about 35 mm Hg the hydrostatic pressure forces fluid and its contained electrolytes and nutrients out into

the tissue space. The capillary wall is essentially impermeable to protein molecules, so the proteins continue to exert an osmotic force tending to attract fluid into the vessel. At the venous end of the capillary the filtration pressure has fallen to 15 mm Hg, considerably smaller than the osmotic pressure exerted by the proteins. Therefore net fluid movement is out of the capillary at one end and into the capillary at the other end, the rates tending nearly to balance each other.

A second mechanism, which facilitates gas transfer, is the role of hemoglobin in transporting carbon dioxide. When hemoglobin enters the capillary and gives up part of its load of oxygen it becomes less acid, because oxyhemoglobin is more acid than reduced hemoglobin. This permits hemoglobin to act as a buffer, to absorb some of the carbon dioxide which is higher in the tissue than in the blood.

The Veins

The venous system is the larger caliber, low resistance collecting system that connects the systemic capillary beds to the right side of the heart. About 50% of the total blood is at any time in the veins. Although veins are much thinner than arteries, they are elastic and they do contain smooth muscle. Consequently they are not just a passive collecting system; under nervous influence the overall tone of the system can increase, reducing volume and temporarily increasing venous return to the heart. This serves as a sort of "instant transfusion" to counter the effects of sudden loss of blood.

The Lymphatics

The lymphatics are a semi-independent system of thin-walled vessels that converge into trunks that empty into the large veins in the abdomen or thorax. Lymphatic capillaries start in tissue spaces, where they pick up protein and excess fluid filtered from regular capillaries. They serve a specific transport function for fat droplets absorbed by cells of the intestinal mucosa. The lymphatic system also plays a role in defense against infectious or noxious materials, since most lymphatic vessels have lymph nodes interposed between tissue spaces and the venous system.

The Pulmonary Circulation

The pulmonary circulation carries the same flow of blood as the systemic circulation but is otherwise quite different. The pulmonary vascular pressures are in general much lower than systemic vascular pressures. Vasoconstriction and consequent local shunting are present in the pulmonary circulation, but much less developed than in the systemic circulation. Diseases of the pulmonary circulation are usually secondary to extensive disease of pulmonary tissue, as in emphysema, fibrosis, and occupational lung diseases.

Integration of Cardiovascular Function

As with other biologic systems, the heart and blood vessels are under nervous and chemical control which tends to stabilize the internal environment. One of the requirements for maintenance of adequate blood flow throughout the body is a sufficient head of arterial pressure. It is, therefore, not surprising to find that any stress tending to

lower arterial pressure (such as hemorrhage, loss of fluids from the body due to severe vomiting or diarrhea, traumatic shock, heat exhaustion) will trigger mechanisms designed to restore blood pressure. These include general arteriolar constriction (except cerebral and coronary arteries), increase in heart rate, and movement of fluid from extracellular space into the blood vessels. The integrated nature of cardiovascular responses to stress often makes it possible to use a simple measurement such as pulse rate to assess the degree of stress (more accurately the degree of response to stress). Thus pulse rate can be used to measure fairly reliably the intensity of exercise or heat stress (assuming given levels of physical fitness or acclimatization to heat).

REGULATION OF WATER AND ELECTROLYTES

As emphasized earlier, the proper functioning of cells in the mammalian body requires near-constancy of the internal environment — the temperature, oxygen supply, nutrient supply, hydrogen ion concentration, and appropriate concentrations of water, sodium, potassium, calcium, magnesium, and other substances. To some extent this constancy can be maintained by internal shifts of elements — from storage reservoirs, or by movement from one compartment to another, as might occur with movement from blood plasma to extracellular fluid to intracellular fluid and the reverse. The real problem is to maintain constancy under the usual conditions of variations of intake and output of a substance. This involves the concept of balance — how is output of water (or sodium, or calcium) controlled so that the "right" amount is retained when intake is varied?

The balance for water, as an example, involves a daily intake of about 2.5 liters in a normal adult under average conditions: 1 liter from food, 0.3 L from metabolic conversions, and 1.2 L from drinking water or beverages. An equal amount is lost each day — by urination 1.5 L, by evaporation from lungs and skin 0.9 L, and the remainder by sweating or in feces.

The major role in regulating body water, electrolytes and other substances is performed by the kidneys. These small organs, weighing less than 1% of total body weight, receive nearly one-quarter of the output of the heart in serving this regulatory role.

The kidney serves its unique function by a combination of three processes. Each microscopic unit of the kidney (or nephron) includes a capillary tuft (glomerulus) which filters plasma into a surrounding space (Bowman's capsule), which is the beginning of a tubule. The tubule processes the glomerular filtrate in complex ways before joining other tubules which ultimately constitute the system for carrying urine to the exterior of the body.

The glomerular filtrate contains all the components of plasma except proteins, which are generally too large to pass through capillary walls and capsule membranes. The amount of filtrate is large — about 180 liters per day for both kidneys — and if most of it were not reabsorbed the

body would be in a precarious position in a matter of minutes. A simple calculation will show that the entire plasma volume passes through the glomeruli some 60 times a day. Fortunately the "wanted" substances are reabsorbed to a high degree, if not totally. Ninety-nine percent of the water is reabsorbed by the tubules, together with 99.5% of the sodium and 100% of the glucose, compared to about 50% for urea, a waste product. The reabsorption involves both active and passive transport. Sodium is reabsorbed by an energy-consuming process which requires the presence of aldosterone, an adrenal cortical hormone. Water reabsorption to some extent follows sodium reabsorption, but is also very much influenced by the anti-diuretic hormone produced in the hypothalamus. Glucose is actively reabsorbed by a process which normally returns all the filtered glucose to peritubular capillaries, but the process can be overloaded if blood glucose is elevated above a certain limit. The excess of sugar filtered into the glomeruli then escapes into the urine, as is frequently the case in diabetes.

The third renal mechanism is of particular importance in toxicology, because many foreign substances are eliminated in the urine by secretion from tubular cells. Like tubular reabsorption, tubular secretion involves both active and passive transport. Of the many substances secreted, only a few, such as hydrogen ion and potassium, are normally found in the body. How mechanisms evolved for transporting the large numbers of foreign substances is a mystery.

Analysis of the balance of water and many ions, combined with study of the ways these substances are handled by the kidney, shows that the concentrations of most of the ions which determine the properties of the extracellular fluid are regulated primarily by the kidneys. Thus the kidneys are not "glorified garbage disposal" units for elimination of nitrogenous wastes so much as they are guardians of the minute to minute composition of all the body fluids and electrolytes.

THE DIGESTIVE SYSTEM

The function of this system is to accept raw materials in the form of food stuffs, minerals, vitamins and liquids in the external environment, to prepare such materials for absorption, and to absorb them into capillaries or lymphatics for distribution to the body. The system also has a limited role in excreting materials from the body.

Since the digestive tract is largely a tube open at both ends, in a real sense the contents of the gastro-intestinal tract remain exterior to the body. In order to gain access to the body, ingested materials must run a gamut of extreme acidity in the stomach and a series of enzymatic attacks starting in the mouth and extending to the large intestine. Some large molecules such as cellulose remain unaltered and are excreted in the feces. Other large molecules which could not otherwise pass through membranes are broken down into constituent amino acids or monosaccharides which are readily absorbed.

Almost all digestion and absorption of food and water takes place in the small intestine. The

volume of fluid absorbed is far greater than that taken in as food and beverages. The latter average about 800 gm of food and 1200 ml of water/day in adults. To this is added 1.5 L of saliva in the mouth, about 2 L of acidic gastric secretions, 2 L of pancreatic and biliary secretions and 1.5 L of intestinal secretions; this adds up to about 8.5 L absorbed per day, with only 0.5 L passing into the large intestine.

Most of the carbohydrate ingested is in the form of starch. The starch is split to disaccharides by the amylases from saliva and from the pancreas. Further splitting into monosaccharides is brought about by enzymes in the small intestinal mucosa, after which the sugar molecules are actively transported into the blood.

Proteins are broken down first into peptides, then into free amino acids which are actively transported across intestinal cells. In adults very little protein is absorbed as such, but in the newborn child proteolytic enzymes are absent; thus a newborn child can absorb protective antibodies from its mother's milk.

Most digestion of fat occurs in the small intestine from the combined actions of pancreatic lipase and bile salts secreted by the liver. The latter act primarily as emulsifying agents. Fatty acids are resynthesized to triglycerides in the intestinal cells, whence they are secreted into the lymphatics as small lipid droplets.

The large intestine has relatively little capacity to absorb or secrete. Water and sodium continue to be absorbed from contents of the large intestine. The remaining contents are largely desquamated epithelial cells from the small intestine, bacteria, and the indigestible residue of food. Contrary to popular opinion, there is no absorption of toxic materials from unexpelled contents of the large intestine.

REGULATION OF ENERGY BALANCE

The energy released in the breakdown of organic molecules in the body performs biologic work (muscle contraction, synthesis of new molecules, or active transport) or appears as heat in the cells. The biologic work done by skeletal muscles in moving external objects (or raising the body to a height by walking uphill) is considered external work. The internal work done by skeletal muscles, by heart muscle and by other tissues appears ultimately as heat. Thus all energy utilized in the body is converted to heat, except during growth and during periods of net fat synthesis, when energy is being stored.

The metabolic rate is the total energy expenditure, measured in kilocalories, per unit time. During fasting conditions, when there can be no net energy storage, the rate of metabolism can be measured either directly or indirectly. The direct method is simple in theory but difficult in practice — it consists of measurement of total heat produced per unit time when the individual is enclosed in a whole-body calorimeter. The easier method is to measure the rate of oxygen utilization, assuming that fats, carbohydrates, and proteins are being utilized in a constant ratio, and that the oxygen-heat equivalents are the same for the three

classes of compounds. These assumptions are sufficiently accurate for most purposes, one liter of oxygen being required for the combustion of approximately 4.8 kilocal. of fat, protein, or carbohydrates.

The oxygen utilization of a healthy adult under standard conditions of rest, 12 hours fasting and a relaxing environment corresponds to a heat production of 40 kilocal. per hour per square meter of surface area — about equal to the heat production of a 100 watt light bulb. Metabolic rate is higher in the young than in adults and is lower in females than in males of equal weight. In late adulthood the resting metabolic rate declines, for reasons which are not clear. The ingestion of food increases metabolic rate by 10 to 20%, due to a specific action of protein and not due to increased activity of the digestive processes.

The above factors influence the standard metabolic rate by amounts which are trivial compared to the effects of physical activity. Since hard physical work can increase metabolic rate by about fifteen-fold it is most important that the average level of physical activity be considered in estimating the energy requirements of the body.

Two hormones also have a very significant effect on metabolic rate: epinephrine release, as occurs during emotional or physical stress, may cause a rapid increase of oxygen utilization by as much as 30%; thyroxin administration, or release of the hormone from the thyroid, causes a slower but very prolonged increase of oxygen utilization which affects all cells of the body except those of the brain.

Control of Food Intake

Normal adults live for long periods with an essentially constant body weight. This must mean that food intake exactly balances the internal heat produced and the external work done. There is no net storage or loss of energy from fat sources. A number of theories have been developed to explain this adjustment — the levels of blood sugar or fat storage affecting appetite centers in the hypothalamus, and other possibilities. The role of specific afferent inputs to the hypothalamic centers has not been well-defined. Clearly there are influences from higher brain centers as well. One of the most intriguing relationships is that between levels of physical activity and food intake. It is generally known that high levels of physical activity are accompanied by increased appetite and increased food intake to keep body weight constant. A few studies have suggested that this relationship does not hold below certain levels of activity that in a sense are "optimal"; below these levels an inverse relation holds — the more sedentary an individual becomes the more likely he is to overeat.

Obesity

When the mechanisms which govern the balance between energy intake and energy expenditure are malfunctioning, the most likely result is "overeating" and obesity. This is often called America's No. 1 health problem because obesity is so prevalent and mortality rates are about 50% higher in the overweight than in those of standard

weight. If obesity, because of the obvious importance of social and economic factors in its etiology, is considered an environmental health problem, it must share with cigarette smoking a ranking as two of the most important environmental health problems in this country.

As in many other diseases and conditions predisposing to disease, there are undoubtedly multiple factors in the etiology of obesity. Experimental obesity has been produced in rats by injuries to the hypothalamus. Obesity is associated with certain endocrine disorders. There are undoubtedly many "constitutional" factors which influence the metabolism and storage of foodstuffs and which presumably make one person more "susceptible" to obesity than another. Ultimately, however, the defect is failure of food-intake control mechanisms to adjust to energy expenditure over a long enough period of time for obesity to develop. Often the predominant cause seems to be psychological or psycho-social.

Regulation of Body Temperature

With the evolution of mechanisms for maintenance of a constant body temperature, the mammals and birds achieved freedom from the marked extremes of temperature that characterize the atmosphere near the surface of the earth. The nearly constant temperature, around 90-103° F in mammals and around 108° in birds, greatly facilitates the action of enzymes in the chemical processes which go on continuously in cells.

The body temperature is in fact variable over a substantial range — from about 96° F in early morning after sleep to as much as 104° (rectally) during heavy exercise. Such excesses of temperature quickly return to about 98° when exercise is over. In fever the temperature may be equally high or higher, but in this case the heat control mechanism ("thermostat") is set at a higher level. Under extreme heat stress, the control mechanisms may fail and the temperature reach 107° or higher. At such temperature the brain is severely affected and death may ensue (heat stroke).

The usually quoted body temperature of 97.6-98.6° F is about the diurnal range of normal oral temperature. Deep body temperatures are a degree or so higher and skin temperatures are several degrees lower.

The body temperature is a measure of the balance between heat gain (metabolism, incident radiation from warm bodies) and heat loss. With changes in heat gain or heat loss, adaptive changes take place to keep body temperature essentially constant. In cold exposure, heat gain could theoretically be increased by secretion of epinephrine and thyroid hormone; this rarely if ever occurs. Heat gain is in fact increased by increases in skeletal muscle tone, involuntary shivering, and voluntary muscular activity. Heat loss is curtailed by vasoconstriction of blood vessels supplying the skin and by various behavioral adjustments such as changing body contours to reduce surface area, increasing insulation by use of clothing, and seeking shelter.

More important environmental exposures in industry are heat stresses from excessive tempera-

ture and humidity and from radiant heat load. These exposures, and the physiologic and behavioral responses thereto, will be considered in a separate chapter.

DEFENSE MECHANISMS AGAINST INFECTION

At least as important as physical and chemical factors in the environment are the hosts of microbiologic agents in the environment. Two classes of microorganisms are of particular concern to man — the bacteria and viruses. Most bacteria are complete cells, capable of reproducing themselves. The viruses, essentially nucleic acid cores in a protein coat, lack the enzyme machinery for energy production and the ribosomes necessary for protein synthesis. They can survive only inside other cells, whose metabolic mechanisms they utilize.

The first line of defense against microorganisms is the complex of anatomic and microchemical barriers provided by external and internal body surfaces. The skin, with its thick layers of cells and secretions, is almost impervious to microorganisms. The mucous membranes contain secretions which inhibit bacterial growth and they usually flow toward the exterior, as in the case of tracheobronchial mucus.

When microorganisms gain access to the body, they may multiply and produce toxins, producing the signs and symptoms of an infection. The mechanisms for controlling growth or killing microorganisms and for neutralizing toxins involve the formation of antibodies, the action of complement, and the activities of phagocytic cells. These phenomena are interrelated.

Most of the phagocytic cells are either in the blood stream (white blood cells) or are closely associated with the vascular and lymphatic systems, including lining cells of bone marrow, liver, spleen and other lymphoid tissue. Despite the great importance of these cells, there is little knowledge of the mechanisms controlling their production. Most bacterial infections result in prompt increases of circulating granulocytic cells; viral infections tend to increase lymphocytes, but decrease other white blood cells.

Antibodies are specialized plasma proteins capable of combining chemically with the specific antigens which induced their formation. Most antigens have molecular weights greater than 10,000; however, smaller molecules may act as antigens after attaching themselves to proteins of the host cells. The antigens involved in infection are usually bacterial toxins or proteins of the

microorganism's surface. Components of almost any foreign cell can act as antigens.

The plasma proteins known as complement are normally present in plasma and are not induced by antigens. The complement assists in killing bacteria, after an antibody has combined with its specific antigen in the wall of a bacterium. The complement apparently kills the bacterium after damaging the wall at the site of the antigen-antibody complex. Complement and antibodies also predispose bacteria to phagocytosis by phagocytes in the vicinity.

In addition to antibody formation and phagocytosis, a third defense mechanism plays a significant role in resistance to viral infections. This is the formation of the protein *interferon* in response to a viral infection of a particular cell. Unlike antibodies, interferon is not specific; all viruses stimulate production of the same interferon, and interferon inhibits the growth and multiplication of many different viruses. At present there is no way of using this information to improve treatment of virus infection.

Allergy

Allergy is an acquired hypersensitivity to a particular substance — an antigen-antibody reaction that results in cell damage. The term is usually reserved for the response to nonmicrobial antigens. The addition of complement to the antigen-antibody complex probably triggers cell damage and inflammatory response. The puzzling feature is why the response is so inappropriate to the antigen stimulus. Symptoms are often localized to the surface exposed, for example the respiratory response to aero-allergens such as ragweed pollen. Generalized allergic responses may also occur with widespread liberation of histamine to produce hives, extensive skin eruption, bronchospasm, rapid heart rate and hypotension. In extreme examples, death can occur, as for example, from the sting of a single bee.

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CHAPTER 7

INDUSTRIAL TOXICOLOGY

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INTRODUCTION

Toxicology is the study of the nature and action of poisons. The term is derived from a Greek word referring to the poison in which arrows were dipped. Mythology, legend and history indicate the growth of toxicological knowledge. The early emphasis was on ways to poison people. The 19th century saw the development of tests for identification of various poisons, such as the Marsh test for arsenic. These found use in legal medicine and criminology, the area known as forensic toxicology. Since about 1900, there has been increasing social concern for the health of workers exposed to a diversity of chemicals. This has led to intensive investigations of the toxicity of these materials in order that proper precautions may be taken in their use. This is the area of industrial toxicology which concerns us here.

Some industrial hazards have been known for centuries. For example, clinical symptoms of lead poisoning were accurately described in the 1st century A.D. The Romans used only slave labor in the great Spanish mercury mines at Almaden, and a sentence to work there was considered equivalent to a sentence of death. French hatters of the 17th century discovered that mercuric nitrate aided greatly in the felting of fur. Such use led to chronic mercury poisoning so widespread among members of that trade that the expression "mad as a hatter" entered our folk language. Exposure to other hazardous substances is an outgrowth of modern technology. In addition to newly developed chemicals, many materials first synthesized in the late 19th century have found widespread industrial use. The hydrides of boron, for example, have been known since 1879, but the first report on their toxicity appeared in 1951 as a series of case histories of people, mostly young chemical engineers, who had been exposed to boron hydrides in the course of their work.

Toxicological research now has its place in assessing the safety of new chemicals prior to the extension of their use beyond exploratory stages. Information on the qualitative and quantitative actions of a chemical in the body can be used to predict tentative safe levels of exposure as well as to predict the signs and symptoms to be watched for as indicative of excessive exposure. An elucidation of the mechanism of action of the chemical can hopefully lead to rational rather than symptomatic therapy in the event of damage from excessive exposure. Both in the application of newer refined research techniques of toxicology and in his communication of knowledge vital to the public health, the toxicologist considers old as well as new

hazardous substances. This point was well made by Henry Smyth¹ who said "Most people are careful in handling a new chemical whether or not they have been warned specifically of its possible toxicity. Despite the potential hazards of hundreds of new chemicals each year, most injuries from chemicals are due to those which have been familiar for a generation or more. It is important for the perspective of the toxicologist that he keep this fact well to the forefront of his mind. He must not neglect talking about the hazards of the old standbys, lead, benzene and chlorinated hydrocarbons just because this week he discovered the horrifying action of something brand new. Part of his responsibility is a continuing program of communication aimed at informing everyone of the means required to handle safely any chemical whatsoever."

DISCIPLINES INVOLVED IN INDUSTRIAL TOXICOLOGY

In order to assess the potential hazard of a substance to the health of workers industrial toxicology draws perforce on the expertise of many disciplines.

Chemistry: The chemical properties of a compound can often be one of the main factors in its toxicity. The vapor pressure indicates whether or not a given substance has the potential to pose a hazard from inhalation. The solubility of a substance in aqueous and lipid media is a guiding factor in determining the rate of uptake and excretion of inhaled substances. The toxicologist needs to determine the concentration of toxic agents in air and in body organs and fluids. It is important to know if a substance is, for example, taken up by the liver, stored in the bones, or rapidly excreted. For this, analytical methods are needed which are both sensitive and specific.

Biochemistry: The toxicologist needs knowledge of the pathways of metabolism of foreign compounds in the body. Such information can serve as the basis for monitoring the exposure of workmen, as for example the assessment of benzene exposure by the analysis of phenol in the urine. Differences in metabolic pathways among animal species form one basis for selective toxicity. Such knowledge is useful, for example, in developing compounds that will be maximally toxic to insects and minimally so to other species. Such knowledge can also serve as a guide in the choice of a species of experimental animal with a metabolic pathway similar to that of man for studies which will be extrapolated to predict safe levels for human exposure. Rational therapy for injury from

toxic chemicals has as its basis an understanding of the biochemical lesion they produce. One outstanding example is the development of B.A.L. (British Anti-Lewisite, 1,2-dimercaptopropanol) which arose from studies of the inhibition of sulfhydryl enzymes and the manner of binding of arsenic to these enzymes. This led to the use of B.A.L. in therapy for industrial poisons (such as mercury) which interfere with sulfhydryl enzymes. Studies of the nature of the reaction of organic phosphorus esters with the enzyme acetylcholine esterase led to the development of 2-PAM (2-pyridine aldoxime methiodide) which reverses the inhibition of the enzyme. In conjunction with atropine, 2-PAM provides rational therapy for treatment of poisoning by these compounds. In the important area of joint toxic action, understanding comes from elucidation of biochemical action. If, for example, Compound A induces enzymes which serve to detoxify Compound B, the response to the combination may be less than additive. On the other hand, if Compound A should act to inhibit the enzyme that serves to detoxify Compound B then the response may be more than additive.

Physiology: The toxicologist obviously needs to know something of the normal functioning of organ systems. Modern toxicology is moving more and more towards the search for means to detect reversible physiological changes produced by concentrations of toxic substances too low to produce irreversible histological damage or death in experimental animals. Measurement of increases in pulmonary flow-resistance has proved a sensitive tool for assessing the response to irritant gases and aerosols. Tests of pulmonary function can be used to assess response of workmen to industrial environments. Renal clearance and other kidney function tests can serve to detect renal damage. The effects of exercise or non-specific stress on the degree of response to toxic chemicals is another important research area in modern toxicology.

Pathology: The toxicologist is concerned with gross and histological damage caused by toxic substances. Most toxicological studies include a thorough pathological examination which may include examination of subcellular structure by electron microscopy.

Immunology and Immunochemistry: It is recognized that immunology and immunochemistry constitute an important area for investigation in industrial toxicology. The response to many chemicals, especially inhaled products of biologic origin, has as its basis the immune reaction.

Physics and Engineering: The toxicologist who is concerned with inhalation as the route of exposure needs some knowledge of physics and engineering in order to establish controlled concentrations of the substances he studies. If the toxic materials are to be administered as airborne particles, knowledge is needed of methods of generation of aerosols and methods of sampling and sizing appropriate to the material studied. Without careful attention to these factors, toxicological studies are of limited value. An understanding of the factors

governing penetration, deposition, retention and clearance of particulate material from the respiratory tract requires knowledge of both the physical laws governing aerosol behavior and the anatomy and physiology of the respiratory tract. The growing interest in prolonged exposure to closed atmospheres encountered in manned space travel or deep sea exploration has led to experimental studies involving round-the-clock exposures of experimental animals for long periods. Such studies raise additional engineering problems above and beyond those of maintaining the more conventional exposure chambers.

Statistics: Statistics are used in the analysis of data and in the establishing of an experimental design that will yield the maximum of desired information with the minimum of wasted effort. The toxicologist relies heavily on statistics, as the calculation of the LD_{50} (Lethal Dose — 50% probable) is a statistical calculation. Experimental studies of joint toxicity are planned in accord with established statistical designs.

Communication: The ultimate aim of the toxicologist is (or should be) the prevention of damage to man and the environment by toxic agents. One important function is the distribution of information in such terms that the people in need of the information will understand it. The toxicologist's responsibility does not end with the publication of his research results in a scientific journal for the erudition of his peers. He is called upon to make value judgments in extrapolation of his findings in order to advise governmental agencies and others faced with the problem of setting safe levels, be they air pollution standards or Threshold Limit Values for industrial exposure or tolerance levels of pesticide residues in food. In addition to this, when he makes such value judgments, he should above all be honest with himself and with those he advises, that they are value judgments and as such should be subject to frequent review as new knowledge and experience accumulate.

DOSE-RESPONSE RELATIONSHIPS

Experimental toxicology is in essence biological assay with the concept of a dose-response relationship as its unifying theme. The potential toxicity (harmful action) inherent in a substance is manifest only when that substance comes in contact with a living biological system. A chemical normally thought of as "harmless" will evoke a toxic response if added to a biological system in sufficient amount. For example, the inadvertent inclusion of large amounts of sodium chloride in feeding formulae in a hospital nursery led to infant mortality. Conversely, for a chemical normally thought of as "toxic" there is a minimal concentration which will produce no toxic effect if added to a biological system. The toxic potency of a chemical is thus ultimately defined by the relationship between the dose (the amount) of the chemical and the response that is produced in a biological system.

In preliminary toxicity testing, death of the animals is the response most commonly chosen. Given a compound with no known toxicity data,

the initial step is one of range finding. A dose is administered and, depending on the outcome, is increased or decreased until a critical range is found over which, at the upper end, all animals die and, at the lower end, all animals survive. Between these extremes is the range in which the toxicologist accumulates data which enable him to prepare a dose-response curve relating percent mortality to dose administered.

From the dose-response curve, the dose that will produce death in 50 percent of the animals may be calculated. This value is commonly abbreviated as LD_{50} . It is a statistically obtained value representing the best estimation that can be made from the experimental data at hand. The LD_{50} value should always be accompanied by a statement of the error of the estimated value, such as the probability range or confidence limits. The dose is expressed as amount per unit of body weight. The value should be accompanied by an indication of the species of experimental animal used, the route of administration of the compound, the vehicle used to dissolve or suspend the material if applicable, and the time period over which the animals were observed. For example, a publication might state "For rats, the 24 hr. ip LD_{50} for "X" in corn oil was 66 mg/kg (95% confidence limits 59-74)." This would indicate to the reader that the material was given to rats as an intraperitoneal injection of compound X dissolved or suspended in corn oil and that the investigator had limited his mortality count to 24 hours after administering the compound. If the experiment has involved inhalation as the route of exposure, the dose to the animals is expressed as parts per million, mg/m³, or some other appropriate expression of concentration of the material in the air of the exposure chamber, and the length of exposure time is specified. In this case the term LC_{50} is used to designate the concentration in air that may be expected to kill 50 percent of the animals exposed for the specified length of time. Various procedures have been recommended for the estimation of the LD_{50} or LC_{50} . For information on the more commonly used techniques, papers such as those of Bliss,² Miller and Tainter,³ Litchfield and Wilcoxon⁴ or Weil⁵ may be consulted.

The simple determination of the LD_{50} for an unknown compound provides an initial comparative index for the location of the compound in the overall spectrum of toxic potency. Table 7-1 shows an attempt at utilizing LD_{50} and LC_{50} values to set up an approximate classification of toxic substances which was suggested by Hodge and Sterner.⁶

Over and above the specific LD_{50} value, the slope of the dose-response curve provides useful information. It suggests an index of the margin of safety, that is the magnitude of the range of doses involved in going from a non-effective dose to a lethal dose. It is obvious that if the dose-response curve is very steep, this margin of safety is slight. Another situation may arise in which one compound would be rated as "more toxic" than a second compound if the LD_{50} values alone were compared but the reverse assessment of rel-

ative toxicity would be reached if the comparison was made of the LD_{50} values for the two compounds because the dose-response curve for the second compound had a more gradual slope. It should thus be apparent that the slope of the dose-response curves may be of considerable significance with respect to establishing relative toxicities of compounds. For an excellent non-mathematical discussion of the underlying concepts of dose-response relationships, Chapter 2 of Loomis⁷ is well worth reading.

TABLE 7-1
Toxicity Classes

Toxicity Rating	Descriptive Term	LD_{50} -Wt/kg Single oral dose Rats	4 hr Inhalation LC_{50} — PPM Rats
1	Extremely toxic	1 mg or less	<10
2	Highly toxic	1-50 mg	10-100
3	Moderately toxic	50-500 mg	100-1,000
4	Slightly toxic	0.5-5 g	1,000-10,000
5	Practically non-toxic	5-15 g	10,000-100,000
6	Relatively harmless	15 g or more	>100,000

By similar experiments dose-response curves may be obtained using a criterion other than mortality as the response and an ED_{50} value is obtained. This is the dose which produced the chosen response in 50 percent of the treated animals. When the study of a toxic substance progresses to the point at which its action on the organism may be studied as graded response in groups of animals, dose-response curves of a slightly different sort are generally used. One might see for example, a dose-response curve relating the degree of depression of brain choline esterase to the dose of an organic phosphorus ester or a dose-response curve relating the increase in pulmonary flow-resistance to the concentration of sulfur dioxide inhaled.

ROUTES OF EXPOSURE

Toxic chemicals can enter the body by various routes. The most important route of exposure in industry is inhalation. Next in importance is contact with skin and eyes. The response to a given dose of toxic agent may vary markedly depending on the route of entry. A cardinal principle to remember is that *the intensity of toxic action is a function of the concentration of the toxic agent which reaches the site of action*. The route of exposure can obviously have an influence upon the concentration reaching the site of action.

Parenteral: Aside from the obvious use in administration of drugs, injection is considered mainly as a route of exposure of experimental animals. In the case of injection, the dose administered is known with accuracy. Intravenous (iv) injection introduces the material directly into the circulation, hence comparison of the degree of response to iv injection with the response to the dose administered by another route can provide information on the rate of uptake of the material by the alternate route. When a material is administered

by injection, the highest concentration of the toxic material in the body occurs at the time of entrance. The organism receives the initial impact at the maximal concentration without opportunity for a gradual reaction, whereas if the concentration is built up more gradually by some other route of exposure, the organism may have time to develop some resistance or physiological adjustment which could produce a modified response. In experimental studies intraperitoneal (ip) injection of the material into the abdominal fluid is a frequently used technique. The major venous blood circulation from the abdominal contents proceeds via the portal circulation to the liver. A material administered by ip injection is subject to the special metabolic transformation mechanisms of the liver, as well as the possibility of excretion via the bile before it reaches the general circulation. If the LD_{50} of a compound given by ip injection was much higher (i.e., the toxicity is lower) than the LD_{50} by iv injection, this fact would suggest that the material was being detoxified by the liver or that the bile was a major route of excretion of the material. If the values for LD_{50} were very similar for ip and iv injection, it would suggest that neither of these factors played a major role in the handling of that particular compound by that particular species of animal.

Oral: Ingestion occurs as a route of exposure of workmen through eating or smoking with contaminated hands or in contaminated work areas. Ingestion of inhaled material also occurs. One mechanism for the clearance of particles from the respiratory tract is the carrying up of the particles by the action of the ciliated lining of the respiratory tract. These particles are then swallowed and absorption of the material may occur from the gastro-intestinal tract. This situation is most likely to occur with larger size particles (2μ and up) although smaller particles deposited in the alveoli may be carried by phagocytes to the upward moving mucous carpet and eventually be swallowed.

In experimental work, compounds may be administered orally as either a single or multiple dose given by stomach tube or the material may be incorporated in the diet or drinking water for periods varying from several weeks or months up to several years or the lifetime of the animals. In either case, the dose the animals actually receive may be ascertained with considerable accuracy. Except in the case of a substance which has a corrosive action or in some way damages the lining of the gastro-intestinal tract, the response to a substance administered orally will depend upon how readily it is absorbed from the gut. Uranium, for example, is capable of producing kidney damage, but is poorly absorbed from the gut and so oral administration produces only low concentrations at the site of action. On the other hand, ethyl alcohol, which has as a target organ the central nervous system, is very rapidly absorbed and within an hour 90 percent of an ingested dose has been absorbed.

The epithelium of the gastro-intestinal tract is poorly permeable to the ionized form of or-

ganic compounds. Absorption of such materials generally occurs by diffusion of the lipid-soluble non-ionized form. Weak acids which are predominately nonionized in the high acidity (pH 1.4) of gastric juice are absorbed from the stomach. The surface of the intestinal mucosa has a pH of 5.3. At this higher pH weak bases are less ionized and more readily absorbed. The pK of a compound (see Chapter 5) thus becomes an important factor in predicting absorption from the gastro-intestinal tract.

Inhalation: Inhalation exposures are of prime importance to the industrial toxicologist. The dose actually received and retained by the animals is not known with the same accuracy as when a compound is given by the routes previously discussed. This depends upon the ventilation rate of the individual. In the case of a gas, it is influenced by solubility and in the case of an aerosol by particle size. The factors that influence the dose of a substance retained in an inhalation exposure will be discussed later. For the moment, suffice it to say that the concentration and time of exposure can be measured accurately and this gives a working estimate of the exposure. Two techniques are sometimes utilized in an attempt to determine the dose with precision and still administer the compound via the lung. One is intratracheal injection which may be used in some experiments in which it is desirable to deliver a known amount of particulate material into the lung. The other is so called "precision gassing." In this technique the animal or experimental subject breathes through a valve system and the volume of exhaled air and the concentration of toxic material in it are determined. A comparison of these data with the concentration in the atmosphere of the exposure chamber gives an indication of the dose retained.

Cutaneous: Cutaneous exposure ranks first in the production of occupational disease, but not necessarily first in severity. The skin and its associated film of lipids and sweat may act as an effective barrier. The chemical may react with the skin surface and cause primary irritation. The agent may penetrate the skin and cause sensitization to repeated exposure. The material may penetrate the skin in an amount sufficient to cause systemic poisoning. In assessing the toxicity of a compound by skin application, a known amount of the material to be studied is placed on the clipped skin of the animal and held in place with a rubber cuff. Some materials such as acids, alkalis and many organic solvents are primary skin irritants and produce skin damage on initial contact. Other materials are sensitizing agents. The initial contact produces no irritant response, but may render the individual sensitive and dermatitis results from future contact. Ethyleneamines and the catechols in the well known members of the Rhus family (poison ivy and poison oak) are examples of such agents. Chapter 34 is devoted to the damaging effects of industrial chemicals on the skin. The physicochemical properties of a material are the main determinant of whether or not a material will be absorbed through the skin. Among the important factors are pH, extent of ionization,

water and lipid solubility and molecular size. Some compounds such as phenol and phenolic derivatives can readily penetrate the skin in amounts sufficient to produce systemic intoxication. If the skin is damaged, the normal protective barrier to absorption of chemicals is lessened and penetration may occur. An example of this is a description of cases of mild lead intoxication that occurred in an operation which involved an inorganic lead salt and also a cutting oil. Inorganic lead salts would not be absorbed through intact skin, but the dermatitis produced by the cutting oil permitted increased absorption.

Ocular: The assessment of possible damage resulting from the exposure of the eyes to toxic chemicals should also be considered. The effects of accidental contamination of the eye can vary from minor irritation to complete loss of vision. In addition to the accidental splashing of substances into the eyes, some mists, vapors and gases produce varying degrees of eye irritation, either acute or chronic. In some instances a chemical which does no damage to the eye can be absorbed in sufficient amount to cause systemic poisoning. The extreme toxicity of fluoroacetate was discovered accidentally in this manner by a group of Polish chemists who tested it for lachrymatory action in a rabbit. They had hoped that fluoroacetate would be as irritating to the eyes as iodoacetic acid. The latter had proved unsuitable for warfare purposes because of the purple cloud of iodine vapor that betrayed its presence when it was exploded in a bomb. Their rabbit showed no signs of eye irritation, but alerted their interest when it had convulsions and died. An excellent reference on ocular effects of toxic chemicals is "Toxicology of the Eye" by Grant.⁸

CRITERIA OF RESPONSE

After the toxic material has been administered by one of the routes of exposure discussed above, there are various criteria the toxicologist uses to evaluate the response. In modern toxicological research, these criteria are oriented whenever possible towards elucidating the mechanisms of action of the material.

Mortality: As has been indicated, the LD₅₀ of a substance serves as an initial test to place the compound appropriately in the spectrum of toxic agents. Mortality is also a criterion of response in long term chronic studies. In such studies, the investigator must be certain that the mortality observed was due to the chronic low level of the material he is studying; hence an adequate control group of untreated animals subject to otherwise identical conditions is maintained for the duration of the experiment.

Pathology: By examination of both gross and microscopic pathology of the organs of animals exposed, it is possible to get an idea of the site of action of the toxic agent, the mode of action and the cause of death. Pathological changes are usually observed at dose levels which are below those needed to produce the death of animals. The liver and the kidney are organs particularly sensitive to the action of a variety of toxic agents. In some instances the pathological lesion is typical

of the specific toxic agents, for example, the silicotic nodules in the lungs produced by inhalation of free silica or the pattern of liver damage resulting from exposure to carbon tetrachloride and some other hepatotoxins. In other cases the damage may be more diffuse and less specific in nature.

Growth: In chronic studies the effect of the toxic agent on the growth rate of the animals is another criterion of response. Levels of the compound which do not produce death or overt pathology may result in a diminished rate of growth. A record is also made of the food intake. This will indicate whether diminished growth results from lessened food intake or from less efficient use of food ingested. It sometimes happens that when an agent is administered by incorporation into the diet, especially at high levels, the food is unpalatable to the animals and they simply refuse to eat it.

Organ Weight: The weight of various organs, or more specifically the ratio of organ weight to body weight may be used as a criterion of response. In some instances such alterations are specific and explicable, as for example the increase of lung weight to body weight ratio as a measure of the edema produced by irritants such as ozone or oxides of nitrogen. In other instances the increase is a less specific general hypertrophy of the organ, especially of the liver and kidney. In a summary of data from two major industrial toxicology laboratories where a wide variety of compounds had been screened for toxicity,⁹ it was pointed out that in using body growth, liver weight and kidney weight as criteria of response, a change in one or more of these was observed at the lowest dose at which any effect was seen in 80 percent of 364 studies. If liver and kidney pathology were included in the list, then a change in one or more criteria was observed at the lowest dose at which any effect was seen in 96 percent of these studies. The other 4 percent included materials with very specific action such as the organophosphorus insecticides which will produce alterations in acetylcholine esterase at very low levels. Such non-specific increases in organ weight are difficult to interpret and may not of necessity represent a harmful change, but they lower the threshold at which a dose may be termed "no effect."

Physiological Function Tests: Physiological function tests are useful criteria of response both in experimental studies and in assessing the response of exposed workmen. They can be especially useful in chronic studies in that they do not necessitate the killing of the animal and can, if desired, be done at regular intervals throughout the period of study. Tests in common clinical use such as bromsulphalein retention, thymol turbidity, or serum alkaline phosphatase may be used to assess the effect of an agent on liver function. The examination of the renal clearance of various substances helps give an indication of localization of kidney damage. The ability of the kidney (especially in the rat) to produce a concentrated urine may be measured by the osmolality of the urine produced. This has been suggested for the evaluation of alterations in kidney function.¹⁰ Alterations may be detected following inhalation of materials such as chlorotrifluoroethylene at levels of reversi-

ble response. In some instances measurement of blood pressure has proved a sensitive means of evaluating response.¹¹ Various tests of pulmonary function have been used to evaluate the response of both experimental animals and exposed workmen. These tests include relatively simple tests which are suitable for use in field surveys as well as more complex methods possible only under laboratory conditions. Simple tests include such measurements as peak expiratory flowrate (PEFR), forced vital capacity (FVC), and 1-second forced expiratory volume (FEV_{1.0}). More complex procedures include the measurement of pulmonary mechanics (flow-resistance and compliance) and their application in epidemiologic surveys. Information on the effects of various agents on the lungs is discussed in Chapter 33.

Biochemical Studies: The study of biochemical response to toxic agents leads in many instances to an understanding of the mechanism of action. Tests of toxicity developed in animals should be oriented to determination of early response from exposures that are applicable to the industrial scene. Many toxic agents act by inhibiting the action of specific enzymes. This action may be studied *in vitro* and *in vivo*. In the first case, the toxic agent is added to tissue slices or tissue homogenate from normal animals and the degree of inhibition of enzymatic activity is measured by an appropriate technique. In the second case, the toxic agent is administered to the animals; after the desired interval the animals are killed and the degree of enzyme inhibition is measured in the appropriate tissues. A judicious combination of *in vivo* and *in vitro* studies is especially useful when biotransformation to a toxic compound is involved. The classic example of this is the work of Peters¹² on the toxicity of fluoroacetate. This material, which was extremely toxic when administered to animals of various species, did not inhibit any known enzymes *in vitro*. Peters' work demonstrated that fluoroacetate entered the carboxylic acid cycle of metabolism as if it were acetic acid. The product formed was fluorocitrate which was a potent inhibitor of the enzyme aconitase. Biological conversion in the living animal had resulted in the formation of a highly toxic compound. He coined the term "lethal synthesis" to describe such a transformation. An elegant paper by Cremer¹³ on the ethyl lead compounds is worth discussing as an example of research techniques in this area. She injected rats with tetra-, tri-, and di-ethyl lead and with lead acetate. Symptoms of excitability, tremors and convulsions were observed in the animals injected with the tetraethyl and triethyl lead but not in the animals injected with diethyl lead or the inorganic lead. The triethyl lead was more potent than the tetraethyl lead, which suggested that perhaps the toxic response resulted from biologically formed triethyl lead. By analytic methods, she was able to demonstrate the presence of triethyl lead in the tissues of animals poisoned with tetraethyl lead. She found *in vitro* that liver preparations were capable of converting tetraethyl lead to triethyl lead. She measured the metabolism of brain slices from animals treated *in vivo* and found that the oxygen

consumption was lowered in animals receiving tetraethyl or triethyl lead but not in animals treated with diethyl lead or lead acetate. Turning again to *in vitro* experiments, she measured the oxygen consumption of brain cortex slices from normal animals to which the ethyl lead compounds were added. These experiments showed that tetraethyl lead is without effect and that triethyl lead is the active component.

The fundamentals of the metabolism of toxic compounds are discussed in Chapter 5. The classic reference in the field is *Detoxification Mechanisms* by Williams.¹⁴ The term "biotransformation" is in many ways preferable to "detoxication" for in many instances the toxic moiety may be the metabolic product rather than the compound administered. There are some instances, of course, such as the conversion of cyanide to thiocyanate, which are truly "detoxication" in the strict sense.

Tests for the level of metabolites of toxic agents in the urine have found wide use in industrial toxicology as a means of evaluating exposure of workmen. These are commonly referred to as biologic threshold limits which serve as biologic counterparts to the TLV's. The presence of the metabolic product does not of necessity imply poisoning; indeed the opposite is more commonly the case. Normal values have been established and an increase above these levels indicates that exposure has occurred and thus provides a valuable screening mechanism for the prevention of injury from continued or excessive exposure. Table 7-2 lists some of these metabolic products which have been used to evaluate exposure as well as the agents for which they may be used.

TABLE 7-2
Metabolic Products Useful As Indices Of Exposure

Product in Urine	Toxic Agents
Organic Sulfate	Benzene Phenol Aniline
Hippuric Acid	Toluene Ethyl benzene
Thiocyanate	Cyanate Nitriles
Glucuronates	Phenol Benzene Terpenes
Formic Acid	Methyl alcohol
2, 6, dinitro-4-amino toluene	TNT
p-nitrophenol	Parathion
p-aminophenol	Aniline

There are other instances in which a biochemical alteration produced by the toxic agent is useful as a criterion of evaluating exposure. Lead, for example, interferes in porphyrin metabolism and increased levels of delta-aminolevulinic acid may be detected in the urine following lead exposure. Levels of plasma choline esterase may be used to evaluate exposure to organic phosphorus insecticides. Levels of carboxyhemoglobin provide a means of assessing exposure to carbon monoxide. Levels of methemoglobin can be used to evaluate exposure to nitrobenzene or aniline. Hemolysis

of red cells is observed in exposure to arsine. Analysis of blood, urine, hair, or nails for various metals is also used to evaluate exposure, though whether these would be termed "biochemical tests" depends somewhat on whether you are speaking with an engineer or a biochemist.

The use of biologic threshold limit values provides a valuable adjunct to the TLV's which are based on air analysis. The analysis of blood, urine, hair, or exhaled air for a toxic material *per se* (e.g., Pb, As) or for a metabolite of the toxic agent (e.g., thiocyanate, phenol) gives an indication of the exposure of an individual worker. These tests represent a very practical application of data from experimental toxicology. Research in industrial toxicology is often oriented towards the search for a test suitable for use as a biologic threshold which will indicate exposure at a level below which damage occurs.

Behavioral Studies: When any toxic agent is administered to experimental animals, the experienced investigator is alert for any signs of abnormal behavior. Such things as altered gait, bizarre positions, aggressive behavior, increased or decreased activity, tremors or convulsions can suggest possible sites of action or mechanisms of action. The ability of an animal to maintain its balance on a rolling bar is a frequently used test of coordination. The loss of learned conditioned reflexes has also been used and by judicious combination of these tests it is possible to determine, for example, that the neurological response to methyl cellosolve differs from the response to ethyl alcohol.¹⁵ Ability to solve problems or make perceptual distinctions has been used on human subjects, especially in an effort to determine the possible effects of low levels of carbon monoxide and other agents which might be expected to interfere with efficient performance of necessary tasks, thus creating a subtle hazard. Effects on neurological variables such as dark adaptation of the eye are much used by Russian investigators in determining threshold limit values.

Reproductive Effects: It is possible that a level of a toxic material can have an effect on either male or female animals which will result in decreased fertility. In fertility studies the chemical is given to males and females in daily doses for the full cycle of oogenesis and spermatogenesis prior to mating. If gestation is established, the fetuses are removed by caesarean section one day prior to delivery. The litter size and viability are compared with untreated groups. The young are then studied to determine possible effects on survival, growth rate and maturation. The tests may be repeated through a second and third litter of the treated animals. If it is considered necessary the test may be extended through the second and third generation.

Teratogenic Effects: Chemicals administered to the pregnant animal may, under certain conditions, produce malformations of the fetus without inducing damage to the mother or killing the fetus. The experience with the birth of many infants with limb anomalies resulting from the use of thalidomide by the mothers during pregnancy alerted the toxicologists to the need for more rigid testing in

this difficult area. Another example of human experience in recent times was the teratogenic effect of methyl mercury as demonstrated in the incidents of poisoning in Minamata Bay, Japan. The study of the teratogenic potential poses a very complex toxicological problem. The susceptibility of various species of animal varies greatly in the area of teratogenic effects. The timing of the dose is very critical as a chemical may produce severe malformations of one sort if it reaches the embryo at one period of development and either no malformations or malformations of a completely different character if it is administered at a later or earlier period of embryogenesis. For a discussion of a recommended method of teratogenic testing and a summary of the literature in this area, the paper by Cahen¹⁶ may be consulted.

Carcinogenicity: The study of the carcinogenic effects of a toxic chemical is a complex experimental problem. Such testing involves the use of sizeable groups of animals observed over a period of two years in rats or four to five years in dogs because of the long latent period required for the development of cancer. Efforts to shorten the time lag have led to the use of aging animals. This may reduce the lag period one third to one fourth. Various strains of inbred mice or hamsters are frequently used in such experiments. Quite frequently materials are screened by painting on the skin of experimental animals, especially mice. Industrial experience down through the years has made plain the hazard of cancer from exposure to various chemicals. Among these are many of the polynuclear hydrocarbons, beta-naphylamine which produces bladder cancer, chromates and nickel carbonyl which produce lung cancer. An excellent summary of recent experimental work in the area of the production of lung cancer in experimental animals is given by Kuschner.¹⁷

The FDA Advisory Committee on Protocols for Safety Evaluation Panel on Carcinogenesis has recently published in the literature their *Report on Cancer Testing in the Safety Evaluation of Food Additives and Pesticides*.¹⁸ The particular emphasis is on testing materials which would come into contact with man principally through the diet, either as food additives or as contaminating residues on food products as in the case of pesticides; however, many fundamental points pertinent to the overall area of experimental testing for carcinogenesis by the toxicologist are raised and thoughtfully discussed. This reference is highly recommended reading. For ubiquitous substances air quality standards must consider contributions from all sources, food and beverages, water, ambient air, and smoking, as well as those from the industrial environment, e.g., asbestos and lead.

FACTORS INFLUENCING INTENSITY OF TOXIC ACTION

Rate of Entry and Route of Exposure: The degree to which a biological system responds to the action of a toxic agent is in many cases markedly influenced by the rate and route of exposure. It has already been indicated that when a substance is administered as an iv injection, the material has maximum opportunity to be carried by the blood

stream throughout the body, whereas other routes of exposure interpose a barrier to distribution of the material. The effectiveness of this barrier will govern the intensity of toxic action of a given amount of toxic agent administered by various routes. Lead, for example, is toxic both by ingestion and by inhalation. An equivalent dose, however, is more readily absorbed from the respiratory tract than from the gastro-intestinal tract and hence produces a greater response.

There is frequently a difference in intensity of response and sometimes a difference even in the nature of the response between the acute and chronic toxicity of a material. If a material is taken into the body at a rate sufficiently slow that the rate of excretion and/or detoxification keeps pace with the intake, it is possible that no toxic response will result even though the same total amount of material taken in at a faster rate would result in a concentration of the agent at the site of action sufficient to produce a toxic response. Information of this sort enters into the concept of a threshold limit for safe exposure. Hydrogen sulfide is a good example of a substance which is rapidly lethal at high concentrations as evidenced by the many accidental deaths it has caused. It has an acute action on the nervous system with rapid production of respiratory paralysis unless the victim is promptly removed to fresh air and revived with appropriate artificial respiration. On the other hand, hydrogen sulfide is rapidly oxidized in the plasma to non-toxic substances and many times the lethal dose produces relatively little effect if administered slowly. Benzene is a good example of a material which differs in the nature of response depending on whether the exposure is an acute one to a high concentration or a chronic exposure to a lower level. If one used as criteria the 4 hr LC_{50} for rats of 16,000 ppm which has been reported for benzene, one would conclude (from Table 7-1) that this material would be "practically non-toxic" which, of course, is contrary to fact. The mechanism of acute death is narcosis. Chronic exposure to low levels of benzene on the other hand produces damage to the blood-forming tissue of the bone marrow and chronic benzene intoxication may appear even many years after the actual exposure to benzene has ceased.

Age: It is well known that, in general, infants and the newborn are more sensitive to many toxic agents than are adults of the same species, but this has relatively little bearing on a discussion of industrial toxicology. Older persons or older animals are also often more sensitive to toxic action than are younger adults. With aging comes a diminished reserve capacity in the face of toxic stress. This reserve capacity may be either functional or anatomical. The excess mortality in the older age groups during and immediately following the well known acute air pollution incidents is a case in point. There is experimental evidence from electron microscope studies that younger animals exposed to pollutants have a capacity to repair lung damage which was lost in older animals.¹⁹
State of Health: Pre-existing disease can result in greater sensitivity to toxic agents. In the case of

specific diseases which would contraindicate exposure to specific toxic agents, pre-placement medical examination can prevent possible hazardous exposure. For example, an individual with some degree of pre-existing methemoglobinemia would not be placed in a work situation involving exposure to nitrobenzene. Since it is known that the uptake of manganese parallels the uptake of iron, it would be unwise to employ a person with known iron deficiency anemia as a manganese miner. It has been shown that viral agents will increase the sensitivity of animals to exposure to oxidizing type air pollutants. Nutritional status also affects response to toxic agents.

Previous Exposure: Previous exposure to a toxic agent can lead to either tolerance, increased sensitivity or make no difference in the degree of response. Some toxic agents function by sensitization and the initial exposures produce no observable response, but subsequent exposures will do so. In these cases the individuals who are thus sensitized must be removed from exposure. In other instances if an individual is re-exposed to a substance before complete reversal of the change produced by a previous exposure, the effect may be more dangerous. A case in point would be an exposure to an organophosphorus insecticide which would lower the level of acetylcholine esterase. Given time, the level will be restored to normal. If another exposure occurs prior to this, the enzyme activity may be further reduced to dangerous levels. Previous exposure to low levels of a substance may in some cases protect against subsequent exposure to levels of a toxic agent which would be damaging if given initially. This may come about through the induction of enzymes which detoxify the compound or by other mechanisms often not completely understood. It has been shown, for example, that exposure of mice to low levels of ozone will prevent death from pulmonary edema in subsequent high exposures.²⁰ There is also a considerable "cross tolerance" among the oxidizing irritants such as ozone and hydrogen peroxide, an exposure to low levels of the one protecting against high levels of the other.

Environmental Factors: Physical factors can also affect the response to toxic agents. In industries such as smelting or steel making, high temperatures are encountered. Pressures different than normal ambient atmospheric pressure can be encountered in caissons or tunnel construction.

Host Factors: For many toxic agents the response varies with the species of animal. There are often differences in the response of males and females to the same agent. Hereditary factors also can be of importance. Genetic defects in metabolism may render certain individuals more sensitive to a given toxic agent.

CLASSIFICATION OF TOXIC MATERIALS

Within the scope of this chapter it is not possible to discuss the specific toxic action of a variety of materials, although where possible specific information has been used to illustrate the principles discussed. It might, however, be useful to consider several ways in which toxic agents may be

classified. No one of these is of itself completely satisfactory. A toxic agent may have its action on the organ with which it comes into first contact. Let us assume for the moment that the agent is inhaled. Materials such as irritant gases or acid mists produce a more or less rapid response from the respiratory tract when present in sufficient concentration. Other agents, such as silica or asbestos, also damage the lungs but the response is seen only after lengthy exposure. Other toxic agents may have no effect upon the organ through which they enter the body, but exert what is called systemic toxic action when they have been absorbed and translocated to the site of biological action. Examples of such agents would be mercury vapor, manganese, lead, chlorinated hydrocarbons and many others which are readily absorbed through the lungs, but produce typical toxic symptoms only in other organ systems.

Physical Classifications: This type of classification is an attempt to base the discussion of toxic agents on the form in which they are present in the air. These are discussed as gases and vapors or as aerosols.

Gases and Vapors: In common industrial hygiene usage the term "gas" is usually applied to a substance which is in the gaseous state at room temperature and pressure and the term "vapor" is applied to the gaseous phase of a material which is ordinarily a solid or a liquid at room temperature and pressure. In considering the toxicity of a gas or vapor, the solubility of the material is of the utmost importance. If the material is an irritant gas, solubility in aqueous media will determine the amount of material that reaches the lung and hence its site of action. A highly soluble gas, such as ammonia, is taken up readily by the mucous membranes of the nose and upper respiratory tract. Sensory response to irritation in these areas provides the individual with warning of the presence of an irritant gas. On the other hand, a relatively insoluble gas such as nitrogen dioxide is not scrubbed out by the upper respiratory tract, but penetrates readily to the lung. Amounts sufficient to lead to pulmonary edema and death may be inhaled by an individual who is not at the time aware of the hazard. The solubility coefficient of a gas or vapor in blood is one of the factors determining rate of uptake and saturation of the body. With a very soluble gas, saturation of the body is slow, is largely dependent upon ventilation of the lungs and is only slightly influenced by changes in circulation. In the case of a slightly soluble gas, saturation is rapid, depends chiefly on the rate of circulation and is little influenced by the rate of breathing. If the vapor has a high fat solubility, it tends to accumulate in the fatty tissues which it reaches carried in the blood. Since fatty tissue often has a meager blood supply, complete saturation of the fatty tissue may take a longer period. It is also of importance whether the vapor or gas is one which is readily metabolized. Conversion to a metabolite would tend to lower the concentration in the blood and shift the equilibrium towards increased uptake. It is also of importance whether such metabolic products are toxic. For a discussion of the interplay

of factors relating to the uptake of gases and vapors, Chapter 5 of Henderson and Haggard²¹ or Chapter 6 of Patty²² should be consulted.

Aerosols: An aerosol is composed of solid or liquid particles of microscopic size dispersed in a gaseous medium (for our purposes, air). Special terms are used for indicating certain types of particles. Some of these are: "dust", a dispersion of solid particles usually resulting from the fracture of larger masses of material such as in drilling, crushing or grinding operations; "mist", a dispersion of liquid particles, many of which are visible; "fog", visible aerosols of a liquid formed by condensation; "fume", an aerosol of solid particles formed by condensation of vaporized materials; "smoke", aerosols resulting from incomplete combustion which consist mainly of carbon and other combustible materials. The toxic response to an aerosol depends obviously on the nature of the material, which may have as a target organ the respiratory system or may be a systemic toxic agent acting elsewhere in the body. In either case, the toxic potential of a given material dispersed as an aerosol is only partially described by a statement of the concentration of the material in terms of weight per unit volume or number of particles per unit volume. For a proper assessment of the toxic hazard, it is necessary to have information also on the particle size distribution of the material. Understanding of this fact has led to the development of instruments which sample only particles in the respirable size range. Chapters 13 and 14 discuss analytical methods for obtaining the needed data. The particle size of an aerosol is the key factor in determining its site of deposition in the respiratory tract and, as a sequel to this, the clearance mechanisms which will be available for its subsequent removal. The deposition of an aerosol in the respiratory tract depends upon the physical forces of impaction, settling, and diffusion or Brownian movement which apply to the removal of any aerosol from the atmosphere, as well as upon anatomical and physiological factors such as the geometry of the lungs and the air-flow rates and patterns occurring during the respiratory cycle. The interrelationship of these factors has been examined both theoretically and experimentally. The monograph by Hatch and Gross, "Pulmonary Deposition and Retention of Inhaled Aerosols"²³ gives an excellent discussion of the subject and should be required reading for anyone entering the field of environmental toxicology. The most recent theoretical treatment is that of the Task Force on Lung Dynamics²⁴ which also gives an excellent summary of past work.

In the limited space available only one point will be emphasized here, namely, the toxicological importance of particles below 1 μm in size. Aerosols in the range of 0.2-0.4 μm tend to be fairly stable in the atmosphere. This comes about because they are too small to be effectively removed by forces of settling or impaction and too big to be effectively removed by diffusion. Since these are the forces that lead to deposition in the respiratory tract, it has been predicted theoretically and confirmed experimentally that a lesser *percentage* of these particles is deposited in the respiratory tract.

On the other hand, since they are stable in the atmosphere, there are large numbers of them present to be inhaled, and to dismiss this size range as of minimal importance is an error in toxicological thinking which should be corrected whenever it is encountered. Aerosols in the size range below $0.1\mu\text{m}$ are also of major toxicological importance. The percentage deposition of these extremely small particles is as great as for $1\mu\text{m}$ particles and this deposition is alveolar. This fact was predicted theoretically by Findeisen as far back as 1935²⁵ and has been confirmed experimentally.²⁶ Particles in the sub-micron range also appear to have greater potential for interaction with irritant gases, a fact which is of importance in air pollution toxicology.

Chemical Classification: Toxic compounds may be classified according to their chemical nature. Volume II of Patty²² is so structured and is an excellent practical reference. *Industrial Toxicology* by Hamilton and Hardy²⁷ is also arranged more or less according to the chemical classification. Since both of the authors were distinguished as industrial physicians (the late Dr. Alice Hamilton being one of the pioneers in that area), the book is more oriented to medical signs and symptoms than towards experimental toxicology. Several more specialized works deal with certain types of chemical compounds. Among these may be included Browning's *Toxicity of Industrial Metals*²⁸ and *Toxicity and Metabolism of Industrial Solvents*²⁹ and Gerarde's *Toxicology and Biochemistry of Aromatic Hydrocarbons*.³⁰

Physiological Classification: Such classification attempts to frame the discussion of toxic materials according to their biological action. Most such systems (including the present one) have as their basis the now classic scheme proposed by Henson and Haggard.²¹

Irritants: The basis of classifying these materials is their ability to cause inflammation of mucous membranes with which they come in contact. While many irritants are strong acids or alkalis familiar as corrosive to non-living things such as lab coats or bench tops, bear in mind that inflammation is the reaction of a living tissue and is distinct from chemical corrosion. The inflammation of tissue results from concentrations far below those needed to produce corrosion. As was indicated earlier in discussing gases and vapors, solubility is an important factor in determining the site of irritant action in the respiratory tract. Highly soluble materials such as ammonia, alkaline dusts and mists, hydrogen chloride and hydrogen fluoride affect mainly the upper respiratory tract. Other materials of intermediate solubility such as the halogens, ozone, diethyl or dimethyl sulfate and phosphorus chlorides affect both the upper respiratory tract and the pulmonary tissue. Insoluble materials such as nitrogen dioxide, arsenic trichloride, or phosgene affect primarily the lung. There are exceptions to the statement that solubility serves to indicate site of action. One such is ethyl ether and other insoluble compounds that are readily absorbed unaltered from the alveoli and hence do not accumulate in that area. In the upper respiratory passages and bronchi where

the material is not readily absorbed, it can accumulate in concentrations sufficient to produce irritation. Another exception is in materials such as bromobenzyl cyanide which is a vapor from a liquid boiling well above room temperature. It is taken up by the eyes and skin as a mist. In initial action, then, it is a powerful lachrymator and upper respiratory irritant, rather than producing a primarily alveolar reaction as would be predicted from its low solubility.

Irritants can also cause changes in the mechanics of respiration such as increased pulmonary flow-resistance or decreased compliance (a measure of elastic behavior of the lungs). One group of irritants among which are sulfur dioxide, acetic acid, formaldehyde, formic acid, sulfuric acid, acrolein and iodine produce a pattern in which the flow-resistance is increased, the compliance is decreased only slightly and at higher concentrations the frequency of breathing is decreased. Another group among which are ozone and oxides of nitrogen have little effect on resistance, produce a decrease in compliance and an increase in respiratory rate. There is evidence that in the case of irritant aerosol, the irritant potency of a given material tends to increase with decreasing particle size³¹ as assessed by the increase in flow-resistance. Following respiratory mechanics measurements in cats exposed to irritant aerosols, the histologic sections prepared after rapid freezing of the lungs showed the anatomical sites of constriction.²² Long term chronic lung impairment may be caused by irritants either as sequelae to a single very severe exposure or as the result of chronic exposure to low concentrations of the irritant. There is evidence in experimental animals that long term exposure to respiratory irritants can lead to increased mucous secretion and a condition resembling the pathology of human chronic bronchitis without the intermediary of infection.³²⁻³⁴ The epidemiological assessment of this factor in the health of residents of polluted urban atmospheres is currently a vital area of research.

Irritants are usually further subdivided into primary and secondary irritants. A primary irritant is a material which for all practical purposes exerts no systemic toxic action either because the products formed on the tissues of the respiratory tract are nontoxic or because the irritant action is far in excess of any systemic toxic action. Examples of the first type would be hydrochloric acid or sulfuric acid. Examples of the second type would be materials such as Lewisite or mustard gas, which would be quite toxic on absorption but death from the irritation would result before sufficient amounts to produce systemic poisoning would be absorbed. Secondary irritants are materials which do produce irritant action on mucous membranes, but this effect is overshadowed by systemic effects resulting from absorption. Examples of materials in this category are hydrogen sulfide and many of the aromatic hydrocarbons and other organic compounds. The direct contact of liquid aromatic hydrocarbons with the lung can cause chemical pneumonitis with pulmonary edema, hemorrhage and tissue necrosis. It is for

this reason that in the case of accidental ingestion of these materials the induction of vomiting is contraindicated because of possible aspiration of the hydrocarbon into the lungs.

Asphyxiants: The basis of classifying these materials is their ability to deprive the tissue of oxygen. In the case of severe pulmonary edema caused by an irritant such as nitrogen dioxide or laryngeal spasm caused by a sudden severe exposure to sulfuric acid mist, the death is from asphyxia, but this results from the primary irritant action. The materials we classify here as asphyxiants do not damage the lung. Simple asphyxiants are physiologically inert gases which act when they are present in the atmosphere in sufficient quantity to exclude an adequate oxygen supply. Among these are such substances as nitrogen, nitrous oxide, carbon dioxide, hydrogen, helium and the aliphatic hydrocarbons such as methane and ethane. All of these gases are not chemically unreactive and among them are many materials which pose a major hazard of fire and explosion. Chemical asphyxiants are materials which have as their specific toxic action rendering the body incapable of utilizing an adequate oxygen supply. They are thus active in concentrations far below the level needed for damage from the simple asphyxiants. The two classic examples of chemical asphyxiants are carbon monoxide and cyanides. Carbon monoxide interferes with the transport of oxygen to the tissues by its affinity for hemoglobin. The carboxy-hemoglobin thus formed is unavailable for the transport of oxygen. All aspects of current research on carbon monoxide were the subject of a recent conference of the New York Academy of Sciences and the monograph resulting from this meeting is an excellent reference.²⁵ Over and above the familiar lethal effects, there is concern about how low level exposures will affect performance of such tasks as automobile driving, etc. In the case of cyanide, there is no interference with the transport of oxygen to the tissues. Cyanide transported to the tissues forms a stable complex with the ferric iron of ferric cytochrome oxidase resulting in inhibition of enzyme action. Since aerobic metabolism is dependent upon this enzyme system, the tissues are unable to utilize the supply of oxygen, and tissue "hypoxia" results. Therapy is directed towards the formation of an inactive complex before the cyanide has a chance to react with the cytochrome. Cyanide will complex with methemoglobin so nitrite is injected to promote the formation of methemoglobin. Thiosulfate is also given as this provides the sulfate needed to promote the enzymatic conversion of cyanide to the less toxic thiocyanate.

Primary Anesthetics: The main toxic action of these materials is their depressant effect upon the central nervous system, particularly the brain. The degree of anesthetic effect depends upon the effective concentration in the brain as well as upon the specific pharmacologic action. Thus, the effectiveness is a balance between solubility (which decreases) and pharmacological potency (which increases) as one moves up a homologous series of compounds of increasing chain length. The anesthetic potency of the simple alcohols also rises

with increasing number of carbon atoms through amyl alcohol which is the most powerful of the series. The presence of multiple hydroxyl groups diminishes potency. The presence of carboxyl groups tends to prevent anesthetic activity which is slightly restored in the case of an ester. Thus acetic acid is not anesthetic, ethyl acetate is mildly so. The substitution of a halogen for a hydrogen of the fatty hydrocarbons greatly increases the anesthetic action, but confers toxicity to other organ systems which outweighs the anesthetic action.

Hepatotoxic Agents: These are materials which have as their main toxic action the production of liver damage. Carbon tetrachloride produces severe diffuse central necrosis of the liver. Tetrachloroethane is probably the most toxic of the chlorinated hydrocarbons and produces acute yellow atrophy of the liver. Nitrosamines are capable of producing severe liver damage. There are many compounds of plant origin such as some of the toxic components of the mushroom *Amanita phalloides*, alkaloids from *Senecio*, and aflatoxins which are capable of producing severe liver damage and in some instances are powerful hepatocarcinogens.

Nephrotoxic Agents: These are materials which have as their main toxic action the production of kidney damage. Some of the halogenated hydrocarbons produce damage to the kidney as well as to the liver. Uranium produces kidney damage, mostly limited to the distal third of the proximal convoluted tubule.

Neurotoxic Agents: These are materials which in one way or another produce their main toxic symptoms on the nervous system. Among them are metals such as manganese, mercury and thallium. The central nervous system seems particularly sensitive to organometallic compounds, and neurological damage results from such materials as methylmercury and tetraethyl lead. Trialkyl tin compounds may cause edema of the central nervous system. Carbon disulfide acts mainly on the nervous system. The organic phosphorus insecticides lead to an accumulation of acetyl choline because of the inhibition of the enzyme which would normally remove it and hence cause their main symptoms in the nervous system.

Agents which act on the blood or hematopoietic system: Some toxic agents such as nitrites, aniline and toluidine convert hemoglobin to methemoglobin. Nitrobenzene forms methemoglobin and also lowers the blood pressure. Arsenic produces hemolysis of the red blood cells. Benzene damages the hematopoietic cells of the bone marrow.

Agents which damage the lung: In this category are materials which produce damage of the pulmonary tissue but not by immediate irritant action. Fibrotic changes are produced by materials such as free silica which produces the typical silicotic nodule. Asbestos also produces a typical damage to lung tissue and there is newly aroused interest in this subject from the point of view of possible effects of low level exposure of individuals who are not asbestos workers. Asbestosis was the subject of a recent conference of the New York Academy of Sciences and the papers in the re-

sulting monograph present the various aspects of current research in the area.³⁶ Other dusts, such as coal dust, can produce pneumoconiosis which, with or without tuberculosis super-imposed, has been of long concern in mining. Drinker and Hatch³⁷ is a classic reference in this area and Hunter³⁸ discusses at length occupational exposures to dusts. Many dusts of organic origin such as those arising in the processing of cotton or wood can cause pathology of the lungs and/or alterations in lung function. The proteolytic enzymes added to laundry products are an occupational hazard of current interest. Toluenediisocyanate (TDI) is another material which can cause impaired lung function at very low concentrations and there is evidence of chronic as well as acute effects.³⁹ Chapter 33 discusses materials in this category.

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A.M.A. Archives of Environmental Health; American Industrial Hygiene Association Journal and The British Journal of Industrial Medicine have many articles on industrial toxicology.

Journals: (Foreign)

Medicina del Lavoro — Italian
Archives des Maladies Professionnelles — French
Gigiena i Sanitariya — Russian (Translation Available)
Pracovni lekarstvi (Czechoslovakian)
Japanese Journal of Labor Science

Abstracts:

Chemical Abstracts
Excerpta Medica Abstracts in Occupational Health and Industrial Medicine
Bulletin of Hygiene (British)
Scientific Reports on Industrial Hygiene and Occupational Diseases in Czechoslovakia (Published Annually by Inst. of Indust. Hyg. & Occ. Diseases in Prague. In English)

Hygienic Guides:

A series of useful pamphlets published by Am. Industrial Hygiene Association, 210 Haddon Ave., Westmont, N.J. 08108.

PRINCIPLES AND USE OF STANDARDS OF QUALITY FOR THE WORK ENVIRONMENT

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INTRODUCTION

Rationale

Total removal of all potentially harmful agents from the work place is the only absolute method of assuring worker safety and health. Since this optimum is not always possible, exposure to potentially toxic substances is unavoidable. Accordingly, it has become necessary to define quantitatively which exposure levels are *not* attended by a risk to the worker's health or well-being.

Basic Underlying Principles

An understanding of the dose-response relationship (see Chapter 7) is a basic determinant of the feasibility of such standards. In brief, all chemical agents cause biological response as a function of the quantity absorbed and the period of time over which such absorption occurs. Thus, there should be a dose (concentration and time dependent) which does not exceed the capability of the organism to metabolize, detoxify or excrete such compounds. This dose is usually referred to as a "no effect" level.

The "no effect" level — is a puristic concept because there is always some biological or chemical alteration when the organism encounters some exogenous material.^{1,2} Whereas in the United States it is clearly understood that such responses are not deleterious *per se*, in the Soviet Union this is not explicitly recognized. Nevertheless, in the United States a "no effect" level is implied to be one which does not produce any deleterious or undesirable effect upon human health and well-being or overload the normal protective mechanisms of the body.²

Thus a biological accommodation, e.g., a non-specific alteration in brain waves, a decreased serum catalase (an enzyme normally present in the body far beyond stress demands), is seen as probably not having immediate or long-term effect on health. Such changes are not deleterious in and of themselves. By contrast, although exposure to H₂S at concentrations of 30-50 ppm produces no changes other than self-limited eye irritation, such concentrations are, in normal circumstances, unacceptable. This is in keeping with the WHO* definition of health which considers any encroachment upon human well-being as being ill health and, therefore, undesirable.

Problems in Definition of "No Effect Level"

It can be seen that there may be profound differences of opinion as to what constitutes a "no effect" level. The preponderant opinion in the

United States holds that slight deviations within homeostatic limits of biological change are not deleterious.² All necessary life processes required by living organisms are associated with perturbations of a steady state. Thus the basic processes of digestion and absorption are associated with considerable fluxes of, e.g., electrolytes, lipids, proteins, etc., at concentrations which deviate from those found between meals. With each eyelid flicker there are attendant electrical discharges along multiple nerve pathways that previously were essentially quiescent. Therefore, it should be apparent that for all bodily functions there are constant deviations from a "steady state"; such represent necessary accommodative change to environmental alteration in its broadest sense.

While such generalizations are useful, the problem becomes more difficult when one attempts to define the actual limits beyond which change becomes deleterious. Though practically *any* change is considered as being potentially detrimental by the U.S.S.R., it becomes difficult to reconcile this position with the concept of a normal range associated with homeostasis. On the other hand, the question might well be asked whether the accumulated energy expenditures required by accommodation over a lifetime do not contribute to the long-term depletion of life forces which might accelerate the process of aging.

In the strictest sense a "no effect" level does not exist; however, for operational purposes the range of biological response which exceeds homeostatic limits must be ascertained. The problems of defining the effect such stresses (within homeostatic limits) may have over a long-term should be appreciated.

Other Variables Influencing the Use of Workroom Air Quality Standards

Work-rest cycle. All quality standards make certain assumptions regarding the work-rest cycle. Basically, most standards currently utilized in the United States imply an 8-hour day within a 40-hour week.³ Thus, each work period is followed usually by a 16-hour non-exposed period, during which restituting processes (e.g., detoxification, excretion) occur. Where more prolonged work exposure periods occur, the possibility of a greater total dose being absorbed as well as less time being available for restitution make application of the usual quality standards inappropriate. With deviations from the usual work-rest cycles (e.g., as with continuous exposure in submarines or space capsules), other environmental quality status standards must be applied.

*World Health Organization

Worker Health Status. The standards utilized depend upon an essentially healthy work force. This stems from the fact that persons with a compromised function or pathological condition may not be capable of dealing with absorbed chemicals in the expected manner. Accordingly, such individuals may not be able to completely excrete each day's burden of an absorbed agent; this can lead to a progressive accumulation of such materials.

Adverse Climate Conditions. Since adverse climate conditions place an accommodative burden upon an individual, the additional work involved in accommodating to occupational stressors may be excessive. Accordingly, in such circumstances quality standards may require modifications reflecting such additional physiologic loadings.

Special Genetic and Biological Susceptibility. Because of genetic and biological factors (e.g., glucose-6-phosphate dehydrogenase or serum anti-trypsin deficiencies) specific to some few (i.e., 5-10%) individual workers, these workers may possess an undue susceptibility to agents found in the work environment. It is necessary to detect the presence of such unusual persons at special risk prior to work exposure, since quality standards are designed for the normal person and do not apply to special risk workers.⁴

Implications of the Premises Underlying Quality Standards

It becomes immediately apparent that quality standards cannot be utilized without a full understanding of the foregoing premises concerning 1) the work-rest cycle, 2) worker health status, 3) climatic conditions and 4) special susceptibilities. In addition, their use requires concomitant use of adequate environmental monitoring and medical surveillance. The former stems from the need to document the fact that these limits are not being exceeded; the latter requirement, to determine that persons with pathologic or biologic deviations are not exposed (see Chapter 17).

PRINCIPLES FOR DEVELOPING WORKROOM AIR QUALITY STANDARDS

Extrapolation by Chemical Analogy

A. Principle. When dealing with a new chemical, animal or human toxicity data are usually unavailable. Therefore, the prevailing principle is that the quality of response of a chemical may be assumed to be analogous to that produced by similar substances. Chemicals that are structurally similar should produce a similar biological response. Thus, as a first approximation, some *estimate* of toxic potential can be obtained. Obviously, the use of such assessments, since they are not absolute predictors of qualitative effects, may be dubious for prediction of quantitative response. Nevertheless, as of 1968, 24% of all Threshold Limit Values published by the American Conference of Governmental Industrial Hygienists were based upon analogy.⁵

B. Limitations.

- (1) Inconsistency of qualitative effect: Not infrequently one compound in a chemical family of compounds will respond in a totally atypical manner when compared with others of that family. Accordingly,

some risk may be attached to predictions of safety or toxicity based upon chemical analogy.

- (2) Inconsistency of quantitative effect: as fraught with risk as is prediction of qualitative risk on the basis of chemical analogy, estimating quantitative effect is even more hazardous.

Animal Experimentation

Principles and Purposes. Before workers are exposed to any chemical agents in the workplace, it is advisable to know the toxic effect such materials possess. On this basis one can design the protective measures to protect workers and deal with medical problems caused by such materials. However, in the case of new chemicals, there is often little or no information upon which to act. Accordingly, an important method of developing such new information utilizes animal experimentation.

In some cases clinical experience does exist, but it is often fragmentary, and rarely provides the detailed information needed concerning the metabolites produced following chemical absorption. Data on metabolites is useful in estimating the degree of absorption of substances. Experimentation with an animal host which responds to substances in a manner similar to man can provide such information.

The design of animal experiments should reflect the conditions of industrial usage of the substance in question. Since agents encountered in the workplace may act systemically or locally following skin or mucous membrane exposure, skin testing for possible absorption and systemic toxicity, primary irritation or sensitization is indicated. Exposure of animals to vapors, mists, aerosols or gases for determination of pulmonary effects and uptake or systemic toxicity is extremely relevant to the industrial milieu. By contrast, experiments utilizing gastro-intestinal or subcutaneous absorption are less frequently used except for range-finding toxicity purposes.

Difficult questions revolve about the problems of extrapolation of animal information to man. As a rule, it is desirable to seek toxicological information derived from more than one animal species wherever possible. Quite frequently various species respond in differing fashions qualitatively and quantitatively. Since no one species consistently reacts as does man, one can never predict which species is most like man. Accordingly, it is an operating principle, until otherwise demonstrated, that man should be considered as responding as does the most sensitive animal species; design of control programs should be developed from that point of departure.

Another important factor concerns the number of animals of any one species which are put to test. Here again, because even within any one group of animals, biological individuality will operate, enough animals must be tested. Thus, one attempts to ensure, within a reasonable degree of probability, that even the most sensitive of the group will be tested. In this regard, statistical techniques can be utilized with a view toward determining which confidence limits attend upon animal population size choice.

One last consideration relates to dose ranges used in such experiments. Obviously, a wide range of doses is useful for different purposes. The large doses help force the question, "toxic or non-toxic?" while also providing clearcut answers as to the specific organs susceptible to damage. Likewise, a lower range of doses must be used to give a clearer estimate of thresholds of response.

Criteria of Response — Organ Change. While gross changes in structure clearly delineate the bodily organ at risk of damage, such data are of limited usefulness. This follows since all control measures must be designed so as to prevent any serious, irreversible damage. Thus, while such bodily changes delineate serious responses, satisfactory control is achieved only when exposure prevents even a minimal alteration beyond the homeostatic range. Accordingly, more important data derive from functional changes rather than pathological organ alteration.

Functional Response — Biochemical Changes. Detection of altered organ function occurring prior to structural change provides the organism with greater probability of avoiding permanent damage. Such functional changes are frequently expressed when organs of detoxification produce some metabolic alteration of the absorbed chemical agent. Insofar as such organ of detoxification is not presented with an amount of chemical which does not exceed its detoxification rate, it can continue to cope with such chemical exposures. Experimentation should be designed to define such rate limits in terms of what represents both excess loadings as well as those burdens with which the organism can successfully deal. Especially important is definition of the "break point" in detoxification rates. Such experiments help define the safe "dose"; in addition, quantitative biochemical indicators of over-exposure may also be delineated. As an example of this, one can assay how much absorption of an organo phosphorous pesticide is safe in terms of depression of red cell acetylcholine esterase, or how much lead exposure has occurred by estimation of urinary coproporphyrin or delta aminolevulinic acid. Likewise, measurement of the metabolites of trichloroethylene, e.g., trichloroacetic acid, provides useful indicators of the existence and degree of absorption of that solvent.

Neurophysiologic Response. Recently, changes in nervous system function have been studied extensively as a parameter of toxic or subtoxic exposure. Largely as a result of Russian studies, investigation of neurofunctional response has been considered as possibly indicating early change. Where changes in neurologic function impair higher functions, e.g., alertness, cognition, such alterations have obvious industrial implications as regards safety and performance adequacy. However, the relation of certain measurements, e.g., nerve chronaxie, to occupational exposure is problematic. Nevertheless, such studies of higher nervous function increasingly have been undertaken to delineate man's response to his occupational environment.

Other types of response:

(1) Carcinogenesis: Obviously, given the serious implications of occupationally

induced cancer, studies designed to detect such a change are of the utmost importance.

Here, the problems of dose-response relationships become extremely complex, since definition of a threshold of response is problematic. Accordingly, testing here is directed largely toward defining whether such a hazard exists; the use of animal experiments for establishing operational control is directed mainly toward defining the necessity for total isolation or substitution. In the present absence of truly effective therapy, once the malignant alteration has been induced, the value of such preclinical indicators is limited.

(2) Mutagenesis and teratogenesis: Mutagenesis is the process wherein normal cells are converted into genetically abnormal cells. The result of such alteration, particularly since it involves the genetic processes which determine normal cell growth and division, are changes in structure and function. This process may result in malignant or other aberrations. Teratogenesis refers to the process whereby abnormalities of the off-spring are generated. Such usually results from damage to embryonal structures in the first trimester of pregnancy, or because of alteration of germinal elements, i.e., ovarian cells or spermatozoan.

While these responses are extremely important — especially where women may be at a risk, the danger of mutagenesis could theoretically also affect male generative tissue. While little such testing has been undertaken with a view toward protection of working populations, serious consideration should be given to such studies in the future.

Application of Animal Data

Principles of Application:

- (1) Use of the most sensitive species: because the detoxification represents in essence a genetically controlled metabolic degradation process, it follows that various animal species will respond differently to toxic chemical exposure. Unfortunately, just how any species — including man — will respond is not predictable. Accordingly, when the human quantitative response to a chemical agent is unknown, prudence would dictate that the design of environmental quality standards assume that man responds as does the most sensitive species.
- (2) Application of the dose-response curve to setting standards: primarily, environmental quality standards are intended to quantitatively indicate the amount of contaminant which may be present in the workplace without causing harm to man. Obviously, experiments should be directed toward determining the concentra-

tion at which "no effect" is produced, i.e., one which is safe.

Experiments which permit the development of a dose-response curve indicate the several ranges of response. In this manner, the doses producing "no response," a minimal response and the more severe response are defined. In most circumstances, a linear relationship between these doses emerges with the use of logarithmic plots. While a dose-response curve can be estimated without data points being available in the "no response" or safe range, downward extrapolation to this area holds some risk. Problems will occur when a break occurs in such a linear response curve; this is seen particularly in the low dose range.

- (3) Safety margins and their bases: because of problems inherent in interpretation of toxicological data (see above), it is desirable to have a margin of safety between the lowest effective dose and a proposed TLV. Expressed mathematically, $TLV = \text{lowest effective dose} / \text{safety factor}$. The safety factor depends upon the nature of the response* produced by such lowest effective dose. Where such responses consist of reversible irritation of skin or mucous membranes, safety factors between the dose producing these phenomena and the recommended TLV tend to be low. By contrast, minimal dose-related responses characterized by toxicity usually possess a greater safety margin or factor. The range of safety factors associated with A.C.G.I.H. TLV's has been estimated to extend between 0.2 and 10.*

A safety factor of 0.2 denotes that the Threshold Limit Value is 0.2 fold (or 20%) higher than the dose which produces a response; a factor of 10 states that the TLV is 10 fold (or 1000%) higher than the dose producing a threshold response.

While the use of safety margins as an extrapolation process for estimation of the "no response" area is useful, their limitations should be recognized. For one thing, departures from the linearity of the dose-response curve are apt to occur in such estimates of lower ranges. Furthermore, given a steep dose-response line, in the biologically reactive range, the "no effect" level tends to be estimated with a high degree of error. Finally, when dealing with agents that appear to be active at extremely low levels, i.e., 5-10 ppm, departures from linearity appear quite

*What constitutes evidence of a "response" varies. In the United States biochemical, physiologic or even reversible changes in organ morphology may constitute the "minimal" response. In the U.S.S.R. more credence is placed upon subtle neurophysiologic change as evidence of a deleterious alteration (see section on Functional Response).

common; this introduces even more chance of an unrealistic standard being set if a 5- or 10-fold safety margin is applied.⁷

It is for such reasons that data in the "no effect" range are preferred by those setting work environmental quality standards.

Problems in the Use of Animal Data for the Establishment of Environmental Quality Standards

In the absence of data based upon human experience, extrapolation from animal experiments must be used in establishing environmental quality standards. But because our concerns are directed toward prevention of human harm, the limitations inherent in animal-derived data should be recognized. Whether man will respond as the most reactive or least reactive species tested frequently cannot be predicted. Further, the question as to whether the most sensitive species has been tested is frequently unanswered. Finally, whether the animal response has any parallel to human responsiveness cannot be answered. (This has occurred in the case of induction of bladder tumors by aromatic amines; unless the dog is tested — a relatively uncommon test animal — such chemicals do not ordinarily produce bladder tumors in the animals usually used in the laboratory.) For these reasons, human exposure data assume considerable importance in quality standard development, though animal-derived information may be commonly the only type in existence.

Sensitization. This type of response, sensitization, is produced with difficulty in animals. Accordingly, if animal testing is relied upon, the potential for such responses may be undetected.

Genetic Defects Peculiar to Man. A number of genetic defects found in various human "strains" have no parallel in animals. Such defects occur commonly in human populations and can deleteriously affect the mode of response to certain environmental chemicals (e.g., glucose-6-phosphate dehydrogenase defects will impede the detoxification process among persons having this aberration who are exposed to various aromatic amines). Accordingly, animal testing alone will not predict whether a chemical might cause untoward reactions in such susceptible populations.

HUMAN DATA AND INDUSTRIAL EXPERIENCE AS A BASIS FOR STANDARD DEVELOPMENT

The Necessity for Human Data

It should be readily apparent from the foregoing that animal data form a problematic basis for the development of occupational environment quality standards. While such data are highly useful in developing a broader understanding of biological response (e.g., metabolism, full range of effects), such information in itself has obvious shortcomings in setting quality standards. It is for this reason that experience based upon human exposure to the substance in question is of ultimate importance in determining standards of safety.

Such data can result from inadvertent or intentional experimental exposure. Concerning the latter, the availability of animal experiments becomes critical; only after thorough exposition of toxicity by this method is human experimentation justified.

Specific Needs Fulfilled by Human Toxicity Data

1. Irritation and nausea: since the less severe degree of irritation can only be detected by subjective means, it is obvious that animal experimentation may not provide such information in this response range.
2. Allergic response: since animals rarely demonstrate this type of response, human experience is necessary if such effect is to be detected.
3. Odor evaluation: since no quantitative measures of odor are presently practicable, this response can only be evaluated by questioning the experimental subject. Obviously, animal experiments are useless in this regard.
4. Higher nervous function effects: an important consideration in occupational safety and health revolves about environmental effects upon human performance. While animal experimentation increasingly involves measurement of neurophysiologic response, extrapolation of such test procedures for the assessment of, e.g., visual performance, manipulation of various devices leads to obvious inadequacies. Thus human testing, particularly where relevant work tasks are performed, meets a unique need in occupational safety evaluation.
5. Human metabolic pathways: while much of such information can be derived from animal experiments, ultimately application of such data for hazard assessment and control design represents an extrapolatory exercise. Thus human exposures will provide the ultimate quantitative and qualitative information regarding human metabolism of the substance in question.

The Use of Data Derived from Occupational Experience

Validity requirements:

1. Environmental sampling adequacy: in order to relate human safety or damage to environmental agents, it is necessary to have some quantitative measurement of its presence. Usually this means extensive sampling of the work environment over time and space, but especially as related to worker absorption opportunities. That is, good industrial hygiene sampling practice (see Chapter 10) is necessary to adequately assess quantitative exposure. In brief, in the cases of gases, vapors or dusts, samples should be taken at breathing zones. In addition, in the case of dusts, quantitative characterization of the particulates of respirable size are especially pertinent. Obviously, care should be exercised that sufficient numbers of samples are taken to represent adequately the full

- range as well as average of concentrations.
2. Human surveillance adequacy: for data based on human experience to be valid, the human portion of the agent-host interaction also must be characterized. Indeed, if no untoward effect is claimed, detailed medical evaluation of those exposed is required. In addition, it is possible to evaluate environmental concentrations by measurement of metabolites or of the agents themselves in biological media. Although such correlations between concentrations in biological material and the work environment may be constructed from occupational exposure situations, usually insufficient data or range of exposures mitigate against development of such a regression line. However, such measurements taken under experimental exposure conditions have been extremely useful (see below, Human Experimentation).

Problems Encountered in the Use of Occupational Exposure Data

1. Irregularity of exposure: most occupational exposures are of a fluctuating character, both in terms of duration and concentrations. Thus the need for having sufficient samples representative of the "peaks," "valleys" and mean concentrations encountered becomes essential.
2. Mixed exposures: occupational exposures to a single agent are rather uncommon. Thus, while the material in question might be specifically measured in the environment, it becomes problematic whether the human response results from exposure to that particular agent *per se*. Furthermore, the biological response can rarely be rationally apportioned as a function of the relative concentration of multiple agents. Whether such agents are acting additively, synergistically or antagonistically can markedly alter responses. Hence, since occupational exposures are mixed, this limitation on their use for occupational environmental quality standard development must be recognized. For a more detailed discussion of evaluation of mixtures, see reference (3).
As regards the agents in such a mixed exposure, the question of the specificity of the measurement technique for the material of interest becomes significant. This is especially pertinent where mixtures of chemically similar substances are encountered; interferences may also make such measurements of the components of such mixtures non-specific.
3. Absence of long-term data: while measurements of human response over the short-term experience are readily observed, the long-term effects of such exposures are infrequently available. While drastic effects of long-term exposure may be detected — and then with difficulty, e.g., bladder tumors, subtle effects are infrequently reported or investigated.

4. **Special susceptibility:** unless sufficiently large populations of exposed workers are studied, the few persons who may be at special risk because of genetically determined special susceptibility will not be encountered. Such persons may be at special risk either for reasons that are well-defined, e.g., defects in metabolism, or because of poorly understood reasons (allergic sensitivity). Indeed, while such persons may constitute a small proportion of a potential population at risk, this does not constitute a reason for such effects being ignored if they could potentially be prevented.

Human Experimentation

Ethical Considerations. While it has long been recognized that each man has a moral duty to act charitably toward others, e.g., make blood or skin graft donations, some subtle and gross abuses of human experimentation have made reassessment of that practice necessary. Accordingly, a number of moral codes have been drawn up to protect the person of such subjects (Nuremberg Tribunal Code, the World Medical Association's 1964 Declaration of Helsinki, American Medical Association, etc.).

Minimally, at least four requirements should be met before experiments are considered:

1. Safety should have been extensively established in animal species;
2. Volunteers must be free of any coercion whatsoever and be fully and completely informed of all possible effects in a clearly understood fashion;
3. There must be no possibility of permanent damage, and the subject must be completely free to terminate the experiment at any time;
4. A written agreement of the volunteer to participate in the experiment which is fully described should be obtained.

Practically, it is mandatory that there be sufficient insurance coverage for each subject to compensate him voluntarily in the event of injury.

Design Requirements

1. In testing with airborne narcosis producing materials, assuming sufficiently large chambers and modalities for testing behavioral and other functional parameters, exposures are made in 3 ranges, i.e., "no effect," at borderline levels and at levels producing measureable, though minimal, narcosis in most subjects. In this manner, 3- to 4-hour exposures can aid in estimating the safety factor for human exposure, the safe limit and the rates of uptake and elimination of the agent. The latter two are determined by plotting blood concentrations against atmospheric concentrations as a function of time; such data are extremely valuable in estimating the extent of previously unknown exposure given a blood concentration at any given time after exposure.⁴
2. In testing with airborne irritants, utilizing the aid of an otolaryngologist, examinations are performed both before and after

exposure in a dynamic chamber. Because of the possibility of the development of accommodation, exposures should last at least 15 minutes; such exposures should be repeated 10 times in order to establish whether — and to what degree — accommodation occurs. A repetition of these exposures after 10 to 14 days will help establish whether sensitization occurs. Further, repetition has another urgency, since experience has shown that single exposure tests usually lead to unnecessarily low limits.⁵

3. Testing cutaneous irritation and sensitization (see Chapter 34).

Measurement of Response. Since a major reason for permitting the use of human volunteers is the eliciting of data indicative of minor functional change, the criteria of response should accordingly reflect this need. Thus, functional measurement of biochemical (e.g., enzymatic, immunochemical), neurophysiologic (e.g., EEG, conditioned and unconditioned reflexes) organ activity (EKG, liver or kidney function tests) and other parameters (comfort, esthetic) should be measured at the most sensitive and systematically higher levels. While functional change may represent normal and reasonable homeostatic adaptation mechanisms rather than being deleterious, each such change must be carefully elucidated and individually evaluated for its broadest implication as regards potential human harm.

STANDARDS OF QUALITY FOR THE WORKPLACE IN COMMON USE

Quality Standards Used in the United States

United States Historical Development. In 1941 the American Conference of Governmental Industrial Hygienists (A.C.G.I.H.) established a committee of industrial hygienists for the purpose of establishing the maximal allowable concentrations (MAC) for atmospheric contaminants in the workplace. Five years later such a list of recommended MAC values was suggested for use in industry. However, certain difficulties attended this designation, MAC. For one, these values were based upon time-weighted averages (see below) and did not represent a *maximal* ceiling value inherent in the name. For another, inherent in the title was an implication that such concentrations were "allowable," and thus a certain approbation was attached to concentrations below *and up to* such concentrations. At other times and places, this latter problem was associated with the use of the designation, Maximal Permissible Concentrations, or MPC.

In order to obviate these problems, in the 1960's the term Threshold Limit Value (TLV) was substituted for MAC. This new term, TLV, did not suffer these problems; without the implications associated with "allowable," more emphasis could be given to the practice of attempting to keep ambient concentrations below any designated value to the most practicable extent.

The A.C.G.I.H. Threshold Limit Values (TLV)

Nature of the TLV of air for occupational environments — TLV values refer to airborne

concentrations of substances and represent conditions under which it is believed that nearly all workers may be exposed eight hours a day for a forty-hour week over a working lifetime without adverse effect. Because of wide variation in individual susceptibility, exposure of an occasional individual at, or even below, the Threshold Limit may not prevent discomfort, aggravation of a pre-existing condition or occupational illness.

The TLV's represent eight-hour, time-weighted averages, i.e., airborne concentrations averaged with regard to their duration, occurring over an eight-hour period.

Certain chemical agents are associated with a "c" or ceiling designation; exposure to concentrations in excess of this value should not be permitted regardless of duration. Such designations stem from the fact that such agents may provide irritation, sensitization or acute poisoning immediately, or after a short latent period, upon even short exposures. Examples of such compounds among the respiratory irritants are chlorine, formaldehyde, vinyl chloride; narcotic agents such as methyl chloride; sensitizers such as toluene-2,4-diisocyanate; or those compounds which rapidly accumulate, such as benzene.

For those substances not given a "c" designation, excursions above the TLV are permitted. These agents produce their principal effects by cumulative, repeated exposure; thus, short excursions will not necessarily produce deleterious effects. The TLV's for such substances should be considered as average values integrated in relation to time. In general, the permissible range of fluctuations depends upon: the nature of the poison in general, the intensity of concentration required to produce acute effects, the frequency with which the average maximum tolerable concentration is exceeded, the duration of such excesses, and the cumulative effects of the exposure. For such a complex of reasons, it should be apparent that expert opinion should shape the use and interpretation of the TLV's. However, the A.C.G.I.H. gives some guidance for determining how great an excess above the TLV is permissible. For substances not having a "c" designation, the following guides apply:

TLV Range ppm* or mg/M ³ **	Excursion TLV Factor
0 to 1	3
>1 to 10	2
>10 to 100	1.5
>100 to 1000	1.25

*Whichever unit is applicable

Thus, a substance having a TLV of 5 ppm may fluctuate above the TLV, reaching a value of 10 ppm for periods of up to 15 minutes. However, the time-weighted average for an eight-hour day should not exceed 5 ppm. It is noted that the "Excursion TLV Factor" decreases as the magnitude of the TLV increases. Not to decrease this factor and increasing TLV magnitude would per-

mit exposure to large absolute quantities, a condition that is minimized at low TLV's. Moreover, larger factors at the lower TLV's are consistent with the difficulties in analyzing and controlling trace quantities.³

Where the TLV's previously were given in terms of a volume per volume basis, i.e., parts per million, the trend appears to be for statement of TLV's on the basis of mass per volume, e.g., milligrams per cubic meter (mg/M³) in addition to "ppm." Most toxic dusts are listed in terms of million particles per cubic foot and in mg/M³ of respirable dust.

Procedure for Establishment of Values. Experts in industrial hygiene and toxicology annually review a list of over 400 substances. On the basis of literature data and personal information known to committee members, TLV's are recommended. Opportunities are afforded for comment by interested persons or organizations. In the case of a new substance being added or a change in the TLV of a material on the list, such new value is listed for two years as a "tentative" value, so that such parties may submit any additional information for the committee's consideration. In addition, periodically the committee publishes a "Documentation of TLV's;" this provides a detailed review for each substance and the bases utilized in assigning the TLV's.³

American National Standards Institute (formerly, American Standards Association) Z-37 Committee Standards (ANSI)

Nature of ANSI, Z-37 workplace quality standards, maximal acceptable concentrations:

Time-weighted average: This Standard is essentially the same as the time-weighted eight-hour average of the A.C.G.I.H. Threshold Limit Value (TLV).

Acceptable Ceiling Concentration. The Standard establishes the maximum level allowable concentration during the period of exposure, assuming that the time-weighted eight-hour average concentration is not exceeded. However, excursions above this ceiling may be permitted under certain conditions, as in:

Maximum Acceptable Peak Concentrations. These constitute the exceptions to the ceiling level noted above. The peak concentrations noted are specified as to their concentration, the duration of such excursion(s), and the number of time(s) such peaks may occur in one eight-hour day.

Formulation Procedure. The Z-37 committee of ANSI is composed of governmental, industrial, professional society and university-based experts in industrial toxicology, hygiene and medicine. Assignments for standard development are given to committee members or others having experience with the material in question. The committee votes upon the standard which is then sent forward for other Institute approval and ultimate publication as a Standard. Maximal acceptable concentrations are published for a number of materials as individual documents which give the basis for such judgments. In addition, analytical and sampling methods are recommended; the Standard publication also describes the toxicity of

the material as well as its physical and chemical properties.

Federal Standards

Under the Occupational Safety and Health Act of 1970, the National Institute for Occupational Safety and Health (NIOSH) has the responsibility for developing criteria and recommended standards and the Department of Labor has the responsibility for promulgating standards.

The initial compilation of health and safety standards promulgated by the Department of Labor's OSHA was derived from national consensus standards and recognized Federal Standards. In addition to these sources there have been, and are being developed, documents by NIOSH from formulations which are reviewed by NIOSH and its consultants. Inputs from selected professional societies, other Federal agencies and such interested parties as organized labor and trade associations are also obtained. Finally, the criteria document with the recommended standard is forwarded to the Secretary of Labor. His considerations benefit from any additional review he deems appropriate.

The Secretary of Labor has the responsibility for promulgating standards. In some cases he may refer for study and review a recommended standard to an advisory committee in accordance with provisions of the Act. However, regardless of whether this step is taken, if this is a 6 b regulation, he must publish it as a proposed regulation and standard so that objections and comments can be heard before such a standard is effective.

Note: Standards promulgated under authority of Section 6 a of the Act and emergency standards under Section 6 c of the Act can be promulgated without going through the "proposed" stage.)

In addition, under the Federal Coal Mine Health and Safety Act of 1969 (P.L. 91-173) NIOSH has the responsibility for transmitting to the Secretary of Interior recommended health standards. After a similar review and hearing process such standards are promulgated by the Department of the Interior.

State Regulations and Standards

While most states have lists of in-plant Air Quality Standards, the majority have essentially adopted those of the ACGIH TLV's. Accordingly, these are all eight-hour time-weighted averages, although Pennsylvania has also developed a series of short-term limits. These latter differ from the ACGIH values in that specific exposure durations for such excursions are stated in the Pennsylvania regulations.

WORKPLACE QUALITY FORMULATIONS IN USE OUTSIDE THE UNITED STATES

U.S.S.R.

Philosophy. Standards are absolute limits that may not be exceeded during any part of the working day, regardless of lower concentration that may have existed during that day. These Standards are legally binding.

The major scientific bases utilized in setting MAC's in the U.S.S.R. derive from reactions of the higher nervous system and physiological alteration. Feasibility does not seem to be consid-

ered in the standard setting process, although there is some question as to whether such standards represent goals or working realities. Thus, because such minimal physiological or neurofunctional changes (= adaptive responses?) are considered as designating the borderline between harm and safety, and since a safety margin is then applied, the Soviet Standards tend to be lower than those found in the United States. However, close examination of these differences reveals that in actuality only relatively few cases of gross differences (more than 4-fold) exist.¹⁹

Formulation Procedures. Much of the work involved in establishing standards is performed by the Academy of Medical Sciences, and The Institute of Industrial Hygiene and Occupational Diseases in Moscow, as well as other institutes. The data are then evaluated by the Permanent Committee for the setting of MAC's. Ultimately, standards are promulgated as Soviet Standard 245-63 by the U.S.S.R. Ministry of Health.

West Germany

Maximum allowable concentrations (MAK-Werte) are developed by an expert commission of the German Research Association (Deutschen Forschungsgemeinschaft) and are adopted in total by the Ministry of Labor & Welfare. In essence, they reflect the values adopted by the A.C.G.I.H. with some variations. The values adopted represent legal standards. A documentation is presently in preparation.

United Kingdom

The Factory Inspection Service of the Department of Employment utilizes a list of standards which act as benchmarks for the inspectorate. The values used are essentially those of the A.C.G.I.H.

France

Although French legal codes are extremely detailed regarding precautionary measures (e.g., medical, technical) for the protection of workers exposed to toxic substances, only a very few, specific materials are given numerical values in French codes. This stems from recognition of the reality that such values *do not* represent inflexible, absolute dividing lines between safety and hazard.

Others

Eastern Bloc Nations. Legal standards specifically stated in terms of numerical values are the rule. These are then promulgated by the Ministries of Health or those relating to production and are legally binding. It is of interest to note that most frequently (except for Bulgaria) the values cited are not identical with those adopted in the U.S.S.R. *Asiatic.* Several of these recommend tests of standards of air quality in workplaces. The most notable of these is Japan; the numbers recommended by the Japanese Association of Occupational Health largely reflect those published by the A.C.G.I.H.

UTILIZATION OF STANDARDS OF QUALITY FOR THE OCCUPATIONAL ENVIRONMENT

The Philosophic Basis of Their Use

Consideration of the foregoing should clearly indicate that the formulation of quality standards

has no *absolute* informational basis. The variability of biological response, the judgmental elements which enter into evaluation of environmental and biological data, the imprecise nature of the biological response — all of these imply that after such evidence is weighed, a less than absolute decision must be reached. While a numerical value is ultimately decided upon, the non-absolute nature of the data upon which it is based should suggest that such value must not be taken to represent an *absolute* boundary between the positively safe and the positively unsafe. Thus, for example, if the "safe" value is 50, this cannot be taken to mean that 49 is *always* safe or that 51 represents an unsafe area. At best, such values represent *benchmarks*, or *guides* for protective action. Within this context, if a time-weighted average of 49 is attained, this should not be understood to mean that a lower value should not be pursued. Conversely, a value of 51 does not mean that damage to the individual so exposed will necessarily ensue. Within the context of legal codes such values do indicate the boundary between "safe" and "unsafe." Application of TLV's must take into account the multiple biological considerations discussed in this chapter and elsewhere and the elements of professional judgment inherent in the formulation of such standards (see section on Principles for Developing Workroom Air Quality Standards).

Obviously, repeated excursions above an air quality standard should not be tolerated. Where "c" or ceiling values are listed (see above), such excursions may lead to health or functional impairment, e.g., for liposoluble volatile solvents with narcotic properties as trichloroethylene or carbon disulfide. With substances not having such ceiling designations, excursions above such TLV's may only be permitted consistent with the recommended level (see above discussion of A.C.G.I.H. values).

In the event that a survey indicates excursions above TLV's, the competent authority is responsible for more definitive evaluation of such situations. Thus, repeated samples of the work environment representative of temporal and spatial variations in worker exposure should be obtained, consistent with good sampling procedures (see Chapter 10).

In addition, medical biological evaluation of the workers at possible risk is indicated. The appropriate medical examinations should delineate whether health damage, actual or potential, is occurring. Samples of biological media (blood, urine, expired air, tissues such as hair) should be analyzed to determine whether undue body burdens are being taken up.

If such more definitive evaluations indicate the presence of an occupational risk to worker health and safety, appropriate control action is necessitated.

That such values represent indicators for further evaluation and control action must be clearly understood. Such values can only be properly utilized by those possessing knowledge regarding these facts as well as an understanding of health implications of the specific environmental agent concerned. Thus a considerable element of judgmental evaluation is required; *there should be*

no automatic, unthinking application of such values for the protection of worker safety and health.

Appropriate Application of Standards

Health and Medical Control. Possibly the most important use of quality standards relates to their use for medical control. Since medical and clinical laboratory testing imply certain costs, judicious planning for their deployment requires some guidelines to determine the frequency and extent of medical surveillance *consistent with worker safety and health*. Thus, if threshold limit values are repeatedly exceeded, more frequent and extensive medical surveillance is indicated while and after control measures are being accomplished. Certainly, as such quality standards are exceeded, the nature of medical testing becomes quite different than if these standards are never approached. It should be clearly indicated that even if such quality standards are *not* exceeded, medical surveillance *cannot* be neglected or omitted. However, their stringency should reflect the degree to which standards are approached or exceeded. It should be emphasized that medical action becomes useless as regards prevention unless coordinated with appropriate engineering action for amelioration of workplace contamination.

Design of Engineering Controls and Practices. Given such numerical values, it becomes possible for the design engineer to ascertain that engineering control of the process is required. With a knowledge of the physical properties of the material in question, the amounts used and the possible loss from the process, one can then formulate the ventilation or enclosure requirements necessary which will capture the contaminant in question and prevent its escape to the work environment.

Good engineering practice should never permit the workplace concentration to reach the quantitative level prescribed by the standard. It should be recognized that the economic cost of controls may mount geometrically as lower levels of workplace contamination are sought. Consequently, there is decreasingly less merit in attempting to attain absolute levels of capture, nevertheless, while the lowest level feasible should be sought, it can be seen that quality standards do provide benchmarks against which performance can be measured, consistent with economic considerations.

Surveillance of Adequacy of Control and Maintenance Practices. Once such control equipment is installed, its performance should be monitored. Given accumulation of material in ducts or fans, wear and aging of equipment, the performance of such equipment will tend to deteriorate. The point at which maintenance or replacement is required — with its attendant economic cost — can be determined by monitoring the work area. Since such decisions and the attendant depreciation costs may be considerable, the benchmarks for environmental quality become useful in rational planning of maintenance and replacement.

Use for Development of Analytical Techniques. In the realm of environmental monitoring, the design of analytical methodologies requires that some specific range of sensitivity should be sought if the method is to have practical use. Thus, the analyst

can use such quality standards in ascertaining how such analysis need be carried out. For example, while wet chemical methods may be quite adequate for the measurement at the 100 ppm level, at one-thousandth of this level other techniques may be called for, e.g., gas chromatography. Thus, knowing what concentration range must be measured is of obvious value; quality standards clearly indicate such ranges.

Basis for Communication and Interaction Among the Various Specialty Disciplines in the Occupational Health Team

Misuse of Standards — Comparison of Standards with Single Environmental Determinations. Generally speaking, to properly evaluate environmental quality in the workplace, the obtaining of a short-period single determination has little or no value. Likewise, to compare such short-period sample with an 8-hour environmental quality standard represents a misuse of such standards. Since most standards represent time-weighted averages (see above), one sample probably cannot provide such an evaluation, unless it is an eight-hour sample or can be reliably related to the full-shift exposure. Even where ceiling values (see above) are exceeded, a single sample may be invalid unless it is clearly related to the worker, e.g., in relation to his breathing zone. Obviously, quality standards have meaning only when adequate industrial hygiene sampling techniques are utilized (see Chapter 10).

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CHAPTER 9

THE SIGNIFICANCE AND USES OF GUIDES, CODES, REGULATIONS, AND STANDARDS FOR CHEMICAL AND PHYSICAL AGENTS

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INTRODUCTION

The passage of the Social Security Act (1935), assured the eventual acceptance in the United States of the philosophy that the worker had the right to earn a living without endangering his health. During the period since 1935 a number of states^{1,2,3,4} adopted codes and regulations governing conditions of work to prevent injury to health and in many instances established threshold limit values which limited levels of exposures in the working environment.

The adoption of state codes and regulations governing the control of the working environment led to greatly accelerated research to obtain data both for the establishment of rational threshold limit values and for their extension to cover as many agents as possible. This research, in turn, led to new procedures for studying the effects of environmental agents on worker health.⁵ Significantly, this research revealed that many agents which gave rise to acute responses from high exposure levels over a relatively short period of time elicited a different response to lower levels of exposure to the same agents over a prolonged period of time.

Through data obtained both from epidemiologic and animal research, a body of knowledge has been acquired which permits establishing the rationale for threshold limit values. This rationale is succinctly stated by Hatch:⁶ "1) There exists a systemic dose-response relationship between the magnitude of exposure to the hazardous agent and the degree of response in the exposed individual, and 2) there is a graded decrease in the risk of injury as the level of the exposure goes down, which risk becomes negligible when exposure falls below a certain tolerable level. Thus, in the face of recognized potential dangers associated with certain physical and chemical agents, these principles say that such agents can be dealt with safely at some acceptable level of contact above zero and, therefore, that they do not have to be eliminated altogether from industry in order to protect the workers' health."

PROMULGATION OF GUIDES, CODES, REGULATIONS AND STANDARDS

Two general procedures are used in the establishment of occupational safety and health laws. The first is through statutes promulgated by legislative action. The second procedure is through

codes, regulations and standards promulgated by agencies with rule-making authority. The latter procedure is, by far, the most common one and is more readily responsive to need for changes. Promulgations through either course of action have the same force and effect of law.

A code is a body of law established either by legislative or by administrative agencies with rule-making authority. It is designed to regulate completely, so far as a statute may, the subject to which it relates. "New York State Industrial Code Rule No. 12 Relating to Control of Air Contaminants in Factories" is an example of such a code.⁷

A regulation is an authoritative rule dealing with details of procedure; or, a rule or order having the force of law, issued by an executive authority of government. The State of Michigan "Regulation Governing the Use of Radioisotopes, X Radiation and All Other Forms of Ionizing Radiation" is an example.⁸

A standard is any rule, principle or measure established by authority. The term "occupational safety and health standard" under the Occupational Safety and Health Act of 1970 means "a standard which requires conditions, or the adoption or use of one or more practices, means, methods, operations, or processes, reasonably necessary or appropriate to provide safe or healthful employment and places of employment."⁹

A guide is an instrument that provides directive or guiding information. Examples of guides are the "American Industrial Hygiene Association Guides"¹⁰ and the "Threshold Limit Values of Airborne Contaminants and Physical Agents" adopted by the American Conference of Governmental Industrial Hygienists.¹¹ Although such guides, per se, do not have the force of law, their values may be incorporated into codes, regulations and standards that do have the force of law.

SOURCES OF DATA FOR EXPOSURE LIMIT VALUES

Exposure limit values are based on data arising out of experimental animal and human studies and from data on industrial experience obtained through clinical and epidemiologic studies of workers. Interrelated data from the three sources give the most rational data upon which to base exposure limits. Animal and human experimental data are most suitable for deriving biologic re-

sponse data on single substances or specific combinations of substances. Workers, however, are seldom exposed to such limited combinations of substances in their work environment. Also, the personal habits of workers, such as cigarette smoking, consumption of alcoholic beverages, and use of drugs may alone have a profound influence on the health profile of workers, or they may have an additive or synergistic action on exposures in the work environment. The health of the worker represents the influence of his twenty-four hour a day environment over a lifetime. Thus procedures and data are needed which will distinguish between health patterns from on and off-the-job stresses. Well designed epidemiologic studies can delineate the influence of multiple on and off-the-job stresses in the environment and have the advantage of being able to study workers over a lifetime.

Research to obtain biologic response data upon which to base exposure limit values is very costly and time consuming. The resources for such studies come mainly from government, industry and foundations. The research may be carried out at facilities operated by the government, educational institutions, foundations, consultants and industry. The Occupational Safety and Health Act of 1970 will stimulate research at all these levels for obtaining data upon which to base exposure limit values.

NATURE AND SOURCES OF EXPOSURE LIMIT VALUES

As stated previously, occupational health codes, regulations and standards may be both general and specific in their coverage depending on their objectives and the procedures intended for their implementation. Any one act may cover a single or several elements to accomplish the stipulated requirements including such areas as threshold limit values, methods and procedures for monitoring the environment, methods of control, use of respiratory protective equipment and protective clothing, and handling of waste.

The establishment and use of exposure limit values are so fundamentally a part of occupational health, codes, regulations and standards that special attention is devoted to their development, significance and use.

The American Conference of Governmental Industrial Hygienists publishes annually a list of "Threshold Limit Values of Airborne Contaminants and Physical Agents."¹¹ The lists are reviewed annually and values are updated as relative data becomes available. Intended changes are published as a part of the annual list and comments supported with data are requested. The threshold limit values of the American Conference of Governmental Industrial Hygienists are airborne concentrations of substances and levels of physical agents below which values it is believed that nearly all workers may be exposed repeatedly eight hours per day, forty hours per week, without adverse effect. In the use of these values, medical surveillance is recommended to detect workers who are hypersusceptible to specific chemicals or physical agents, so that they can be removed from the exposure or given special protection. Ceiling

values in connection with threshold limit values represent exposure values which should not be exceeded and relate to substances which are fast acting and whose threshold limits are more appropriately based on a particular biologic response. In instances where the cutaneous route is an important source of absorption, substances are marked with the notation "skin" to stress this property since the threshold limit value refers only to inhalation as the source of entry of the agents into the body.

The American National Standards Institute, Inc., publishes consensus standards of acceptable concentrations for chemical and physical agents.¹² The standards are useful in establishing engineering procedures for the prevention of objectionable levels of chemical and physical agents in the work environment. Acceptable concentration values are presented in terms of a time-weighted eight-hour workday, acceptable ceiling concentrations within an eight-hour workday, and acceptable maximum peak concentrations for short specified durations. American National Standard acceptable concentrations are values below which ill effects are unlikely. The values are not to be used as the basis for establishing the presence of occupational disease.

The Commonwealth of Pennsylvania Department of Health has established a list of short-term limits as a part of the "Regulations Establishing Threshold Limit Values in Places of Employment."¹³ The short-term limit is the upper limit of exposure for which a workman may be exposed to a contaminant for a specified short period. Short-term episodes are included in the daily average concentrations for compliance with the established threshold limit values for contaminants to which workers may be exposed for an eight-hour workday.

The Committee on Toxicology of the National Research Council (operating arm of the National Academy of Sciences and National Academy of Engineering) publishes a list of recommended emergency exposure limits.¹⁴ These recommended emergency exposure limits are not intended to be used as guides in the maintenance of healthful working environments but rather as guidance in advance planning for the management of emergencies.

The American Industrial Hygiene Association publishes a Hygienic Guide Series¹⁵ covering an extensive list of chemicals. A hygienic guide for a given material contains the following information: Significant Physical Properties; Hygienic Standards (limits) for eight-hour, time-weighted exposures, short exposure tolerance, and atmospheric concentrations immediately hazardous to life; Toxic Properties, including exposure via inhalation, ingestion, skin contact and eye contact; Industrial Hygiene Practice, including industrial uses, evaluation of exposures, hazards and their recommended controls; and Medical Information, including emergency treatment and special medical procedures.

The National Institute for Occupational Safety and Health, Public Health Service, Department of Health, Education, and Welfare has a responsi-

bility for developing and publishing criteria dealing with toxic materials and harmful physical agents which will describe safe levels of exposure for various periods of employment.⁹ The Institute also is responsible for conducting and publishing research, including industry-wide studies, which will lead to the development of criteria documents.

A number of official agencies and organizations publish recommended exposure limits for specific agents. Examples include: National Bureau of Standards Handbook No. 59 "Permissible Dose for Ionizing Radiation"¹⁵ and Handbook No. 93 "Safety Standards for Non-medical X Ray and Sealed Gamma Ray Sources;"¹⁶ "Intersociety Guidelines for Noise Exposure Control"¹⁷ developed by an Inter-society Committee representing the American Industrial Hygiene Association, American Conference of Governmental Industrial Hygienists, Industrial Medical Association, and the American Academy of Ophthalmology and Otolaryngology.

A number of organizations have programs for developing threshold limits for biologic materials, i.e., urine and blood. The National Institute for Occupational Safety and Health, Office of Research and Standards Development,¹⁸ has developed a procedure whereby consultants are appointed to a committee for the purpose of establishing biologic threshold limits for specific substances. The Permanent Commission and International Association on Occupational Health¹⁹ has established a committee for developing international standards for levels of contaminants and their metabolites in biologic materials. The American Industrial Hygiene Association established a Committee on Biochemical Assays to study and recommend procedures for determining levels of specific contaminants and their metabolites in biologic materials, and recommend levels indicative of excessive exposure.

The International Labour Office,²⁰ Geneva, Switzerland, publishes model codes, codes of practice, guides and manuals in the areas of occupational safety and health. The publications cover both chemical and physical exposures and treat the subject in depth.

SIGNIFICANCE AND USE OF EXPOSURE LIMIT VALUES

Exposure limit values are the crux of most occupational health codes, regulations and standards. If there is no exposure to a harmful agent it follows that the presence of this agent does not create a health problem. Also the toxicity of a material *per se*, though extremely important, is not the sole criterion of whether or not a health problem is present where the material is encountered. The terms "toxicity" and "hazard" are not synonymous. Many factors, in addition to the toxic nature of a material, are important in evaluating a hazard potential. These include the chemical and physical properties of the toxic substances, the ability of the toxic substances to interact with surrounding materials, and the influence of surrounding conditions such as temperature and humidity on the toxic substances, as well as the concentration, stability, and conditions of use of

the toxic substances and the conditions under which they are encountered.

The toxicity of a substance expressed in terms of a threshold limit value, however, is an important criterion and concept in evaluating the presence of a health hazard. As stated in the introduction, threshold limit values are based on the concept of a dose-response relation between the agent and its health effects on the worker, that this is of a graded nature, and that consequently there is a lower level of exposure at which level the substance will exert no deleterious effect on the worker. The application of this knowledge to assure that workers are not exposed to concentrations above these threshold values is an important concept in the prevention of occupational diseases. Due to individual variations in susceptibility and the many unknown factors in the working environment and their effects on a given toxic material, the threshold limit value of a material is not a fine distinction between a safe and dangerous condition. Though levels of exposure may be kept within a designated threshold limit value, this is no assurance that an individual worker may not show some deleterious effects if he has unusual susceptibility. The importance of ceiling levels, skin absorption, etc. must also be considered especially if they are contained as an integral part of the threshold limit value.

Biologic standards, i.e., the concentration of a specific agent in the urine or blood, represents the body burden of that agent and may be used as a monitor of the exposure of a worker to a specific substance. Thus biologic levels of a material represent the integrated relation of a combination of the complex chemical and physical characteristics of an exposure on the worker and can be used to indicate where excessive exposures have occurred, when removal from further exposure is indicated, etc. As with threshold limit values, biologic standards do not represent a fine line of distinction between safe and dangerous conditions and alone are not definitive of a state of disease. It must also be stressed that the body burden of an agent represents all sources and routes of exposure and is not limited to industrial exposures. Habits, hobbies, etc. that may involve factors which influence the absorption and retention of a substance may be important.

The application of exposure limit values in the evaluation of the work environment requires a knowledge of the limit values, of their application and meaning, and of acceptable methods and procedures for measuring exposure levels. The latter is discussed separately under the heading "Selection of Methods and Procedures for Measuring Exposure Levels."

Threshold limit values are expressed as time-weighted averages for an eight-hour workday and forty-hour workweek. The time-weighted averages for specific substances, unless designated by special categories or ceiling limits, permit limited excursions above the threshold limit value provided they are compensated by offsetting excursions below the value.¹¹

In the application of threshold limit values to mixtures of toxic substances, in the absence of

other information, their effects are considered additive. Thus their additive factor should not exceed unity in terms of their individual exposure concentrations over the threshold limit values.

Threshold limit values are becoming increasingly significant since they are used in most occupational health codes, regulations, and standards as the yardstick for measuring compliance. Exceeding the values can bring on severe penalties. It is extremely important that the employer have worker exposure monitoring data assuring compliance with relevant standards. These monitoring data should include time-weighted averages, extent of excursions above time-weighted averages, ceiling levels, and short-term exposure levels as relevant.

In addition to data monitoring exposure levels, data on levels of exposure in the general room area and at contaminant disseminating sites are useful in assuring the ability of the control system to adequately contain the contaminant and of its continuing satisfactory performance.

SELECTION OF METHODS AND PROCEDURES FOR MEASURING EXPOSURE CONCENTRATIONS

The measurement of exposure concentrations in the working environment assume utmost importance since compliance to standards are based upon comparison of existing levels of exposure with values stipulated in the standards. In the adoption of exposure limit values into standards, it must be assumed that there are valid, tested and reproducible procedures for the collection and analysis of the agent involved. Seemingly small errors or departures from accepted practices may have a considerable impact, on the one hand on the health protection afforded the workers through application of the standard should inadvertently low values be obtained, and on the other hand on the economic loss involved for compliance should inadvertently high values be obtained in measuring exposure levels.

In some standards acceptable methods and procedures are listed for measuring exposure levels for compliance. Where this is not done, reliance must be placed upon the experience and competence of the persons involved. The decisions include not only methods and procedures to be used but also the assurance of representative samples, the proper calibration of equipment, the use of internal controls, and a sampling regimen that will satisfy compliance requirements. For these reasons, laboratories engaged in measuring worker exposure levels, either through the collection of airborne samples or biologic fluids, should be accredited for this purpose.²¹

ENACTMENT OF OCCUPATIONAL HEALTH GUIDES, CODES, REGULATIONS, AND STANDARDS

A number of official agencies have rule-making authority for the enactment of occupational health legislation for the protection of the worker.

The most recent and comprehensive legislation of this nature, Public Law 91-596 enacted by the 91st Congress,⁹ "establishes authority in the Secre-

tary of Labor for the adoption and enforcement of standards for safe and healthful working conditions of working men and women employed in any business affecting commerce." The safety and health standards promulgated under the Walsh-Healey Act, as well as other established federal standards relating to construction work, ship repairing, shipbuilding, shipbreaking and longshoring operations were adopted as safety and health standards under the Federal Occupational Safety and Health Act, and are subject to revision under that Act. Exceptions to this primarily relate to the Atomic Energy Act of 1954, and the Federal Coal Mine Health and Safety Act of 1969 since the Occupational Safety and Health Act of 1970 does not apply where other federal agencies regulate under applicable federal law.

The Occupational Safety and Health Act established a National Institute for Occupational Safety and Health within the Department of Health, Education, and Welfare to conduct research and training, develop criteria, publish a list of toxic substances, and make inspections relative to these responsibilities. The Act also provides for the participation of state official agencies in carrying out the provisions of the Act.

The Federal Metal and Nonmetallic Mine Safety Act²² vests authority in the Secretary of the Interior for promulgating and carrying out health and safety standards "for the purpose of the protection of life, the promotion of health and safety, and the prevention of accidents in Metal and Non-metallic Mines."

The Federal Coal Mine Health and Safety Act of 1969²³ vests authority in the Secretary of the Interior to promulgate and enforce standards for the protection of life and the prevention of injuries in a coal mine. The Act directs the Secretary of Interior to develop and promulgate, as may be appropriate, improved mandatory safety standards and to promulgate mandatory health standards transmitted to him by the Secretary of Health, Education, and Welfare. The Act also provides cooperation and assistance to states in the development and enforcement of effective state coal mine health and safety programs.

The Bureau of Mines, Department of Interior, also has responsibility for the approval of respiratory devices for protection against the inhalation of gaseous and particulate substances.²⁴

The Atomic Energy Commission has authority for establishing radiation standards in a number of areas. Examples include "Standards for Protection Against Radiation"²⁵ and "Licenses for Radiography and Radiation Safety Requirements for Radiographic Operators."²⁶ The former sets forth a very detailed set of standards which have the effect of law. The latter specialized standard was published because of the large number of isotope sources used for radiography and the fact that many overexposures had occurred during radiographic procedures.

Several state agencies have responsibilities for establishing and enforcing standards for protecting the health of workers coming within their jurisdictions. The enactment of the Occupational Safety and Health Act of 1970, however, had a

profound influence on the Federal-State relationship in this area since the latter covers all workers engaged in activities related to commerce. Designated state agencies with standards and programs approved by the Department of Labor can by agreement undertake the enforcement of the Federal Act within their boundaries.

SIGNIFICANCE AND IMPACT OF OCCUPATIONAL SAFETY AND HEALTH ACT OF 1970

The Occupational Safety and Health Act of 1970 has brought important, new dimensions in safeguarding the health of workers and in the practice of industrial hygiene. Although the impact of many of these newer dimensions is immediate, new interpretations and applications of the Act are made by the courts as the need arises. Thus it will be many years before the full impact of the Act is fully realized.

The coverage of the Act is comprehensive and has brought into its jurisdiction numerous workers heretofore excluded from such benefits. Generally, the Act applies to all workers employed in places of work, engaged in a business affecting commerce, except for government employees.

To appreciate the impact of the Occupational Safety and Health Act it is necessary to review briefly the coverage by regulations and the practices prior to its enactment.

Prior to 1936 the only regulations and guides relating to occupational health were administered by state and local governmental agencies. In most instances the guides and regulations were very general, difficult of enforcement, and relied on professional judgment with respect to compliance. Most of the states had no programs relating to occupational health, and those that existed were far too minimal in staffs and funds to carry out effective programs.

The Walsh-Healey Act of 1936 (41 U.S.C. 35; 49 Stat. 2036) which enabled the Federal Government to establish standards for safety and health in work places engaged in activities relating to Federal contracts, was the forerunner in establishing today's concepts of occupational health regulations. The 1936 Act stimulated research into the cause, recognition, and control of occupational disease and led to the development of occupational health programs by official organizations, insurance companies, foundations, managements and unions. Subsequently other Federal legislation had further impact on the promulgation of Federal safety and health standards. These include the Service Contract Act of 1965 (41 U.S.C. 351; 79 Stat. 1034), Public Law 85-742, Act of 1958 (33 U.S.C. 941; 72 Stat. 835), Public Law 86-54, Act of 1969 (40 U.S.C. 333; 83 Stat. 96), and the National Foundation of Arts and Humanities Acts (79 Stat. 845). The interim period between 1936-1970 also saw a number of states issuing occupational safety and health regulations to cover workers in their jurisdictions. None of the occupational health programs in official agencies during this period, however, were adequate in scope, staff, or funds to carry out their responsibilities.

The lack of uniformity within the various regulations established by Federal, state and local official agencies led to great confusion in industries that operated interstate. Programs by industry for compliance with regulations had to vary from state to state and could not be established on a uniform corporate-wide basis.

The Occupational Safety and Health Act of 1970 has brought a restructuring of programs and activities relating to safeguarding the health of the worker. Uniform occupational health regulations now apply to all businesses engaged in commerce, regardless of their locations within the jurisdiction. Threshold limit values have been incorporated into the regulations and now have the effect of law.

In the earlier years, the establishment of threshold limit values, whether with the effect of law or used as guides, was done more on the basis of professional opinion and judgment than on the basis of facts. Data were minimal on the health effects of exposures to most materials encountered in industry. Uniformity of procedures and methods for the collection and analysis of airborne contaminants was generally lacking. The interpretation of compliance with a regulation or threshold limit value was often that of professional judgment. Information on investigations and inspections relative to violations and compliance of standards was usually restricted to the official agency and management concerned. Likewise, medical data obtained through the examination of workers in many instances were not available to the medical department of the industry.

The Occupational Safety and Health Act of 1970 has more clearly defined procedures for establishing regulations, the conduct of investigations for compliance, and the handling and availability of exposure data on workers, the keeping of records, etc.

The Act provides for a greatly accelerated program by the National Institute for Occupational Safety and Health (NIOSH) to conduct research on the health effects of exposures in the work environment, to develop criteria for dealing with toxic materials and harmful agents, including safe levels of exposure, to train professional personnel for carrying out various responsibilities prescribed by the Act, and in general, to conduct research and assistance programs for protecting and maintaining worker health.

The first standard promulgated on the basis of a criteria document developed by NIOSH was "Standard for Exposure to Asbestos Dust" (*Federal Register* Vol. 37, No. 110 — Wednesday, June 7, 1972). This standard is especially significant because as the first of such permanent standards for a number of target hazardous materials, it is anticipated that it will serve as the basic model for other standards to come.

The asbestos standard includes sections on definitions; permissible exposures; methods of compliance; work practices; personal protective equipment; method of measurement; monitoring, both personal and environmental; caution signs and labels; housekeeping; recordkeeping, including

employee notification; medical examinations; and medical records.

This standard differs from prior standards in OSHA regulations, which specified only the permissible concentrations of airborne contaminants or permissible levels at physical exposures (Occupational Safety and Health Standards, Paragraphs 1910.93, 1910.95, 1910.96 and 1910.97 of the *Federal Register*, Vol. 36; No. 105, May 25, 1971). The far reaching provisions of the new standard include the specification of methods of compliance, which include engineering controls such as ventilation and wet methods; personal protective equipment such as respirators, and including shift rotation of employees to reduce exposure; caution signs and labels, not only for the work place in which asbestos is handled but also for products containing asbestos fibers; recordkeeping, including a requirement that employees exposed to airborne concentrations of asbestos fibers in excess of the limits shall be notified in writing of the exposure as soon as practicable but not later than five days of the finding; and medical examinations, including preplacement, annual and termination of employment examinations and specifying the minimum requisite examination procedures and tests which shall be included.

The interpretation of the general duty clause requirements for providing a safe and healthful working environment and the publication of the permanent asbestos standards add new dimensions to the protection of employee health. Both emphasize that final responsibility for compliance with the provisions of the Occupational Safety and Health Act remains with the employer.

The Act prescribes procedures for use by the Secretary of Labor in promulgating regulations. It is of special interest that threshold limit values for exposures to toxic materials and harmful agents are contained in the regulations, and have the effect of law. Since procedures are given for measuring exposure levels to specific materials and agents in the standards promulgated by the Department of Labor, the use of professional judgment as required in the past for such activities is largely obviated, as is also the interpretation of the values obtained. The employee or his representative now has the right to observe monitoring procedures and have access to data on exposure levels. Disagreements on the validity of monitoring data and its meaning are now relegated to the courts for settlement. Professional skills and judgments are still required, however, in applying the intent of the many aspects of the Act in safeguarding workers' health.

The Act has had a similar impact on the medical and nursing programs in industry.²⁷ Many medical programs in industry had already seen the transformation from the earlier emphasis on the treatment of traumatic injuries to the modern concept of the prevention of occupational diseases and injuries. This trend, however, has not been universal and the fact remains that a vast number of workers still do not have immediate access to medical and nursing services.

Among the changes in industrial medical programs brought on by the Act is the maintenance

of medical records on employees and the access to data contained in them. All practicing physicians representing employers are now required to keep records of the occupational injuries and illnesses of their employees. Standards for specific materials and agents prescribe the nature of medical examinations to be given the employees, the length of time the employer must maintain the records, and who may have access to these records data. Specifically, both the Assistant Secretary of Labor for Occupational Safety and Health and the Director, National Institute for Occupational Safety and Health, and authorized physicians and medical consultants may have access to these data. Also, medical data from examinations required by the regulation shall be given the employer, and upon request by the employee, must be given to the employee's physician.

The industrial physician, with the knowledge that the employee has information on both his exposure levels to toxic materials and harmful agents and on his health status, must now maintain a preventive program for follow-up of situations where excessive exposures have occurred or where biochemical or medical tests indicate early or impending changes in employee health patterns. Since the health profile of a worker represents the effect of his twenty-four hours a day environment, the industrial physician is finding it prudent to obtain information on workers' off-the-job activities and habits, such as hobbies, smoking, use of drugs, that either may directly affect their health or may have an additive influence to on-the-job stresses.

There has been a similar change in the practices of industrial nursing over the past decades.²⁸⁻²⁹⁻³⁰ The Occupational Safety and Health Act of 1970 will provide a major impetus not only in increasing the number of industrial nurses available for medical services to workers, but also in using their fullest capability both in carrying out preventive medical programs and in maintaining and promoting the optimal health of the worker. In the early practice of industrial nursing, activities were largely centered around the emergency treating of traumatic injuries and were prescribed in written orders of a physician. Advancing industrial technology along with modern concepts of preventive medical services soon assured that the industrial nurse could no longer accept such a limited role. The industrial nurse, in addition to giving specific medical services, is now called upon to give broad health counseling to the worker in his overall environment. The Act will increasingly propel the industrial nurse to give a more comprehensive service in promoting worker health. This will necessitate a close working relationship with both the industrial hygienist and the safety officer, and will require a knowledge of the toxic materials and harmful agents in the in-plant environment.

A number of sources are available for keeping informed on enforcement aspects relating to the Act as well as citations and their review by the Occupational Safety and Health Review Commission where appeal has been made by the employer.³¹⁻³²⁻³³ The following citations issued by the Occupational Safety and Health Administration

and their review, where appealed, by the Review Commission, show the impact which the Act will have on occupational health and the practice of industrial hygiene and of the importance of keeping informed on these decisions.

A landmark ruling defining the employer's responsibilities with respect to providing a safe and healthful working environment is contained in Case 10 before a Hearing Examiner of the Occupational Safety and Health Review Commission, U.S. Department of Labor. The case involves the Omaha, Nebraska plant of the American Smelting and Refining Company (ASARCO) and a citation dated July 7, 1971. The citation alleged that ASARCO, at a plant in Omaha, Nebraska, was in violation of Section 5 (a) (1) of the Act, which provides that "Each employer shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or likely to cause death or serious physical harm to his employees."

The following description of the alleged violation is set forth in this citation:

"Airborne concentrations of lead significantly exceeding levels generally accepted to be safe working levels, have been allowed to exist in the breathing zones of employees working in the lead-melting area, the retort area, and other work places. Employees have been, and are being exposed to such concentrations. This condition constitutes a recognized hazard that is causing or likely to cause death or serious physical harm to employees."

ASARCO contended that the levels of airborne lead found in its Omaha plant during an OSHA inspection, in excess of the threshold limit value (TLV) of 0.2 milligram per cubic meter of air (0.2 mg Pb/M³) did not constitute a recognized hazard causing or likely to cause death or serious physical harm to its employees in view of the protective safety measures in effect. These included the use of respirators, transferring employees from high exposure jobs and its biological sampling program.

The Act, however, places the responsibility upon employers to provide safe and healthful working conditions for its employees, as far as possible. It does not allow employers to provide unsafe, unhealthful or hazardous working conditions for its employees even though the adverse effects of such working conditions are attempted to be minimized. ASARCO's first responsibility, as set forth by the Hearing Examiner, was to provide safe and healthful working conditions, by reducing the levels of airborne concentrations of lead to the generally recognized safe level of 0.2 mg Pb/M³, or as close to that figure as possible.

ASARCO argued that no hazard likely to cause death or serious physical harm to employees existed at its Omaha plant because no evidence was presented that any of its employees suffered from lead intoxication or had been in any way injured by the airborne concentrations of lead found to exist at its plant. It should be stated here that ASARCO also collected air samples and the results of analyses generally confirmed the findings of the OSHA representative. The Hear-

ing Examiner, however, found that proof of a violation of Section 5 (a) (1) of the Act does not depend upon proof that a hazard has produced injury. All that is required is a showing that the hazard is likely to cause serious physical harm or death.

During the hearing, it was found that ASARCO's preventive program, consisting of blood lead determinations, transferring of employees from job to job and the availability of approved respirators in work places having high concentrations of lead "simply has not worked."

The Hearing Examiner, after review of all evidence, found that the levels of airborne concentrations of lead significantly in excess of the threshold limit value (TLV) of 0.2 mg Pb/M³ constituted a violation of Section 5 (a) (1) of the Act, upheld the original citation and affirmed the proposed penalty of \$600.00. This finding, that concentrations of an airborne material above the threshold limit value alone constitutes a violation of the Act, is a profound interpretation of the employer's responsibilities with respect to providing a safe and healthful working environment.

On May 28, 1971, the Occupational Safety and Health Administration issued a citation for serious violation for exposure to mercury.³⁴ Excessive concentrations of mercury vapor in the work environment were found by investigators from the National Institute for Occupational Safety and Health. Visible pools of mercury were found in many areas. In response to the citation, the management claimed that the pools of mercury resulted from pipeline leakage when the mercury cell operation was shut down for scheduled maintenance and equipment installation. The management stated that the condition had been corrected and that steps had been taken to tighten up maintenance and housekeeping procedures.

A citation for serious violation of section 5 (a) (1) of the Act was issued by the Occupational Safety and Health Administration following an accident in which three employees were killed and two seriously injured from exposure to hydrogen sulfide gas.³⁵ The quantity of hydrogen sulfide gas evolved at an operation from the slurry, when partially decomposed fish were treated with a mild solution of sulfuric acid, could not have been sufficient to cause serious injury or death. A further investigation revealed that deadly quantities of hydrogen sulfide gas could have been evolved through another operation. Another worker cut a hole for ventilation through a metal floor-ceiling resulting in the reaction of the iron with the sulfur in phenothiozene thus forming iron sulfide, which reacted with the sulfuric acid. Judge William J. Bronz, Occupational Safety and Health Review Commission (Docket No. 31), dismissed the citation and proposed penalty. He ruled that past experience did not indicate the need for protection when working with the slurry. The employer could not have reasonably foreseen the probability of serious injury or death to employees arising out of such an episode.

A citation was issued relative to workers being subjected to noise levels in excess of those permitted under 29 C F R 1910.95 (b) (1).³⁶ The

employer contended that he had complied with the regulation by providing employees with protective equipment. Judge James A. Cronin, Jr., Occupational Safety and Health Review Commission (Docket No. 158), ruled that the citation and penalty were appropriate. He stated that the employer was aware that the employees were not wearing the ear muffs provided for protection from noise, and had taken no affirmative action, even though an inspector from the Occupational Safety and Health Administration had indicated the violation. He further brought out that the Senate Report on the Act did not intend for 5 (b) relating to the employees' duty under the Act to diminish the employer's responsibility.

A citation was issued for the failure of a company to provide protective gloves to employees working with a solvent in violation of 29 C.F.R. 1910.132(a).²⁷ Three employees were working with "Stoddard Solvent" five days a week, 8 hours a day. The "Stoddard Solvent" was a petroleum distillate containing paraffins, naphthenes, and aromatics. Evidence indicated that the solvent could cause irritation upon prolonged exposure. The citation was affirmed by Judge Harold A. Kennedy, Occupational Safety and Health Review Commission (Docket No. 79). It was brought out that although the solvent was not classified hazardous under the context of the consideration by any known agency, this did not mean that it was not a hazard within the meaning of the standard. The fact that employees who had used the solvent intermittently for years had received no injuries did not reduce the inherent risk or the duty to provide protective equipment.

A citation was issued for alleged violation of 29 C.F.R. 1910.252 (f) (2) (i) relative to lack of adequate ventilation at a welding and cutting site.²⁸ The employer asserted that there was no violation of the regulation and that the compliance officer had incorrectly calculated the volume of the welding bays and had failed to establish substantial evidence of lack of mechanical ventilation. Judge Joseph L. Chalk, Occupational Safety and Health Review Commission (Docket No. 262), ruled in favor of the employer. It was noted that the volumes of the welding bays, divided by fiberized glass curtains, could not be calculated to imaginary lines at the ends of the bays and should include all space reasonably open to the welding area.

A citation was issued for serious violation of 29 C.F.R. 1918.93 (a) (1) (i) and (ii).²⁹ Fifty-four employees were working in a ship's hold in concentrations of carbon monoxide between 100 and 200 ppm. The citation was affirmed and the penalty deemed appropriate by Judge John J. Larkin, Occupational Safety and Health Review Commission (Docket 296). The Captain's claim of lack of knowledge of the fact was not mitigating since the current standard under the longshoring law had been in effect for a number of years. The Captain had not examined the testing equipment, nor required that records of measurements be kept as specified by the standard. Following measurements for carbon monoxide by the compliance officer, employees were removed from the hold

of the ship. The employees were returned to the hold before a second measurement for carbon monoxide was made by the compliance officer, which showed no decrease in the carbon monoxide concentration.

SUMMARY

The significance of and guidance from guides, codes, and regulations has changed with advances in the art and science of industrial hygiene and in the enactment of recent laws. The implications, interpretations of, and application of the Occupational Safety and Health Act of 1970 will continue to be developed as standards are promulgated by the Secretary of Labor and as they are interpreted by the administrative and judicial processes specified by the Act.

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GENERAL PRINCIPLES IN EVALUATING THE OCCUPATIONAL ENVIRONMENT

Andrew D. Hosey

INTRODUCTION

Evaluating the occupational environment requires a multidisciplinary approach. A fundamental need exists for the input of the knowledge of engineers, chemists, health physicists, physicians, toxicologists, nurses, production supervisors, and others in the elimination of hazards which threaten workers. The most successful approach coordinates these many disciplines and incorporates effective communication between the employer and employee for the recognition, evaluation and control of potential hazards.

Obviously it is not always practical to enlist such a group of workers, management, and highly skilled professionals in Industrial Hygiene for most plants. It is essential, however, that each person evaluating the work environment be knowledgeable of the contributions of other professions to the solution of specific problems. For example, an engineer studying ventilation control for benzene should know the chemistry of benzene and the influence of benzene upon man. Likewise, the physician studying the work environment should have a knowledge of the engineering requirements for control, as well as the chemical sampling and analytical techniques used.

GENERAL PRINCIPLES

The general principles in evaluating the occupational environment concern recognition of potential hazards, preparation for field study, conducting the field study, and interpretation of the survey results.

The recognition of potential hazards includes becoming familiar with the process, maintaining an inventory of physical and chemical agents encountered, periodically reviewing the different job activities of a work area, and studying the existing control measures. The procedures in the preparation for a field study embrace the selection of proper instruments, calibration of equipment, and the development of the required analytical methods. Factors to consider in conducting a field study are all related to sampling; where, when, how long, and how many samples, as well as the merits of general area versus breathing zone sampling should be weighed. Once the survey has been conducted, the industrial hygienist must interpret the results. Health standards and previous data are available for comparison. Knowledge of proper corrective measures is an integral part of the industrial hygienist's responsibilities.

This chapter presents the guidelines to be considered by an industrial hygienist in planning a

strategy for evaluation of the occupational environment.

RECOGNITION OF POTENTIAL HAZARDS

The investigator must become familiar with all processes used in the particular plant or other establishment. He must learn what chemicals or substances are used and produced and the intermediate products, if any. This information may be obtained by asking questions during the survey, by visual observation, and by a study of process flow sheets usually contained in technical books that describe the particular operation. It is of utmost importance that a list of all chemicals and products used be obtained for future reference during the evaluation of the environment. The variety of substances capable of causing occupational diseases increases steadily. New products are constantly being introduced which require the use of new raw materials or new combinations of older substances, and new processes. It has been estimated that new (and some potentially toxic) substances are introduced into industry at the rate of one every 20 minutes and that about 10,000 such materials are in use today. New uses for physical agents in industrial processes are increasing at a rapid rate. Examples include the use of lasers, microwaves, supersonic welding equipment, and many others. These, too, are potentially hazardous unless proper control measures are instituted.

Toxicity of Raw Materials and Products

It is important for the investigator to recognize that the toxicity of a substance is not the sole criterion, or necessarily the most important, of the existence of a health hazard associated with a particular industrial operation. The terms "toxicity" and "hazard" are not synonymous. The nature of the process in which the substance is used or generated, the possibility of reaction with other agents (physical or chemical), the degree of effective ventilation control or the extent of enclosure of the process materials all relate to the potential hazard associated with each use of a given chemical agent (see Chapter 9). Such an assessment must be made along with due consideration of the type and degree of toxic responses the agent may elicit in both the average and, possibly, hypersusceptible workers.

After the list of chemicals used and produced is obtained, it is necessary to determine which of these are toxic and to what degree. Information of this nature can be found in the latest texts and in scientific journals, Hygienic Guides published by

the American Industrial Hygiene Association (A.I.H.A.),¹ the Z-37 Standards published by the American National Standards Institute (A.N.S.I.),² and by correspondence with toxicologists, technical information centers, and manufacturers. *Toxic Substances*, a recent publication by the National Institute for Occupational Safety and Health³ contains over 8000 substances. The list, which is revised annually, gives the concentration at which each substance is known to be toxic and should serve as an excellent reference source in the area of toxicology. Many companies publish a list of toxic materials used in their plants for use by safety personnel, foremen, and others. Similar information should be obtained also on the potential hazards of physical agents in use. A number of guides, standards, and texts are available for this purpose.

Sources of Air Contaminants

Many potentially hazardous operations can be detected by visual observation during the preliminary survey. The most dusty operations can be easily spotted, although this does not necessarily mean they are the most hazardous. It must be remembered that the dust particles which cannot be seen by the unaided eye are the most hazardous because they are of respirable size. Furthermore, dust concentrations must reach extremely high levels before they are readily visible in the air. Thus the absence of a visible dust cloud does not mean necessarily that a dust-free atmosphere exists. However, those operations that generate fumes, such as welding, can be spotted visually.

Reference to the list of raw materials, products and byproducts will indicate possible air contaminants. In any burning operation, a knowledge of the fuels used will indicate the air contaminants generated. Separation processes can produce chemicals or particulates which are potentially hazardous.

The presence of many vapors and gases can be detected by the sense of smell. Trained observers are able to estimate rather closely the concentration of a limited number of solvent vapors and gases in the workroom air by the odor level. For many substances, however, the odor threshold concentration is greater than the permissible exposure levels. For example, if the odor of carbon tetrachloride vapor is barely perceptible, this indicates the amount is generally too great for a continuous exposure. In fact, concentrations of some vapors and gases may be present in concentrations considerably in excess of the permissible level, but may not be detectable by their odor.

New Stresses — Changes in Processes

As indicated above, new chemical products and physical agents are continually being introduced and used in industrial processes. The investigator must be aware of these and must ascertain the potentially hazardous nature of these before they are used so that any necessary safeguards can be inaugurated. Many companies, especially the larger ones, have such information available and will generally make it accessible to the investigator. Furthermore, the employer should inform employees of these potential hazards and should establish controls for their protection.

Job Activities Review

A review of the worker's routine job requirements should be made. Changes in his job requirements or modifications of techniques to accomplish his work can have a profound effect upon his exposure to health hazards. Overtime requirements for particular jobs should be determined so that the contribution of overtime and the related prolonged exposure of workmen to health hazards can be evaluated.

Control Measures in Use

The preliminary survey would not be complete unless the types of control measures in use and their effectiveness are noted. Control measures include local exhaust and general ventilation, protective respiratory devices, protective clothing, and shielding from radiant heat, ultraviolet light, or other forms of radiant energy. General guides to effectiveness include the presence or absence of dust on floors and ledges; holes in ductwork, fans not operating or rotating in the wrong direction (the latter has been found to occur in many plants and it should be noted that, even though a blower is operated backward, it will still exhaust some air, but not the required amount); or the manner in which personal protective devices are treated by workmen. During the preliminary survey it may be desirable to conduct a check on local exhaust ventilation systems in use to determine if sufficient airflow is provided to remove the contaminants from the workers' breathing zone. The manual, *Industrial Ventilation*,⁴ will serve as a useful guide for this purpose since it describes test procedures and contains examples of many types of systems with the recommended airflows.

Adequate notes must be made during an evaluation of the environment. The speed and accuracy of preparing a report of an investigation will depend largely on information recorded in the form of notes.

SELECTION OF INSTRUMENTS TO EVALUATE THE WORK ENVIRONMENT

Sampling instruments used to evaluate the environment for occupational health hazards are generally classified according to type as follows: (1) direct reading; (2) those which remove the contaminant from a measured quantity of air; and (3) those which collect a known volume of air for subsequent laboratory analysis.

Most of the equipment used by industrial hygienists is found under the first two types. The third group includes various types of evacuated flasks, plastic bags, or other suitable containers for collecting known volumes of contaminated air to be returned to the laboratory for analysis.

The choice of a particular sampling instrument depends upon a number of factors. Among these are: (1) portability and ease of use; (2) efficiency of the equipment or device; (3) reliability of the equipment under various conditions of field use; (4) type of analysis or information required; (5) availability; and (6) personal choice based on past experience and other factors.

No single, universal sampling instrument is available and it is doubtful if such an instrument will ever be developed. In fact, the present trend

is the development of a greater number of specialized instruments such as the direct reading gas and vapor detectors.

In evaluating a worker's exposure or the environment in which he works, an instrument must be used that will provide the necessary sensitivity, accuracy, reproducibility, and, preferably, rapid results. Detailed discussions of instruments used for sampling for particulates are given in Chapter 13, for gases and vapors in Chapter 15, and for direct reading instruments for aerosols, gases and vapors in Chapter 16, as well as in "Air Sampling Instruments for Evaluation of Atmospheric Contaminants" published by the American Conference of Governmental Industrial Hygienists.³ Instruments for assessing noise exposure and for other physical agents are discussed in subsequent chapters of this manual. One of the older, but still valid, discussions on this subject is "Sampling and Analyzing Air for Contaminants" by Silverman.⁴ Those whose responsibilities include the collection and analysis of samples will find this publication a worthwhile reference.

The use of continuous monitoring devices to evaluate the working environment has increased tremendously in recent years. While these devices are normally not designed for field use, many are available in sizes that are convenient for this purpose. In general, however, many industries install these devices in areas where exposures to certain gases or vapors may vary considerably. Examples include the use of continuous monitors for carbon monoxide in tunnels or plant areas where this gas is produced or used, monitors for chlorinated hydrocarbons such as in the production of carbon tetrachloride or trichloroethylene, and monitors for certain alcohols. Many of these continuous detecting and recording instruments can be equipped to sample at several remote locations in a plant and record the general air concentrations to which workers may be exposed during a shift. Many large plants have added computerized equipment to the recorders so that the data may be readily available and summarized for instant review. However, as is the case with other instruments, continuous monitors must be calibrated periodically and the interferences known.

After selecting the instrument, the industrial hygienist, compliance officer, or other person collecting samples must become familiar with the device and its limitations. He must know, for example, whether or not the particular instrument is specific for the contaminant to be determined, what other substances interfere with the test, and the accuracy and sensitivity of the device. He must also be familiar with the response time, which is the time interval from the instant samples are taken to the time the instrument shows a reading or the chemical reaction takes place in a detector tube. Furthermore, in the case of detector tubes, the readings must be made under good lighting conditions, preferably in daylight.^{7-8,9,10-11}

CALIBRATION OF INSTRUMENTS

Instruments and techniques used in calibrating sampling equipment are discussed in detail in Chapter 11. This brief discussion is included to

stress the necessity for following recommended procedures in order that the data resulting from the analysis of field samples (whether by direct reading devices in the field or by equipment that collects samples for subsequent laboratory analysis) will truly represent concentrations in the environment, and particularly concentrations to which the worker is exposed.

Since the amount of sample, whether collected by means of a filter, an impinger, or a bubbler or indicated by a direct reading instrument, depends upon the volume of air sampled and its duration, it is essential that the device operate at a known rate of airflow. Thus, the equipment must be calibrated against a standard airflow measuring device both before and after use in the field. The exact rate of airflow must be recorded so that when it is multiplied by the sampling time, the total volume of air sampled or collected will be known. This volume of air is used in calculating the concentration of contaminant to which the worker was exposed. Furthermore, direct reading instruments and detector tubes must be calibrated against a known concentration of the substance for which they are used. Results obtained during a survey or study are no more accurate than the instruments used to obtain the data. In some situations the investigator must do his own calibrating, but more frequently this is done by others at a central laboratory.

ESTABLISHING PROPER ANALYTICAL METHODS

The use of accurate, sensitive, and reproducible analytical methods is equally as important as the proper calibration of the sampling equipment. In evaluating the occupational environment the concentration of contaminant in the ambient air is generally small. In fact, the direct reading instruments and other devices used to collect samples for subsequent analysis are required to detect quantities of substances in the microgram or part-per-million range. Thus, a sufficient quantity of sample must be collected to enable the analyst to determine accurately this small amount of substance.

When available, standard methods of analysis should always be used. Unfortunately, only a few such methods have been tested under various situations and conditions. In the field of industrial hygiene the A.C.G.I.H. has available a "Manual of Analytical Methods" that contains about 20 methods.¹² Many of the nearly 200 A.I.H.A. Hygienic Guides¹ contain recommended methods of analysis. This same organization also publishes Analytical Guides, which to date cover 61 methods of analysis. The American Public Health Association as prime contractor with the National Air Pollution Control Administration, and through the Intersociety Committee, has been developing methods for air sampling and analysis; the first 60 of these have been published as a manual entitled "Methods of Air Sampling and Analysis," American Public Health Association, 1015 Eighteenth Street, NW Washington, D.C., 1972.¹³ While these methods were developed primarily for the field of air pollution, most of them can be used

for sampling and analysis of environmental conditions in plants.

The American Society for Testing and Materials¹⁴ initiated Project Threshold in March, 1971 to validate test methods in the field of air pollution. Many of these methods can be used also for sampling and analyzing contaminants in the workplace. Several methods have been developed and tested, the latest of which is a tentative fluorescent method for beryllium.

The reason for this lack of tested standard methods is the tremendous amount of time and personnel required to perform the necessary testing. There are nearly 500 substances included in the latest TLV list (A.C.G.I.H.) but there are perhaps less than 100 standardized methods available to determine compliance or non-compliance with the U.S. Department of Labor's regulations under the Occupational Safety and Health Act of 1970. This does not mean that methods other than the standard methods cannot be used. However, these other methods must also be tested and calibrated against known concentrations of the substance in question. Many analytical methods have been published in the literature and the methods should be evaluated in the laboratory prior to performing an analysis.

MAKING THE FIELD SURVEY

The nature of the substance or condition to which workers may be potentially exposed will usually have been determined during the preliminary survey. The problem, then, is to determine the intensity of exposure and to do this one must collect samples of the air or use direct reading instruments. Every effort must be made to obtain samples that represent the worker's exposure. To decide what constitutes a representative sample, the investigator must answer these five basic questions: (1) where to sample; (2) whom to sample; (3) how long to sample (sampling duration); (4) how many samples to take; and (5) when to sample — day or night, what month or season.

Where to Sample

Where the purposes of the sampling are to evaluate a worker's exposure and to determine his daily, time-weighted average exposure, it is necessary to collect samples at or as near as practical to his breathing zone and also in the area adjacent to his normal work station, or general room air. Sometimes it is necessary to sample at the operation itself because of the difficulties of placing a sampling device at his breathing zone or attaching it to his person. On the other hand, if the purpose of sampling is to define a potential hazard, to check compliance with regulations, or to obtain data for control purposes, samples representative of the worker's exposure must be collected. In some cases it is necessary to sample the general room air also to define certain exposures.

Whom to Sample

Personnel exposure is best determined by monitoring the different job tasks in a suspect area. Personnel monitors properly attached to workers directly exposed should give a representative sample to actual breathing zone exposure. Actual ex-

posure sources can be documented with the proper number of personnel samples *combined* with the results from stationary sampling points. Job descriptions for area personnel and the time spent at each task are of primary importance in determining potential exposure.

How Long to Sample

The volume of air sampled and duration of sampling is based upon the sensitivity of the analytical procedure or direct reading instrument; the estimated air concentration; and the Standard or TLV of the particular contaminant. Thus, the volume of air sampled may vary from a few liters, where the estimated concentration is high, to several cubic meters where low concentrations are expected. Knowing the sensitivity of the method, the TLV, and the sampling rate of the particular instrument in use, the minimum sampling time can be determined. The above applies to devices that collect a known volume of air for later analysis. The duration of sampling should represent some identifiable period of time — usually a complete cycle of an operation — to determine an operator's exposure. Another technique is to sample on a regular schedule, for example, so many minutes of each hour. This procedure usually requires more samples than cyclic-type sampling but, when used in conjunction with the cyclic-type sampling, gives more confidence in the results and recommendations.

Evaluation of worker's daily time-weighted average exposures is usually best accomplished when analytical methods will permit, by allowing the worker to work his full 7- or 8-hour shift with a personal breathing zone sampler attached to his person. Techniques have been developed in recent years that allow full shift sampling for many dusts, fumes, gases and vapors. These techniques, which include the use of filters and miniature cyclones to sample airborne dusts and activated charcoal to sample many gases and vapors have been developed successfully in recent years for many airborne contaminants. The concept of full shift integrated personal sampling is much preferred to that of short term or general area sampling if the results are to be compared to standards based on time-weighted average concentrations. When methods that permit full shift integrated sampling are not applicable, time-weighted average exposures can be calculated from alternative short term or general area sampling methods by applying the general formula explained in Chapter 3.

The first step in calculating a worker's or group of workers' daily, time-weighted exposure is to again study the job descriptions obtained for the persons under consideration and ascertain how much time out of each day they spend at various tasks. Such information is usually available from the plant personnel office or foreman on the job. In many situations the investigator must make time studies himself to obtain the correct information. Even though this information was obtained from plant personnel, it should be checked by the investigator because in many situations what the investigator observes and the times given by plant personnel do not agree. From this information and the results of the environmental survey, a

daily, time-weighted average 8-hour exposure can be calculated. This assumes that a sufficient number of samples have been collected or readings obtained with direct reading instruments under various plant operating conditions to give a true picture of the exposure.

Where sampling for the purpose of comparing results with airborne contaminants whose toxicological properties warrant short term and ceiling limit values, it is necessary to use short term or grab sampling techniques to define peak concentrations and estimate peak excursion durations. For purposes of further comparison, the time-weighted average 8-hour exposure can be calculated using the values obtained by short term sampling.

How Many Samples to Take

There is no set rule to determine the number of replicate samples that are necessary to evaluate a worker's exposure, provided that a minimum number are taken to characterize the exposure in time and space. A single sample will never suffice even if the investigator believes that this concentration would be maintained throughout the work shift. If the indicated concentration is near or above the TLV or Standard, repeated sampling should be done. Ordinarily, contaminants are not generated at a constant rate, and the concentration can vary considerably from time to time.

Only rarely does an operation release contaminants into the workroom air at a fairly constant rate. Chapters 13 and 15 describe sampling procedures for particulates, gases, and vapors, including information on the number of samples needed. The concentration found in single sample may have been too high or too low due to a number of factors and if the sample had been collected at another time, the results could very well be considerably different. Several dozen samples may be necessary to define accurately a daily, time-weighted average exposure for a worker who performs a number of tasks during the shift.

When to Sample

Another area to be considered in sampling is *when* to sample — a determination of the work shift or seasonal period during which samples should be collected. If, for example, an operator continues working for more than one shift, samples should be collected during each shift that he works. It has been found that in many situations airborne concentrations of toxic substances or exposure to physical agents may be different for each shift. Furthermore, and this applies to plants located in areas where large temperature differences occur during different seasons of the year, samples should be collected during summer and winter months. Normally, there is more general ventilation during the summer months than in winter, a factor which tends to dilute the concentration of the contaminant.

INTERPRETATION OF FINDINGS

Interpretation of the analyses of samples collected or from direct reading instruments is the final step in evaluating the environment. A great deal of common sense and judgment must be used in interpreting the results of an environmental

study. Before an investigator determines that a worker or group of workers is exposed to a hazard injurious to health, he must have the following facts: (1) nature of substance or physical agent involved; (2) intensity (concentration) of exposure; and (3) duration of exposures, which will have been determined from the preliminary survey and the results of air sampling done during the environmental study. In many cases, adverse effects from exposure to toxic materials or physical agents do not appear until the exposure has occurred for several years. The purpose of TLVs or Standards is to protect against the future appearance of such symptoms.

Comparison of Results with Standards

Results of the environmental study must be compared with standards before an employer can be cited for a violation or control measures can be recommended. It must be emphasized again that the samples collected during the study must be representative of the worker's daily, time-weighted average exposure, if there is a standard for such exposure, before a comparison can be made.

In connection with the enforcement of the Occupational Safety and Health Act, the standards for exposure to gases, vapors, dust, ionizing and non-ionizing radiation are contained in the Code of Federal Regulations (CFR), Title 29, Part 1910, Occupational and Environmental Health Standards. These were first published in the Federal Register, Vol. 26, No. 105, May 29, 1971 and are subject to revision. At this writing, most of these standards are the same as the A.C.G.I.H. 1970 TLVs, but about 20 are the latest A.N.S.I. Z-37 Standards. In 1971, for the first time A.C.G.I.H. published a combined list of Threshold Limit Values for airborne contaminants and physical agents.¹⁵ Included in the latter are guidelines (TLVs) for noise, lasers, microwaves, ultraviolet radiation, and heat stress. Basic Radiation Protection Criteria¹⁶ should be consulted for standards on ionizing radiation. Other guidelines in this area include the A.I.H.A. Hygienic Guides¹ A.N.S.I. Standards,² and the A.S.H.R.A.E. Guide¹⁷ for temperature and humidity.

Many states have adopted standards in the above area, some of which are more stringent than those referred to above. Since a state may qualify to administer and enforce a State Occupational Safety and Health Program under provisions of the Federal Act, the standards in effect in a particular state must be consulted by the investigator. Federal standards adopted to date (1972) are minimum legal requirements and they will no doubt be modified from time to time as new data become available. State standards must be "at least as effective" as Federal standards. When state standards are applicable to products distributed or used in interstate commerce, they must be such as are required by compelling local conditions and do not unduly burden interstate commerce.

Comparison of Results with Previous Data

As indicated earlier in this discussion, many of the larger industrial establishments utilize continuous monitors to maintain a record of concen-

trations of various gases and vapors in certain areas of their plants. These data must be related to worker exposure. Other companies that employ industrial hygienists ordinarily have data on exposures of workmen to various toxic substances as well as certain physical agents. If at all possible, the investigator should make every effort to study these data and compare them with the results of his study. In many cases the data may not be the same and there may be good reasons for the discrepancy. In many instances the data on exposures will be more complete and detailed when taken from company records than when obtained by an investigator from a one- or two-day investigation of certain hazardous operations in that plant. Thus, considerable embarrassment can be avoided if the above suggestion to check other recorded data is followed.

In addition to data available from company records, other sources of such information include the results of previous studies conducted by Federal, state and local agencies, some insurance companies, and consultants. Here again, results of these studies may be different than those obtained by the investigator so great care must be exercised in making comparisons.

SUMMARY

The conduct of environmental surveys and studies is only one phase in the over-all effort in determining occupational health hazards. Such surveys are valuable only if all environmental factors relating to the workers' potential exposures are included. In evaluating workers' exposures to toxic dusts, fumes, gases, vapors, mists, and physical agents, a sufficient number of samples must be collected, or readings made with direct reading instruments, for the proper duration to permit the assessment of daily, time-weighted average exposures and evaluate peak exposure concentrations when needed.

It is essential that the proper instrument be selected for the particular hazard under study and that it be calibrated periodically to insure that it is sampling at the correct rate of airflow and, in the case of direct reading instruments, that they have been calibrated against known concentrations of the contaminant in question. For those samples to be analyzed in the laboratory, a method must be used that is accurate, sensitive, specific, and reproducible for that particular contaminant.

Adequate notes taken during environmental studies are a necessity. An investigator or inspector cannot rely upon his memory after a study is completed to provide the detailed information necessary for the preparation of a report.

Finally, sound judgment should be exercised both during the actual survey and while preparing the report.

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CHAPTER 11
**INSTRUMENTS AND TECHNIQUES USED IN
CALIBRATING SAMPLING EQUIPMENT**

Morton Lippmann, Ph.D.

INTRODUCTION

**Importance of Accurate Calibrations and
Periodic Recalibration**

Air samples are collected in order to determine the concentrations of one or more airborne contaminants. To define a concentration, the quantity of the contaminant of interest per unit volume of air must be determined. In some cases, the contaminant is not extracted from the air; i.e., it may simply alter the response of a defined physical system. An example is the mercury vapor detector, wherein mercury atoms absorb the characteristic ultra-violet radiation from a mercury lamp, reducing the intensity incident on a photocell. In this case, the response is proportional to the mercury concentration and not to the mass flowrate through the sensing zone; hence, it measures concentration directly.

In most cases, however, the contaminant is either recovered from the sampled air for subsequent analysis or is altered by its passage through a sensor within the sampling train, and the sampling flowrate must be known in order to ultimately determine airborne concentrations. When the contaminant is collected for subsequent analysis, the collection efficiency must also be known, and ideally should be constant. The measurements of sample mass, of collection efficiency and of sample volume are usually done independently. Each measurement has its own associated errors, and each contributes to the overall uncertainty in the reported concentration.

The sample volume measurement error will often be greater than that of the sample mass measurement. The usual reason is that the volume measurement is made in the field with devices designed more for portability and light weight than for precision and accuracy. Flowrate measurement errors can further affect the determination if the collection efficiency is dependent on the flowrate.

Each element of the sampling system should be calibrated accurately prior to initial field use. Protocols should also be established for periodic recalibration, since the performance of many transducers and meters will change with the accumulation of dirt, corrosion, leaks, and misalignment due to vibration or shocks in handling, etc. The frequency of such recalibration checks should initially be high, until experience is accumulated to show that it can be reduced safely.

Types of Calibrations

Flow and Volume. If the contaminant of interest is removed quantitatively by a sample collector at

all flowrates, then the sampled volume may be the only air flow parameter that need be recorded. On the other hand, when the detector response is dependent on both the flowrate and sample mass, as in many length-of-stain detector tubes, then both quantities must be determined and controlled. Finally, in many direct-reading instruments, the response is dependent on flowrate but not on integrated volume.

In most sampling situations the flowrates are, or are assumed to be, constant. When this is so, and the sampling interval is known, it is possible to convert flowrates to integrated volumes, and vice-versa. For this reason flowrate meters, which are usually smaller, more portable and less expensive than integrated volume meters, are generally used on sampling equipment even when the sample volume is the parameter of primary interest. Normally, little additional error is introduced in converting a constant flowrate into an integrated volume since the measurement and recording of elapsed time generally can be performed with good accuracy and precision.

Flowmeters can be divided into three basic groups on the basis of the type of measurement made; these are integrated-volume meters, flowrate meters, and velocity meters. The principles of operation and features of specific instrument types in each group will be discussed in succeeding pages. The response of volume meters, such as the spirometer and wet-test meter, and flowrate meters, such as the rotameter and orifice meter, are determined by the entire sampler flow. In this respect they differ from velocity meters such as the thermoanemometer and Pitot tube, which measure the velocity at a particular point of the flow cross section. Since the flow profile is rarely uniform across the channel, the measured velocity will invariably differ from the average velocity. Furthermore, since the shape of the flow profile usually changes with changes in flowrate, the ratio of point-to-average velocity will also change. Thus, when a point velocity is used as an index of flowrate, there is an additional potential source of error, which should be evaluated in laboratory calibrations which simulate the conditions of use. Despite their disadvantages, velocity sensors are sometimes the best indicators available, as for example in some electrostatic precipitators where the flow resistance of other types of meters cannot be tolerated.

Calibration of Collection Efficiency. A sample collector need not be 100% efficient in order to be useful, provided that its efficiency is known

and constant, and taken into account in the calculation of concentration. In practice, acceptance of a low but known collection efficiency is a reasonable procedure for most types of gas and vapor sampling, but is seldom, if ever, appropriate for aerosol sampling. All of the molecules of a given chemical contaminant in the vapor phase are essentially the same size, and if the temperature, flowrate, and other critical parameters are kept constant, they will have the same probability of capture. Aerosols, on the other hand, are rarely monodisperse. Since most particle-capture mechanisms are size-dependent, the collection characteristics of a given sampler are likely to vary with particle size. Furthermore, the efficiency will tend to change with time due to loading; e.g., a filter's efficiency increases as dust collects on it, and electrostatic precipitator efficiency may drop if a resistive layer accumulates on the collecting electrode. Thus, aerosol samplers should not be used unless their collection is essentially complete for all particle sizes of interest.

Determination of Sample Stability and Recovery. The collection efficiency of a sampler can be defined by the fraction removed from the air passing through it. However, the material collected cannot always be completely recovered from the sampling substrate for analysis. In addition, the material can sometimes be degraded or otherwise lost between the time of collection in the field and recovery in the laboratory. Deterioration of the sample is particularly severe for chemically reactive materials. Sample losses may also be due to high vapor pressures in the sampled material, exposure to elevated temperatures, or to reactions between the sample and substrate or between different components in the sample.

Laboratory calibrations using blank and spiked samples should be performed whenever possible

to determine the conditions under which such losses are likely to affect the determinations desired. When the losses are likely to be excessive, the sampling equipment or procedures should be modified as much as feasible to minimize the losses and the need for calibration corrections.

Calibration of Sensor Response. When calibrating direct-reading instruments, the objective is to determine the relationship between the scale readings and the actual concentration of contaminant present. In such tests the basic response for the contaminant of interest is obtained by operating the instrument in known concentrations of the pure material over an appropriate range of concentrations. In many cases it is also necessary to determine the effect of environmental co-factors such as temperature, pressure and humidity on the instrument response. Also, many sensors are non-specific and atmospheric co-contaminants may either elevate or depress the signal produced by the contaminant of interest. If reliable data on the effect of such interferences are not available, they should be obtained in calibration tests. Procedures for establishing known concentrations for such calibration tests are discussed in detail in Chapter 12.

Sampling and Calibration Standards and Errors Use and Reliability of Standards and Standard Procedures. Calibration procedures generally involve a comparison of instrument response to a standardized atmosphere or to the response of a reference instrument. Hence, the calibration can be no better than the standards used. Reliability and proper use of standards are critical to accurate calibrations. Reference materials and instruments available from, or calibrated by, the National Bureau of Standards (NBS) should be used whenever possible. Information on calibration aids available from NBS is summarized in Table 11-1.

TABLE 11-1
NATIONAL BUREAU OF STANDARDS (NBS) — STANDARD REFERENCE MATERIALS (SRM's)* INTENDED FOR USE AS PRIMARY INSTRUMENT CALIBRATION STANDARDS BY AIR POLLUTION LABORATORIES

SRM No.	Description
1625	SO ₂ Permeation Tube, Individually Calibrated, Effective length \cong 10 cm, Permeation Rate \cong 0.28 ug SO ₂ /min. @ 25°C.
1626	Same as above, except that effective length \cong 5 cm.
1627	Same as above, except that effective length \cong 2 cm.
1610	Hydrocarbon in Air compressed gas mixture, 68 standard liters @ 500 psi in disposable cylinder. Concentration = 0.103 ± 0.001 mole percent, calculated as methane, as determined by flame ionization.
1611	Same as above, except that concentration = 0.0107 ± 0.0001 mole %.
1612	Same as above, except that concentration = 0.00117 ± 0.00001 mole %.
1613	Same as above, except that concentration = 0.000102 ± 0.000002 mole %.
1601	Carbon Dioxide in Nitrogen compressed gas mixture, 68 standard liters @ 500 psi in disposable cylinder. Concentration = 0.0308 ± 0.0003 mole %.
1602	Same as above, except that concentration = 0.0346 ± 0.0003 mole %.
1603	Same as above, except that concentration = 0.0384 ± 0.0004 mole %.

* Available from the Office of Standard Reference Materials, Room B 314, Chemistry Bldg., National Bureau of Standards, Washington, D. C. 20234.

Test atmospheres generated for the purpose of calibrating collection efficiency or instrument response should be checked for concentration using reference instruments or sampling and analytical procedures whose reliability and accuracy are well documented. The best procedures to use

are those which have been referee or panel tested; i.e., methods which have been shown to yield comparable results on blind samples analyzed by different laboratories. Such procedures are published by several organizations, which are listed in Table 11-2. Those published by the individual

TABLE 11-2
ORGANIZATIONS PUBLISHING RECOMMENDED OR STANDARD METHODS AND/OR TEST PROCEDURES APPLICABLE TO AIR SAMPLING INSTRUMENT CALIBRATION

Abbreviation	Full Name	Mailing Address
APCA	Air Pollution Control Association	4400 Fifth Avenue Pittsburgh, Pa. 15213
ACGIH	American Conference of Governmental Industrial Hygienists	P.O. Box 1937 Cincinnati, Ohio 45201
AIHA	American Industrial Hygiene Association	66 South Miller Rd. Akron, Ohio 44313
ANSI	American National Standards Institute, Inc.	1430 Broadway New York, N. Y. 10018
ASTM	American Society for Testing and Materials, D-22 Committee on Sampling and Analysis of Atmospheres	1016 Race Street Philadelphia, Pa. 19103
EPA	Environmental Protection Agency Office of Air Programs	5600 Fischer's Lane Rockville, Md. 20852
ISC	Intersociety Committee on Methods for Air Sampling and Analysis	250 W. 57th Street New York, N. Y. 10019

TABLE 11-3
SUMMARY OF RECOMMENDED AND STANDARD METHODS RELATING TO AIR SAMPLING INSTRUMENT CALIBRATION

Organization	No. of Methods	Types of Methods	Panel Tested	Reference
ACGIH	19	Analytic methods for air contaminants	Yes	Manual of Analytic Methods ⁽¹³⁾
AIHA	117	Analytic methods for air contaminants	No	Analytic Guides ⁽¹⁴⁾
ISC	46	Analytic methods for air contaminants	†	Health Laboratory Science 6(2) (Apr. 1969) 7(1) (Jan. 1970) 7(2) (July 1970) 7(4) (Oct. 1970) 8(1) (Jan. 1971)
ASTM	20	Analytic methods for air contaminants	*	Part 23, Annual Book of
ASTM	5	Recommended practices for sampling procedures, nomenclature, etc.	NA	ASTM Standards ⁽¹⁵⁾
APCA	3	Recommended standard methods for continuing air monitoring for fine particulate matter	NA	J. Air Pollut. Cont. Assoc. 13:55 (Sept. 1963)
ANSI	1	Sampling airborne radioactive materials	NA	ANSI N 13.1-1969
EPA	6	Reference methods for air contaminants	No	Fed. Register 36(84) (April 30, 1971)

† All methods will be panel tested before advancing from tentative to standard.

* Seven methods are undergoing panel validation under Phase 1-ASTM Project Threshold. Additional methods will be panel evaluated in subsequent phases.

NA Not applicable.

organizations have been supplemented in recent years by those approved by the Intersociety Committee on Methods for Air Sampling and Analysis, a cooperative group formed in March, 1963, composed of representatives of the Air Pollution Control Association (APCA), the American Conference of Governmental Industrial Hygienists (ACGIH), the American Industrial Hygiene Association (AIHA), the American Public Health Association (APHA), the American Society for Testing and Materials (ASTM), the American Society of Mechanical Engineers (ASME), and the Association of Official Analytical Chemists (AOAC). "Tentative" methods endorsed by the Intersociety Committee have been published at random intervals since April, 1969, in "Health Laboratory Science," a publication of APHA. These "Tentative" methods become "Standard" methods only after satisfactory completion of a cooperative test program. Lists of published "Tentative" and "Standard" methods for air sampling and analysis are summarized in Table 11-3.

Sources of Sampling and Analytical Errors. The difference between the air concentration reported for an air contaminant on the basis of a meter reading or laboratory analysis, and true concentration at that time and place represents the error of the measurement. The overall error is often due to a number of smaller component errors rather than to a single cause. In order to minimize the overall error it is usually necessary to analyze each of its potential components, and concentrate one's efforts on reducing the component error which is largest. It would not be productive to reduce the uncertainty in the analytical procedure from 10% to 1.0% when the error associated with the sample volume measurement is $\pm 15\%$.

Sampling problems are so varied in practice that it is only possible to generalize on the likely sources of error to be encountered in typical sampling situations. In analyzing a particular sampling problem, consideration should be given to each of the following:

- a) Flowrate and sample volume
- b) Collection efficiency
- c) Sample stability under conditions anticipated for sampling, storage and transport
- d) Efficiency of recovery from sampling substrate
- e) Analytical background and interferences introduced by sampling substrate
- f) Effect of atmospheric co-contaminants on samples during collection, storage and analyses.

Cumulative Statistical Error. The most probable value of the cumulative error E_c can be calculated from the following equation:

$$E_c = [E_1^2 + E_2^2 + E_3^2 + \dots + E_n^2]^{1/2}$$

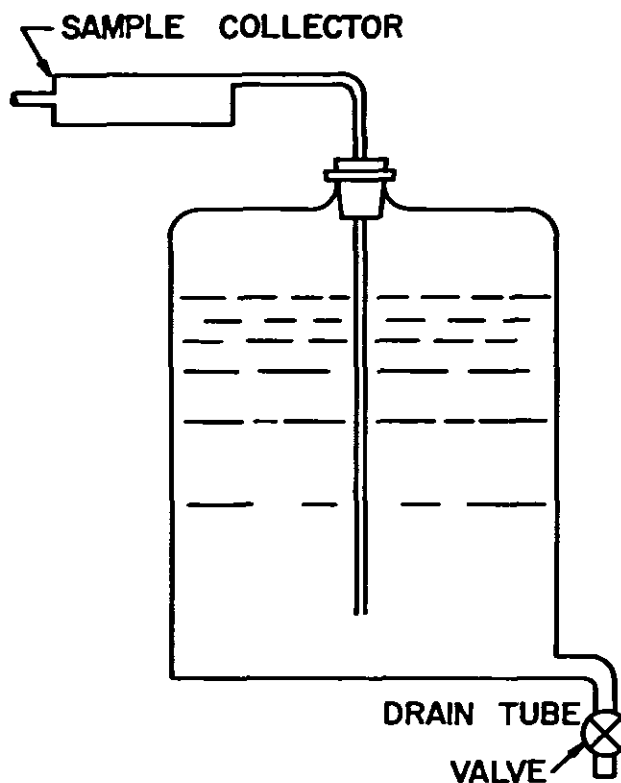
For example, if accuracies of the flowrate measurement, sampling time, recovery, and analysis are ± 15 , 2, 10, and 10% respectively, and there are no other significant sources of error, then the cumulative error would be:

$$E_c = [15^2 + 2^2 + 10^2 + 10^2] = [429]^{1/2} = \pm 20.6\%$$

It should be remembered that this provides an estimate of the deviation of the measured concentration from the true concentration at the time and place the sample was collected. As an estimate of the average concentration to which a workman was exposed in performing a given operation, it would have additional uncertainty, dependent upon the variability of concentration with time and space at the work station.

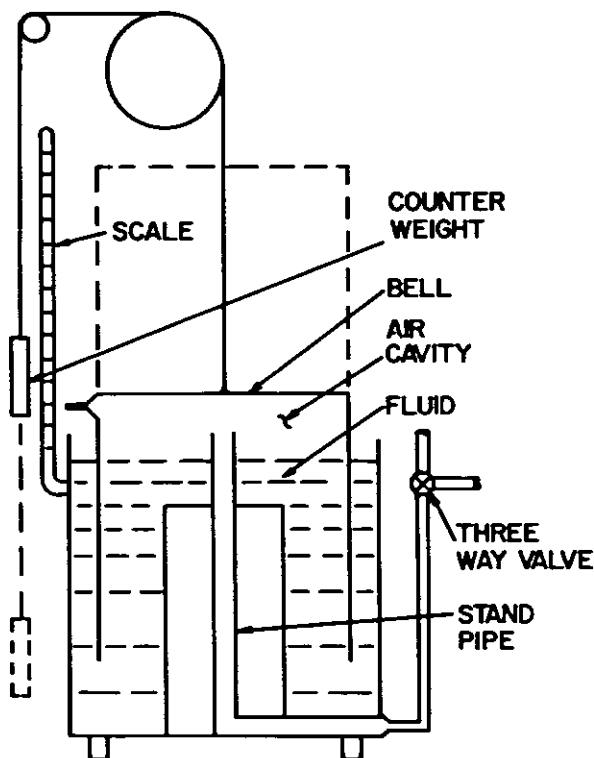
CALIBRATION INSTRUMENTS AND TECHNIQUES FOR FLOW AND VOLUME CALIBRATION

In this section, the various techniques used for measuring sampling rate or sampled volume in samplers and in laboratory calibrations of samplers will be discussed in terms of their principles of operation and their sources of error. Some may be considered primary measurements, while some are secondary or derived. Primary measurements generally involve a direct measurement of volume on the basis of the physical dimensions of an enclosed space. Secondary standards are reference instruments or meters which trace their calibrations to primary standards, and which have been shown to be capable of maintaining their accuracy with reasonable handling and care in operation.



Powell CH, Hosey AD (eds): The Industrial Environment — Its Evaluation and Control, 2nd Edition. Public Health Service Publication No. 614, 1965.

Figure 11-1. Mariotti Bottle



Powell CH, Hosey AD (eds): The Industrial Environment — Its Evaluation and Control, 2nd Edition. Public Health Service Publication No. 614, 1965.

Figure 11-2. Schematic Drawing of a Spirometer

Instruments which Measure or Are Calibrated in Volume Units

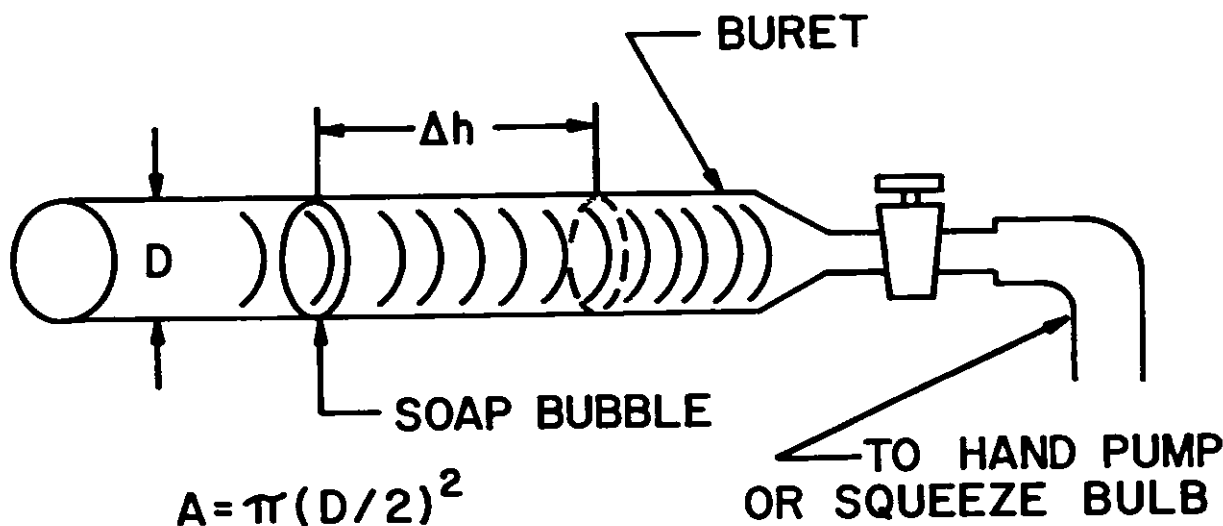
Water Displacement. Figure 11-1 shows a sche-

matic drawing of a Mariotti bottle. When the valve at the bottom of the bottle is opened, water drains out of the bottle by gravity, and air is drawn via a sample collector into the bottle to replace it. The volume of air drawn in is equal to the change in water level multiplied by the cross section at the water surface. The Casella Standard Thermal Precipitation uses a water-filled aspirator with an orifice at the discharge end of the cylinder which limits the flowrate to 7 cm³/min.¹

Spirometer or Gasometer. The spirometer (Figure 11-2) is a cylindrical bell with its open end under a liquid seal. The weight of the bell is counterbalanced so that the resistance to movement as air moves in or out of the bell is negligible. It differs from the Mariotti bottle in that it measures displaced air instead of displaced liquid. The volume change is calculated in a similar manner, i.e., change in height times cross section. Spirometers are available in a wide variety of sizes¹ and are frequently used as primary volume standards.

"Frictionless" Piston Meters. Cylindrical air displacement meters with nearly frictionless pistons are frequently used for primary flow calibrations. The simplest version is the soap-bubble meter illustrated in Figure 11-3. It utilizes a volumetric laboratory buret whose interior surfaces are wetted with a detergent solution. If a soap-film bubble is placed at the left side, and suction is applied at the right, the bubble will be drawn from left to right. The volume displacement per unit time (i.e., flowrate) can be determined by measuring the time required for the bubble to pass between two scale markings which enclose a known volume.

Soap-film flowmeters and mercury-sealed piston flowmeters are available commercially from several sources.⁽¹⁾ In the mercury-sealed piston, most of the cylindrical cross section is blocked off

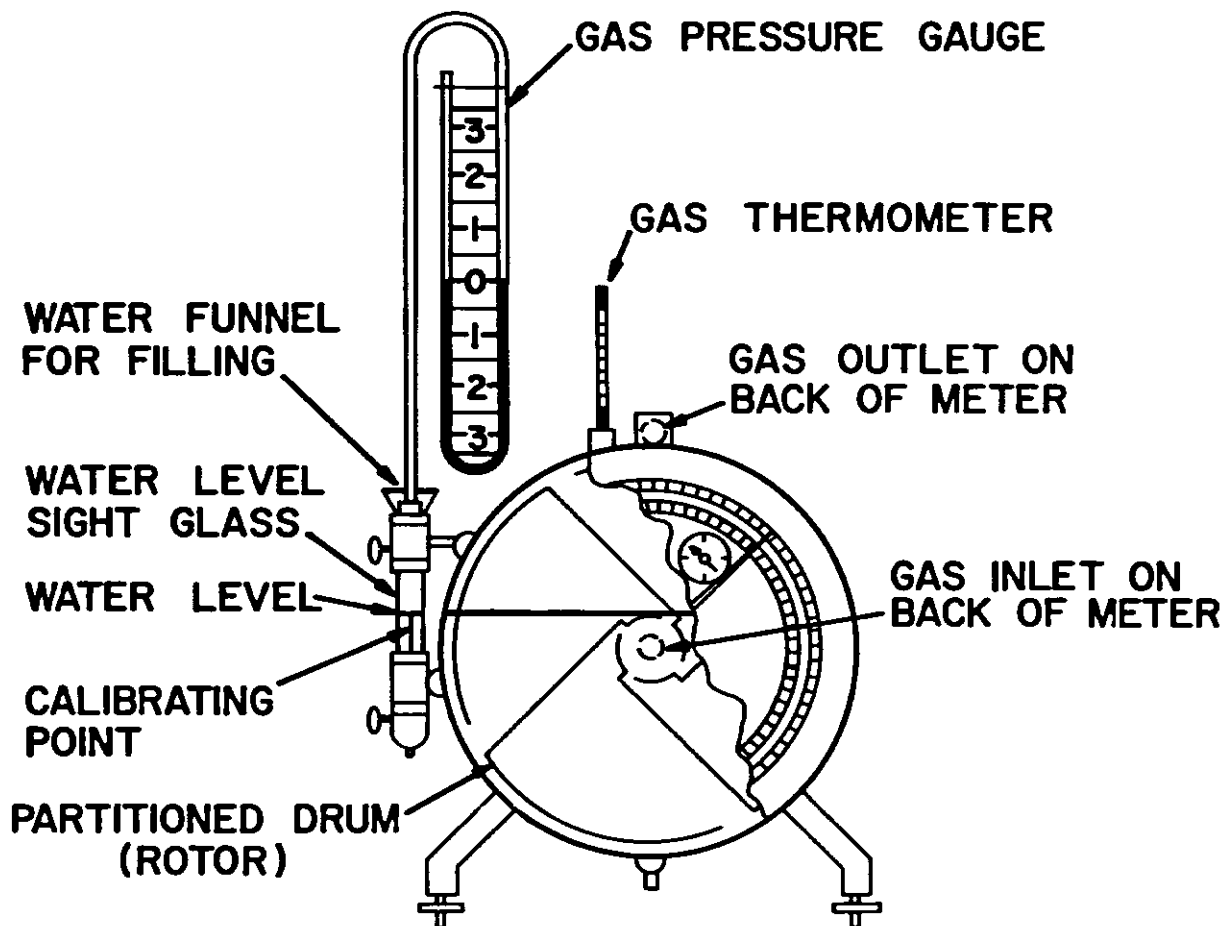


Powell CH, Hosey AD (eds): The Industrial Environment — Its Evaluation and Control, 2nd Edition. Public Health Service Publication No. 614, 1965.

Figure 11-3. Bubble Meter

by a plate which is perpendicular to the axis of the cylinder. The plate is separated from the cylinder wall by an O-ring of liquid mercury which

retains its toroidal shape due to its strong surface tension. This floating seal has a negligible friction loss as the plate moves up and down.



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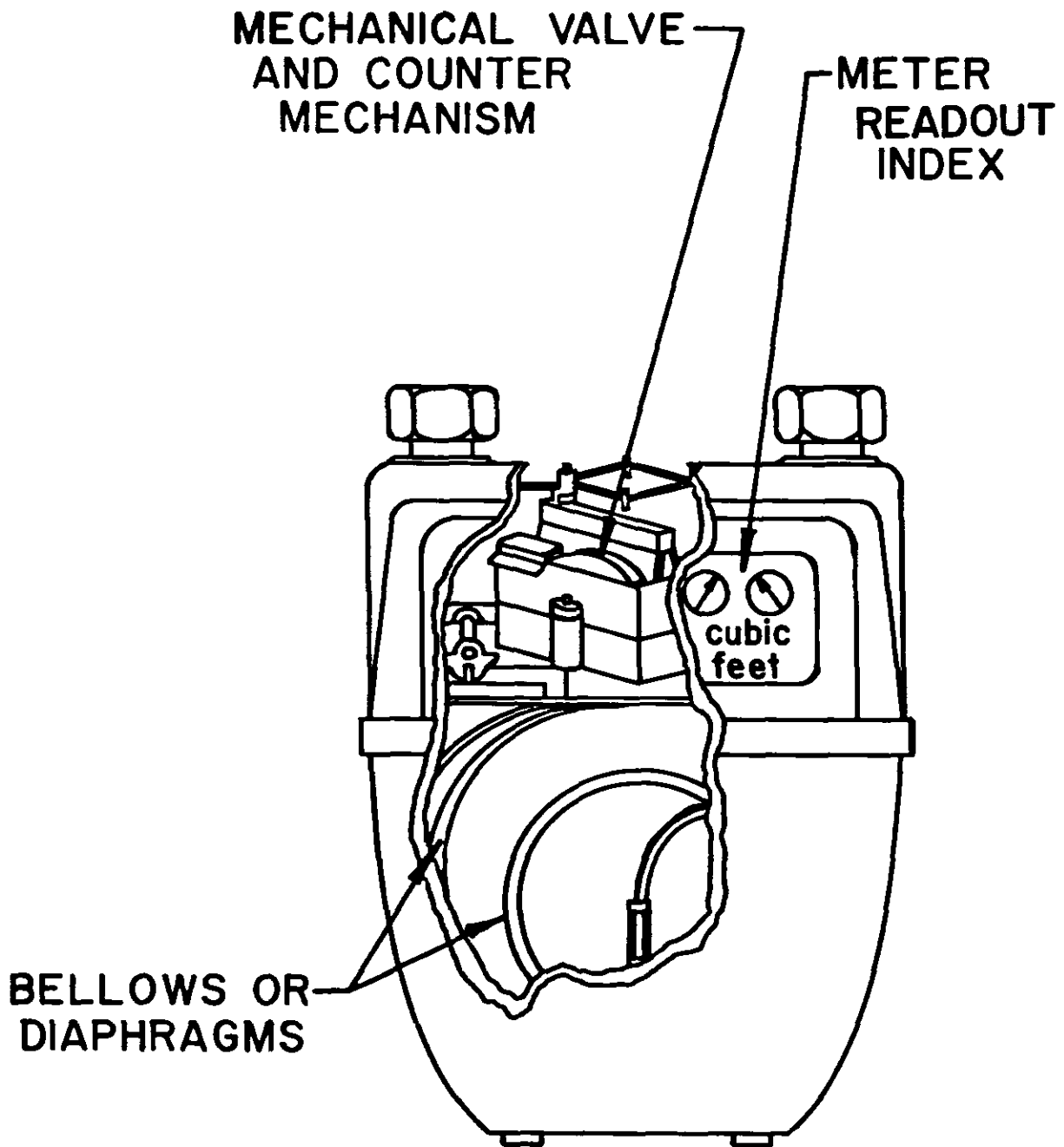
Figure 11-4. Wet Test Meter

Wet-Test Meter. A wet-test meter (See Figure 11-4) consists of a partitioned drum half submerged in a liquid (usually water) with openings at the center and periphery of each radial chamber. Air or gas enters at the center and flows into an individual compartment causing it to rise, thereby producing rotation. This rotation is indicated by a dial on the face of the instrument. The volume measured will be dependent on the fluid level in the meter since the liquid is displaced by air. A sight gauge for determining fluid height is provided and the meter may be leveled by screws and a sight bubble which are provided for this purpose.

There are several potential errors associated with the use of a wet-test meter. The drum and moving parts are subject to corrosion and damage from misuse, there is friction in the bearings and the mechanical counter, inertia must be overcome at low flows (<1 RPM), while at high flows (>3 RPM), the liquid might surge and break the

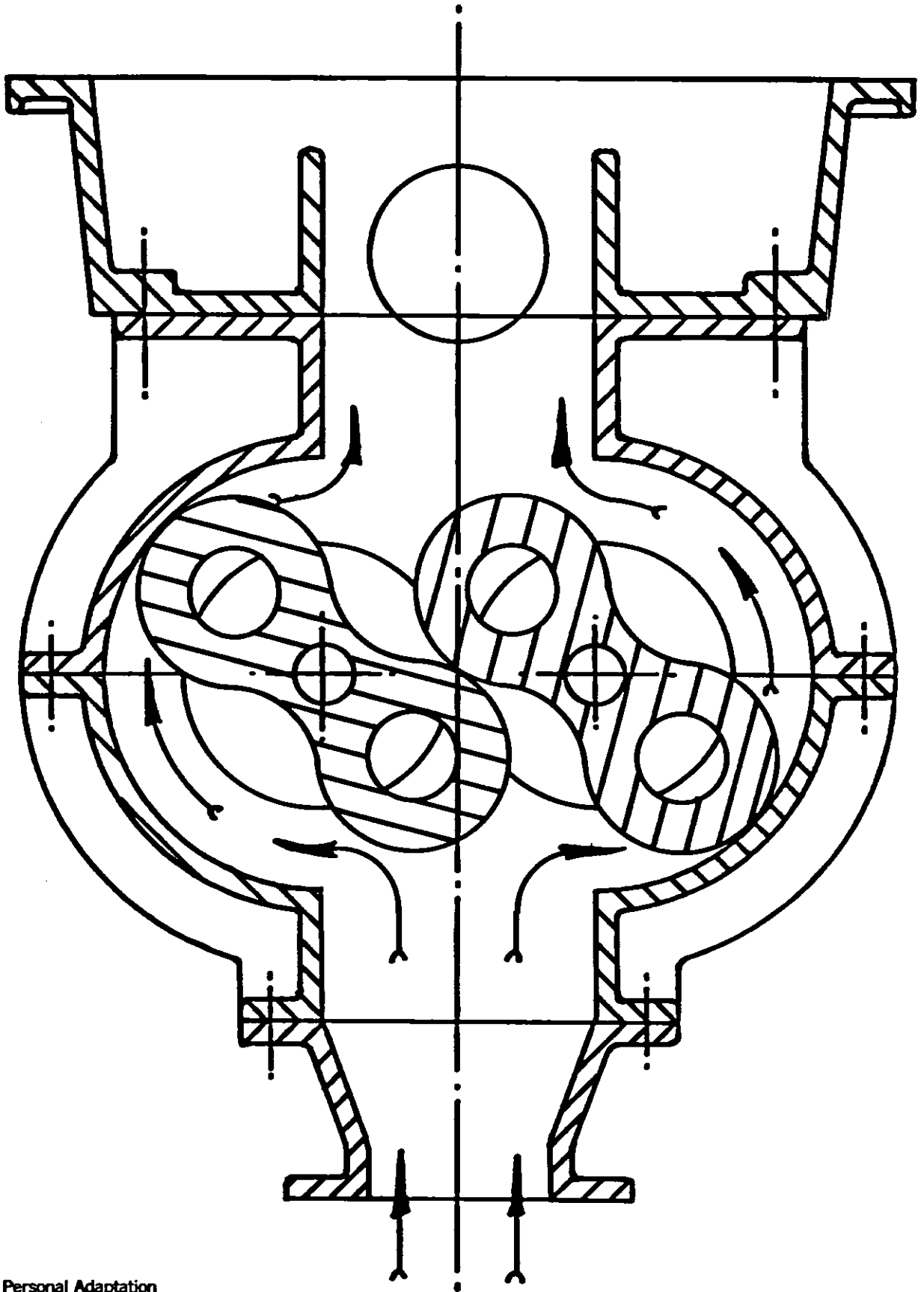
water seal at the inlet or outlet. In spite of these factors, the accuracy of the meter usually is within one percent when used as directed by the manufacturer.

Dry-Gas Meter. The dry-gas meter shown in Figure 11-5 is very similar to the domestic gas meter. It consists of two bags interconnected by mechanical valves and a cycle-counting device. The air or gas fills one bag while the other bag empties itself; when the cycle is completed the valves are switched, and the second bag fills while the first one empties. Any such device has the disadvantage of mechanical drag, pressure drop, and leakage; however, the advantage of being able to use the meter under rather high pressures and volumes often outweighs these errors, which can be determined for a specific set of conditions. The alternate filling of two chambers as the basis for volume measurement is also used in twin-cylinder piston meters. Such meters can also be classified



Powell CH, Hosey AD (eds): The Industrial Environment — Its Evaluation and Control, 2nd Edition. Public Health Service Publication No. 614, 1965.

Figure 11-5. Dry Gas Meter



Personal Adaptation

Figure 11-6. Schematic Diagram Showing Principle of Operation of Twin-Lobed Positive Displacement Meter

as positive displacement meters.

Positive Displacement Meters. Positive displacement meters consist of a tight-fitting moving element with individual volume compartments which fill at the inlet and discharge at the outlet parts. A lobed rotor design is illustrated in Figure 11-6. Another multicompartment continuous rotary meter uses interlocking gears. When the rotors of such meters are motor driven, these units become positive displacement air movers.

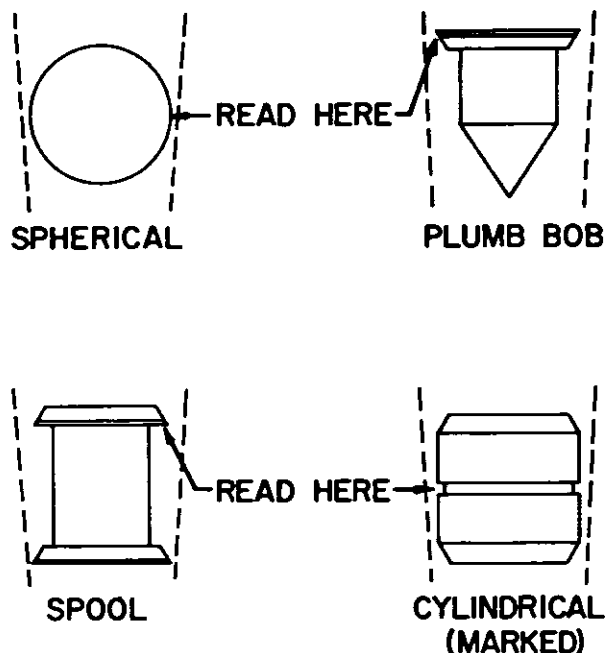
Volumetric Flowrate

The volume meters discussed in the preceding paragraphs were all based on the principle of conservation of mass; specifically the transfer of a fluid volume from one location to another. The flowrate meters in this section all operate on the principle of the conservation of energy; more specifically, they utilize Bernoulli's theorem for the exchange of potential energy for kinetic energy and/or frictional heat. Each consists of a flow restriction within a closed conduit. The restriction causes an increase in the fluid velocity, and therefore an increase in kinetic energy, which requires a corresponding decrease in potential energy, i.e., static pressure. The flowrate can be calculated from a knowledge of the pressure drop, the flow cross section at the constriction, the density of the fluid, and the coefficient of discharge, which is the ratio of actual flow to theoretical flow and makes allowance for stream contraction and frictional effects.

Flowmeters which operate on this principle can be divided into two groups. The larger group, which includes orifice meters, venturi meters, and flow nozzles have a fixed restriction and are known as variable-head meters, because the differential pressure head varies with flow. The other group, which includes rotameters, are known as variable-area meters, because a constant pressure differential is maintained by varying the flow cross section.

Variable-Area Meters (Rotameters). A rotameter consists of a "float" which is free to move up and down within a vertical tapered tube which is larger at the top than the bottom. The fluid flows upward, causing the float to rise until the pressure drop across the annular area between the float and the tube wall is just sufficient to support the float. The tapered tube is usually made of glass or clear plastic and has a flowrate scale etched directly on it. The height of the float indicates the flowrate. Floats of various configurations are used, as indicated in Figure 11-7. They are conventionally read at the highest point of maximum diameter, unless otherwise indicated.

Most rotameters have a range of 10:1 between their maximum and minimum flows. The range of a given tube can be extended by using heavier or lighter floats. Tubes are made in sizes from about 1/8 to 6 inches in diameter, covering ranges from a few cm³/min. to over 1,000 ft³/min. Some of the shaped floats achieve stability by having slots which make them rotate, but these are less commonly used than previously. The term "rotameter" was first used to describe such meters with



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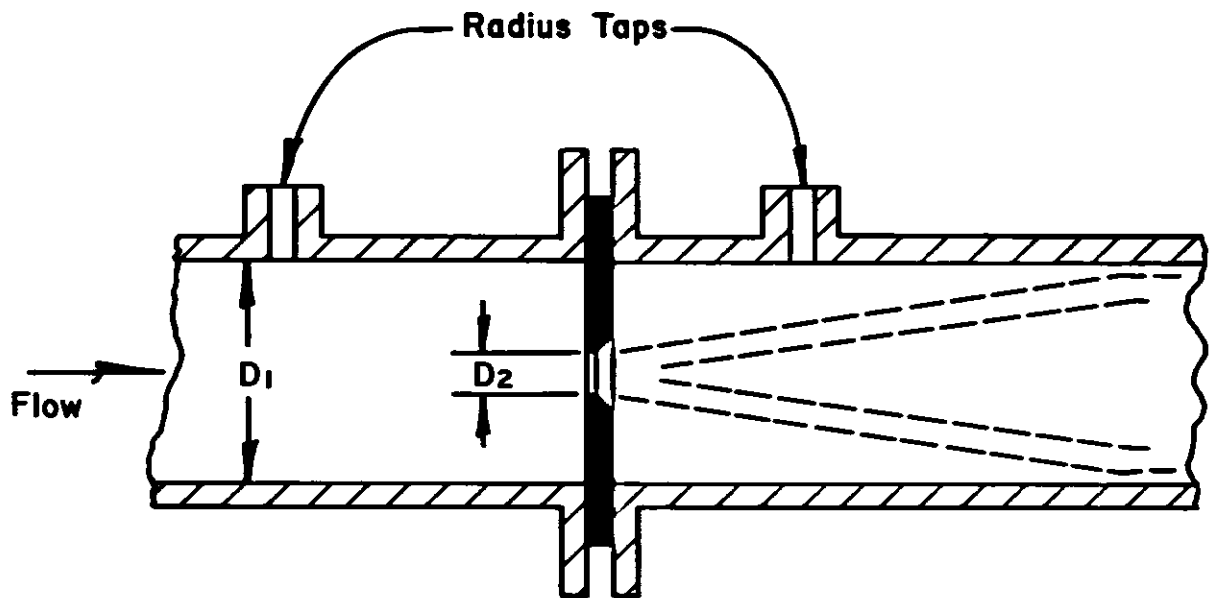
Figure 11-7. Typical Rotameter Floats

spinning floats, but now is generally used for all types of tapered metering tubes.

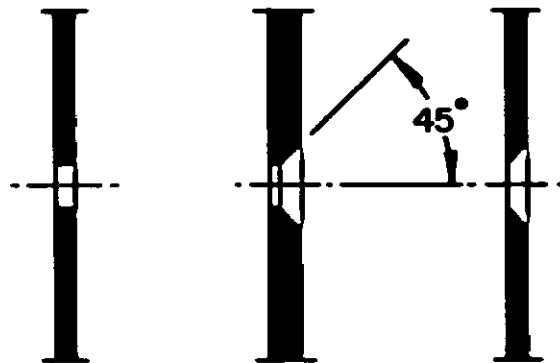
Rotameters are the most commonly used flowmeters on commercial air samplers, especially on portable samplers. For such sampler flowmeters, the most common material of construction is acrylic plastic, although glass tubes may also be used. Because of space limitations, the scale lengths are generally no more than four inches and most commonly nearer to two inches. Unless they are individually calibrated, the accuracy is unlikely to be better than $\pm 25\%$. When individually calibrated, $\pm 5\%$ accuracy may be achieved. It should be noted, however, that with the large taper of the bore, the relatively large size of the float, and the relatively few scale markers on these rotameters, the precision of the readings may be a major limiting factor.

Calibrations of rotameters are performed at an appropriate reference pressure, usually atmospheric. However, since good practice dictates that the flowmeter should be downstream of the sample collector or sensor, the flow is actually measured at a reduced pressure, which may also be a variable pressure if the flow resistance changes with loading. If this resistance is constant, it should be known; if variable, it should be monitored, so that the flowrate can be adjusted as needed, and appropriate pressure corrections can be made for the flowmeter readings.

Variable-Head Meters. When orifice and venturi meters are made to standardized dimensions, their calibration can be predicted with $\sim \pm 10\%$



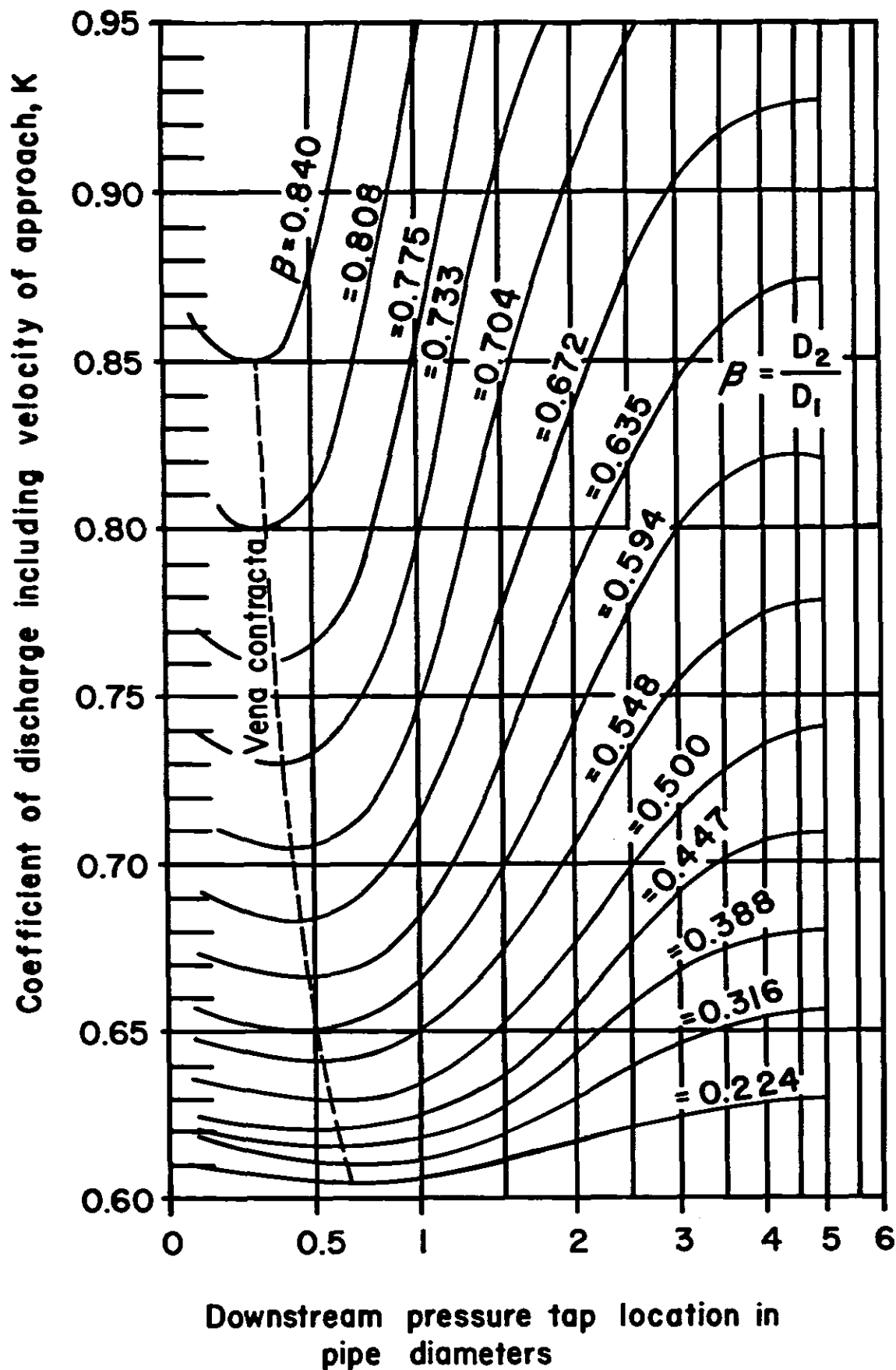
(a)



(b)

Perry JH, et al: Chemical Engineering Handbook, 4th Edition. New York, McGraw-Hill, 1963.

Figure 11-8. Square-Edged or Sharp-Edged Orifices. The plate at the orifice opening must not be thicker than $1/30$ of pipe diameter, $1/8$ of the orifice diameter, or $1/4$ of the distance from the pipe wall to the edge of the opening. (a) Pipe-line orifice. (b) Types of plates.



Perry JH, et al: Chemical Engineering Handbook, 4th Edition. New York, McGraw-Hill, 1963.

Figure 11-9. Coefficient of Discharge for Square-Edged Circular Orifices for $N_{Re2} > 30,000$ with the Upstream Tap Location between One and Two Pipe Diameters from the Orifice Position

accuracy using standard equations and published empirical coefficients. The general equation² for this type of meter is:

$$W = q_1 P_1 = KYA_2 \sqrt{2g_c (P_1 - P_2) \rho_1} \quad (1)$$

where: $K = C / \sqrt{1 - \beta^4}$

C = coefficient of discharge, dimensionless

A_2 = cross-sectional area of throat — ft²

$g_c = 32.17$ ft/sec²

P_1 = upstream static pressure — lb/ft²

P_2 = downstream static pressure — lb/ft²

q_1 = volumetric flow at upstream press. & temp.—ft³/sec.

W = weight-rate of flow — lb/sec.

Y = expansion factor (see Figure 11-10)

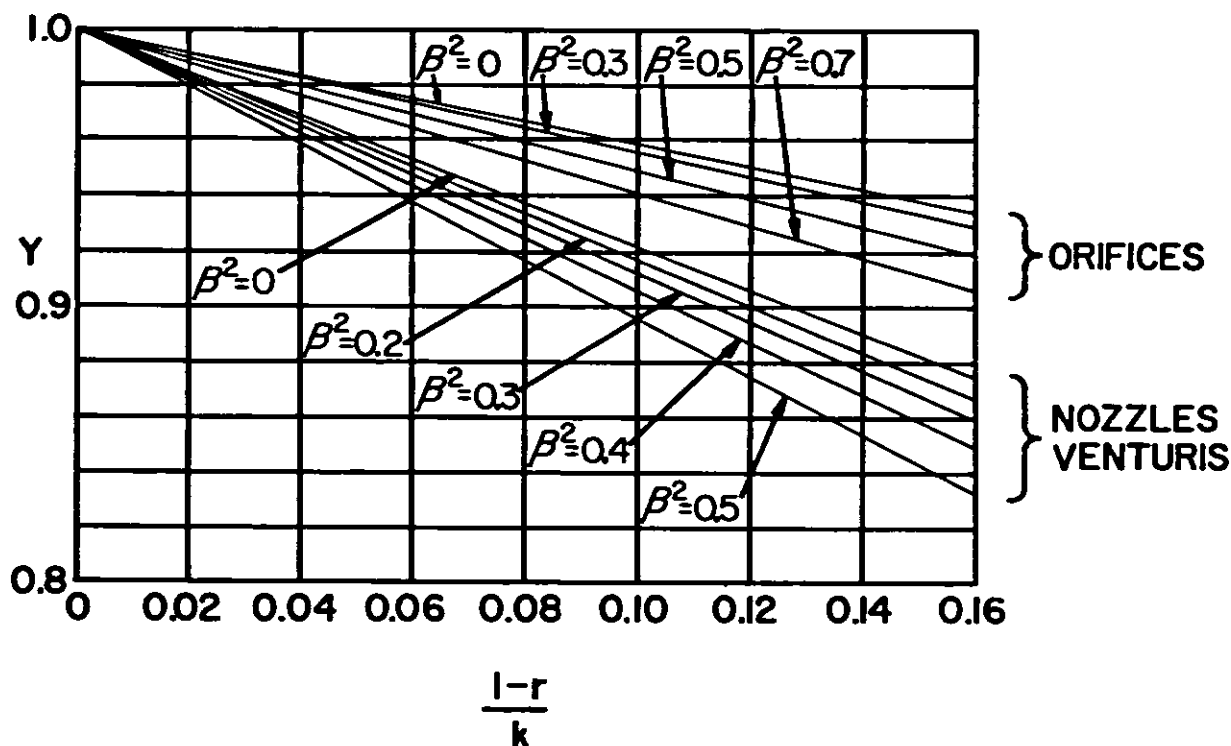
β = ratio of throat diameter to pipe diameter, dimensionless

ρ_1 = density at upstream press. & temp. — lb/ft³.

Orifice Meters. The simplest form of variable-head meter is the square-edged, or sharp-edged orifice illustrated in Figure 11-8. It is also the most widely used because of its ease of installation and low cost. If it is made with properly mounted pressure taps, its calibration can be determined from equation (1) and Figures 11-9 and 11-10. However, even a non-standard orifice meter can serve as a secondary standard, provided it is carefully calibrated against a reliable reference instrument.

While the square-edged orifice can provide accurate flow measurements at low cost, it is inefficient with respect to energy loss. The permanent pressure loss for an orifice meter with radius taps can be approximated by $(1 - \beta^2)$, and will often exceed 80%.

Venturi Meters. Venturi meters have optimal converging and diverging angles of about 25° and 7° respectively, and thereby have high pressure re-



Perry JH, et al: Chemical Engineering Handbook, 4th Edition. New York, McGraw-Hill, 1963.

Figure 11-10. Values of Expansion Factor Y for Orifices, Nozzles, and Venturis

coveries, i.e., the potential energy which is converted to kinetic energy at the throat is reconverted to potential energy at the discharge, with an overall loss of only about 10%.

For air at 70°F and 1 atm. and for $\frac{1}{4} < \beta < \frac{1}{2}$, a standard venturi would have a calibration described by:

$$Q = 21.2 \beta^2 D^2 \sqrt{h} \quad (2)$$

where Q = flow — ft³/min.

β = ratio of throat to duct diameter, dimensionless

D = duct diameter — inches

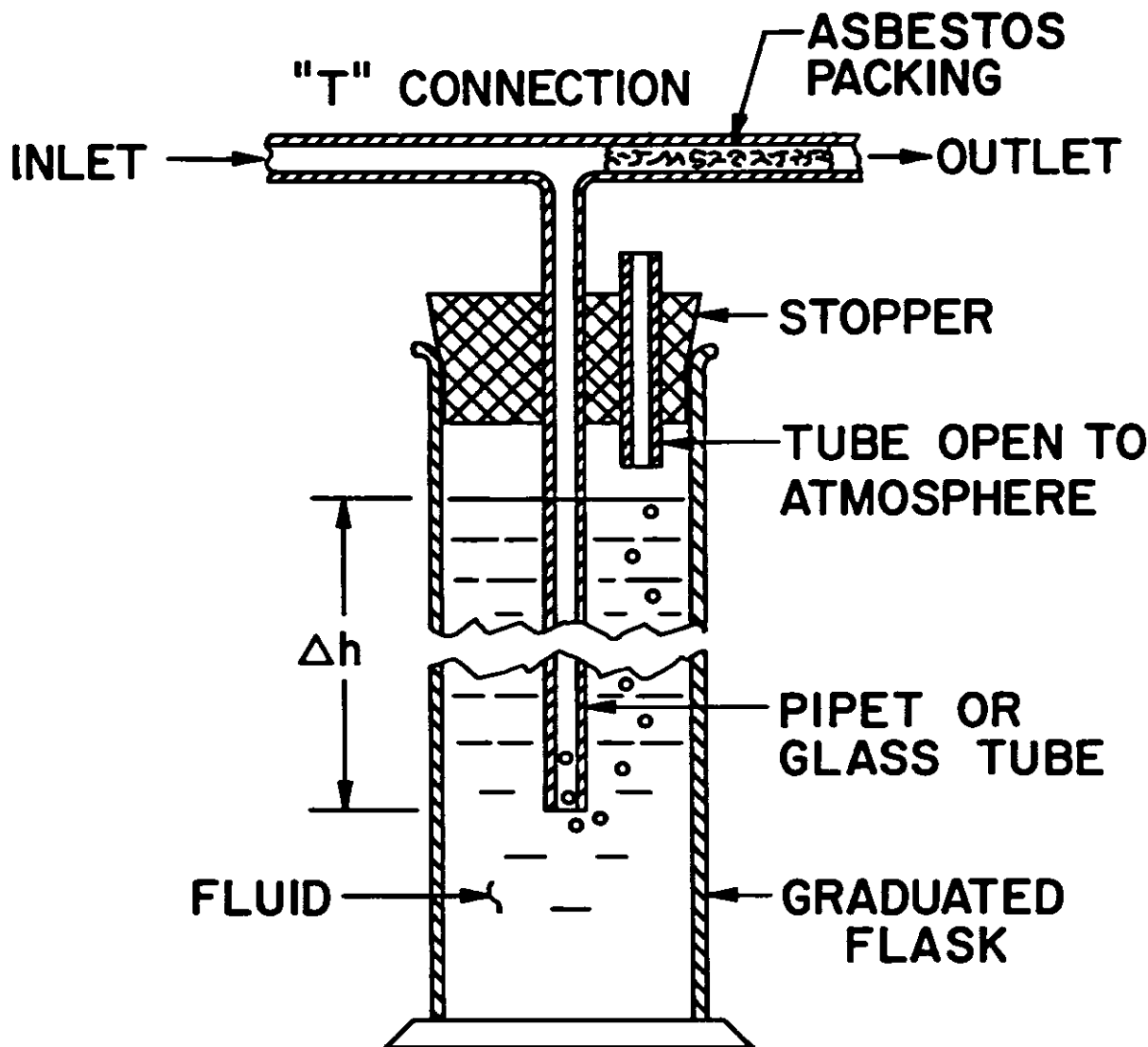
h = differential pressure — inches of water.

Other Variable-Head Meters. The characteristics of various other types of variable-head flowmeters, e.g., flow nozzles, Dall Tubes, centrifugal flow elements, etc. are described in various standard engineering references.^{2,3} In most respects they have similar properties to the orifice meter, venturi meter, or both.

One type of variable-head meter which differs significantly from all of the above is the laminar-flow meter. These are seldom discussed in engineering handbooks because they are used only for very low flowrates. Since the flow is laminar,

the pressure drop is directly proportional to the flowrate. In orifice meters, venturi meters and related devices, the flow is turbulent and flowrate varies with the square root of the pressure differential.

Laminar flow restrictors used in commercial flowmeters consist of egg-crate or tube bundle arrays of parallel channels. Alternatively, a laminar flowmeter can be constructed in the laboratory using a tube packed with beads or fibers as the resistance element. Figure 11-11 illustrates this kind of homemade flowmeter. It consists of a "T"



Powell CH, Hosey AD (eds): *The Industrial Environment — Its Evaluation and Control*, 2nd Edition. Public Health Service Publication No. 614, 1965.

Figure 11-11. Drawing of a Packed Plug Flow Meter

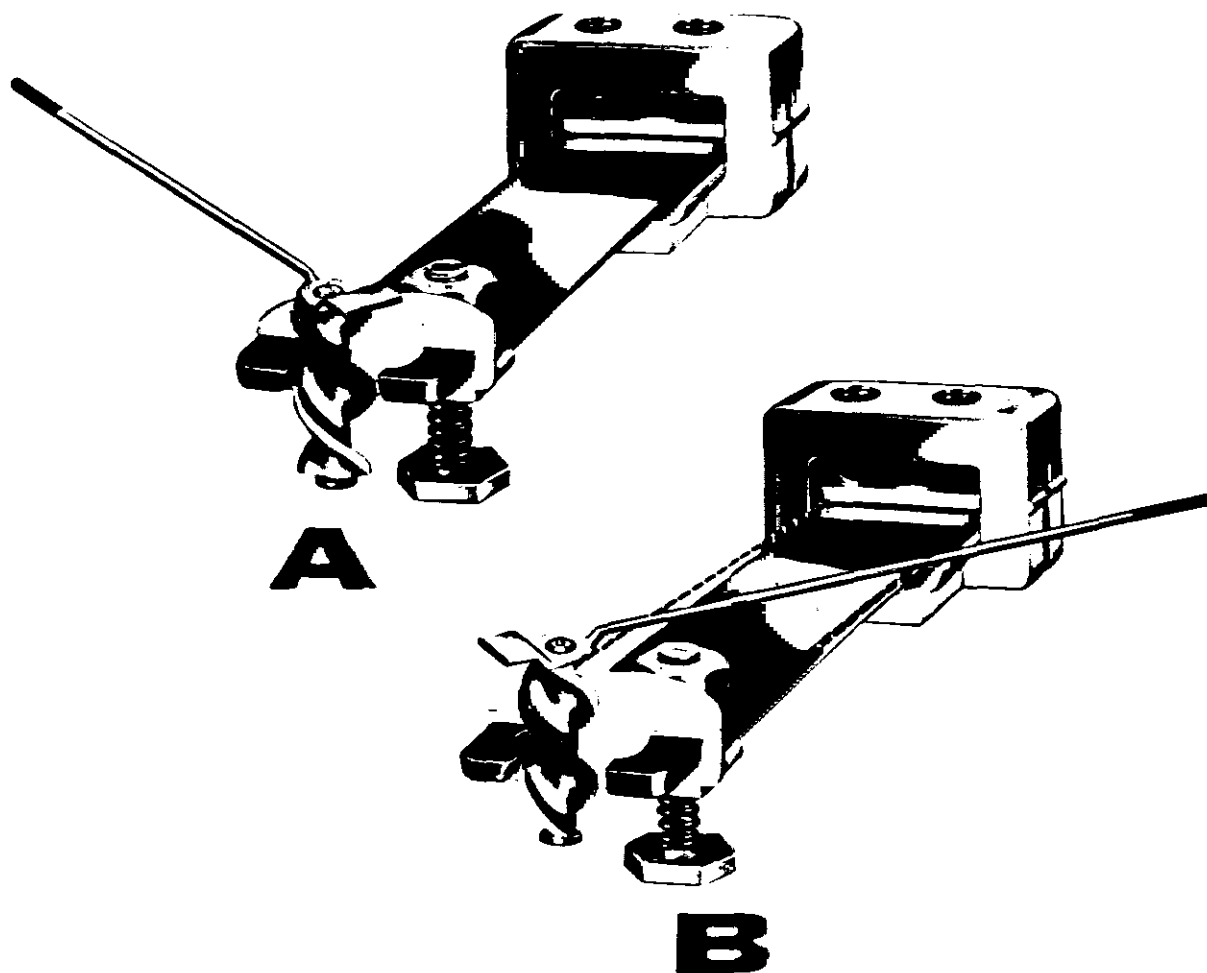
connection, pipet or glass tubing, cylinder and packing material. The outlet arm of the "T" is packed with material, such as asbestos, and the leg is attached to a tube or pipet projecting down

into the cylinder filled with water or oil. A calibration curve of the depth of the tube outlet below the water level versus the rate of flow should produce a linear curve. Saltzman⁴ has used tubes

filled with asbestos to regulate and measure flow-rates as low as 0.01 cm³/min.

Pressure Transducers. All of the variable-head meters require a pressure sensor, sometimes referred to as the secondary element. Any type of pressure sensor can be used, although high cost and fragility usually rule out the use of many electrical and electro-mechanical transducers.

Liquid-filled manometer tubes are sometimes used, and if they are properly aligned and the density of the liquid is accurately known, the column differential provides an unequivocal measurement. In most cases however, it is not feasible to use liquid-filled manometers in the field, and the pressure differentials are measured with mechanical gages with scale ranges in centimeters or inches



Dwyer Instruments, Inc.: Bulletin #A-20. Michigan City, Indiana.

Figure 11-12. How the Magnetic Linkage Works*

*From I. W. Dwyer Co. Literature

12A—At zero position, pressures on both sides of the diaphragm are equal. The support plates of the diaphragm are connected to the leaf spring which is anchored at one end. The horseshoe magnet attached to the free end of the spring straddles the axis of a helix but does not touch the helix. The indicating pointer is attached to one end of the helix.

The helix, being of high magnetic permeability, aligns itself in the field of the magnet to maintain the minimum air gap between the magnet's poles and the outer edge of the helix.

12B—When pressure on the "high" side of the diaphragm increases or pressure on the "low" side of the diaphragm decreases, the diaphragm moves toward the back of the case. Through the linkage, the diaphragm moves the spring and the magnet. As the magnet moves parallel to the axis of the helix, the helix turns to maintain the minimum air gap.

Movement of the diaphragm is resisted by the flat spring which determines the range of the instrument. Precise calibration is achieved by varying the live length of the spring through adjustment of the spring clamp.

of water. For these low pressure differentials the most commonly used gage is the Magnehelic®, whose schematic is illustrated in Figures 11-12A and 11-12B. These gages are accurate to $\pm 2\%$ of full scale and are reliable provided they and their connecting hoses do not leak, and their calibration is periodically rechecked.

Critical-Flow Orifice. For a given set of upstream conditions, the discharge of a gas from a restricted opening will increase with a decrease in the ratio of absolute pressures P_2/P_1 , where P_2 is the downstream pressure, and P_1 the upstream pressure, until the velocity through the opening reaches the velocity of sound. The value of P_2/P_1 at which the maximum velocity is just attained is known as the critical pressure ratio. The pressure in the throat will not fall below the pressure at the critical point, even if a much lower downstream pressure exists. Therefore, when the pressure ratio is below the critical value, the rate of flow through the restricted opening is dependent only on the upstream pressure.

It can be shown,² that for air flowing through rounded orifices, nozzles and venturis, when $P_2 < 0.53 P_1$, and $S_1/S_2 > 25$, the mass-flowrate w , is determined by:

$$w = 0.533 \frac{C_v S_2 P_1}{T_1} \text{ lb/sec} \quad (3)$$

where: C_v = coefficient of discharge
(normally ~ 1)

S_1 = duct or pipe cross section in square inches

S_2 = orifice area in square inches

P_1 = upstream absolute pressure in lb/sq. in.

T_1 = upstream temperature in °R

Critical-flow orifices are widely used in industrial hygiene instruments such as the midget impinger pump and squeeze bulb indicators. They can also be used to calibrate flowmeters by using a series of critical orifices downstream of the flowmeter under test. The flowmeter readings can be plotted against the critical flows to yield a calibration curve.

The major limitation in their use is that the orifices are extremely small when they are used for flows of 1 ft³/min or less. They become clogged or eroded in time and, therefore, require frequent examination and/or calibration against other reference meters.

By-Pass Flow Indicators. In most high-volume samplers, the flowrate is strongly dependent on the flow resistance, and flowmeters with a sufficiently low flow resistance are usually too bulky or expensive. A commonly used metering element for such samplers is the by-pass rotameter, which actually meters only a small fraction of the total flow; a fraction, however, which is proportional to the total flow. As shown schematically in Figure 11-13, a by-pass flowmeter contains both a variable-head element and a variable-area element. The pressure drop across the fixed orifice or flow restrictor creates a proportionate flow through the

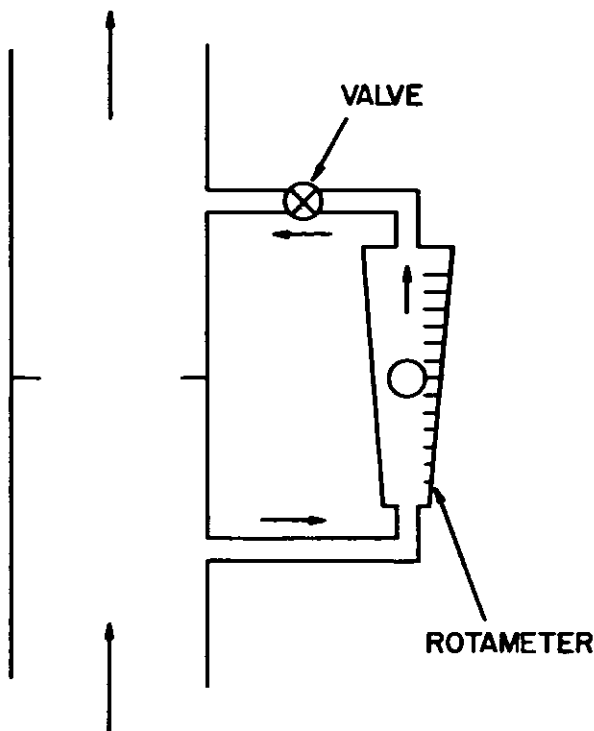


Figure 11-13. Schematic of By-Pass Flow Indicators

parallel path containing the small rotameter. The scale on the rotameter generally reads directly in ft³/min or liters/min of total flow. In the versions used on portable high-volume samplers there is usually an adjustable bleed valve at the top of the rotameter which should be set initially, and periodically readjusted in laboratory calibrations so that the scale markings can indicate overall flow. If the rotameter tube accumulates dirt, or the bleed valve adjustment drifts, the scale readings can depart greatly from the true flows.

Flow Velocity Meters

As discussed previously, point velocity is not the parameter of interest in sampling flow measurements. However, it may be the only feasible parameter to measure in some circumstances, and it usually can be related to flowrate provided the sensor is located in an appropriate position and is suitably calibrated against overall flow.

Velocity Pressure Meters. The Pitot tube is often used as a reference instrument for measuring the velocity of air. A standard Pitot, carefully made, will need no calibration. It consists of an impact tube whose opening faces axially into the flow, and a concentric static pressure tube with 8 holes spaced equally around it in a plane which is 8 diameters from the impact opening. The difference between the static and impact pressures is the velocity pressure. Bernoulli's theorem applied to a Pitot tube in an air stream simplifies to the dimensionless formula

$$V = \sqrt{2g_c P_v} \quad (4)$$

where: V = linear velocity

g_c = gravitational constant

P_v = pressure head of flowing fluid or velocity pressure. Expressing V in linear feet per min., P_v in inches of water (h_v),

$$\text{and } g_c = 32.17 \frac{(\text{lb.-mass}) (\text{ft.})}{(\text{lb.-force}) (\text{sec.}^2)}$$

$$V = 1097 \sqrt{\frac{h_v}{\rho}} \quad (5)$$

where: ρ = density of air or gas in lb./ft.³

If the Pitot tube is to be used with air at standard conditions (70°F and 1 atm.), formula (5) reduces to:

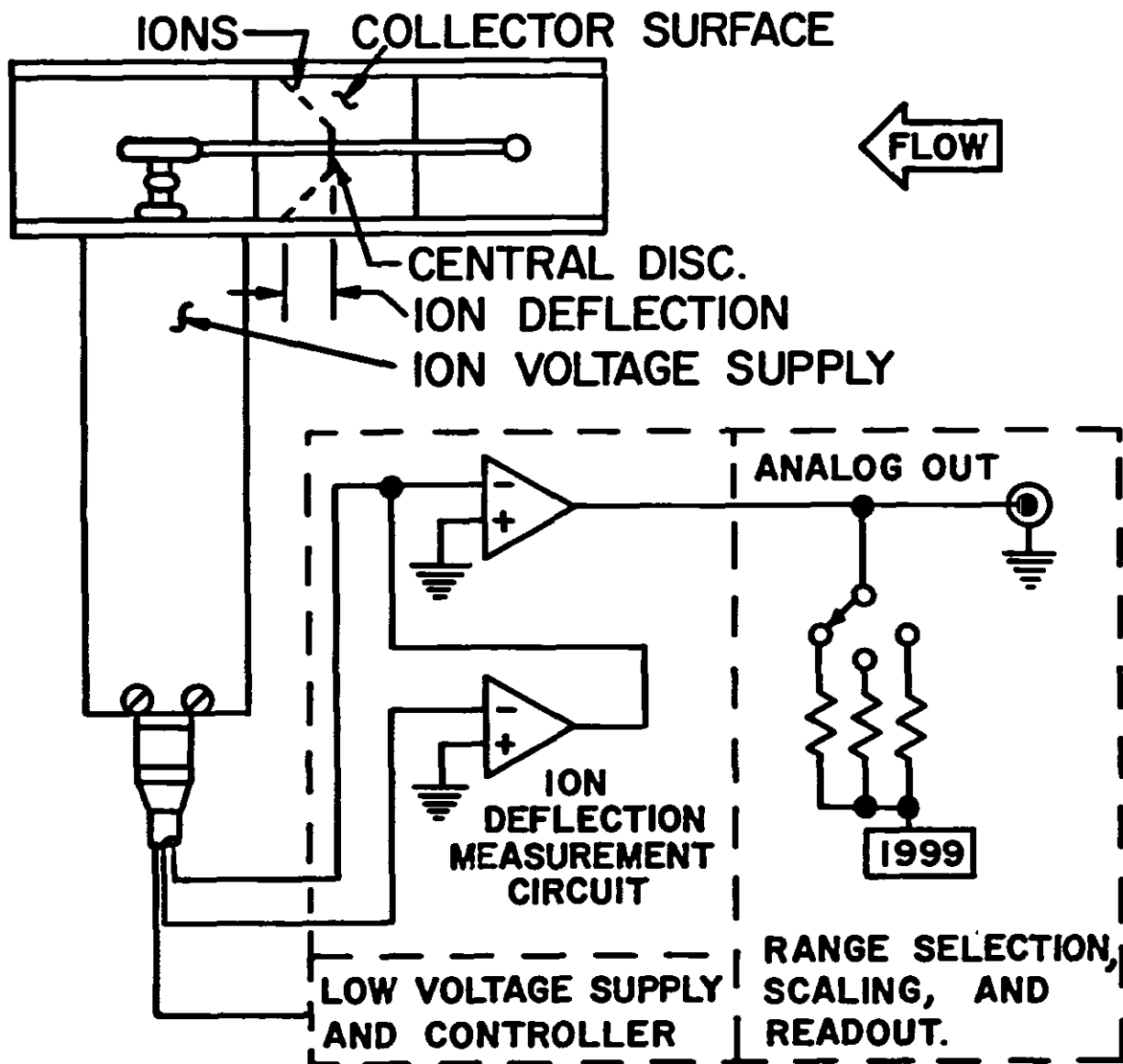
$$V = 4005 \sqrt{h_v} \quad (6)$$

where: V = velocity in ft./min.

h_v = velocity pressure in inches of H₂O

There are several serious limitations to Pitot tube measurements in most sampling flow calibrations. One is that it may be difficult to obtain or fabricate a small enough probe. Another is that the velocity pressure may be too low to measure at the velocities encountered. For example, at 1000 ft./min., $h_v = 0.063$ inches of water, a low value, even for an inclined manometer.

Heated Element Anemometers. Any instrument used to measure velocity can be referred to as an anemometer. In a heated element anemometer, the flowing air cools the sensor in proportion to the velocity of the air. Instruments are available with various kinds of heated elements, i.e., heated thermometers, thermocouples, films, and wires.



Thermo-Systems, Inc.: leaflet "TSI-54100-671." St. Paul, Minnesota.

Figure 11-14. Ion-Flow Mass Flowmeter

They are all essentially nondirectional, i.e., with single element probes, they measure the airspeed but not its direction. They all can accurately measure steady state airspeed, and those with low mass sensors and appropriate circuits can also accurately measure velocity fluctuations with frequencies above 100,000 Hz. Since the signals produced by the basic sensors are dependent on ambient temperature as well as air velocity, the probes are usually equipped with a reference element which provides an output which can be used to compensate or correct errors due to temperature variations. Some heated element anemometers can measure velocities as low as 10 ft./min. and as high as 8,000 ft./min.

Other Velocity Meters. There are several other ways to utilize the kinetic energy of a flowing fluid to measure velocity beside the Pitot tube. One way is to align a jeweled-bearing turbine wheel axially in the stream and count the number of rotations per unit time. Such devices are generally known as rotating vane anemometers. Some are very small and are used as velocity probes. Others are sized to fit the whole duct and become

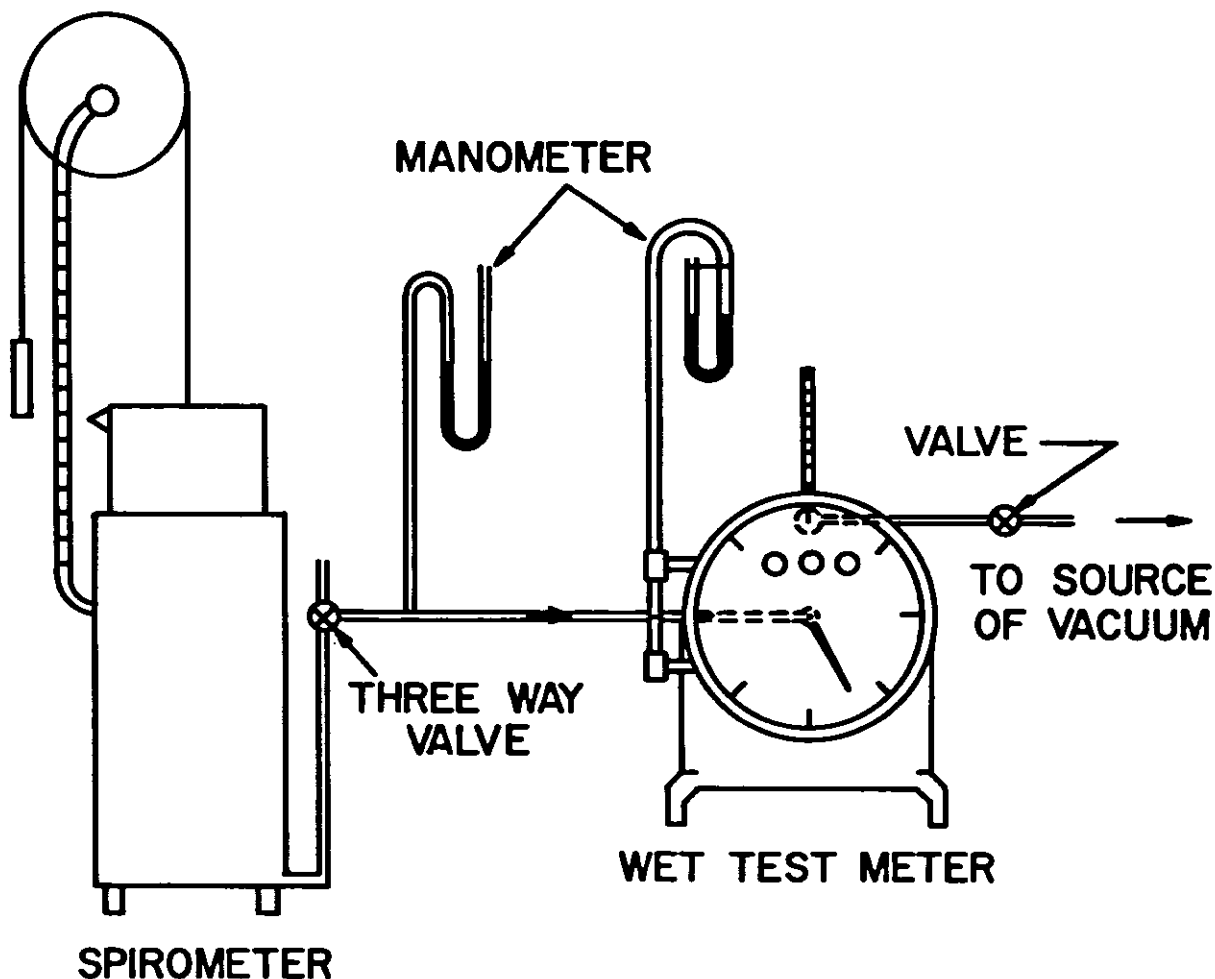
indicators of total flowrate and sometimes are called turbine flowmeters.

The velometer, or swinging vane anemometer described in Chapter 40, is widely used for measuring ventilation air flows, but has few applications in sample flow measurement or calibration. It consists of a spring-loaded vane whose displacement is indicative of velocity pressure.

Mass Flow and Tracer Techniques

Thermal Meters. A thermal meter measures mass air or gas flow rate with negligible pressure loss. It consists of a heating element in a duct section between two points at which the temperature of the air or gas stream is measured. The temperature difference between the two points is dependent on the mass rate of flow and the heat input.

Mixture Metering. The principle of mixture metering is similar to that of thermal metering. Instead of adding heat and measuring temperature difference, a contaminant is added and its increase in concentration is measured; or clean air is added and the reduction in concentration is measured. This method is useful for metering corrosive gas streams. The measuring device may react to some



Powell CH, Hosey AD (eds): The Industrial Environment — Its Evaluation and Control. 2nd Edition. Public Health Service Publication No. 614, 1965.

Figure 11-15. Calibration Setup for Calibrating a Wet Test Meter

physical property such as thermal conductivity or vapor pressure.

Ion-Flow Meters. In the ion-flow meter illustrated in Figure 11-14, ions are generated from the central disc and flow radially toward the collector surface. Airflow through the cylinder causes an axial displacement of the ion stream in direct proportion to the mass flow. The instrument can measure mass flows from 0.1 to 150 standard ft.³/min., and velocities from 1 ft./min. to 12,000 ft./min.

Procedures for Calibrating Flow and Volume Meters

In the limited space available, it is not possible to provide a complete description of all of the techniques available, or to go into great detail on those which are commonly used. This discussion will be limited to selected procedures which should serve to illustrate recommended approaches to some commonly encountered calibration procedures.

Comparison of Primary and Secondary Standards. Figure 11-15 shows the experimental set-up for checking the calibration of a secondary standard (in this case a wet-test meter) against a primary standard (in this case a spirometer). The first step should be to check out all of the system elements for integrity, proper functioning, and interconnections. Both the spirometer and wet-test meter require specific internal water levels and leveling. The operating manuals for each should be examined since they will usually outline simple procedures for leakage testing and operational procedures.

After all connections have been made, it is a good policy to recheck the level of all instruments and determine that all connections are clear and have minimum resistance. If compressed air is used in a calibration procedure it should be cleaned and dried.

Actual calibration of the wet-test meter shown in Figure 11-15 is accomplished by opening the by-pass valve and adjusting the vacuum source to obtain the desired flowrate. The optimum range of operation is between one and three revolutions per minute. Before actual calibration is initiated the wet-test meter should be operated for several hours in this setup to stabilize the meter fluid as to temperature, absorbed gas, and to work in the bearings and mechanical linkage. After all elements of the system have been adjusted, zeroed and stabilized several trial runs should be made. During these runs, should any difference in pressure be indicated, the cause should be determined and corrected. The actual procedure would be to instantaneously divert the air to the spirometer for a predetermined volume indicated by the wet-test meter (minimum of one revolution), or to near capacity of the spirometer, then return to the by-pass arrangement. Readings, both quantity and pressure of the wet-test meter, must be taken and recorded while it is in motion, unless a more elaborate system is set up. In the case of a rate meter, the interval of time that the air is entering the spirometer must be accurately timed. The bell should then be allowed to come

to equilibrium before displacement readings are made. A sufficient number of different flowrates are taken to establish the shape or slope of the calibration curve with the procedure being repeated three or more times for each point. For an even more accurate calibration the setup should be reversed so that air is withdrawn from the spirometer. In this way any unbalance due to pressure differences would be cancelled.

A permanent record should be made of a sketch of the setup, data, conditions, equipment, results, and personnel associated with the calibration. All readings (volume, temperatures, pressures, displacements, etc.) should be legibly recorded, including trial runs or known faulty data, with appropriate comments. The identifications of equipment, connections and conditions should be so complete that the exact setup with the same equipment and connections could be reproduced by another person solely by use of the records.

After all of the data have been recorded, the calculations such as correction for variations in temperature, pressure and water vapor are made using the ideal gas laws:

$$V_s = V_1 \times \frac{P_1}{760} \times \frac{273}{T_1} \quad (7)$$

where V_s = volume at standard conditions (760 mm & 0°C)

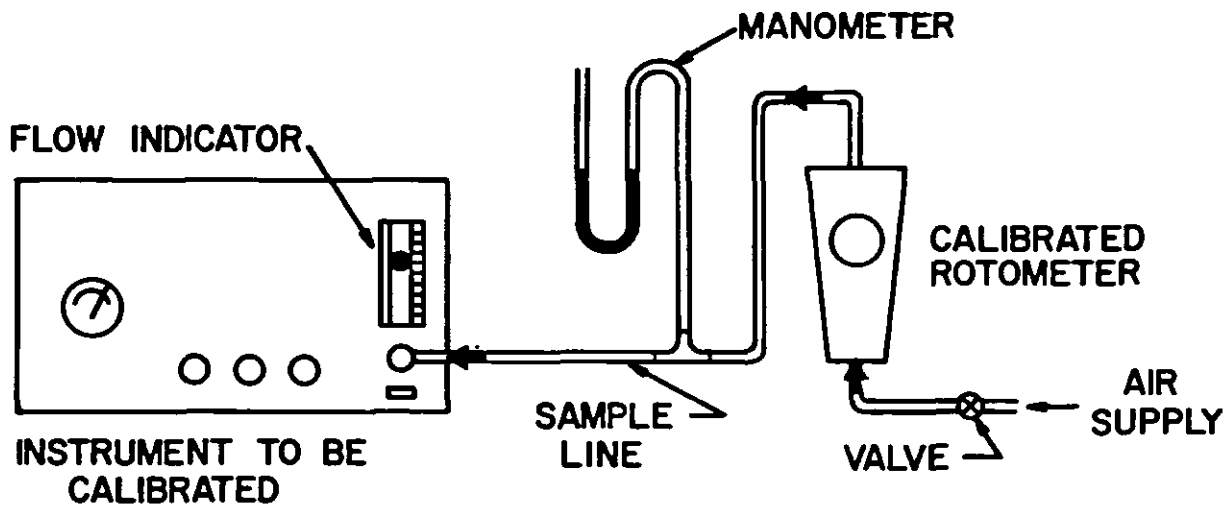
V_1 = volume measured at conditions P_1 and T_1

T_1 = temperature of V_1 in °K

P_1 = pressure of V_1 in mm Hg

In most cases the water vapor portion of the ambient pressure is disregarded. Also, the standard temperature of the gas is often referred to normal room temperature, i.e., 21°C rather than 0°C. The manipulation of the instruments, data reading and recording, calculations and resulting factors or curves should be done with extreme care. Should a calibration disagree with previous calibrations or the supplier's calibration, the entire procedure should be repeated, and examined carefully to assure its validity. Upon completion of any calibration the instrument should be tagged or marked in a semi-permanent manner to indicate the calibration factor, where appropriate, date and who performed the calibration.

Reciprocal Calibration by Balanced Flow System. In many commercial instruments it is impractical to remove the flow-indicating device for calibration. This may be because of physical limitations, characteristics of the pump, unknown resistance in the system⁵ or other limiting factors. In such situations it may be necessary to set up a reciprocal calibration procedure, that is, where a controlled flow of air or gas is compared first with the instrument flow, then with a calibration source. Often a further complication is introduced by the static pressure characteristics of the air mover in the instrument.⁶ In such instances supplemental pressure or vacuum must be applied to the system to offset the resistance of the calibrating device. An example of such a system is illustrated in Figure 11-16.



Powell CH, Hosey AD (eds): *The Industrial Environment — Its Evaluation and Control*. 2nd Edition. Public Health Service Publication No. 614, 1965.

Figure 11-16. Setup for Balanced Flow Calibration

The instrument is connected to a calibrated rotameter and source of compressed air. Between the rotameter and the instrument an open-end manometer is installed. The connections, as in any other calibration system, should be as short and resistance-free as possible.

In the calibration procedure the flow through the instrument and rotameter is adjusted by means of a valve or restriction at the pump until the manometer indicates "0" pressure difference to the atmosphere. When this condition is achieved the instrument and rotameter are both operating at atmospheric pressure. The indicated and calibrated rates of flow are then recorded and the procedure repeated for other rates of flow.

Dilution Calibration. Normally gas-dilution techniques are employed for instrument response calibrations; however, several procedures^{6,7,8} have been developed whereby sampling rates of flow could be determined. The principle is essentially the same except that different unknowns are involved. In air-flow calibration a known concentration of the gas (i.e., carbon dioxide) is contained in a vessel. Uncontaminated air is introduced and mixed thoroughly in the chamber to replace that removed by the instrument to be calibrated. The resulting depletion of the agent in the vessel follows the theoretical dilution formula:

$$C_t = C_0 e^{-bt} \quad (8)$$

where: C_t = concentration of agent in vessel at time, t

C_0 = initial concentration at $t = 0$

e = base of natural logarithms

b = air changes in the vessel per unit time

t = time

The concentration of the gas in the vessel is determined periodically by an independent method. A linear plot should result from plotting concen-

tration of agent against elapsed time on semi-log paper. The slope of the line indicates the air changes per minute (b) which can be converted to the rate (Q) of air withdrawn by the instrument from the following relationship: $Q = bV$; where V = volume of the vessel.

This technique offers the advantage that virtually no resistance or obstruction is offered to the air flow through the instrument; however, it is limited by the accuracy of determining the concentration of the agents in the air mixture.

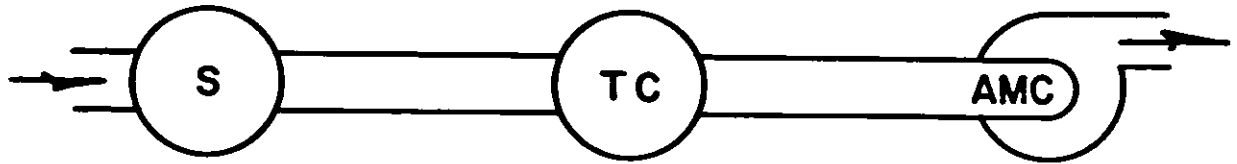
CALIBRATION OF SAMPLER'S COLLECTION EFFICIENCY

Use of Well Characterized Test Atmospheres

In order to test the collection efficiency of a sampler for a given contaminant it is necessary either: 1) to conduct the test in the field using a proven reference instrument or technique as a reference standard, or 2) to reproduce the atmosphere in a laboratory chamber or flow system. Techniques and equipment for producing such test atmospheres are beyond the scope of this chapter. They are discussed in detail in Chapter 12 and in various other sources.^{9,10,11,12} In the discussion to follow, it will be assumed that appropriate test atmospheres are available.

Analysis of Sampler's Collection and Downstream Total Collector

The best approach to use, when it is feasible, is to operate the sampler under test in series with a downstream total collector, as illustrated in Figure 11-17. The sampler's efficiency is then determined by the ratio of the sampler's retention to the retention in the sampler and downstream collector combined. When the penetration is estimated from downstream samples there may be additional errors if the samples are not representative.



S = Sample Under Test
TC = Total Collector
AMC = Air Mover, Flowmeter
and Flow Control

Figure 11-17. Sampler Efficiency Evaluation with Downstream Total Collector: Analysis of Collections in S and TC

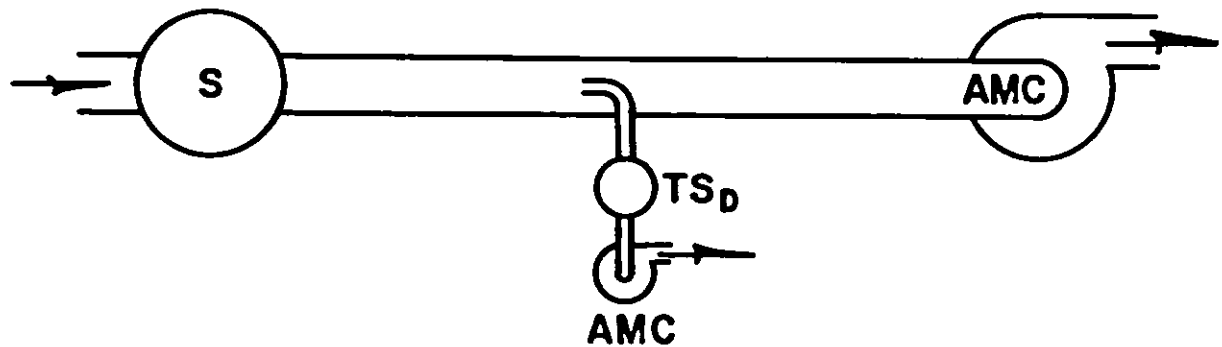
Analysis of Sampler's Collection and Downstream Samples

In some situations it is not possible or feasible to quantitatively collect all of the test material which penetrates the sampler being evaluated. For example, a total collector might add too much flow resistance to the system, or be too bulky for efficient analysis. In this case, the degree of penetration can be estimated from an analysis of a sample of the downstream atmosphere, as illus-

trated in Figure 11-18. When this approach is used, it may be necessary to collect a series of samples across the flow profile rather than a single sample, in order to obtain a true average concentration of the penetrating atmosphere.

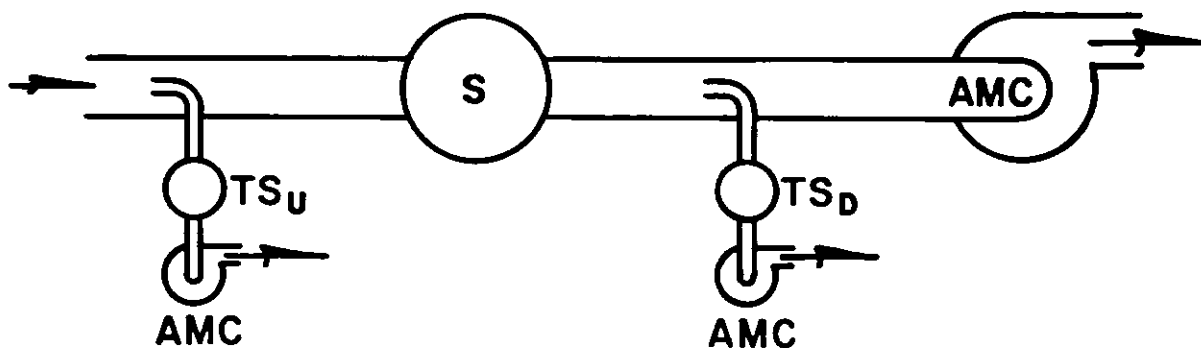
Analysis of Up-and Downstream Samples

In some cases, it may not be possible to recover or otherwise measure the material trapped within elements of the sampling train such as sampling probes. The magnitude of such losses



TS_D = Downstream Sampler
Total Collector

Figure 11-18. Sampler Efficiency Evaluation with Downstream Concentration Sampler: Analysis of Collections in S and TS_D



TS_U = Upstream Sampler Total Collector

Figure 11-19. Sampler Efficiency Evaluation with Upstream and Downstream Concentration Samplers: Analysis of Collections in TS_U and TS_D

can be determined by comparing the concentrations up-and downstream of the elements in question as illustrated schematically in Figure 11-19.

DETERMINATION OF SAMPLE STABILITY AND/OR RECOVERY

For trace contaminants the stability and recovery from sampling substrates are difficult to predict or control. Thus, these factors are best explored by realistic calibration tests.

Analysis of Sample Aliquots at Periodic Intervals after Sample Collection

If the sample is divided into a number of aliquots which are analyzed individually at periodic intervals, it is possible to determine the long term rate of sample degradation or any tendency for reduced recovery efficiencies with time. These analyses would not however provide any information or losses which may have occurred during or immediately after collection which had different rate constants. Such losses should be investigated using spiked samples.

Analysis of Spiked Samples

If known amounts of the contaminants of interest are intentionally added to the sample substrate, then subsequent analysis of sample aliquots will permit calculation of sample recovery efficiency and rate of deterioration. These results will be valid only insofar as the added material is equivalent in all respects to the material in the ambient air. There are two basic approaches to spiked sample analyses: 1) the addition of known quantities to blank samples, and 2) the addition of radioactive isotopes to either blank or actual field collected samples.

When the material being analyzed is available in tagged form, the tag can be added to the sample in negligible or at least known low concentrations. If there are losses in sample processing or analysis,

the fractional recovery of the tagged molecules will provide a basis for estimating the comparable loss which took place in the untagged molecules of the same species.

CALIBRATION OF SENSOR RESPONSE

Direct-reading instruments are generally delivered with either a direct-reading panel meter, a set of calibration curves, or both. The tendency of the unwary and inexperienced user is to believe the manufacturer's calibration, and this often leads to grief and error. Any instrument with calibration adjustment screws should of course be suspect, since such adjustments can easily be changed intentionally or accidentally, as in shipment.

All instruments should be checked against appropriate calibration standards and atmospheres immediately upon receipt and periodically thereafter. Procedures for establishing test atmospheres are discussed earlier in this chapter and in Chapter 12. Verification of the concentrations of such test atmospheres should be performed whenever possible using analytical techniques which are refereed-tested or otherwise known to be reliable.

With these techniques, calibration curves for direct reading instruments can be tested or generated. When environmental factors such as temperature, ambient pressure, and radiant energy may be expected to influence the results, these effects should be explored with appropriate tests whenever possible. Similarly, the effects of co-contaminants and water vapor on instrument response should also be explored.

SUMMARY AND CONCLUSIONS

Because the accuracy of all sampling instruments is dependent on the precision of measurement of the sample volume, sample mass or sample concentration involved, extreme care should

be exercised in performing all calibration procedures. The following comments summarize the philosophy of air sampler calibration:

1. Use standard devices with care and attention to detail.
2. All standard materials and instruments and procedures should be checked periodically to determine their stability and/or operating condition.
3. Perform calibrations whenever a device has been changed, repaired, received from a manufacturer, subjected to use, mishandled or damaged and at any time when there is a question as to its accuracy.
4. Understand the operation of an instrument before attempting to calibrate it and use a procedure or setup which will not change the characteristics of the instrument or standard within the operating range required.
5. When in doubt about procedures or data, assure their validity before proceeding to the next operation.
6. All sampling and calibration train connections should be as short and free of constrictions and resistance as possible.
7. Extreme care should be exercised in reading scales, timing, adjusting and leveling, and in all other operations involved.
8. Allow sufficient time for equilibrium to be established, inertia to be overcome and conditions to stabilize.
9. Enough points or different rates of flow should be obtained on a calibration curve to give confidence in the plot obtained. Each point should be made up of more than one reading whenever practical.
10. A complete permanent record of all procedures, data and results should be maintained. This should include trial runs, known faulty data with appropriate comments, instrument identification, connection sizes, barometric pressure, temperature, etc.
11. When a calibration differs from previous records, the cause of change should be determined before accepting the new data or repeating the procedure.
12. Calibration curves and factors should be properly identified as to conditions of calibration, device calibrated and what it was calibrated against, units involved, range

and precision of calibration, date and who performed the actual procedure. Often it is convenient to indicate where the original data is filed and to attach a tag to the instrument indicating the above information.

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CHAPTER 12

PREPARATION OF KNOWN CONCENTRATIONS OF AIR CONTAMINANTS

Bernard E. Saltzman, Ph.D.

INTRODUCTION

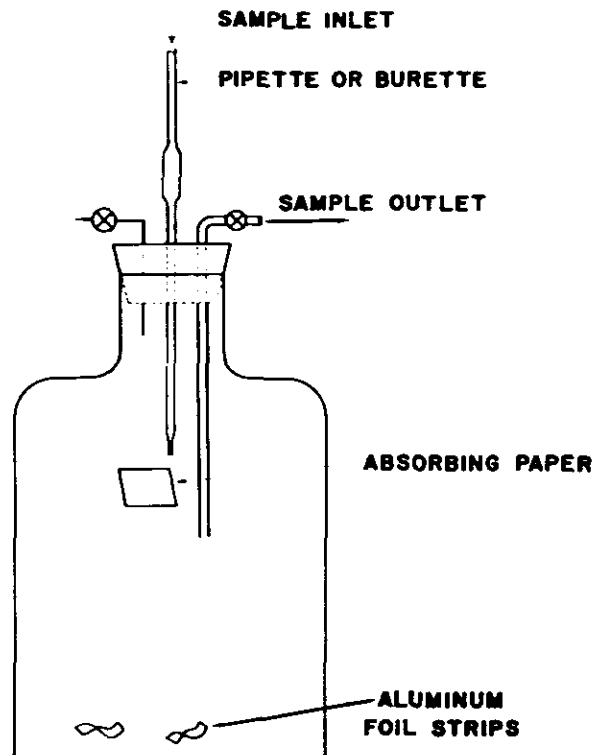
Known low concentrations of air contaminants are required for many purposes. There has been a technical explosion in recent years in the development of a great variety of monitoring instruments for measuring concentrations of air contaminants, based upon electronic means. These devices are invaluable; however, they are secondary measuring devices and must be calibrated. New chemical analytical procedures for air contaminants have been developed by extrapolating methods from the high concentrations at which they have been demonstrated to the low concentrations of interest. It is essential that these procedures be tested to demonstrate their validity. An extensive program of collaborative testing of methods at accurately known low concentrations is now beginning because of 1) the increase in regulatory activities and 2) the legal and economic consequence of measurements required to determine compliance. Another use for known concentrations is for toxicological and scientific investigations of the effects of these concentrations. Such work provides the basis for control standards. Thus known concentrations are essential for calibrating instruments, for collaborative testing of analytical methods and for scientific studies. When a highly precise system is employed, accurately known concentrations may be attained. With less accurate systems, the values are nominal. These may suffice for many purposes, or may be determined accurately by use of a standard or reference analytical procedure.

Two general types of systems are used for generating known concentrations. Preparation of a batch mixture has the advantage of simplicity and convenience in some cases. Alternatively, a flow-dilution system may be employed. This has the advantage of being capable of providing theoretically unlimited volumes at known low concentrations, which can be rapidly changed if desired, and of compactness. A flow-dilution system requires a metered source of diluent air, and a source for supplying known amounts of gases, vapors or aerosols; these flows are combined in a mixing device. The techniques will be described in detail below. Many articles have been published on this subject. Broad coverage is given in papers by Saltzman,¹ Cotabish et al.,² and Hersch.³ A comprehensive book by Nelson is cited in the Preferred Reading section.

PREPARATION OF BATCH MIXTURES OF GASES AND VAPORS

Introduction

Known concentrations of gases and vapors were first prepared by introducing accurately measured quantities of the test compound into an appropriate chamber containing clean air. Various modified systems have been developed for certain special purposes. These methods generally require relatively simple equipment and procedures. However, a serious disadvantage is the fact that only limited quantities of the mixture can be supplied. In certain cases erroneously low concentrations result from appreciable adsorption losses of the test substance on the walls of the vessel. Losses in excess of 50% are common.^{4,5} When air dilutions of solvents or other combustible materials are prepared, it should be borne in mind that there is a serious explosive hazard un-



Amer. Ind. Hyg. Assoc. J. 22:392, 1966.

Figure 12-1. 5 Gallon Mixing Bottle

less care is taken to keep the concentration outside of the explosive limits. These methods are convenient for many substances which are not too reactive. They may be used to prepare nominal concentrations, to be verified by chemical analyses. They should not be used as primary standards without such verification or prior experience.

Bottles

Figure 12-1 illustrates a simple technique for preparation of vapor mixtures utilizing a 5-gallon glass bottle. A quantity of volatile liquid is pipetted into the bottle onto a piece of paper to assist in its evaporation. The bottle may then be tumbled with aluminum foil inside to facilitate air and vapor mixing. The mixture is withdrawn through a glass tube from the bottom of the bottle rather than from the top to avoid leakage and losses occurring around the stopper. As the mixture is withdrawn, air enters the top of the bottle to relieve the vacuum. A sealed chamber may be used in a similar manner, with mixing provided by an electric fan. (Danger! Sparks from brushes may explode some mixtures!)

It can be seen that the disadvantage of this technique is that the concentration decreases during the withdrawal process. Assuming the worst possible case of complete turbulent mixing in the bottle or chamber, the change in concentration is given by equation 1.

$$C/C_0 = e^{-W/V} \quad (1)$$

Where C = final concentration in bottle or chamber

C_0 = initial concentration

W = volume withdrawn, liters

V = original volume of mixture, liters

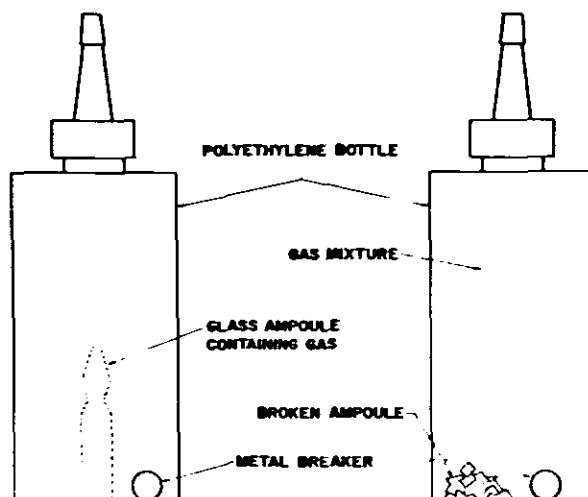
Some calculated values are shown in Table 12-1.

TABLE 12-1
Decrease in Concentration vs. Fractional Volume Withdrawn

W/V	0.05	0.10	0.25	0.50
C/C ₀	0.962	0.905	0.779	0.606

This table shows the maximum depletion errors produced by withdrawal of the mixture. Smaller errors result if the incoming air does not mix completely with the existing mixture. Up to 5% can be withdrawn without serious loss. These errors are avoided by use of plastic bags or pressure cylinders, as described below.

Figure 12-2 indicates a simple commercial assembly for calibrating explosive-gas meters. A sealed glass ampoule containing a hydrocarbon, such as methane, is placed inside a polyethylene bottle and broken by shaking against a steel ball. The mixture is then carefully squeezed into the instrument to be calibrated, taking care not to suck back air. Another similar instrument manufactured by Mine Safety Appliances Co. is comprised of a cartridge of isobutane which is used to fill a small syringe. This is injected into a larger syringe which is then filled with air. The latter syringe serves as a gas holder for the mix-



Amer. Ind. Hyg. Assoc. J. 22:392, 1966.

Figure 12-2. J-W Gas Indicator Test Kit

ture. These devices are relatively simple, convenient and sufficiently accurate for this purpose.

Plastic Bags

A variety of plastic bags have been found to be very useful for preparing known mixtures in the laboratory. Long term stability is generally good only with relatively inert vapors such as of halogenated solvents and hydrocarbons. Among the materials used have been Mylar, Scotchpak, Saran and polyvinyl chloride. Bags are fabricated from sheets by thermal sealing. Mylar bags are popular because of their strength and inertness. This material requires a special thermal plastic adhesive tape (Schjeldahl). Tedlar, Teflon and Kel-F are considerably more expensive materials, which also require expensive sealing equipment capable of providing regulated pressures and high temperatures. They are preferred for use in photochemical studies involving ultraviolet irradiation. Surprisingly, for most applications the less expensive materials give superior performance. Volatile contaminants may be baked out of the sheets by keeping them in an oven for a few days. A valve of the type used for tires, or a rigid plastic tube may be sealed to a corner to serve as the inlet. The inlet tube to the bag may be closed with a rubber stopper or serum cap, a cork or a valve according to the material being handled. Bags are available commercially. The 3' x 3' or 2' x 4' size contains over 100 liters.

The major advantage of using flexible bags is that no dilution occurs as the sample is withdrawn. These bags also are very handy for sampling purposes since the empty bags are transportable. Bags should be tested frequently for pinhole leaks. This may be done by filling them with clean air and sealing them. If no detectable flattening occurs within 24 hours, the leakage is negligible.

A simple arrangement may be used for preparing a known mixture in a plastic bag. The bag is alternately partly filled with clean air and then

completely evacuated several times to flush it out. Then clean air is metered into it through a wet or dry test meter. The test substance is added to this stream at a tee just above the entrance to the bag. If it is a volatile liquid, it can be injected with an accurate syringe through a septum. Sufficient air must subsequently be passed through the tee to completely transfer the injected material. When the desired volume has been introduced, the bag is disconnected and plugged or capped. Its contents may be mixed by gently kneading the bag with the hands.

Adsorption and reaction on the walls is no great problem for relatively high concentrations of inert materials.⁶ However, low concentrations of reactive materials such as sulfur dioxide, nitrogen dioxide and ozone are partly lost, even after prior conditioning of the bags.^{4,5,7,8} Larger sizes are preferable to minimize the surface-to-volume ratio. Losses of 5 or 10% frequently occur during the first hour, after which the losses are a few percent a day. Conditioning of the bags with similar mixtures is essential to reduce these losses. The similar or identical mixture is stored for at least 24 hours in the bag, and then evacuated just before use.

A recent compilation by Schuette⁹ lists the commercial sources of these plastic sheets and needed accessories. A tabulation is presented of uses described in 12 papers, listing the plastic material, the gas or vapor stored, their concentrations and comments. Another recent study¹⁰ focussed upon industrial hygiene applications. Good stability in Saran bags was found for mixtures containing benzene, dichloromethane and methyl alcohol; and for Scotchpak bags containing benzene, dichloromethane and methyl isobutyl ketone. Percentage losses were greater for lower concentrations (i.e., 50 ppm). Losses greater than 20% were observed in the first 24 hours for Saran bags containing methyl isobutyl ketone vapors, and for Scotchpak bags containing methyl alcohol vapors; however, concentrations stabilized after 2 to 3 days. These results are typical of those obtained by the other investigators previously cited.

It is difficult to draw generalized conclusions from these reports, other than the need for caution in applying plastic bags for low concentrations. Losses should be determined for each material in each type of bag. Even the past history of the bag must be considered. For laboratory applications properly conducted, known mixtures can be prepared very conveniently in plastic bags.

Pressure Cylinders

Preparation of certain gas mixtures can be done conveniently in steel cylinders.² This is very useful for mixtures such as hydrocarbons in air or carbon monoxide in air, which can be stored for years without losses. With other substances, there are losses due to factors such as polymerization, adsorption, or reaction with the walls. In some cases, as the pressure decreases in the cylinder, material desorbs from the walls and yields a higher final concentration in the cylinder than was initially present. Concentrations should be

low enough to avoid condensation of any component at the high pressure in the cylinder, even at the lowest temperature expected during its use. Care must be taken to use clean regulators, of appropriate materials, which will not adsorb or react with the contents of the cylinder. A serious safety hazard exists in preparation of compressed gas mixtures. As mentioned previously, there is a possibility of explosion of combustible substances. This may occur because of the heat of compression during a too rapid filling process. Excessive heat also may cause errors in the gas composition. Certain substances with a high positive heat of formation, such as acetylene, can detonate even in the absence of oxygen. Also, explosive copper acetylid can be produced if this metal is used in the manifolds and connections. Proper equipment, including armor-plate shielding, and experience are required for safe preparation. Because these and accurate pressure gauges are not ordinarily available, it is recommended that the mixtures be purchased from the compressed gas vendors who have professional staff, experience and equipment for such work. These vendors can prepare mixtures either by using accurate pressure gauges to measure the proportions of the components or by actually weighing the cylinders as each component is added. They also can provide an analysis at a reasonable extra charge; however, these figures are not always reliable.

Calculations

The calculations for preparation of batch mixtures are based upon the close adherence to the Perfect Gas Law that is usual at low partial pressures. Calculations for dilute gas concentrations are based upon the simple ratio of the volume of test gas to the volume of mixture, as shown in equation 2.

$$\text{P.P.M.} = 10^6 v/V \quad (2)$$

Where P.P.M. = parts per million by volume
 v = volume of test gas in mixture, liters
 V = volume of mixture, liters

In the case of volatile liquids the calculation is based upon the ratio of moles of liquid to moles of gas mixture, equation 3. The moles of liquid are determined by dividing the weight injected by the molecular weight of the liquid. The moles of gas mixture are calculated by dividing the total volume of mixture by the molecular volume calculated from equation 4 for the temperature and pressure of the mixture.

$$\text{P.P.M.} = \frac{10^6 w/M.W.}{V/\bar{V}} \quad (3)$$

$$\bar{V} = 24.47 \left(\frac{760}{P} \right) \left(\frac{t + 273.2}{298.2} \right) \quad (4)$$

where w = weight of volatile liquid introduced, grams

M.W. = gram molecular weight of liquid
 \bar{V} = gram molecular volume of mixture under ambient conditions, liters
 P = ambient pressure, Torr
 t = ambient temperature, °C

These calculations are illustrated by the following:

Example 1. A volume of 5 ml of pure carbon monoxide is added to a plastic bag into which 105 liters of air are metered. What is the concentration (ppm by vol.) of the carbon monoxide?

Answer:

$$\text{P.P.M.} = 10^6 \times 0.005 / 105 = 47.6$$

Example 2. A dish containing 12.7 g of carbon tetrachloride is placed in a sealed cubical chamber with inside dimensions of 2.1 meters for each edge. The final temperature is 22.5° C, and the barometer reading is 755 mm. Hg. What concentration (ppm by vol.) is achieved?

Answer:

$$\text{M.W. of CCl}_4 = 12.01 + 4 \times 35.457 = 153.84$$

$$\bar{V} = 24.47 \times \left(\frac{760}{755}\right) \times \left(\frac{295.7}{298.2}\right) = 24.43$$

$$\text{P.P.M.} = \frac{16^3 \times 12.7 / 153.84}{1000 \times (2.1)^3 / 24.43} = 217.7$$

FLOW-DILUTION SYSTEMS

Introduction

Flow-dilution systems offer the advantage of being very compact. Since it is possible to operate them continuously, there is no theoretical limit to the volumes of gas mixture that can be provided. In a properly designed system, concentrations can be changed very rapidly. Because of the relatively small gas volume of this system, the explosive hazard is less than that of batch systems. Any losses by adsorption on surfaces occur only in the initial minutes of operation. After a brief period, the surfaces are fully saturated and no further losses occur. Because of these advantages, flow-dilution systems are popular for accurate work with most substances.

Gas-Metering Devices

A variety of devices can be used to monitor the flows in a flow-dilution system. The accuracy of final concentration is, of course, dependent upon the accuracy of the measurements of the component flows. Rotometers are commonly used. Orifice meters and critical orifices are also frequently employed. The calibration equations and techniques are given in detail in Chapter 11. Because rotometers are very commonly used, a few points of importance to this application will be discussed.

The pulsating flows provided by the diaphragm pumps utilized in many systems may result in serious errors in most meter readings. Rotometer readings may be high by a flow factor of as much as 2, depending upon the wave form of the pulsating flow. It is therefore essential for accurate measurements to damp out such pulsations by assembling a train comprised of the pump, a surge chamber and a resistance, such as a partially closed valve. The error can be determined by running the pulsating flow through the rotometer and into a wet-test meter, and comparing the two measurements. The latter should be taken as correct. The reason for this error is that although the flowrate passing through the rotometer is pro-

portional to the first power of the gas velocity, the lifting force on the ball is proportional to the velocity raised to a power of between 1 and 2. For completely turbulent flows, which are common, the exponent is 2; in this case if the velocity fluctuates in a sine wave the ball position will correspond to the root mean square value, which is 1.414 times the correct mean value. If the wave form is spiked, even greater deviations occur.

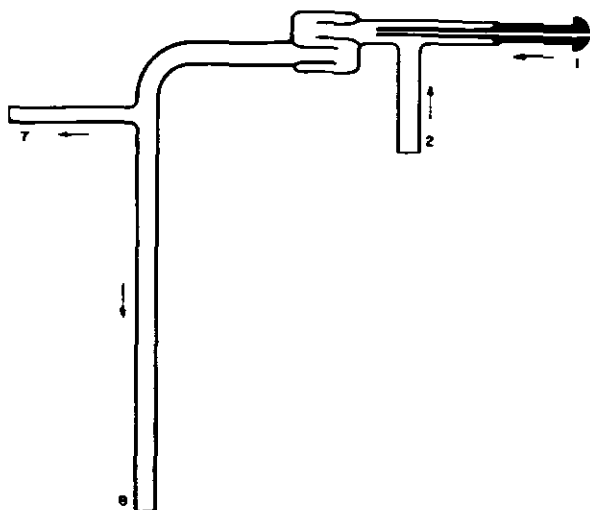
There are two types of corrections of flow meter calibrations for ambient pressure and temperature. The first is the correction to the actual flow because of the fact that the measured value is dependent upon the density and in some cases the viscosity of the gas flow, both of which are affected by ambient pressure and temperature. Application of the appropriate correction factor to the value from a calibration graph made under standard pressure and temperature conditions then will give the correct actual gas flowrate under ambient conditions. A second correction may be applied to convert the actual gas flowrate to that under standard conditions. This latter correction is made on the basis of the perfect gas equation. It should be kept clearly in mind that the first calibration correction is dependent upon the specific device being employed. The two bases, ambient or standard conditions, should not be confused, and the proper one must be employed for the application.

Construction and Performance of Mixing Systems

A flow-dilution system is comprised of a metered test substance source, a metered clean-air source and a mixer to dilute the test substance to the low concentration required. The total flow of mixture must be equal to or greater than the flow needed. It is highly desirable to use only glass or Teflon parts for constructing the system. Some studies have been made with metal and plastic tubing which have shown that these must be conditioned with the dilute mixtures for periods of hours or days before they cease absorbing the test substances.^{4,5,11}

Two other factors must be kept in mind in the construction of a mixing system. The pressure drops must be very small and the system should preferably be operated at very close to atmospheric pressure. Otherwise, any changes in one part of the system will require troublesome readjustment of the flows of other components. The interactions may require several time-consuming reiterative adjustments. The second factor to consider is that the dead volume of the system must be minimized to achieve a rapid response time. For example, assume that we are metering a flow of 0.1 ml/min. into a diluent air stream, and that the dead volume of the system to the dilution point is 1 ml. To accomplish one volume change will require 10 minutes. In order to be certain that this dead volume is completely flushed out, five volume changes are needed, corresponding to a time lag of 50 minutes before the full concentration of test gas reaches the dilution point.

Figure 12-3 illustrates a convenient all-glass system for making gas dilutions. The test gas is connected at the extreme right through a ball joint



Anal. Chem. 33:1100, 1961.

Figure 12-3. All Glass System

and capillary tube. The dilution air is metered into the side arm. A trap-like mixing device insures complete mixing with very little pressure drop. The desired flow can be taken from the side arm, and the excess vented through the waste tube which may be connected to a Tygon tube long enough to prevent entrance of air into the flow system. If desired, this vent tube can be run to a hood or adjacent window. By clamping down on the vent tube any desired pressure can be obtained in the delivery system.

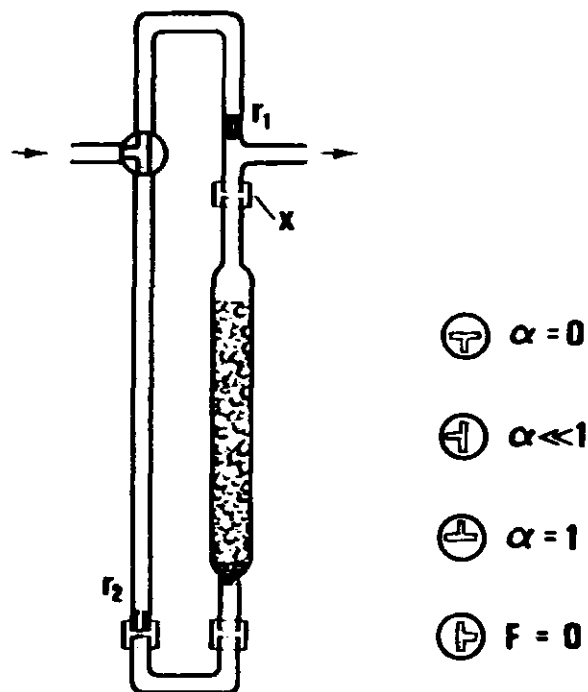
The dilution air must be purified according to the needs of the work. Air can be passed over a bed of carbon, silica gel, or ascarite, or bubbled through a scrubbing mixture of chromic acid in concentrated sulfuric acid if necessary. Another convenient method of purification is to pass the air flow through a universal gas mask canister. The purification system must be designed according to the specific needs of the work.

SOURCE DEVICES FOR GASES AND VAPORS

Introduction

A variety of source devices are described below for providing high concentrations of gases and vapors which can be diluted with pure air to the level desired. Each possesses specific advantages and disadvantages. Selection of a device depends upon the needs of application and the equipment available to the user. Figure 12-4 shows a self-dilution device that can be generally applied to reduce the concentration provided by the source when necessary for work at very low concentrations. The flow of gas or vapor passes through two branches in proportions determined by restricters R_1 and R_2 . An appropriate absorbent such as carbon, soda lime, etc. in the latter branch completely removes the gas or vapor from the stream. Thus the combined output of the two

branches provides the same flow at a fractional concentration of the input depending upon the relative values of the two flow restricters. Furthermore, rotation of the three-way stopcock also provides either the full concentration or zero concentration, or completely cuts off the flow.



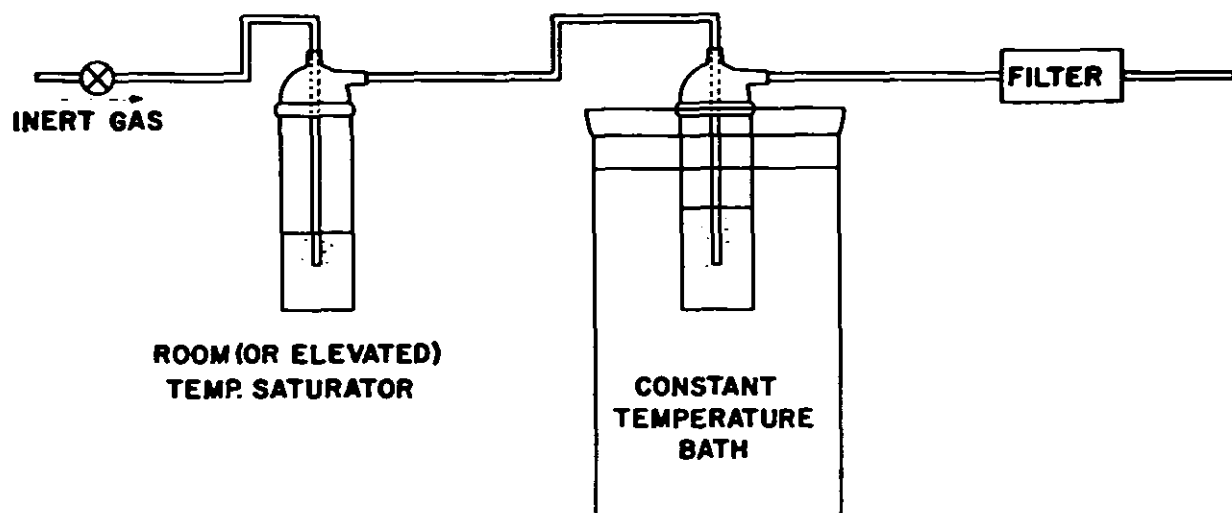
J. Air Pollution Control Assoc. 19:164, 1969.

Figure 12-4. Self-Dilution Device

Vapor Pressure Method

Figure 12-5 illustrates the vapor pressure method for providing a known concentration of a volatile liquid. A flow of inert gas or purified air is bubbled through a container of the pure liquid. Liquid mixtures are less desirable because the more volatile components evaporate first and the vapor concentrations change as the evaporation proceeds. In the common bubbler only 50 to 90% of the saturation vapor pressure is usually obtained. Equilibrium concentrations therefore are obtained by operating the bubbler at ambient or elevated temperature and passing the vapor mixture through an accurately controlled constant temperature bath which cools it down. The excess vapor is condensed, and the final concentration is very close to equilibrium vapor pressure at the cooling bath temperature. A filter must be included to insure that a liquid fog or mist does not escape. It is desirable to operate the constant temperature bath below ambient temperature so that liquid does not condense in the cool portions of system downstream. The application of this method to carbon tetrachloride has been described recently.¹²

Another version of this arrangement is shown in Figure 12-6. This utilizes a wick feed from a small bottle containing the additive as a source of



Amer. Ind. Hyg. Assoc. J. 22:392, 1966.

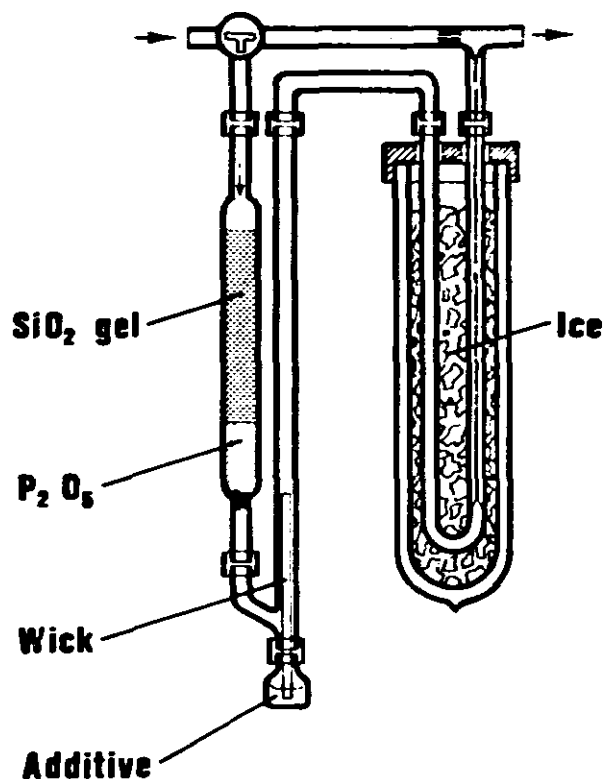
Figure 12-5. Vapor Saturator

the vapor, and an ice bath for the constant temperature.

Motor Driven Syringes

Figure 12-7 illustrates a system using a 50 or 100-ml glass hypodermic syringe which is driven

by a motor drive at uniform rates that can be controlled to empty it in periods varying from a few minutes to an hour. A gas cylinder containing the pure component or mixture is connected at the right side. The bubbler is a safety device to protect the glass apparatus from excessive pressures if the tank needle valve is opened too wide. The tank valve is cautiously opened and a slow stream of gas vented from the bubbler. The syringe is manually filled and emptied several times to flush it with the gas. This is done by turning the three-way stopcock so that on the intake stroke the syringe is connected to the cylinder and on the discharge stroke to the delivery end. After flushing, the syringe is filled from the cylinder and the motor drive is set to discharge it over the desired period of time. This motor drive should include a limit switch to shut off the motor before it breaks the syringe, and a revolution counter for measuring the displacement. From the known gear ratio, the screw pitch and a measurement of the plunger diameter with a micrometer, the rate of feed can be calculated with an accuracy and reproducibility of parts per thousand.



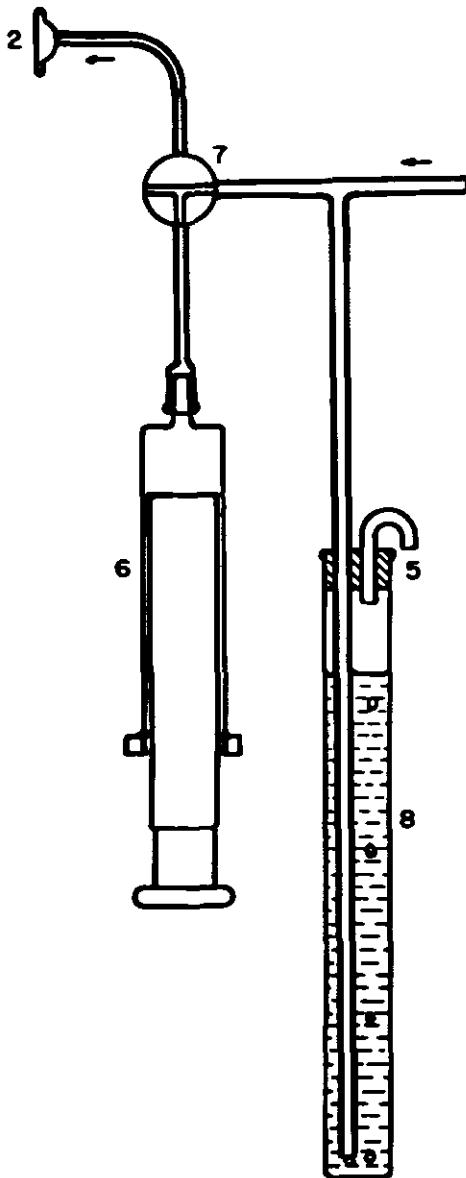
J. Air Pollution Control Assoc. 19:164, 1969.

Figure 12-6. Vapor Saturator

At low delivery rates the back diffusion of air into the syringe from the delivery tip may cause an error. Thus, if the syringe is set to empty over a one-hour period, towards the end as much as half of the gas mixture contents could be air that has diffused in backwards. This error is easily minimized by inserting a loose glass wool plug in the delivery system and using capillary tubing for the delivered flow.

Diffusion Systems

Figure 12-8 illustrates a diffusion system that can provide constant concentrations of a volatile liquid. The liquid is contained in the bottom of a long thin tube and is kept at a constant known temperature. As the air flow is passed over the top, vapor diffuses up through the length of the



Anal. Chem. 33:1100, 1961.

Figure 12-7. Motor Driven Syringe

tube at a reproducible rate and mixes with the stream. The rate is determined by the vapor pressure of the liquid, the dimensions of the tube and the diffusion constants of the vapor and of air. If substantial amounts of a liquid are evaporated and the liquid level drops, the diffusion path length increases slightly. The quantity of liquid evaporated can be determined from volume markings on the tube or by weighing the tube at the beginning and end of the period of use. Experimental values have been tabulated and the limitations of this method described.⁽¹²⁾

Porous Plugs

Figure 12-9 illustrates a micrometering system^{1,14} that both measures and controls small flows of gas in the range of 0.02 to 10 ml/min.

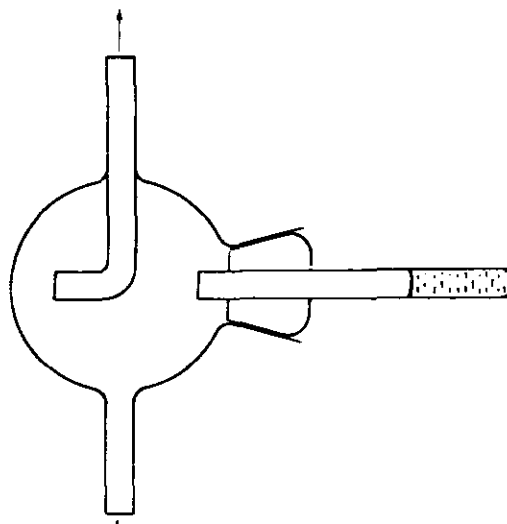


Figure 12-8. Diffusion System

This is based on the principle of diffusion of test gas through an asbestos plug under a controlled pressure difference. The input is connected to a

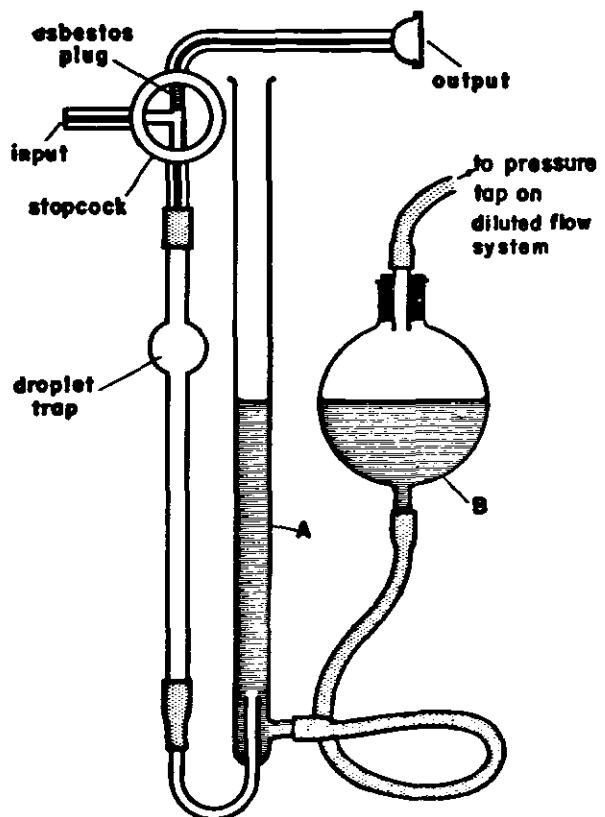


Figure 12-9. Micrometering System

cylinder containing pure gas or gas mixture. The asbestos plug is contained in one leg of the "T" bore of a 3-way stopcock as shown in the figure. The asbestos fiber is acid-washed, of the type used in the laboratory for Gooch crucibles. The degree of tamping is determined by trial and error to provide the desired flow range. The cylinder needle valve is opened cautiously to provide a few bubbles per minute from the waste outlet in the lower portion of the figure. The height of water or oil above the waste outlet determines the fixed pressure on the lower face of the asbestos plug, which produces a fixed rate of diffusion of the gas through the plug to the capillary delivery tip. The meter is calibrated by connecting the delivery end to a graduated 1-ml pipette with the tip cut off, containing a drop of water. The motion of the drop past the markings is timed with a stop watch. This is repeated for different heights of liquid obtained by adjustment of the levelling bulb. The calibration plot of flowrates in ml/min. against the heights of liquid over the waste outlet in cm. is usually a straight line passing through the origin. The gas cylinder should never be disconnected until the liquid pressures equalize; otherwise the liquid may surge up and wet the asbestos plug. If this occurs, it must be discarded, the bore dried and repacked and the new plug calibrated.

This device is a very convenient and precise method for metering low flows in the indicated range. The output flow remains constant for weeks, but should be checked occasionally. The delivery tip is connected to the mixer shown in Figure 12-3. For low delivery rates, the dead volume is minimized by using capillary tubing.

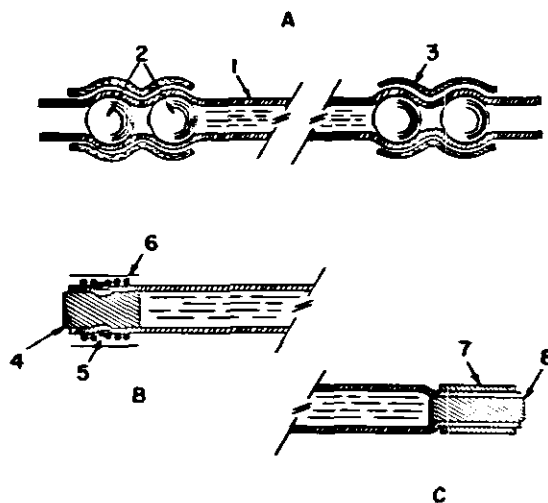
The levelling bulb vent is connected to a tap on the diluted gas manifold. This provides a correction for back pressure of the system into which the flow is being delivered. An appreciable back pressure changes the pressure differential across the asbestos plug. The bulb vent connection causes the liquid level to rise in the vent tube. If the vent area is small compared to the area of the liquid surface in the bulb, this compensates almost exactly for the back pressure by increasing the upstream pressure on the plug enough to maintain a constant pressure differential.

Permeation Tubes

Permeation tubes are very useful sources for liquifiable gases. Because of their potential precision, recent collaborative tests of methods have employed them when applicable. The National Bureau of Standards now certifies the sulfur dioxide type. Because of their importance as primary standards, they are described below in some detail.

In these devices the liquid is sealed under pressure in inert Teflon tubes. The vapor pressure may be as high as 10 atmospheres. The gas permeates out through the walls of the tube at a constant rate of a few milligrams per day for

periods as long as a year. Figure 12-10 illustrates three types of seals: steel or glass balls, a Teflon plug bound with wire and a Teflon plug held by a crimped metal band. Figure 12-11 shows some other types of seals and construction. In order to

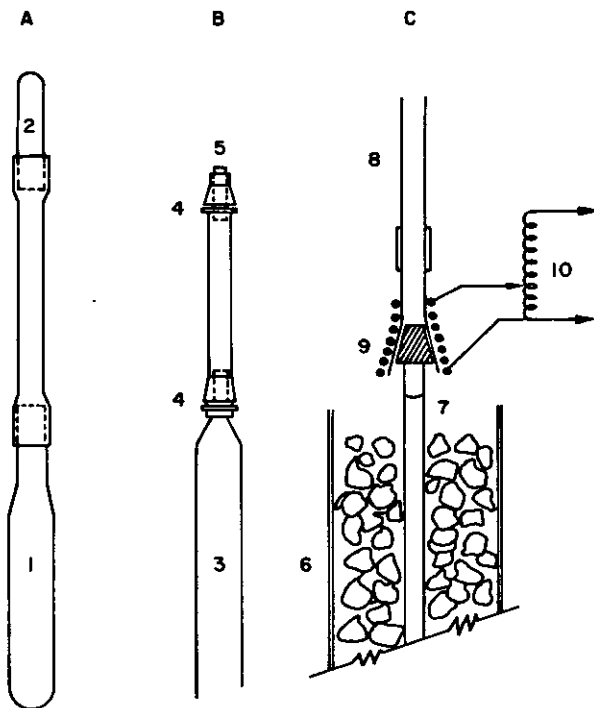


International Symposium on Identification and Measurement of Environmental Pollutants, c/o National Research Council of Canada, Ottawa, Ontario, Canada, 1971.

Figure 12-10. Three Types of Seals: (1) Steel on Glass Balls, (2) a Teflon Plug Bound with Wire, and (3) a Teflon Plug Held by a Crimped Metal Band

extend the lifetime of some tubes, a glass or stainless steel bottle containing the liquified gas may be attached to the Teflon tubing, as shown in Figure 12-11A or B. At low pressure, such as in permeation tubes containing nitrogen dioxide (b.p. 21.3°C), a sufficiently tight seal may be obtained by pushing the Teflon tube onto the neck of the glass bottle and by pushing a glass plug in at the top. For higher pressures, such as in tubes containing propane (vapor pressures 10 atm. at 25°C), a stainless steel bottle is used, as shown in Figure 12-11B. The seals are made by crimping ¼" Swagelok ferrules on the ends of the Teflon tube. Another type of seal is illustrated in Figure 12-11C in which a FEP Teflon plug is fused to a FEP Teflon tube by means of heat.

All tubes, especially if the contents are under pressure, should be handled with caution. If they have been chilled in dry ice during filling, room for expansion of the liquid upon warming to ordinary temperatures should be provided. Tubes should be protected from excessive heat. They should not be scratched, bent, or mechanically



Env. Sci. Tech. 5:1121, 1971.

Figure 12-11. A & B. A Glass or Stainless Steel Bottle Attached to Teflon Tubing
Figure 12-11C. An FEP Teflon Plug Fused to an FEP Teflon Tube

abused. After a new tube has been prepared, several days or weeks are required before a steady permeation rate is achieved at a thermostated temperature. Saltzman, Burg, et al.¹⁷ reported that tubes made of FEP Teflon should be annealed at 30°C for a period in order to equilibrate the Teflon and achieve a steady rate. Otherwise, a pseudo-stable rate is achieved which is not reproduced after appreciable temperature fluctuations.

Gravimetric calibrations may be made by weighing the permeation tubes at intervals and plotting the weight against time. The slope of the line fitted by the method of least squares to the measured points is the desired rate. This process may take as long as several weeks with an ordinary balance because of the necessity of waiting to obtain measurable weight differences. However, if a good micro balance is available, the calibration can be shortened to a day. Static charges which develop on some permeation tubes can cause serious weighing errors unless discharged with a polonium strip static eliminator. For a corrosive gas, the balance may be protected from corrosion by inserting the permeation tubes into glass-stoppered weighing tubes. The weight history of a nitrogen dioxide tube over a 37 week period is shown in Figure 12-12. The tubes are used by passing a metered air flow over them in a vessel thermostated to $\pm 0.1^\circ\text{C}$, as illustrated in

Figure 12-13. Close temperature control is essential because the temperature coefficient is high.

A relatively inexpensive apparatus may be used for volumetric calibration purposes^{16,17} which makes possible a calibration in less than an hour. A Gilmont Warburg compensated syringe manometer measures the evolved gas from a permeation tube with a sensitivity of 0.2 microliter.

Exposures of some types of permeation tubes must be very carefully controlled. Thus, nitrogen dioxide tubes exposed to high humidity develop blisters and long term changes in permeation rates; even the moisture content of the flowing gas passing over the tube affects the rate. These effects are likely due to the formation of nitric acid within the Teflon walls and/or inside the tube in the liquid nitrogen dioxide. A similar problem occurs with hydrogen sulfide tubes, which precipitate colloidal sulfur within the walls of the tube when exposed to oxygen. It is therefore desirable never to remove such tubes from their operating environments. Figure 12-14 illustrates a system which accomplishes this. A slow stream (50 ml/min.) of dry nitrogen from a cylinder is passed over the tube to flush away the permeated gases. This stream can be blended with a metered pure air flow in a flow dilution system to produce known concentrations of the gas. When calibration is desired, the gas flow from the nitrogen cylinder is temporarily shut down and a volumetric calibration performed within an hour or so. High precision has been obtained in this manner.

The quantitative relationships for permeation through a tube of unit length are given¹⁶ by equation 5:

$$G = 730 P \times \text{M.W.} \times p_1 / \log(d_2/d_1) \quad (5)$$

where G = mass permeation rate, $\mu\text{g}/\text{min.}$ per cm of tube length

P = permeation constant for the gas through the plastic, in $\text{cc}(\text{STP}) \text{ cm}/\text{cm}^2\text{sec}(\text{cm Hg})$

M.W. = molecular weight of gas

d_2 = outside diameter of tube

d_1 = inside diameter of tube

p_1 = gas pressure inside tube, mm Hg

\log = logarithm to base 10

The permeation rates have high temperature coefficients. Equation 6 shows the usual relationship in the form of the Arrhenius equation.

$$\log \left(\frac{G_2}{G_1} \right) = \frac{E}{2.303 R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \quad (6)$$

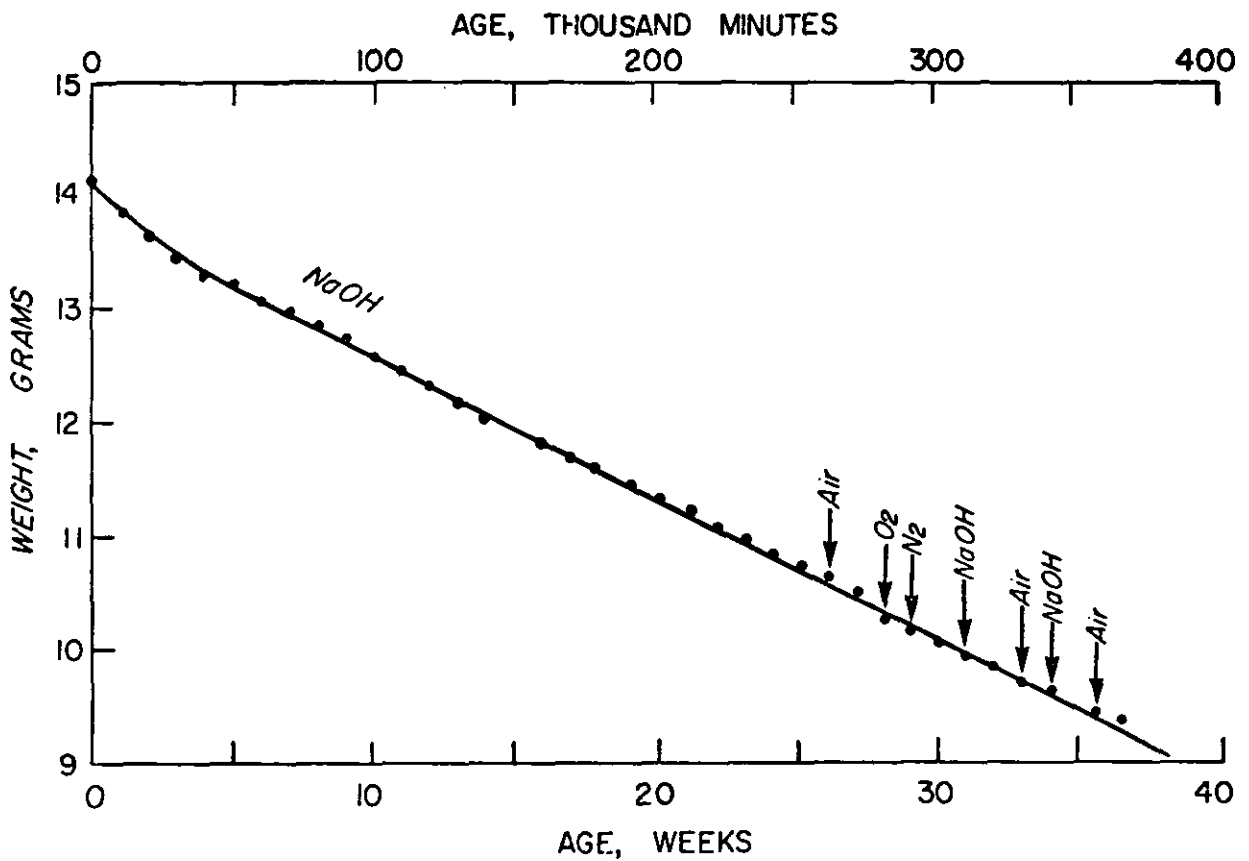
where G_1, G_2 = gravimetric rates at different temperatures

T_1, T_2 = corresponding temperatures, $^\circ\text{K}$ ($= ^\circ\text{C} + 273.16$)

E = activation energy of permeation process, $\text{cal}/\text{g mol}$

R = gas constant, $1.9885 \text{ cal}/\text{g mol } ^\circ\text{K}$

Table 12-2 lists permeation rates for various tubes, some of which are commercially available, together with some data for activation energies.



Env. Sci. Tech. 5:1121, 1971.

Figure 12-12. Weight History of a Nitrogen Dioxide Tube over a 37-Week Period

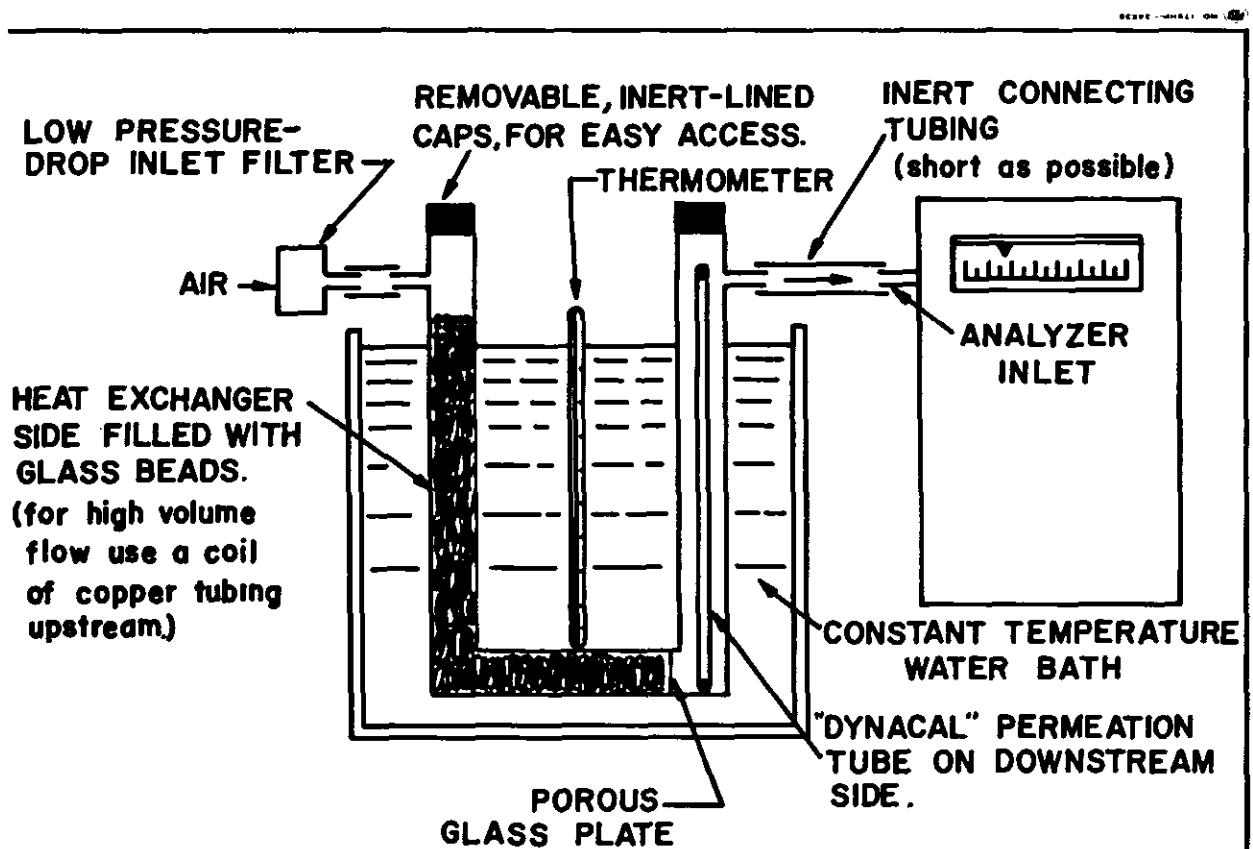
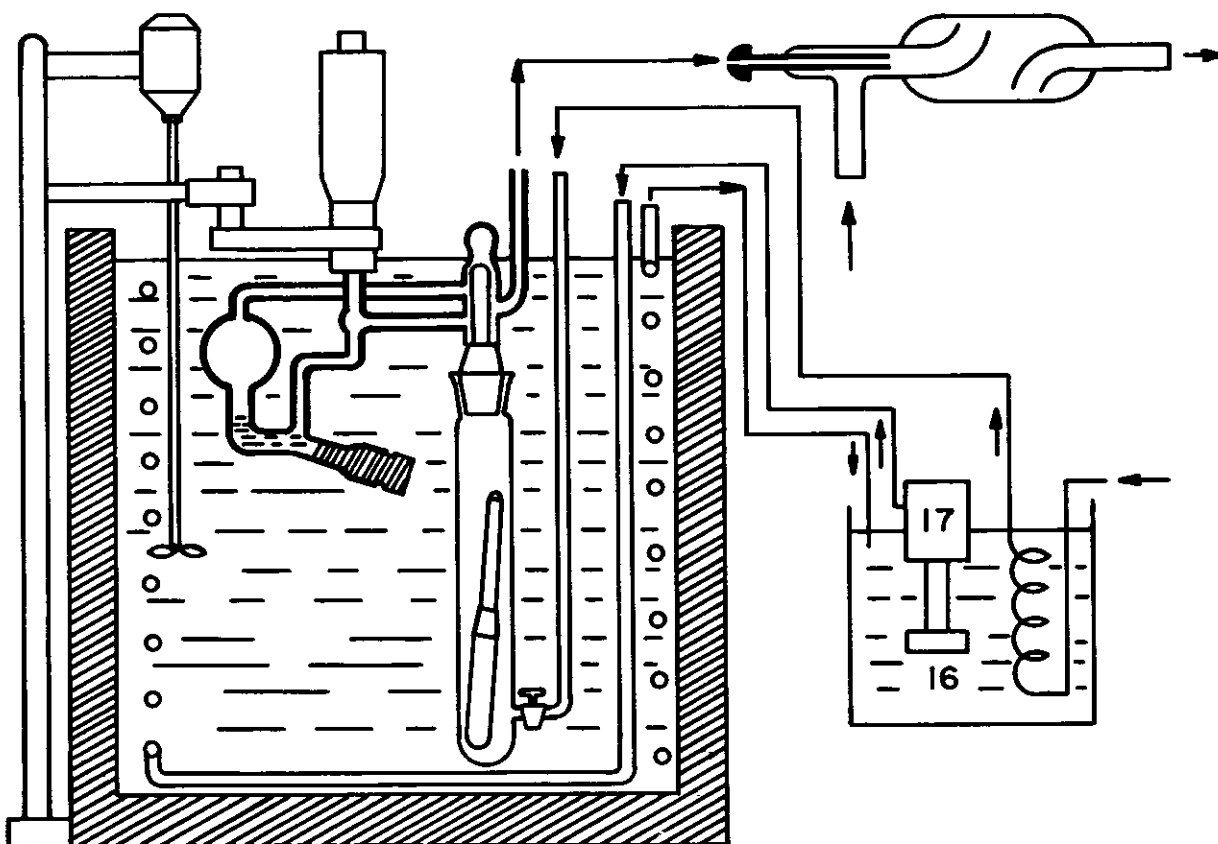


Figure 12-13. Passage of a Metered Air Flow over Tubes



Env. Sci. Tech. 5:1121, 1971.

Figure 12-14. A System Never Requiring Removal of Tubes From Their Operating Environment

Table 12-2
PERMEATION RATES FOR SOME TEFLON PERMEATION TUBES¹⁶

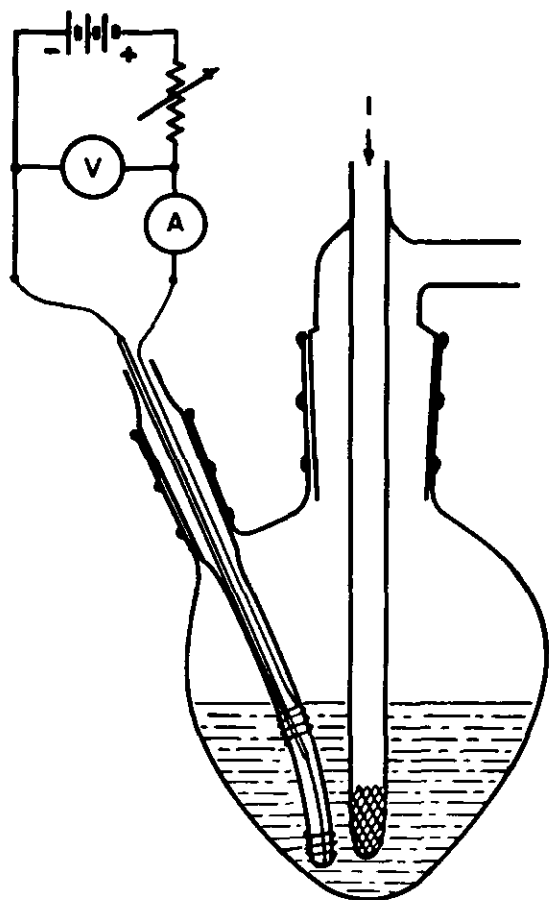
Rates are in ug/min. cm
Activation Energies, E, are in Kcal/g. mol

Substance	Dynacel Tubes ^a		A.I.D. Tubes ^b	FEP Teflon ^c		TFE Teflon ^c	
	Rate	E		Rate	Rate	E	Rate
SO ₂	0.422	13.8	0.279				
NO ₂	1.714	14.7	1.230	2.09	14.6		
HF	0.185						
H ₂ S	0.457	16.0	0.229				
Cl ₂	2.418	14.0	1.430				
NH ₃	0.280		0.165				
CH ₃ SH	0.036	10.0	0.030				
Propane	0.080	15.0	0.035	0.132	16.2	1.86	13.0
Propene	0.240			5.13	15.4		
n Butane			0.012	0.024	15.8	0.258	12.7
Butene-1				0.0316	14.8	0.368	12.4

^a Available from Metronics Associates, Inc., Palo Alto, Calif. 94304. Tubes are 3/16" O.D., 1/8" I.D. Rates are at 30°C.

^b Available from Analytical Instrument Development, Inc., West Chester, Pa. 19380. Tubes are FEP Teflon, 0.250" O.D. and 0.062" wall thickness except for methyl mercaptan, which is 0.030" wall thickness. Rates are at 30°C.

^c 0.250" O.D. and 0.030" wall thickness, as reported by Saltzman et al.¹⁷ Rates are at 25°C.



Anal. Chem. 33, 1100, 1961.

Figure 12-15. Electrolytic Generator

Miscellaneous Generation Systems

Figure 12-15 illustrates an electrolytic generator that was developed¹ as a suitable source of arsine and stibine. The solution is electrolyzed by passing a DC current through the platinum wire electrodes (0.41 mm diameter x 3 cm long) shown in the figure. The lower electrode is the cathode at which hydrogen and small quantities of arsine or stibine are liberated. The stream of purified air bubbles through the fritted tube end near the cathode and flushes the gas mixture into the outlet. At low current densities there was an appreciable time lag before arsine or stibine appeared. The generation rate of arsine or stibine was not proportional to the current but was accelerated at higher currents. To achieve high current densities wire electrodes rather than plates were used.

Another system used successfully was an aerated chemical solution mixture.¹ Thus, a 30% w/v solution of potassium cyanide served as a source of hydrogen cyanide. A relatively constant concentration could be obtained for as long as 10 hours. The strength and pH of the solution affected the concentration of hydrogen cyanide

produced. The air bubbled through the solution should be free from carbon dioxide, since carbonic acid can displace hydrogen cyanide. Because the dissolved salt tended to crystallize at the air inlet and plug it, the aeration was stopped every hour for a few moments to allow the solution to re-enter the inlet and redissolve the accumulated salt. In another application, hydrogen chloride was obtained by aeration of a 1 : 1 concentrated hydrochloric acid-water mixture. Bromine was obtained by aerating saturated bromine water in contact with a small amount of liquid bromine. In all of these procedures it is, of course, desirable to thermostat the bubbler to provide constant concentrations.

An interesting technique for preparing highly reactive or unstable mixtures is to utilize chemical conversion reactions. A stable mixture of a suitable compound is passed over a solid catalyst or reactant to produce the desired substance in the air stream. A table of reactions presented by Hersch² indicated some of these possibilities. Others may be determined from the literature. Multistep conversions also may be utilized.

SOURCE DEVICES FOR AEROSOLS

Introduction

Preparation of aerosol mixtures is much more complex and difficult than that of gas and vapor mixtures. A major consideration is the size distribution of the particles. Commonly a log normal distribution describes the values; this is characterized by a geometric mean and a standard geometric deviation. The usual aerosol source device supplies a range of sizes. However, certain special types supply uniform-sized particles. If the standard geometric deviation is less than 1.1, the particles are considered homogeneous, or monodisperse. There is also a great variety of particular shapes, including spherical, crystalline, irregular, plate-like, spiked, and rod-shaped or fibrous. If the material is a mixture of compounds, the composition may vary with size. Certain substances may be present on the surfaces, which also can be electrostatically charged. All of these properties are affected by the source devices and the methods of treatment. In the generation of known concentrations of aerosols, the choices of the operating parameters are determined by the objectives of the study, which may be to duplicate and study a complex aerosol existing naturally or in industry, or to prepare a simple pure aerosol for theoretical examination. A good general treatment of this subject with 257 references was published by Raabe.¹⁸

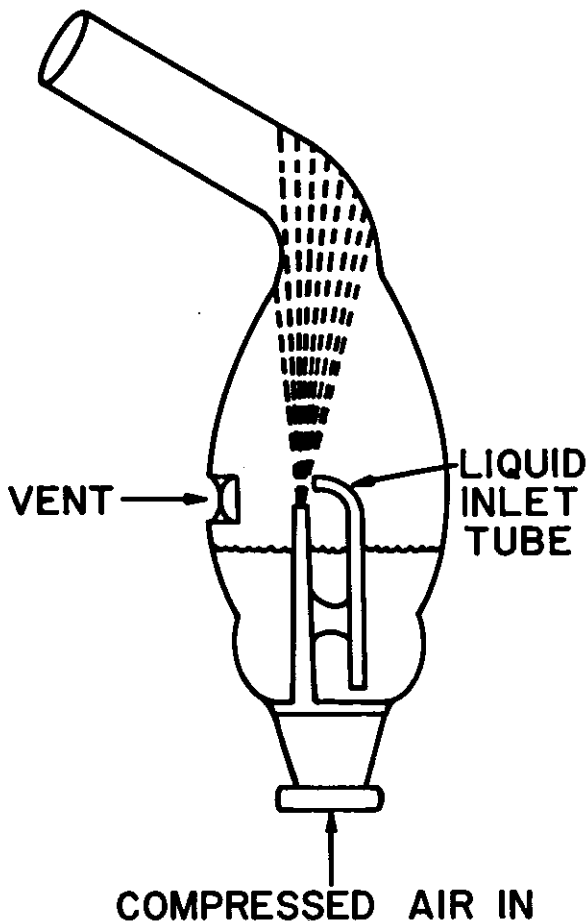
Dry Dust Feeders

A comprehensive description of methods of producing solid aerosols was given by Silverman and Billings.¹⁹ One of the most convenient and widely used methods is to redisperse a dry powder. Standard test dusts are available, such as road dust, fly ash, silicates, silica, mineral dust and many pigment powders and chemicals. Because these may tend to agglomerate, the degree of packing of the powder must be controlled and reproducible. A simple method consists of shaking the

powder on a screen into the air stream. Mechanical systems attempt to provide a constant feed rate by use of moving belts or troughs, or by rotating turn tables, screws or gears. Because of the erratic behavior of loosely packed dust, the popular Wright dust feed mechanism achieves closer control by compressing the dust in a tube into a uniform cake. A rotating scraper advanced by a screw slices off a thin layer of the cake continuously. In all of these devices the dust is dispersed by an air jet, which also serves to break up some aggregates. The dusty cloud is passed into a relatively large chamber, which serves to smooth out any rapid fluctuations. Concentrations may fluctuate $\pm 20\%$ over a period of a half hour, due to variations in the packing of the dust or laminations in the cake. Settling chambers, baffles, or cyclones may be added to the system to remove coarse particles, and ion sources to remove electrostatic charges.

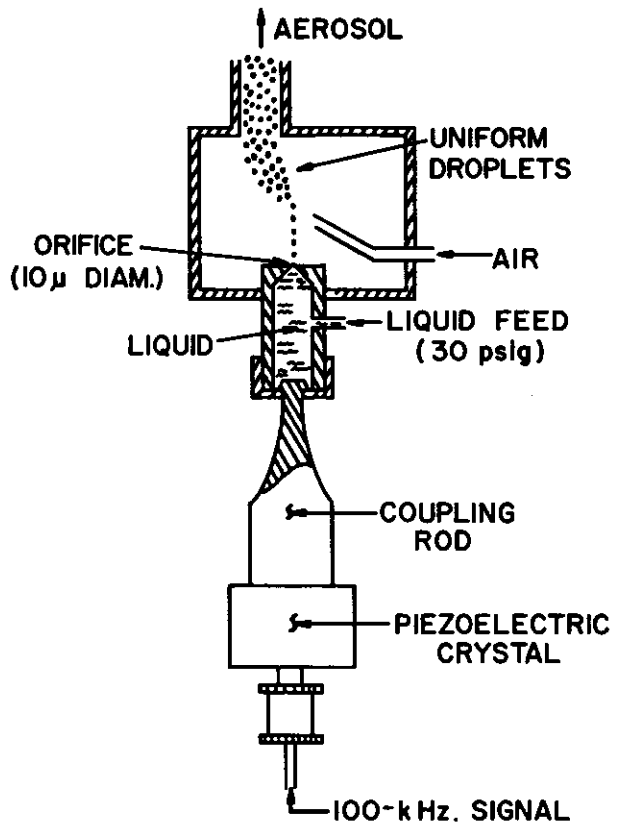
Nebulizers

The compressed air nebulizer, Figure 12-16, is a convenient and useful device to produce aerosols from liquids. The liquid stream is drawn through a capillary tube and shattered into fine droplets by the air jet. The DeVilbiss nebulizer



Amer. Ind. Hyg. Assoc. J. 29.66, 1968.

Figure 12-16. Compressed Air Nebulizer



Inhalation Carcinogenesis, April 1970 (CONF0691001, AEC Symposium Series 18).

Figure 12-17. Ultrasonic Droplet Generator

is simple, but holds only about 10 ml of liquid. Modifications can be added,¹⁸ such as utilizing a recirculating reservoir system for the liquid (Lauterbach), providing baffles to intercept and return coarse droplets (Dautrebande), droplet shattering baffles (Lovelace) and nozzle controls. The characteristics of these devices have been described in detail.²⁰

Rather coarse sprays are obtained by pumping the liquid mechanically through tangential nozzles, as is done in fuel oil burners. The air flow merely carries off the droplets. Somewhat different is the ultrasonic droplet generator, Figure 12-17, which utilizes an intense acoustic field to produce fine droplets. In the version illustrated the pressurized liquid is ejected from the orifice as a fine stream, which is disrupted by the vibrations of the coupling rod into remarkably uniform-sized droplets (coefficient of variation $< 1\%$).

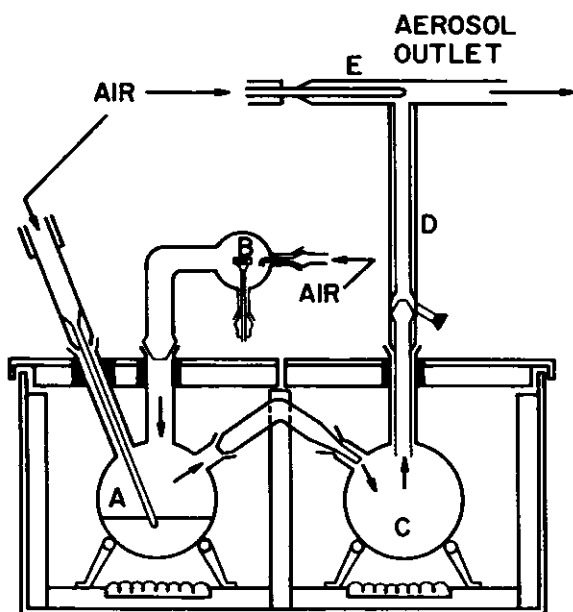
Commercial aerosol cans utilize a mixture of liquid to be atomized and a volatile propellant (usually a Freon compound such as dichlorodifluoromethane). The rapid evaporation of the propellant from the liquid emerging from the nozzle orifice shatters the stream into droplets having a broad size range. Electrostatic dispersion also has been utilized to break up a liquid stream by electrically charging the orifice. The droplets

should be discharged by passage near an ion source soon afterwards.

These liquid sources can be readily applied to supply solid aerosols by dispersing a solution or colloidal suspension. The solvent evaporates from the droplets naturally or upon warming, leaving a smaller particle of crystalline solute, or a clump of one or more colloidal particles according to their theoretical probabilities of occurrence in the volume of the droplet. The nature of the materials and of the drying process often affects the nature of the particles, which may exhibit shells or crusts. Passing the particles through a high temperature zone may be employed to chemically decompose them (e.g., production of metal oxides from their salts) or to fuse them into spherical particles.

Vaporization and Condensation of Liquids

The principle of vaporization and condensation was utilized in the Sinclair-LaMer generator for materials such as oleic acid, stearic acid, lubricating oils, menthol, dibutyl phthalate, dioctyl phthalate and tri-*o*-cresyl phosphate, as well as for sublimable solids. The system is illustrated in Figure 12-18 (from Fuchs and Sutugin—see



Davies CN (ed): *Aerosol Science*. New York, Academic Press, 1966.

Figure 12-18. Sinclair LaMer Generator

Preferred Reading). Filtered air or nitrogen is bubbled through the hot liquid in the flask on the left. Another portion of the entering air is passed over a heated filament coated with sodium chloride, to provide fine condensation nuclei. The vapor passes into the empty superheater flask on the right, in which any droplets are evaporated, and then up the chimney in which it is slowly cooled. The supersaturated vapor condenses on the sodium chloride particles to produce a monodisperse aerosol. Although the condensation nuclei vary in size they have only a slight effect on

the final aerosol droplet size, which is much larger. This system has been widely utilized as a convenient monodisperse source in the 0.02 to 30 micron size range.

Spinning Disc Aerosol Generators

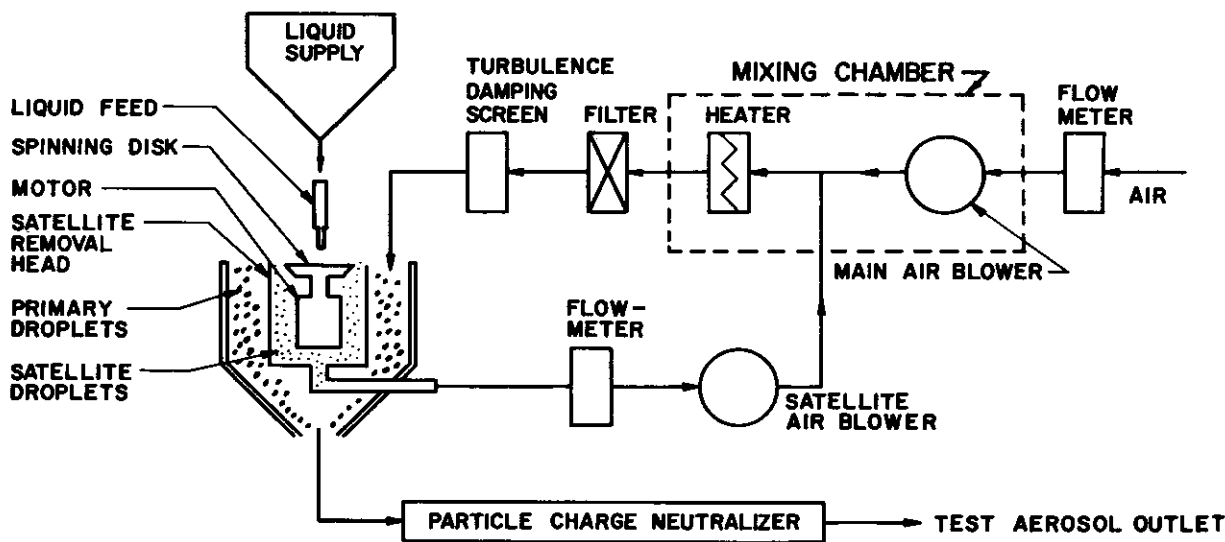
A very useful generator for monodisperse aerosols is based upon feeding the liquid continuously onto the center of a rapidly spinning disc (60,000 rpm). When the droplet on the edge of the disc grows to a sufficient size, the centrifugal force exceeds that of surface tension and the droplet is thrown off. A commercial system, illustrated in Figure 12-19, produces liquid droplets in the 1 to 10 micron size range. Smaller satellite drops are diverted down by an air stream into a compartment around the disc. The larger particles escape to the outer compartment, and are passed around a sealed radioactive ion source to remove the electrostatic charges, then to the outlet. Solid particles also can be generated from solutions and suspensions. The sizes are controlled by varying the concentrations.

Miscellaneous Generation Systems

Many dusts can be produced by means duplicating their natural formation. Thus, hammer or impact mills, ball mills, scraping, brushing and grinding of materials have been employed. Combustion (e.g., tobacco smoke), high voltage arcing, and gas welding or flame cutting torches can be used. Organic metallic compounds (e.g., lead tetraethyl) may be burned in a gas flame. Metal powders can be fed into a flame, or burned spontaneously (thermit and magnesium). Molten metals may be sprayed from metallizing guns. Metal wires can be vaporized by electrical discharges from a bank of condensers. A fluidized bed may be utilized as a reproducible source of particulate material. Gaseous reactions also may be employed to produce aerosols, such as reaction of sulfur trioxide with water vapor, or of ammonia and hydrogen chloride. Finally, photochemical reactions can be utilized. The natural process for producing oxidative smog has thus been duplicated by irradiating automobile exhaust.

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Figure 12-19 Spinning Disc Aerosol Generator

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SAMPLING AIR FOR PARTICULATES

S. A. Roach, Ph.D.

INTRODUCTION

The particulates of significance to industrial hygienists include all particles, solid or liquid, which are suspended in air and may be inhaled. The particles may be of all sizes from molecular dimensions up to about 100 microns in diameter. The three main types of particulates are dust, mist and fume.

Primary Airborne Dust

Primary airborne dust consists of solid particles rendered airborne during the crushing, grinding or attrition of hard, rock-like materials. Dust particles generally have irregular shapes.

Secondary Airborne Dust

Secondary airborne dust is produced by dispersion into the air of fine powder from a bulk source or from previously settled primary airborne dust. Airborne particles, on close examination, are often found to consist of clumps or aggregates of smaller particles adhering together.

Mist

A mist is formed from a material which is liquid at room temperature. Mist particles are the airborne droplets rendered airborne by bubbling, boiling, spraying, splashing or otherwise agitating a liquid and also by condensation from air super-saturated with the vapor of the substance. Mist particles are generally spherical in shape.

Primary Fume

A fume is formed from a material which is solid at room temperature. Fume, like certain mist formations, is produced by condensation from air super-saturated with the vapor of the material. More commonly, fume is the airborne solid particulate formed in the air above molten metal, by vaporization of the metal, oxidation of the vapor and condensation of the oxide. Fume particles generally have irregular shapes.

Secondary Fume

Secondary airborne fume is produced by dispersion into the air of fume from a bulk source or by redispersion of settled primary fume. The airborne particles of secondary fume are almost always much coarser than those of the primary type, consisting of clumps of innumerable, very fine particles.

Sampling is performed by drawing a measured volume of air through a filter, impingement device, electrostatic or thermal precipitator, cyclone or other instrument for collecting particulates. The concentration of particulate in air is denoted by the weight or number of particles collected per unit volume of the air sample. The weight of collected material is determined by direct weighing or by chemical analysis, as appropriate.

The number of particles collected is determined by counting the particles in a known portion of the sample. This is accomplished using a microscope with a travelling stage and eyepiece graticule or with an automatic particle counter. The size of the particles is determined by separating them according to size during sampling or by separating out the different sizes of collected particulate in the laboratory, using a microscope (Walton, 1954)¹ or liquid settling (Drinker and Hatch, 1954).²

When a particle is released from rest and falls in air, it is subject to the downward force of gravity and the opposing aerodynamic drag of the atmosphere. Balance between these forces is readily attained and the particle falls with a steady velocity known as its terminal velocity. Over a wide range of sizes, from approximately 1 to 50 microns, the terminal velocity is proportional to the specific gravity of the particle, ρ , and the square of its diameter, d . When the diameter is expressed in microns, the terminal velocity of a spherical particle falling freely in air is approximately $0.003 \rho d^2$ cm/sec or $0.006 \rho d^2$ ft/min. The terminal velocity of particles is dependent on the aerodynamic properties which also determine the proportion of inhaled particulate that deposits in the respiratory tract and the site of deposition (Lippmann, 1970).³

The preferred 'diameter' or size of a particle is its 'equivalent', or 'aerodynamic' diameter. This is equal to the diameter of spherical particles of unit density which have the same falling velocity in air as the particle in question. For some types of particles with extreme shape, other parameters are sometimes used. Thus, asbestos fibers, which are very long in relation to their diameter, are characterized by their length.

Amongst particles which are inhaled, those with an equivalent diameter greater than 20 microns are deposited by impingement in the nose and upper respiratory tract. Smaller ones down to 0.5 micron in diameter are carried into the smaller airways and alveoli, and are deposited there under gravity.

Those between 0.1 and 0.5 micron in diameter are also inhaled, but are mostly exhaled with the air since their terminal velocity is so low that there is not sufficient time for them to be deposited in the time the air is in the respiratory tract. The very smallest, those whose diameter is less than 0.1 micron, have such a small volume and mass that they have significant Brownian motion from the irregular impact of gas molecules, and are deposited readily. However, their weight is so small that particles smaller than 0.1 micron dia-

meter seldom make up a hygienically significant proportion of the inhaled particulate. The above diameters refer to the size of the separate airborne entities, each of which may consist of several particles clumped together. It is the aerodynamic properties of these clumps rather than those of the individual particles which determine where they will be deposited.

THE PURPOSE OF SAMPLING

The main reason for sampling for atmospheric particulates is to estimate the concentration in the air which is inhaled by the employees. A determination may be made of the concentration of all the particles or just those which have particular sizes or shapes. This is done in order to assess whether there is a risk to the health of workers exposed to the environment. This judgment is made by comparing the results against hygiene standards.

The results obtained by atmospheric sampling depend very much on the time and place where the samples are taken and the type of instrument used. Those concerned with setting hygiene standards usually take account of the wide variation in the results that may be obtained, and take great care that there shall be no misinterpretation of the values inserted in the standards.

Variations in Time

Dust concentrations can vary around the average value from zero up to 2½ times the average, even in conditions where the work appears to be done at a steady rate. The appropriate hygiene standard may place an upper limit on the average concentration over a work shift, or on the maximum concentration during this period, or both.

Variations in Space

It is important to determine the concentration in air which may be inhaled. When planning and executing a survey of the particulates in workroom air, one should bear in mind that the concentration close to a machine or process is usually quite different from the concentration in the inhaled air. As a general rule, the concentration may vary considerably over a distance of a few feet, or even over a distance of a few inches. This is especially true when there are few sources of contaminant and the employees work close to a source. There should be no physical obstruction between the air sampler inlet and the operative's nose and mouth. Whenever there is any doubt, the sampler inlet should be within a foot of the operative's nose and mouth, and yet be out of the line of sight.

Variations between Instruments

Unfortunately, no two different types of airborne particulate sampler yield the same result. It takes the most painstaking tests to yield similar results from two identical instruments. Therefore, the instrument used must be the same type and must be used in the same way as that inferred in the hygiene standard. Thus, when using the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) of airborne contaminants as hygiene standards (Threshold Limits Committee, ACGIH, annually) the documentation on particular sub-

stances must be consulted to verify the methods to be used. (Threshold Limits Committee, 1971).⁴ As a general rule the substances in the main list of values should be collected with total dust sampling instruments and the weight concentration should be determined. Those listed under "Mineral Dusts" should be collected according to type, either with an impinger, total dust sampler, respirable dust sampler, or membrane filter. It is inadvisable to rely upon converting the results from one type of sampling instrument or method into those which might be obtained from another sampling instrument or method.

THE VOLUME OF THE SAMPLE OF AIR

People at work inhale about 10 cubic meters of air in 8 hours, depending on their energy expenditure. Those who work physically hard may inhale 20 cubic meters and those with sedentary occupations only 5 cubic meters. However, the volume of the sample of air taken for assessment of particulate concentration need not equal, or even be related to the volume of air inhaled. The primary need is to obtain a representative sample of the air of sufficient volume to contain enough particles that can be accurately weighed, counted or chemically analyzed. The volume of the sample of air may be as little as 5 ml or more than 50 cubic meters. The whole sample or a small fraction of it, perhaps 1 percent or less, may be assessed. The concentration of particulates in atmosphere which may be safely inhaled is very low, so a high flowrate is generally desired to collect the required quantity of particulate in a short time. The sampling gear should also be sufficiently portable to enable sampling at the place of work, as near to the operative's nose and mouth as practicable. Particulate sampling instruments which have the highest flowrates tend to be the least portable. Some portability may also be sacrificed so as to collect a large quantity of particulate and thereby to simplify the laboratory assessment.

The limit to the sensitivity of a given weighing procedure or analytical technique effectively sets a minimum to the required volume of air which constitutes a sample. The sampling procedure and method of assessment should be sensitive enough to measure the concentration in air of one-tenth the hygiene standard. Therefore, the minimum volume of the sample of air must be

$$\frac{10 \times \text{analytical sensitivity}}{\text{hygiene standard concentration}}$$

When the analytical sensitivity is measured in milligrams and the hygiene standard in milligrams per cubic meter, the volume of the sample of air is given in cubic meters.

THE DURATION OF EACH SAMPLE PERIOD

The minimum duration of the run for each sample depends upon the volume flowrate of the sampler.

$$\text{Minimum duration per sample} = \frac{10 \times \text{analytical sensitivity}}{\text{Hygiene standard concentration} \times \text{flowrate}}$$

Units should, of course, be consistent in the above formula.

The sensitivity of different weighing or analytical procedures can be very different. Therefore, the analytical sensitivity must be known in order to proceed with the sampling in an orderly and effective manner. For example, a common element in many particulate sampling procedures is a cellulose filter paper which is weighed before and after sampling. The filter paper may weigh anything from 0.05g to 5g according to size. The sensitivity of the weighing procedure is limited by difficulties arising from the equilibrium water content of the cellulose in moist air, which varies with humidity and temperature. When the filter papers are dried to constant weight or comparison unused filters are used as a 'tare', cellulose papers may be weighed to 0.1 percent of the weight of the paper. Thus,

$$\text{Minimum duration of sampling} = \frac{0.01 \times \text{weight of paper}}{\text{Hygiene standard concentration} \times \text{flowrate}}$$

Where the duration of the sampling is expressed in minutes, the hygiene standard is in mg/M³, the flowrate is in liters per minute and the weight of the paper is in milligrams:

$$\text{Minimum duration of sampling (mins)} = \frac{10 \times \text{weight of paper (mg)}}{\text{TLV (mg/M}^3\text{)} \times \text{flowrate (l/min)}}$$

Another useful form of the same equation is given by calculating the volume of air to be sampled. Thus,

$$\frac{\text{TLV (mg/M}^3\text{)}}{10} = \frac{\text{wt. of paper (mg)}}{\text{vol. of sample (l)}}$$

Similar expressions can be found for other weighing or analytical procedures and as such are extremely useful for choosing a satisfactory combination of sampling method, duration of sampling and flowrate.

INSTRUMENTATION

Sampling Trains

A sampling train for particulates has the following critical elements in this order: air inlet orifice, particulate separator, air flowmeter, flowrate control valve and suction pump. Equally important are the motor and power supply for the pump and the power supply, if any, for the particulate separator.

The Air Inlet. The air entry orifice should be as short as possible to keep wall losses to a minimum. Nevertheless, it is sometimes necessary to have a probe tube connected to the air inlet as in the case when the concentration of particulate is highly localized. Having the entry at a floor- or bench-mounted instrument might result in a false reading. Wall losses may be excessive in probe tubes which are longer than three feet or have sharp bends. In such cases the particulate in the tube must be dissolved or washed off and added to the sample. If the particulate separator is small and light, a length of tubing may be inserted between it and the air flowmeter to avoid the problem of wall losses in a probe tube upstream of the separator.

The Particulate Separator. The particulate separator is the most important element in the sampling train. The efficiency must be high and reliable. The pressure drop across the separator should be low in order to keep to a minimum the size of the necessary suction pump and motor. It may consist of a single element such as a filter or impinger or there may be two or more elements in series, so as to separate the different sizes of particles.

The Air Flowmeter. The air flowmeter is commonly an air rotameter, but may be a gas-meter or an orifice meter.

Where the flowrate is constant or automatically controlled, there may be only an on-off indicator that the device is functioning. In such cases the flowrate through the sampling train is measured in the laboratory and checked after sampling. The flowrate should be checked with the sample of particulate in place since sometimes the filters affect the flowrate drastically.

Similar considerations apply in sampling trains with an integral flowmeter. The value shown by a rotameter, gas-meter or orifice meter is partly dependent upon the air pressure at the entry to the meter, and upon the magnitude and frequency of pulsations in the air flow. Measurement of the air flowrate, or calibration of the flowmeter should be performed before and after sampling, with all the elements of the sampling train in circuit.

Flow Control

The flowrate control may be manually operated if in the form of a needle valve or a simple pinch valve. When filters are employed the flowrate control may need repeated adjustment while sampling, since particulates clog the filter. This effect may be mitigated by using a sampling train with a high internal resistance. Automatic flowrate control may be obtained with a critical orifice. Otherwise, electrical or pneumatic means may be utilized.

A critical orifice is a simple and popular means of achieving constant flow. The principle of the method is to draw the air through the orifice under "critical" flow conditions and constant upstream pressure.

The volume flowrate of a gas into an orifice increases as the pressure differential across it increases until a point is reached when the air is moving through the orifice at a velocity equal to the velocity of sound through the gas. The volume flowrate then stays the same for any further increase in pressure differential. The downstream to upstream pressure ratio below which the volume flowrate becomes constant is known as the critical pressure ratio. This is approximately 0.53 for air through a well-rounded orifice. At atmospheric pressure upstream, the flow becomes critical as the downstream pressure is reduced below 400 mm mercury. The orifice is placed in the sampling train at the entry or at a point where the upstream pressure is constant, and the pressure differential is maintained in excess of 400 mm mercury. The critical pressure drop, 400 mm mercury, reflects a resistance to flow. This may be reduced by making a gradual enlargement or easé on the discharge side of the orifice in the

form of a 1-in-5 enlargement for 15 orifice diameters. This reduces the necessary overall pressure drop because of the pressure recovery in the expansion piece. In practice, an orifice having an overall pressure drop of 100 mm mercury at critical flow is made fairly easily.

A critical orifice should be calibrated from time to time as it may become worn by the particulates passing through it.

If a critical orifice is not used the flowrate may be maintained constant with devices downstream of the particulate separator, such as by having a flow-regulating valve followed by a pressure-regulating valve downstream. The pressure drop necessary to maintain control with this latter system is about 250 mm mercury.

Even with particulate separators which have a resistance independent of the dust loading, it is advisable to have a pressure-regulator as the performance of most pumps tends to vary with time.

The Pump

The suction pump is commonly a motor driven rotary pump but other kinds are also used, including diaphragm pumps, centrifugal fans, hand operated crank pumps or piston pumps. The pump must produce sufficient air horse-power and draw the necessary flowrate through the sampling train under the most adverse conditions of air-flow resistance. When making up a sampling train, it is helpful to measure the air-flow resistance contributed by each element, as it is often found that a high resistance contributed by a secondary element such as tubing, elbows, connections or other fittings can be easily reduced. The weight of the necessary pump and motor increases roughly in proportion to the pressure drop and the flowrate through the system. Rotary pumps utilized in this work to produce a fairly high pressure drop of 50-350 mm of mercury are generally the sliding vane type although multi-lobe blowers or gear pumps can be used. Centrifugal fans are suitable where the pressure drop through the sampling train is less than 10 mm of mercury. Somewhat higher pressure drops, up to 100 mm of mercury, can be sustained with small multi-stage centrifugal turbines. If the required sample volume flowrate is less than 5 liters per minute, diaphragm pumps and piston pumps can be used. The very lowest flowrates, less than 100 cc per minute, are accommodated by water displacement apparatus.

Power Supply

The power supply is commonly line current, but nickel-cadmium rechargeable batteries may be used on the smaller sampling trains and are essential for the greatest portability. Otherwise, manual operation is used. Disposable dry cells are not very suitable but they have been used. Sometimes electricity is not available on site or is banned for reasons of safety, so hand power or approved coal mine dust personal sampler pumps may have to be used, or compressed air or water ejectors may be feasible. Compressed air ejectors can provide flowrates up to 200 liters/minute against 400 mm of mercury pressure drop, utilizing compressed air at a pressure of 20 lbs. per square inch. Low sampling flowrates, up to

10 liters per minute, may also be obtained with small ejectors working from bottled Freon, carbon dioxide or compressed air.

COLLECTION DEVICES

Particulate Separators

Usually particulate separators are suitable for determining either the mass concentration or the number concentration. Nowadays, the mass concentration instruments are divided into two broad categories, those with and those without a pre-selector.

The pre-selector separates those particles which are larger than about 5 microns. (Task Group on Lung Dynamics, 1966).⁵

Filtration

Many instruments used in assessing the mass concentration of airborne particulates incorporate a filter. Common filter paper consists of an irregular mesh of fibers about 20 microns in diameter or less. Air passing through the filter changes direction around the fibers and the particles in suspension impinge there.

The largest particles, those greater than about 30 microns, also deposit to a significant extent by direct interception or by sieving action, and the very finest particles, less than 0.5 micron, also deposit through their diffusion caused by Brownian motion. With particles greater than 0.5 micron diameter deposition efficiency generally increases with the velocity of the airstream and with the density and diameter of the particles. Deposition by diffusion dominates over deposition by impingement of the very smallest particle sizes and decreases as the diameter of the particles increases. Consequently, there is a size at which the combined efficiency by impingement and diffusion is a minimum. This is always below 0.5 micron diameter and usually below 0.2 micron diameter.

The weight of particles below 0.5, and certainly of those below 0.2, micron diameter, is usually less than 2% of the airborne dust of hygienic significance so that in practice the amount of deposition by diffusion may be ignored. Samples which consist primarily of freshly formed metal fumes would be exceptions.

Cellulose fiber filter papers are relatively inexpensive, are obtainable in an almost unlimited range of sizes, have high tensile strength, show little tendency to fray during handling and are low in ash content. Their main disadvantage is their hygroscopicity, which must be allowed for in the weighing procedure. Whatman No. 41 is the most widely used cellulose filter as it combines good efficiency with low flow resistance.

Filters made of glass, asbestos, ceramic, carbon or polystyrene fibers less than 20 microns in diameter have a higher efficiency than cellulose filters and may be favored for this reason. However, their principal advantage over cellulose filters is the ease of determining the blank weight, and this is the reason that glass fiber papers have become very popular in recent years. The resistance of a filter increases with thickness and compression of the filter mat and with the dust loading.

A good filter material for particulate sampling

is made of thickly matted fine fibers and is small in mass per unit face area.

Membrane Filters

Membrane filters may be used to collect samples of particulates for examination under the microscope. They are thus used to determine number concentration as well as mass concentration.

A membrane filter is a micro-porous plastic film made by precipitation of a resin under controlled conditions. The polymers used are cellulose esters, polyvinyl chloride or acrylonitrile. These filters are not very stiff and are therefore supported on a metal gauze or other grid. Special types have an integral nylon support to give added strength. In manufacture the pore size is controlled within close limits, and membrane filters are obtainable with mean pore sizes of from 0.01 micron to 10 microns in diameter. They are usually 140 microns thick, and have an efficiency close to 100% for particles larger than the mean pore size. On the surface, the particles are filtered out in a sieving action so they may be examined under the microscope as on a glass slide although many particles smaller than the nominal pore size are trapped within the filter. They are obtainable with a grid stamped on, which facilitates counting over a known area. They may also be obtained black, which is advantageous for certain white, opaque dusts. Common types are soluble in cyclohexane or other organic solvents, which facilitates separation of the particulates when required.

When immersion oil is placed on a membrane filter, it becomes transparent and the particles may be examined under the microscope by transmitted light. Difficulties arise with minerals whose refractive index is close to that of the filter material.

Membrane filters may be used in the determination of mass concentration where it is feasible to employ a low air sampling flowrate. They have a high air-flow resistance. A common membrane filter used for dust sampling has a nominal pore size of 5 microns.

Impingement on a flat plate

Some particulate separators rely upon impingement on a flat plate held close to a jet of the air containing the particles in suspension. These have been used for many years. Their popularity is waning but they still are an important type. These instruments are operated by drawing air at very high velocity, 50-300 meters per second, through a small jet. The jet may be circular or rectangular in cross-section, 0.5 mm to 1.0 mm in diameter or width, and 1 mm to 5 mm from the deposition surface. Particles down to about 1 micron diameter are efficiently thrown out by the centrifugal force as the air in the jet turns through 90 degrees or more.

The forces involved are not sufficient to remove particles much smaller than 1 micron in diameter. With high velocity jets the coarser particles are thrown with increasing force against the plate and may bounce off, or break up. The surface of the deposition plate is usually wetted or greased to cushion the particles and trap them.

The collected particles are counted by eye under a microscope and the result is a useful comparative index of the concentration of particulates in the sampled air. The count obtained in a particular concentration is very dependent on the specific type of instrument and the nature of the particulate so that the counts obtained with other types may be different by a factor of up to 10. Therefore, it is imperative to use the same type of impingement instrument when making repeat surveys in a given environment.

Electrostatic Precipitation

Electrostatic precipitation has been utilized successfully in atmospheric sampling. These systems have the advantages of negligible flow resistance, no clogging and precipitation of the dust on a metal cylinder whose weight is unaffected by humidity. A power pack is needed to supply the high voltage and precautions have to be taken to guard against electric shock.

The wire and tube or "tulip" system is used. The tube is a light alloy cylinder about 6 in. long and 1½ in. dia., held horizontally. The tube is grounded.

A stiff wire, supported at one end, is aligned along the center of the tube and serves as the charged electrode. The tip of the wire is sharpened to a point. A high d.c. voltage, between 10 kv, and 20 kv, is applied to this central electrode. The corona discharge from the tip charges the particles in suspension in air drawn into the tube. Under the action of the potential gradient between the wire and the tube the charged particles migrate to the inside surface of the tube.

The migration velocity of the charged particles greater than 1 micron in diameter increases in proportion to particle diameter. On the other hand, migration velocity is approximately independent of particle diameter for particles smaller than 1 micron in diameter. Therefore, very high separation efficiencies are attainable with electrostatic precipitators and they are ideal for particles smaller than 1 micron in diameter.

Thermal Precipitation

A particle in a thermal gradient in air is subject to differential molecular bombardment from the gas molecules, so that it is subject to a force directed away from the hot sources. This is the principal mechanism involved in thermal precipitation. The air is drawn past a hot wire or plate and the dust collects on a cold glass or metal surface opposite the hot element. A high thermal gradient is needed so the gap between the wire or plate and the deposition surface is kept small (0.5-2 mm). The migration velocity induced by the thermal gradient is small, and very nearly independent of particle diameter. However, the system has severe limitations in the maximum flowrate possible with high deposition efficiency. It is, therefore, used only for collecting sufficient particulate for examination under the microscope. Due to the temperature involved it is not suitable for mists except those of liquids with high boiling point.

When the particulate is collected on a glass coverslip and viewed dry, the visibility of the

particles under the orthodox light microscope is far better than that obtained with a membrane filter.

Elutriators

Elutriators are an important and sometimes essential feature of sampling trains used for mineral dusts. They are used as pre-selectors, ahead of other particulate separators to remove the larger particles. There are two classes of elutriators employed in sampling air for particulates: horizontal elutriators and vertical elutriators.

A single element of a horizontal elutriator used in this work is a thin, horizontal, rectangular duct. Commonly the horizontal elutriator package consists of several such elements stacked one above the other, connected in parallel to a common exit. (Walton, 1954).⁶ The theory is fairly easily understood and performance closely matches theory. Suppose a flowrate, Q , of air is passing uniformly along a horizontal duct of length L , width W and height H . The time, T , it takes for air to pass through the duct is LWH/Q . Among the particles entering the duct those which, in time T , would fall freely under gravity a distance greater than H would all deposit on the floor of the duct. Thus, the minimum terminal velocity (V_c) for 100% capture by the elutriators, is

$$V_c = H/T = Q/LW.$$

Also, among those particles with terminal velocity, V , (V less than V_c) a proportion would be captured by deposition on the floor of the duct. The percentage captured in this way is $100(V/V_c)\%$. The proportion, P , not captured by the elutriator would be $100(1-V/V_c)\%$ of those with terminal velocity less than V_c .

$$P = 100 (1-V/V_c)\% = 100 (1-VLW/Q)\% \quad (1)$$

Thus, P is independent of the height of the duct, provided the floor area and flowrate are constant. It may also be shown that under streamline flow conditions, errors in the above formulae through assuming uniform flow cancel out. Flow is maintained streamline by making H small. Since the performance is independent of its height, the duct may be made as thin as practicable. All ducts with the same ratio of floor area to flowrate (LW/Q) have the same performance under streamline flow conditions.

A vertical elutriator is a single vertical tube, either parallel sided or in the shape of an inverted, truncated cone. The air with particles in suspension is drawn or blown upwards through the tube. Suppose a flowrate, Q , of air is passing uniformly up a parallel sided, vertical duct, cross-sectional area A . The upward air velocity is Q/A , equal to V_c . None of the particles which have a terminal velocity in air exceeding V_c , would be carried up the tube by the air. The particles with zero terminal velocity in air would be carried up the tube with velocity V_c . Those with a terminal velocity, V , between zero and V_c , would be carried up at a velocity $V_c - V$ and proportionately fewer would pass through the tube. The percentage, P , passing through the tube,

$$P = 100 (1-V/V_c)\% = 100 (1-VA/Q)\% \quad (2)$$

P is independent of the length of the tube, pro-

vided the cross-sectional area and flowrate are constant. It is important to maintain streamline flow in elutriators so their cross-sectional area must be small. However, since the performance of a vertical elutriator is dependent on cross-sectional area, this type is only used in sampling at very low flowrates.

The conical form of vertical elutriator, with a small entry at the tip at the bottom, is used to promote smooth flow through the elutriator. A parallel portion is usually arranged at the top, where the cross-sectional area is largest and the final performance therefore determined.

Perfect streamline flow is not realized in practice even with horizontal elutriators. The effects of a disturbance to streamline flow on the collection characteristics may be understood by considering the collection characteristics of a horizontal elutriator under conditions of perfect mixing. At a point a distance l from the entrance to an elutriator element of width W , length L and height H the average forward velocity of the airstream,

$$\frac{dl}{dt} = \frac{Q}{WH}$$

The horizontal base area of small element length $d1$ is $Wd1$. The number of particles of terminal velocity V falling on this area in time dt is thus

$CVW d1$ particles per minute, where C is the concentration of particles in the air over the element.

The volume of the air above the element is $WH d1$, thus the rate of change of concentration with time,

$$\begin{aligned} \frac{dC}{dt} &= \frac{-CVWd1}{WHd1} \\ &= \frac{-CV}{H} \end{aligned}$$

From which

$$C = C_0 \exp - (Vt/H),$$

where C_0 is the concentration at t_0 , when the air enters the elutriator. The time to pass through the elutriator is LWH/Q , so that the concentration at

the exit is $C_0 \exp - (VLW/Q)$. Thus the percentage, P , of particles in the air entering the elutriator which pass through it without depositing,

$$P = 100 \exp - (VLW/Q) \quad (3)$$

Elutriators are commonly designed on the assumption of uniform flow, and so as to capture 50% of particles of 5 microns equivalent diameter. (Orenstein, 1960).⁷ The expected performance of such an elutriator under streamline flow (equations 1 and 2) and under perfect mixing conditions (equation 3) are shown in Fig. 13-1.

Streamline flow is often nearly achieved and the performance comes close to theoretical. (Hamilton, 1967).⁸ Such elutriators have an inherent fail-safe feature in that if due to distortion of the plates or poor design streamline flow is seriously disturbed, capture of coarse particles is reduced and the estimated sample concentration errs on the high side. On the other hand, flowrate control is

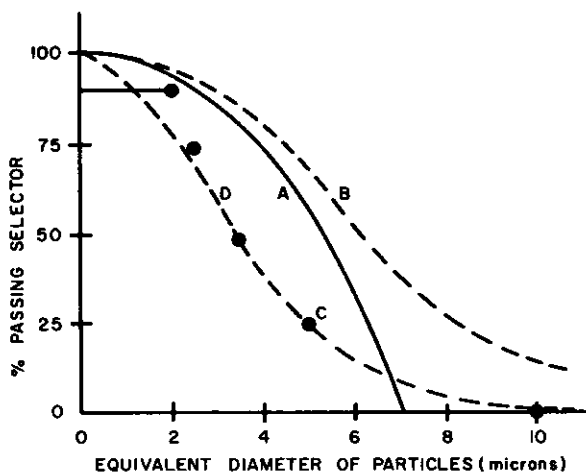


Figure 13-1. The Performance of Horizontal Elutriators Line A - Streamline flow conditions; elutriator designed to allow 50% of particles of 5 microns equivalent diameter to pass through — Line B - Perfect mixing in elutriator designed as for Line A — Points C - Size selector characteristics recommended by the ACGIH for “respirable” dust sampling — Line D - Perfect mixing conditions; elutriator designed to allow 50% of particles of 3.5 microns equivalent diameter to pass through.

particularly important. If the flowrate is low, coarse particles are removed to a greater extent, giving an additional error on the low side. The reverse occurs when the flowrate is high.

Cyclones

Miniature cyclones of simple construction have been used in recent years as pre-selectors ahead of other particulate separators, and serve the same purpose as elutriators. Cyclones 10 mm to 50 mm diameter are employed, for example, when testing compliance with current Threshold Limit Values for “free” silica; that is, quartz, cristobalite, tridymite and fused silica dust (Threshold Limits Committee, 1972).⁹

The air enters a cyclone tangentially at the side of a cylindrical or inverted cone shaped body, swirls around inside and leaves along the axis from a tube at the top. Coarse dust is thrown to the side and collects in the base of the cyclone. The air velocities in a cyclone are very high and the flow is highly turbulent.

The centrifugal acceleration of a particle in the rotating airstream turning at an angular velocity, ω , is $\omega^2 r$, where r is the radius of rotation. The diameter of cyclones in common use and the flowrates employed give centrifugal accelerations in excess of one hundred times gravitational acceleration. The air in a cyclone rotates several times before leaving and consequently the dust deposits as it would in a horizontal elutriator of floor area several times the cyclone outer surface area, and under a force over one hundred times gravity. Consequently, the volume of a cyclone is

much smaller than a horizontal elutriator with the same flowrate and efficiency.

The characteristics of a size selector for testing compliance with current Threshold Limit Values for free silica are indicated in Fig. 13-1, at points C, and the size-efficiency performance of an elutriator under perfect mixing conditions to simulate this are indicated in Fig. 13-1 at line D.

Cyclones have similarly shaped size-efficiency performance curve. However, the detailed pattern of air-flow through a cyclone depends so much on the design adopted that the performance of cyclones of particular design must be checked experimentally.

The orientation of a cyclone is not as critical as that of an elutriator so a small one may safely be fastened to an operative’s clothing. Further, small errors in flowrate are counter-balanced to some extent by changes in the size-efficiency characteristics. Thus, if flowrate is low, coarse particles are removed to a lesser extent, giving an opposite error, and the reverse occurs when the flowrate is high.

The air-flow resistance of a cyclone is higher than that of an elutriator for the same flowrate. Nevertheless, the resistance is largely independent of dust loading and small in comparison with the resistance of customary filters downstream.

CHOICE OF SAMPLING INSTRUMENTS

There are at least 50 different types of sampling instruments used in particulate sampling, each with its own proponents. Further, there are new ones being developed every month. Amongst those in regular use at the present time for determining concentration as mass of particulate per unit volume of air are the electrostatic precipitator and many filter paper methods. The common instruments for determining the concentration as number of particles per unit volume of air are: the impinger, the membrane filter method, the thermal precipitator and the light scattering automatic particle counter. All these instruments and many others are described in “Air Sampling Instruments.” (American Conference of Governmental Industrial Hygienists, 1972).¹⁰

The choice of instrument in particular circumstances is very often dictated by the limited choice of instruments actually in the hands of the hygienist at the time the measurements are needed. The problem may be one of deciding which of two not very suitable instruments is least likely to give rise to erroneous conclusions rather than one of choosing the ideal instrument. For example, when sampling for a mineral dust, a “respirable” dust sampler may be needed. However, the sampling equipment available for total dust measurements is simpler and less expensive than that for respirable dust. If the proportion of fine dust in all the airborne dust is known, the concentration of fine dust in the air could then be inferred from a simple measurement of the concentration of all the atmospheric dust (total dust).

In particular cases, upper limits can be placed

on the proportion of fine dust, recognizing that in effect an additional factor of safety is thereby incorporated. Again, in the absence of any precise information on the proportion of fine dust, the total dust concentration may be used as a working limit. Obviously, if the total dust concentration is less than a certain value, any fraction of it will also be less than this same value.

Thus, lack of elutriators, cyclones or other pre-selectors need not necessarily be a bar to proceeding with mineral dust sampling in an orderly and effective manner. In many cases the simplest of measurements will suffice. In others, the proportion of fine dust is so small that a more sensitive and precise method incorporating a pre-selector is justified.

Similarly, in addition to the particulate being studied, background material and other contaminants are also collected. It is necessary to consider whether simply to weigh all the particulate, recognizing the safety factor that would be incorporated by assuming it was uncontaminated, or to analyze the particulate in the laboratory. The procedure selected influences the choice of sampling instruments as each procedure possesses a different sensitivity. Taking an example from number count instruments, when determining an airborne asbestos dust exposure, it has to be borne in mind that the thermal precipitator, impinger and Royco particle count are progressively simpler techniques from the operational standpoint, but less easily related to the membrane filter fiber count needed for asbestos dust.

Electrostatic Precipitators

Electrostatic precipitators normally do not have a preselector ahead of the collecting tube. They are therefore suitable for all those particulates listed in the TLV document of the ACGIH except mineral dusts evaluated by count. They may also be used for nuisance particulates. Because of the high efficiency for separating particles smaller than 1 micron in diameter, they are very often used when sampling for fumes. The two types commercially available are the Mine Safety Appliances Electrostatic Sampler and the Bendix Electrostatic Air Sampling System. The former has a fixed flowrate of 66 l/min from a 50 c/sec frequency supply, and the latter is variable between 90 l/min and 200 l/min. The ionizing voltage should be maintained sufficiently high to collect all the particles but not so high as to produce arcing between the central electrode and the collecting tube. A check that the dust has all been collected is to observe that the downstream end of the collecting tube is clear of dust. There is a practical limit of about 100 mg to the amount of dust that can be collected on each tube, as a thick layer of dust is easily dislodged and may be lost on handling. For very high dust concentrations, a coiled filter paper liner may be used to enable higher dust loads to be carried successfully. The ends of the sampling tube should be capped when the sample has been collected and the outside of the tube wiped clean. The dust may be washed or wiped off the tube. If the tube is washed, it

should be allowed to return to room temperature before weighing, or balance errors will occur. The tube can be weighed on a semi-micro balance to 0.25 mg.

Filter Methods

So-called 'respirable' dust sampling instruments include a pre-selector to separate the coarser particles before collection. (Aerosol Technology Committee, 1970).¹¹ These instruments normally incorporate filters to collect the fine particulate. Such instruments without a pre-selector are suitable for other particulates in the ACGIH list of TLVs.

The Casella Gravimetric Dust Sampler Type 113A incorporates a horizontal elutriator for a flowrate of 2.5 l/min (Dunmore, Hamilton and Smith, 1964)¹² and the Casella Hexhlet incorporates a horizontal elutriator for a flowrate of 50 l/min (Wright, 1954).¹³ In both instruments the fine dust is collected on a filter.

In the Dorr-Oliver and Mine Safety Appliances respirable dust samplers the size selection is achieved by using a small cyclone upstream of a filter. Where a 10-mm nylon cyclone is used, the flowrate is 1.7 l/min and for the UNICO ½-inch HASL cyclone, 9 l/min.

With all respirable dust samples, it is particularly important to maintain a constant and non-pulsating sampling flowrate to ensure correct size selection characteristics.

A particulate sampler without a pre-selector and incorporating a filter may be made up from parts available in the laboratory. Whatman No. 41 cellulose filter paper or GF/A glass filter paper are used.

The principal source of error in weighing cellulose papers arises from the hygroscopic nature of the paper. This error can be kept within bounds by strict observance to a drying and weighing routine. The flowrate, sampling interval and size of filter are then chosen to yield a weight of dust amounting to at least one percent of the paper, and preferably more than two percent.

Glass fiber filters are available either with or without an organic binder. The binder increases the mechanical strength of the paper. Glass fiber filters without binder are used when the binder would constitute an interference in the analysis for organic matter in the particulate. Even with the binder, glass fiber filters are quite friable and must be handled with care. Analysis of the dust for iron, aluminum, sodium, potassium, magnesium and silica is not possible because of interference from large amounts of these in the glass fibers.

Polystyrene fiber filters such as the Microsorban filter, have a flow resistance which is relatively low, being comparable to Whatman No. 41, while their efficiency of collection is relatively high and is comparable to that of glass filters. Since they have poor mechanical strength, they must be well supported in the filter holder.

Membrane filters have a low mass and low ash content. However, they have a high flow resistance. Cellulose filter paper such as Whatman

No. 41 has an air flow resistance of 10 in. water gauge when the face velocity through the paper is 50 cm per sec, whereas a membrane filter with a pore size of 2 microns or less has an air flow resistance of at least 50 in. water gauge under the same conditions. Particle collection takes place almost exclusively at the surface of the filter, and when more than a single layer of dust particles is collected on the surface, the resistance rapidly increases and there is a tendency for the deposit to slough off the paper.

A filter holder should be used which provides a positive seal at the edge, without leakage. It must not abrade or tear the filter. A screen or other mechanical support may be required for the filter, to prevent rupture or displacement in service. A back-up screen is necessary with glass fiber, polystyrene and membrane filters.

Filter thimbles are available in cellulose fiber and cloth. They are sometimes filled with loose cotton wool to reduce clogging. The advantage of a filter thimble is that large samples can be collected before clogging.

A typical procedure for weighing filters is as follows:

The weighing vessels used in a typical procedure are light screw-top cans with a pin-hole in the lid.

1. Remove the lid from a weighing vessel, place the filter inside and place the weighing vessel in a drying oven at 110°C. (60°C for membrane filters). Dry for 2 hrs exactly.
2. Screw on the lid of the weighing vessel and cool it in a desiccator with silica gel for exactly 20 min.
3. Weigh immediately.
4. Repeat steps 1 to 3. The two weights should check to 0.1 percent. Otherwise repeat procedure.

For most chemical analyses, it is necessary either to remove the sample from the filter, or to destroy the filter. Inorganic particles are usually recovered from cellulose paper filters by wet ashing (digesting in concentrated acid) or dry ashing (muffling, incinerating) the filter. Samples can be recovered from polystyrene and membrane filters by dissolving the filter in a suitable solvent.

The background level on the filter of the material to be analyzed must be determined. Filters contain various elements as major, minor and trace constituents, and the filter medium of choice for analyzing particular elements must be one with little or no background level for the elements being analyzed.

Impinger

The impinger is the instrument used in the series of studies by the U.S. Public Health Service 1925-1940 in dusty trades on which the Threshold Limit Values of the American Conference of Governmental Industrial Hygienists for Mineral Dusts were largely based. It is still a common method for mineral dust sampling in the United States, although it is being superceded by dry filtration. The dust-laden atmosphere is drawn

through a glass jet, the end of which is set a fixed distance from the bottom of a flask. The jet is immersed in water or alcohol and the particles strike the bottom of the flask and become suspended in the liquid.

A sample of the liquid is then placed in a counting cell and the particles are counted using a low-power microscope. The sampling time is usually 10-30 min or more. When long sampling times are used, the suspension can be diluted to the point where coincidence errors are insignificant.

The following method represents standardized methodology for the impinger sampling technique:

The sampling instrument is the standard impinger, operated at a rate of 1.0 cfm \pm 5 percent at 3 in. mercury negative pressure, or the midget impinger operated at 0.1 cfm \pm 5 percent at 12 in. water negative pressure. The sampling instrument and the indicating gauge on the flow-producing apparatus should be calibrated at regular intervals.

Counting Cell

The counting cell should be no more than 1.0 mm and no less than 0.25 mm in depth with an allowable variation of \pm 5 percent from the nominal depth.

Optical System

- A. The microscope should be equipped with the following:

objective	10X (16 mm) 0.25 N.A.
ocular (eyepiece)	20X
condenser	0.25 N.A.

- B. The counting area is defined by an ocular grid such as a Whipple disc and should be accurately measured by means of a stage micrometer.

- C. Kohler illumination is used except that after this has been achieved, the eyepiece is removed and the iris diaphragm of the microscope condenser is closed until the disc of light seen in the back lens of the objective is about one-half of the lens. Further reduction of brightness may be accomplished, if desired, with neutral density filters.

Collecting Liquid

The collecting liquid usually is 95% ethyl alcohol although distilled water or mixtures of distilled water and alcohol (ethyl or isopropyl) may be used.

Treatment of Collected Samples

- A. All glass-ware must be clean and the equipment protected against dust contaminants in the field. One impinger flask, a "blank" flask, is treated exactly like the others except that no air is drawn through it.
- B. The diluting liquid should be 95% ethyl alcohol.
- C. The impinger nozzle is rinsed down inside and out with diluting liquid as the sample is made up to a known value. Samples

having a low concentration of dust are diluted as little as possible. Dense samples are diluted so that no more than about 2,000 particles/mm² will appear in the counting area of the cell. Not less than 5 ml of original or diluted sample should be taken for further dilution, and dilutions should be made in steps not exceeding 10 parts of dilution liquid to 1 part of original or diluted sample. The dust suspension must be shaken vigorously by hand for at least 30 sec. before a portion is removed for dilution.

Preparation for Counting

- A. The sample to be counted is shaken to ensure a uniform suspension and a portion is transferred immediately to a clean cell by means of a clean pipette, taking care to prevent the inclusion of air bubbles.
- B. Two cells are filled from each sample and from a "blank" flask.
- C. Sample counting should start at the end of the settling time and should be completed in 10 min. The settling time should be 30 min/mm of cell depth.

Counting

- A. Before counting, the ocular grid should be cleaned to remove dust particles.
- B. The counting plane is the bottom liquid-glass interface of the cell. The microscope is focused up and down slightly with the fine focus adjustment in order to bring individual particles in and out of focus for more positive detection and counting.
- C. Fields selected for counting should be uniformly distributed over the counting plane of the cell. Observation should not be made through the microscope while fields are being selected.
- D. At least five fields of equal area should be counted in each of two cells. For a dust sample, when the first five fields of the first cell counted yield a total count of less than 100 particles, additional fields of known area should be counted; the total area counted is recorded and used in calculation of concentration. For each cell from the "blank" flask only five fields need be counted.
- E. The same total area should be counted in the second cell as is counted in the first.
- F. Total counts from the two cells of the same sample should be compared; and when the ratio of the greater to the lesser count is larger than 1.2, additional pairs of cells should be counted until a pair yields counts which satisfy this criterion. The count of this pair should be used for calculating the concentration of the sample.
- G. Five fields of the same area as that used for dust sample counting should be counted in each of two cells from a "blank" flask. The average blank count should be used in calculation of net count. If the blank count exceeds 30 particles/mm² of counted area, all the samples should be rejected.

H. Observers are cautioned that their ability to see particles probably improves during the first few minutes of counting as their eyes become accustomed to the task. A brief period of counting is suggested prior to recording data. Fatigue can cause a deterioration in counting efficacy; conservative judgment should be exercised on when to discontinue counting because of fatigue.

Membrane Filters

The membrane filter method is commonly used for assessing asbestos dust exposure.

In order to view the dust under the microscope it is necessary to use immersion oil to render the filter transparent. The refractive index of membrane filters is about 1.5, close to that of chrysotile asbestos ($N_D = 1.55$), so that under ordinary illumination the chrysotile may itself be very nearly invisible when using an immersion oil closely matched to the filter. A phase contrast microscope is therefore used to increase the visibility of the chrysotile. The method given below is based on the standardized techniques recommended by the National Institute for Occupational Safety and Health.

Sampling Procedure

Samples for evaluation of asbestos exposure are collected on Millipore AA Membrane filters (37 mm diameter, 0.8 μ m pore size) by personal samplers operated by battery-powered pumps, worn by the employees. The filters are contained in plastic filter holders and are supported on thick pads which also aid in controlling the distribution of air through the filter. The face cap of the filter holder is removed and filter used open face during sampling. The sampling rate is about 2 liters/min. A minimum sampling period of 15 minutes (for evaluation of excursion limit) and several samples of up to 4 hours for evaluation of 8-hour average are normally required. Samples with a visible deposit may be too heavy to count; compare the appearance of the collected samples with a clean filter. Heavy concentrations of visible dust in the air (100 to 500 fibers/ml) may require short sampling periods of only 5 minutes, or less. The following specifications should be considered minimum for the microscope used for counting of asbestos fibers.

1. Microscope body with a binocular head and a fine focus accuracy of 0.005 mm.
2. Binocular with 10X Huygenian eyepieces
3. Porton reticle
4. Mechanical stage
5. Kohler illumination (preferably built in and having provisions for adjusting light intensity)
6. Abbe condenser with an adjustable iris
7. 40-45X (0.65-0.75 N.A.) Positive (bright field) phase-contrast objective
8. Annular ring condenser diaphragm (corresponding to the objective)
9. Phase ring centering telescope
10. Green filter
11. Stage micrometer

Counting

To prepare samples for microscopic examination, a drop of the mounting medium is placed on a freshly cleaned standard (25 mm x 75 mm) microscope slide, using a dropper or applicator.

Mounting the sample

The mounting medium used in this method is prepared by dissolving 0.1 g of membrane filter per ml of a 1:1 solution of dimethyl phthalate and diethyl oxalate. The exact proportions of the 3 components are not critical, but the medium must have as high a viscosity as possible without being difficult to handle. The index of refraction of the medium thus prepared is $N_D = 1.47$.

The volume of the drop is approximately 0.05 ml. A wedged piece about 1 cm x 2 cm is excised from the filter using a scalpel and forceps, and placed dust side up on the drop of mounting solution. A #1-1/2 coverslip carefully cleaned with lens tissue is placed over the filter wedge. Slight pressure on the coverslip achieves contact between it and the mounting medium. Clearing of the filter with this method is slow, requiring about 15 min. The sample may be examined as soon as the mount is transparent.

A minimum of twenty fields, located at random on the sample, or a sufficient number of fields to provide a minimum of 100 fibers, are counted and fibers having length greater than $5\mu\text{m}$ are recorded. Any particle having an aspect-ratio of 3 or greater is considered a fiber.

Royco Particle Count Method

In the Royco particle counter a thin filament of the particulate laden air is drawn past an intense light beam and the light scattered at right angles is sensed by a photo cell. Air is continuously drawn through the center of a hollow cube or chamber with windows in the sides. Particles in suspension scatter light from a tungsten filament lamp focused on the center of the chamber. The scattered light is viewed by a lens system and photomultiplier. The pulse train from the photomultiplier passes to a linear variable-gain amplifier and fixed-level discriminator and then to a decade counter.

Time switches automatically switch a sequence of size discrimination channels so that the count may be restricted to successive size ranges or to all particles above a lower size-limit. The standard model counts above 0.3 micron and in 14 stages up to 10 microns at 0.3-, 1-, or 3- or 10-minute intervals. The counts are read off, plotted on a pen recorder, or printed out. An optional filtered dilution system can be incorporated to reduce coincidence errors in high concentration.

Overall calibration is performed against monodisperse polystyrene latex spheres. The air is filtered through a membrane filter after passing the counting chamber so that the sample may be subsequently check-counted by eye, under the microscope.

The instrument is extremely expensive, large, complicated and not very portable. Its great advantage is that it is automatic and suitable for de-

termining the size distribution of mists. It must be noted that the accuracy of the Royco particle counter is dependent upon the surface characteristics, including shape, of the particles being counted.

Thermal Precipitators

Two types of thermal precipitators are at present in use, namely the "standard" thermal precipitator, manufactured by Casella, and the "long running thermal precipitator," designed and developed at the Mining Research Establishment, manufactured in clockwork pump form by Ottway and Casella, and in an all electric form by Casella.

In the standard thermal precipitator, dust-laden air is drawn vertically into the sampling head and down a narrow vertical channel between two circular glass coverslips. Halfway between these two coverslips is stretched a horizontal wire, heated electrically. Dust is deposited by the thermal effect, opposite the wire, in two strips on the coverslips.

At the sampling site, the instrument is assembled in the sampling position so that the air channel through the head is vertical. Current for the heating wire is supplied by a 6 V rechargeable battery. Alternatively, line power may be used with a transformer having a 6 V outlet in series with a rheostat and AC ammeter. Air is drawn through the sampling head at 5-7 cm^3/min .

In the laboratory the coverslips are mounted, dust side down, on microscope slides, and are viewed under the microscope.

The slide should first be examined under the 16-mm objective for any unevenness in density along its length, and any contamination of the cover-glass in areas remote from the deposit. The extent of the deposit should be clearly defined, and if, owing to heavy contamination, the edge of the deposit is not easily seen, the sample should be rejected.

The length of the deposit should be measured with a stage vernier under a 16-mm objective. A traverse should be selected either centrally or 2 mm from either end.

If the examination of the deposit under the 16-mm objective has shown that there is a defect where a traverse would normally be made, a new position should be chosen which is clear of defect, yet as near as possible to the original position.

The total length of the traverse counted should be 2 mm, 1 mm either side of the center of the dust deposit.

The projected areas of the particles are compared with the areas of the globes or circles on the eyepiece graticule. All particles whose sizes are greater than the 1-micron circle are usually counted. These may be either single particles or aggregates. The criteria for including an individual particle or aggregate in the count are as follows:

1. It falls within the specified size range.
2. At some stage in focusing, a clear margin

of separation is visible between the particle and all its neighbors.

The airborne dust is deposited over a very small area on the cover glasses and to avoid overcrowding, it is necessary to restrict the volume of air sampled. An endeavor should be made to obtain slides with an optimum of 50,000 particles larger than 1 micron with outside limits of 25,000-75,000. Slides with densities above and below these limits are liable to give a seriously inaccurate estimate of the dust concentration. The recommended method of illumination in the microscope is the Kohler system. A compensating 15 x or 17 x eye-piece is recommended with the achromatic type objective.

In the long running thermal precipitator (LRTP) the dust-laden air is drawn down a vertical passage, and along a horizontal channel, the floor of which is formed by a glass coverslip. Particles settle out from the air by gravity and the remainder are precipitated thermally beneath a heated wire. A sample of up to 8 hours duration can be obtained with this instrument, compared with 10-30 min for a sample using a standard instrument.

The instrument is hung or supported in the sampling position, with the top surface approximately horizontal. To reduce contamination, the sampling head may be sealed during the journey to and from the sampling position. The instrument should not be subjected to excessive bumping during the journey back to the laboratory and should remain in an upright position until the sample can be removed.

The counting procedure to be followed for LRTP samples is generally the same as described for standard thermal precipitator samples, the following being the main points of differences:

1. The slides should be set up on the microscope with the thermally precipitated zone to the left of the microscope stage.
2. The length of the traverse to be counted should be estimated by marking the position of the thermally precipitated zone under the 16-mm objective and then moving the microscope stage 1 mm to the left of this position and counting 14.5 mm to the right of this point — any particles outside these limits are to be regarded as contamination.
3. The traverse to be counted should be 6 mm from the most clearly defined end of the thermally precipitated zone.
4. The width of the deposit, to be used in calculating the result, should be measured at the thermally precipitated zone.
5. The dust deposits on these slides are occasionally heavy and the use of the full 60-micron graticule width may entail prolonged counts, producing fatigue and a falling-off in the counting accuracy. In such cases use may be made of the subdivision of the graticule to count either 40- or 20-micron traverses.

STATISTICAL CONSIDERATIONS

In order to determine how many samples to take, and where and when to take them, it is necessary to keep in mind the objective of the survey and to understand how to cope with the variations in the results that are obtained.

Begin by making a list of the people who are employed in a particular work-place or work-places. The place to sample follows from inquiry about where they are working. Surveys vary from "one time" to "continuous monitoring." In a one-time survey the objective is to find out as quickly as possible if the concentration exceeds the hygiene standard at the time the samples are being taken. Continuous monitoring refers to regular sampling over a period of weeks, months or even years to check whether the environment is deteriorating (or improving).

Representative Sampling

When several employees are doing similar jobs, the question arises which employees to investigate. For example, the sampling may be based on the reasoning that if the environment of those whose exposure is the greatest complies with the recommendations of the TLV document, then the environment of every employee in the group will comply. The hygienist should judge which employees are representative of those with the highest exposure. They may be those in the location where there is the most dust, or those who do their job in such a way as to produce the highest airborne dust concentration.

The alternative is to use a random sampling procedure through the whole group. Individuals from a group may be chosen by selecting names at random. They may be further subdivided into smaller groups exposed to markedly different dust concentrations, and each group sampled separately.

The spacing of samplings over the period under study should be planned ahead of time. The atmospheric samples may be taken at regular intervals or at times chosen at random beforehand. If taken at regular intervals the interval should not coincide with any other regular cycle of events which might be related to the concentration of atmospheric particulates.

Sampling by the Workday

Threshold Limit Values refer to the time-weighted average concentration for a 7- or 8-hour workday and 40-hour workweek. Samples of the atmosphere are often taken for periods of 5 to 30 minutes or for a full shift, depending on the apparent particulate concentration, the assessment procedure to be used, and the duration of the operation being studied. A 15-minute sample duration is used in many cases. The maximum number of such 15-minute results taken with one sampling instrument in an 8-hour workday is 32. Such a set of 32 results, whose average was lower than the TLV, could be taken as showing that the environment complied with the TLV document on that workday with respect to the airborne particulates being determined.

Particulate sampling procedures differ from this because often, for good practical reasons, only

a few results have been obtained, perhaps as few as four or five. When fewer than 32 15-minute results are obtained it is necessary that the acceptable upper limit of their average be made lower than the TLV to compensate for the loss of information.

The distribution of averages of two or more results is a normal distribution when the parent distribution is normal. More important, even if the parent distribution is not normal, the distribution of the average tends rapidly to normal form as the number of results increases. In most cases it may be assumed for all practical purposes that with four or more results their average is distributed normally. Consequently, the error of this average can, in practice, be estimated by reference to a table of the normal distribution. (Roach, Baier, Ayer and Harris, 1967).¹⁴ The standard deviation of the average of n results is σ/\sqrt{n} , where σ is the standard deviation representing the dispersion between the individual results.

Suppose, for example, the individual results obtained over the course of a shift varied about their average with a coefficient of variation of 35%. With 32 results, the 90% confidence limits of the average would be $\pm 10\%$ of the average. Thus, since only one side of the distribution is of concern, one would be at least 95% confident, when the observed average equals the TLV, that the true average did not exceed that TLV by more than 10%. If fewer than 32 results are available the same degree of confidence can be obtained only by lowering the acceptable upper limit of their average until the upper confidence limit again equals $1.1 \times$ TLV. In practice, the coefficient of variation may be less than, or vary much greater than, the example 35%. A general formula for the acceptable upper limit to the average, \bar{x} (max) given in terms of the standard deviation, σ , and the number of results, n , is:

$$\bar{x}(\text{max}) = \text{TLV} - 1.6 \left(\frac{1}{\sqrt{n}} - \frac{1}{\sqrt{32}} \right) \sigma.$$

When the standard deviation is not known from previous results, it has to be estimated from the sampling results. A simple and efficient estimate from a few samples is obtainable from the range. The possibility of error in this estimate is also taken into account by lowering the acceptable upper limit to the average accordingly. The limit so calculated may be found conveniently from Table 13-1.¹⁴ The limit is $\text{TLV} - (k \times \text{range})$, where k is found in the table, from the number of results obtained.

When the limit so calculated is less than the observed average, the environment cannot safely be said to have complied; and when the limit is higher than the observed average, it can be stated with some assurance that the environment did comply. In this way the hygienist can make a simple confidence test for compliance and make proper allowance for the number of sample results actually obtained.

Whereas it is possible to state that the conditions examined on a particular workday complied with the TLV document, it is not possible to infer from the results of sampling on one day

TABLE 13-1
k Values for the Range

Number of Results	k
32	0.
10-31	0.1
6-9	0.2
5	0.3
4	0.4
3	(0.8)
2	(0.9)

whether these conditions were representative of any other period.

The hygienist may choose the day to be sampled with the aim of sampling a day representative of the highest concentration. However, it must be borne in mind that, even with careful observation of the processes, cross-questioning of the employees, ventilation measurements, and studies of air contaminant control equipment, the judgment may be little more than intelligent guesswork.

The average concentration will vary not only from time to time during a day but also from one day to another, from one week to another, and from one year to another.

The results of successive visits to a workplace may be plotted on a control chart for prediction purposes. This is a useful means for predicting ahead when an environment is getting out of control, as might happen, for example, with an increase in production or with seasonal fluctuations.

The successive averages are plotted by date. The chart is set up by first considering a sample of, say, 20 visits. A warning line is drawn 2 standard deviations above the grand average, and an action line 3 standard deviations above this average. The standard deviation here is that between the average concentrations from the 20 visits. The warning line should, of course, be at or below the TLV at the outset. Subsequent results should all fall below the warning line. A point falling above this line should be followed by a repeat visit. A repeated point falling above this warning line or a single point falling above the action line indicates that there is good cause for immediate action to be taken to reduce the dust concentration.

A supplementary chart may be drawn up for the range. This, in combination with the control chart for averages, will show whether loss of control is due to an increase in average dust concentration or to dust "floods" occurring within each shift. The latter condition will show up as points above the action line on both charts.

Sampling by the Week

Some particulate sampling methods necessitate a minimum sampling duration of 8 hours in order that the sample can be determined with sufficient sensitivity. In order to collect enough samples in a workshop to be representative of average conditions, it is necessary to have several instruments

being used at the same time and/or to extend each survey over several days.

In such situations a workplace may be defined in terms of the area in which people work on one or a group of identical or similar machines. A workplace can then be assigned its dust category, above or below the hygiene standard, according to the time-weighted average concentration of people working there. This could be determined by sampling continuously or at representative intervals during working hours over one week. The sampling should have been carried out at a minimum of 5 locations, or at a minimum of 5 locations on successive shifts in the area, each location being selected to provide a representative sample of air to which one fifth of the employees are exposed or exposed for a fifth of their time.

In a workplace where the weekly average exposure lies below the TLV, an occasional shift average may exceed the hygiene standard. Accordingly, provided no more than one shift exposure exceeds the hygiene standard and the time-weighted average concentration for the workplace does not exceed the hygiene standard, it may be classified favorably. The k — values given in Table 13-1 may be used for deciding whether the grand average allows a favorable report.

Sampling by the Quarter

Continuous monitoring permits the environment to be assessed at quarterly intervals. Since mineral dust pneumoconiosis are the result of at least some years of exposure, health may be protected provided the quarterly or 6-monthly average mineral dust concentration is below the corresponding TLV. Shorter period surveys or sample durations are really only necessary in these circumstances through the practical inconvenience of the longer period.

A workplace may thus be assigned its category according to the time-weighted average concentration determined by sampling continuously or at representative intervals during the previous quarter.

Time weighted average concentration =

$$\frac{\text{Average concentration during working hours} \times \text{No. of hours worked per quarter}}{520}$$

520

Three months is sometimes an inconveniently long time to wait in uncertainty, such as in a new environment, or in a workplace where use of the mineral has just begun, or airborne dust measurements have not previously been made.

The common situation exists where the mineral is used regularly and is likely to continue in use for some time. In such a situation a procedure is needed which develops into a regular 3-monthly schedule of sampling. However, there are other situations in which the mineral may be used rarely or sporadically or for only a short period, possibly for a few days, with no expectation of repeated use. In these cases, there is a need for rules on the acceptable maximum concentration for short periods.

At a new workplace, in order to give early warning should the time-weighted concentration be especially high, it should first be assigned a

category according to the level of the time-weighted average concentration over a full shift. After one week of sampling it should be reclassified according to the level of the time-weighted average concentration adjusted to 40 hours.

Subsequent reclassification might then be made quarterly, based upon results from samples taken during the previous quarter. Provided no more than one week exposure exceeds the hygiene standard and the average for the workplace does not exceed the hygiene standard, it is classified in the favorable category.

The spacing of the samples over a 13-week sampling period should be planned in advance. The samples should be taken at regular intervals or at times chosen beforehand, whether the duration of each sample is a few minutes, a shift, a week or even 13 weeks. The longer the duration of each sample and the more samples that are taken, the more accurately will the average concentration be estimated. Sufficient assurance that the average concentration lies below a given level would be gained by showing that the upper 90% confidence limit of the average lies below that level. In a workplace where the long-term average concentration lies below the threshold limit value, an occasional quarterly average may exceed the threshold limit value. Accordingly, even though the most recent quarterly average exposure exceeds the threshold limit value, an environment could be classified favorably if the time-weighted average concentration during the last four successive quarters lies below the threshold limit value.

There are workplaces where the conditions change through applying new methods of work, through replacing machines or through changes in the ventilation systems. A workplace that has undergone such changes which may affect its classification should be regarded as a new one. Further, a workplace where the material is used irregularly, or for a few days at a time, or where its regular use cannot be foreseen, should be assigned a category according to the time-weighted average concentration over a single workday.

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SIZING METHODOLOGY

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CHARACTERISTICS OF AIRBORNE PARTICLES

The most important single parameter useful in predicting or explaining the behavior of airborne particles is a description of their size. This fact can be appreciated more clearly when the wide range of sizes likely to be present is considered. Particle sizes may range from 10^{-7} cm. in diameter for condensation nuclei to 10^{-3} cm., the upper limit for respirable particles, thus covering four orders of magnitude. If the smallest size is visualized as a steel ball 1 mm. in diameter, then at the same scale, the largest size would be 10 meters in diameter. It would be surprising if these particles obeyed the same laws or indeed if they could be measured using the same instrument. If the relative masses of these two particles is considered, the comparison becomes truly astounding (10^{12}). With the same scale a molecule of air would be less than half a millimeter in diameter and the average distance between molecules of air would be approximately 10 cm. Thus, one could visualize particles smaller than 10 cm. on our scale, for example of the order of 0.1 micrometer (0.1 μ m), floating about with only occasional contact with molecules of air. When contact did occur, however, the exchange of energy in the collision would be sufficient to alter the course of the particle. On the other hand, a large particle on this scale of perhaps a meter in diameter would be bombarded constantly by air molecules and its motion hindered considerably. In this case however, a collision with a single air molecule would probably go unnoticed. Thus, in attempting to describe the behavior of an airborne particle the most important description has to be its size; many characteristics of dust clouds such as rate of settling, agglomeration, Brownian motion, and diffusion must be primarily size-dependent.

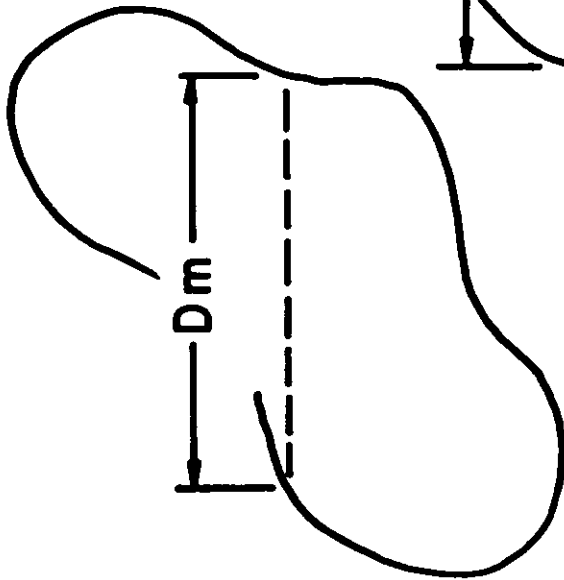
On the other hand, if one wished to compare the behavior of two dust clouds having approximately the same size of particles, other factors could become important. The density of the particles might differ by a factor as high as two or three, and the shape could range from spherical for liquid droplets to needles for fibers or flat platelets in the case of mica or graphite. Certainly these differences would also alter the predicted behavior of the particles.

The hazard of airborne particles results from interaction with the tissue of the lung. In order to reach the deep lung, the particles must pass through the nasopharyngeal region, the trachea, and the bronchi. In each of these regions the air-flow is quite turbulent and larger particles tend

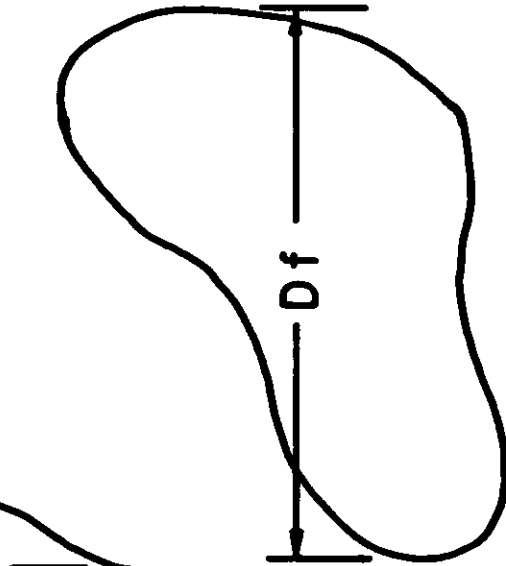
to be removed by impaction. These particles are transported to the mouth by the mucociliary flow, and therefore enter the gastrointestinal tract. Particles smaller than approximately ten micrometers in diameter, however, can penetrate into the deeper regions of the lung and be deposited where the mechanism for removal involves phagocytosis, a much slower process. Thus the size of particles of concern as a health hazard is generally considered to be below 10 micrometers in diameter. The lower size of the respirable range is less well defined. Particles smaller than a few tenths of a micrometer in diameter are subject to Brownian motion and are deposited in the lung by diffusion with reasonable efficiency. Since it would require millions of these small particles to equal the mass of one 10-micrometer particle the actual dose to the lung may be quite small. There are, of course, certain specific cases as radioactive materials where particles smaller than 0.1 μ m in diameter are most important.

Quite apart from physiological considerations there are physical factors which affect the numbers and sizes of particles found in the air. These particles comprise a dynamic system which is constantly changing. Large particles tend to be removed rapidly by sedimentation while smaller ones are likely to agglomerate. In the production of small particles from a bulk material the amount of energy required to reduce relatively coarse material to extremely fine particles may be phenomenal and therefore many industrial processes such as grinding or crushing may be incapable of producing particles smaller than 0.1 micrometers in diameter. Welding operations, on the other hand, produce copious quantities of 0.01 micrometer fumes. Any given sample of airborne dust may therefore contain a wide variety of shapes as well as sizes of particulate matter.

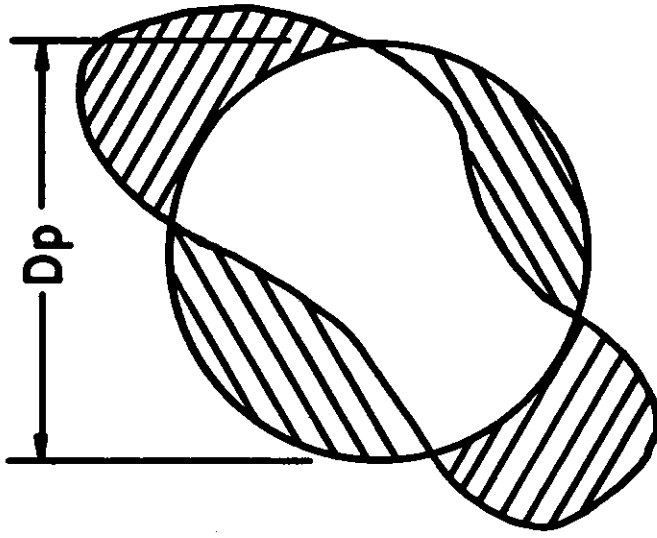
This, of course, makes a description of particle distribution somewhat difficult. If all the particles were of one size, one would merely have to measure that size to define the distribution. If they were all spherical one could measure a sample of the particles and perhaps report an average size. If the shapes are irregular, however, one must first decide what dimension is to be considered as the particle diameter. Three possibilities are shown in Figure 14-1. Martin's diameter is the length of a line which divides the particle into two equal areas. This line could be drawn in any direction for the first particle to be measured, but all other particles should be measured in a direction parallel to the first. If the particles are randomly oriented and a large number



MARTIN'S DIAMETER



FERET'S DIAMETER



PROJECTED AREA DIAMETER

Figure 14-1. Geometric Diameters for Irregularly Shaped Particles

are measured, the direction of measurement is not important. Feret's diameter is the distance between the extreme boundaries of the particle. Again all measurements should be made in the same direction. The projected area diameter is the diameter of a circle having the same cross-sectional area as the particle. Other possibilities would be to measure the longest or shortest dimension of the particle. Estimates of the average size obtained by measuring the shortest diameter would yield the smallest value. Martin's diameter would be followed next by the projected area diameter and Feret's diameter. Measuring the longest dimensions would yield the greatest average diameter. Which then would be nearest to the correct or most useful estimate? Obviously neither the shortest nor the longest dimensions accurately describe the mass of the particles measured although recent work has indicated the smallest dimension may most nearly predict the aerodynamic behavior of fibrous particles. Martin's diameter would seem to underestimate the true size and Feret's diameter would appear to be an over-estimate. The projected area diameter therefore would seem to offer the best estimate of the true size. It is worth noting that for spherical particles all of these estimates would be the same. This statement may take on more significance when one realizes that as particle-size decreases all particles tend to approach the spherical or at least an isometric shape.

STATISTICAL CONSIDERATIONS

A sample of airborne dust will always yield particles of many different sizes and therefore can be called polydisperse. When we consider the behavior of airborne particles, the degree of this polydispersity is usually far more important than factors of shape and perhaps even density. Therefore a simple statement of the average diameter is not very useful in describing these particles. It would indeed be desirable to also be able to describe the degree of polydispersity. If we would assume that the sizes of the particles followed the normal or Gaussian distribution (bell shaped) we could use the powerful techniques of statistics to describe and analyze the distribution¹. Thus we could say that 67% of all the particles had sizes falling between the limits of plus or minus 1 standard deviation from the mean, 95% between plus or minus 2 standard deviations and 99.7% between plus or minus 3 standard deviations. The average size of the distribution would be given simply by:

$$\bar{d} = \frac{\sum_{i=1}^n i N_i d_i}{\sum_{i=1}^n N_i}$$

where \bar{d} is the average size of the distribution, and N_i is the number of particles of size d_i ; the stan-

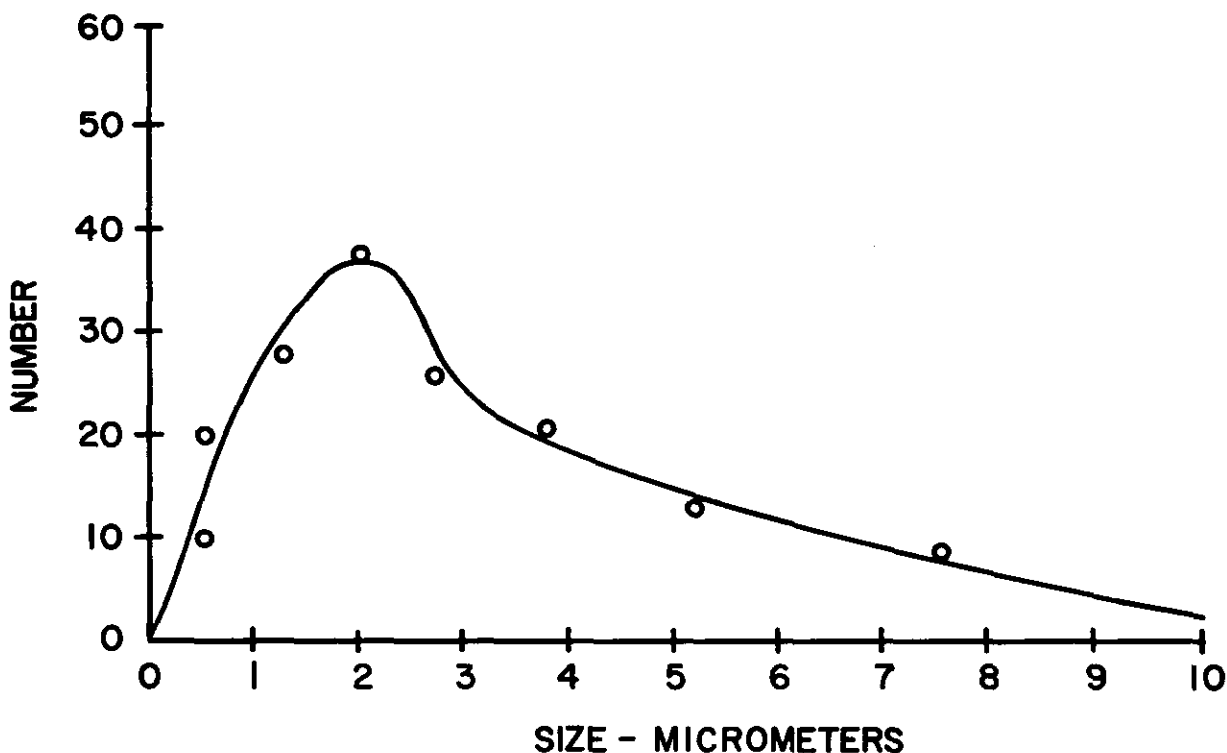


Figure 14-2. Log — Normal Size Distribution

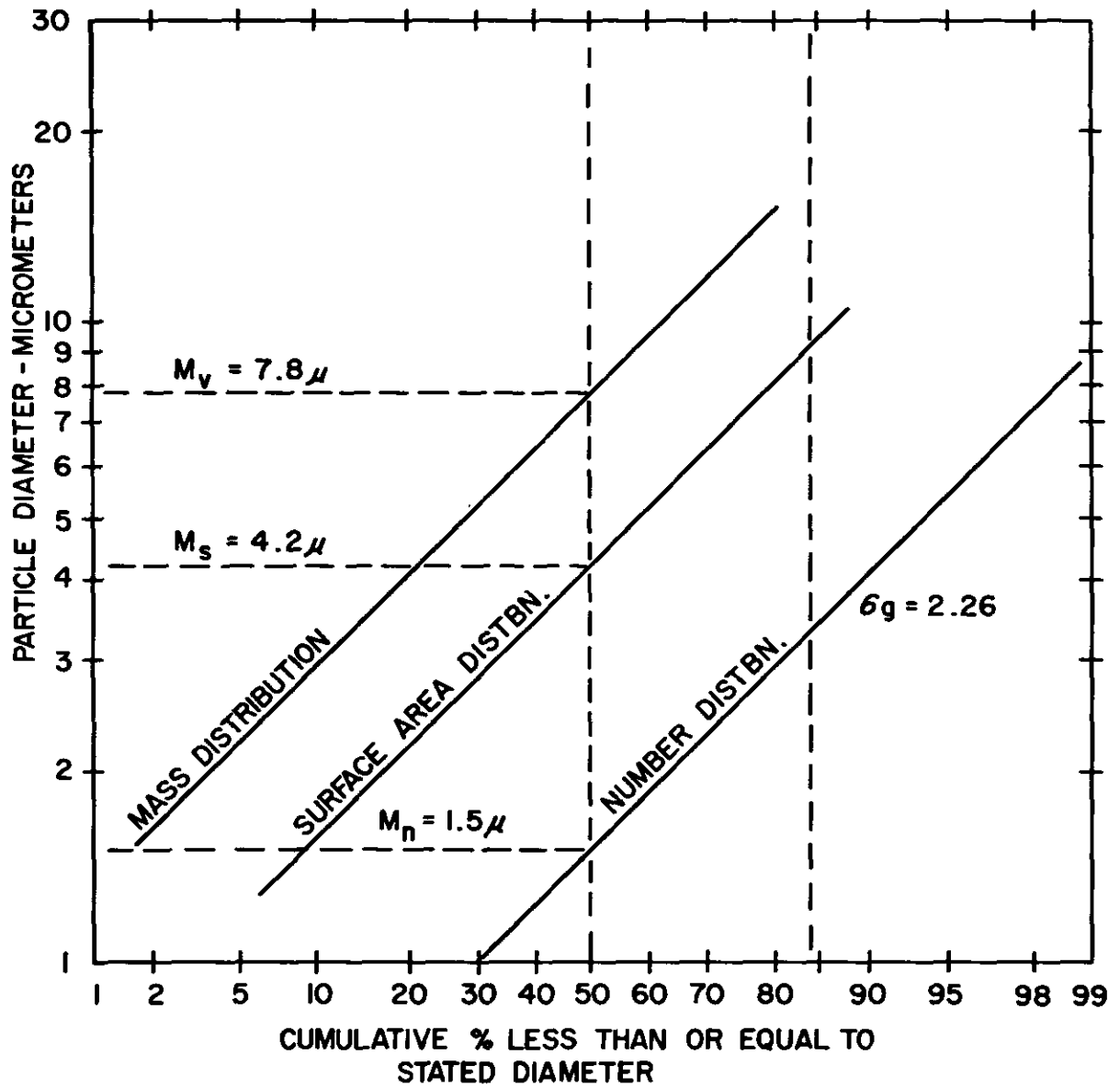


Figure 14-3. Summated Size-Number, Size-Surface and Size-Mass Distributions Plotted on Log-Probability Paper

standard deviation would be a measure of polydispersity:

$$\sigma = \left(\frac{\sum (d_i - \bar{d})^2 N_i}{\sum N_i - 1} \right)^{1/2}$$

Unfortunately, the particle sizes of most aerosols are not normally distributed due to the loss of larger particles by sedimentation and other factors mentioned above. Instead the curve is usually skewed toward the smaller sizes. A typical skewed distribution is shown in Figure 14-2; the data is given in Table 14-1. Hatch² showed, how-

TABLE 14-1: Particle-Size Distribution

size- μm	number	$\sum n$	$\sum \%$
0.5	10	10	5
0.7	22	32	16
1.0	26	58	29
1.4	29	87	43
2.0	37	124	62
2.7	28	152	76
3.8	22	174	87
5.4	14	188	94
7.7	8	196	98
10.9	4	200	100

ever, that if one plotted the logarithm of the particle size instead of the actual size the result closely approximated a normal distribution. Thus, we can say that:

$$\bar{d} = \log^{-1} \left(\frac{\sum N_i \log d_i}{\sum N_i} \right)$$

and

$$\sigma = \log^{-1} \left(\frac{\sum (\log d_i - \log \bar{d})^2 N_i}{\sum N_i - 1} \right)^{1/2}$$

We are saying that the log-normal distribution provides a reasonably good approximation of the particle-size distribution usually found in airborne dusts. It should be noted, however, that other possibilities do exist and such occurrences as bimodal distribution or the mixing of dusts from two entirely different sources (smoke and dust for instance) happen frequently.

If we accept the log-normal distribution as representing the actual size-distribution of airborne particles, we can simplify our calculations by resorting to a graphical solution. If we plot the summated size-distribution on logarithmic-probability paper, the result should be a straight line if the assumption of a log-normal distribution is correct. The lower line of Figure 14-3 is such a plot of the data from Figure 14-2. From this graph we can read directly the median or 50% size. In the illustration 50% of the particles are larger than 1.5 micrometers and 50% are smaller. We can also read any other points on the curve. 80% of the particles measured were smaller than 3.0 micrometers in diameter and 95% were smaller

than 5.0 micrometers. As a measure of the polydispersity we can also find the standard deviation by dividing the 84.13% size by the 50% size, in this case 3.4 micrometers, divided by 1.5 micrometers gives a standard geometric deviation, σ_g , of 2.26, a dimensionless number. The same value for σ_g could, of course, be obtained from the other end of the curve by dividing the 50% size by the 15.87% size. The standard geometric deviation therefore represents the slope of the line and along with the median size is sufficient to describe the distribution.

The log-probability distribution described above is expressed mathematically as follows:

$$F(d) = \frac{\sum N}{\log \sigma_g \sqrt{2\pi}} \exp. \left[- \frac{(\log d - \log \bar{d}_g)^2}{2 \log^2 \pi_g} \right]$$

where $F(d)$ is the frequency of occurrence of the diameter d , $\sum N$ is the total number of particles, σ_g is the standard geometric deviation and \bar{d}_g is the geometric mean diameter. This function predicts the existence of all sizes of particles from zero to infinity. Since the number of particles contributing to the extremes of the distribution is small, the confidence bands around the two ends of the line are wide and become narrowest at the 50% size. It can be shown that in order to estimate the median size within 10% of the true mean with 95% confidence, a minimum of 200 particles must be measured. If, on the other hand, we wished our estimate of the median size to be within 5% of the true mean with the same degree of confidence, we would have to measure at least 1000 particles. In the example given above we estimate the median size to be ± 0.15 micrometers. For most purposes this is an adequate estimate and therefore the measurement of 200 particles is sufficient.

The number-size distribution of the particles having been established, other parameters of interest can also be determined. If we wished to examine the distribution of mass among these particles, assuming a constant density, we could multiply the frequency of occurrence of particles in each of our size ranges by the cube of the average diameter for that range and summate these weighted frequencies. This is shown in Table 14-2.

TABLE 14-2: Size-Mass Distribution Data

size	n	d	d ³	d ³ n	$\sum d^3 n$	$\sum \% d^3 n$
0.5	10	0.25	0.02	0.2	0.2	0.0
0.7	22	0.6	0.22	4.9	5.1	0.0
1.0	26	0.85	0.61	16.	21.1	0.3
1.4	29	1.2	1.7	46.	67.1	0.8
2.0	37	1.7	6.1	230.	297.1	3.0
2.7	28	2.3	10.2	290.	587.1	7.0
3.8	22	3.2	32.0	700.	1287.1	16.0
5.4	14	4.6	93.0	1300.	2587.1	33.0
7.7	8	6.5	260.	2100.	4687.1	59.0
10.9	4	9.3	790.	3200.	7887.1	100.0

Plotting these data as summated percentages on log-probability paper produces a curve which represents the mass distribution of the aerosol. This is plotted as the upper curve of Figure 14-3. From this curve we can obtain the mass-median diameter or the size below or above which half of the mass of the particles would occur. It should be noted that had the density of the particles been included in weighting each frequency range in the above calculation, the density factor would have cancelled when dividing through by the grand summation to reduce the data to percentages. It is also apparent that the standard geometric deviation of the size-mass distribution (the slope of the line) is identical to that of the number distribution. The size-mass distribution is often useful in predicting the actual dose to the lung resulting from the inhalation of a given amount of dust or the weight of material collected by a filter or other collection device which is efficient only for particles larger than a given size.

A similar technique can be used to describe the distribution of surface-area for the particles in question, assuming spherical symmetry of the particles. In this case the number-frequency of particles in each range is weighted by multiplying by the square of the average diameter of the range. This has been done in Table 14-3 and plotted as

TABLE 14-3: Size-Surface Distribution

size	n	d	d ²	d ² n	Σd ² n	Σ% d ² n
0.5	10	0.25	0.06	0.6	0.6	0.04
0.7	22	0.6	0.36	7.9	8.5	0.6
1.0	26	0.85	0.72	19.	27.5	2.0
1.4	29	1.2	1.4	41.	68.5	6.8
2.0	37	1.7	3.6	140.	208.5	14.8
2.7	28	2.3	5.3	149.	357.5	25.3
3.8	22	3.2	10.0	220.	577.5	40.8
5.4	14	4.6	20.1	180.	757.5	53.5
7.7	8	6.5	40.2	320.	1077.5	76.0
10.9	4	9.3	83.0	332.	1409.5	100.0

the middle line of Figure 14-3. The surface-area distribution is sometimes useful in comparing or predicting surface related phenomena such as the scattering of light, adsorption of vapors or the reaction of insoluble particles with biological tissues. Hatch² has proposed equations which permit the direct calculation of the mass-median (M_g) and surface-median (S_g) diameters from the size-median diameter without the weighting procedures described above. The most important of these is given below:

$$\log M_g = \log d_g + 6.9078 \log^2 \sigma_g$$

Since σ_g is the same for the mass and number distributions, calculation of M_g permits the curve describing the entire mass distribution to be drawn immediately.

MEASUREMENT TECHNIQUES

The technique of measuring the size of airborne particles has to begin with the selection of

the sampling instrument. The factors which must be considered to prevent bias of the sample in favor of either larger or smaller particles have been described in Chapter 13. Once a representative sample has been obtained a specimen of this must be prepared for observation and measurement using a standardized technique. Care must be taken that the preparation of this specimen and the measurement technique itself does not introduce bias and destroy the representative nature of the specimen.

Optical Microscopy

In order to serve as a standard method in the field of Industrial Hygiene, a technique should be suitable for use generally in laboratories across the nation. This may preclude the use of certain exotic instruments that are so expensive or complicated that they are found only in a few highly specialized laboratories. For the counting and sizing of airborne dust particles, the optical microscope is usually available and can be operated by a trained technician. For particle-size analysis any good quality clinical microscope is adequate. Because the size of the smallest particles to be measured will approach the theoretical limit of resolution of the optical system, the illumination either built into the microscope or provided by the operator should meet the requirements of either Kohler or critical illumination. Thus the operator must have some knowledge of the optical system that he will use.

The optical microscope³ is comprised of five basic components: (1) the light source, (2) the condenser lens which focuses the light on the specimen, (3) the specimen stage which holds and makes possible movement of the specimen, (4) the objective lens which produces an intermediate and magnified image of the object and (5) the ocular which further magnifies the intermediate image and presents it as a virtual image to the eye. The heart of the instrument is the objective lens, for the quality of the final image can be no better than that of the intermediate image produced by this lens. The quality of the image is better described as the resolution or fineness of detail that is preserved by this lens. The limit of resolution is given by the Abbé equation:

$$d = \frac{0.61\lambda}{\eta \sin \alpha}$$

where d is the shortest distance separating two fine lines at which the two lines can still be distinguished; λ is the wave-length of the light used; η is the index of refraction of the medium between the specimen and the lens; and α is the half angle subtended between the axis of the optical system, the periphery of the lens and the specimen. It is, therefore, the maximum angle through which the lens can receive light from the specimen. This angle, of course, can not exceed 90° or the specimen would have to be inside of the lens. The sine of α can approach 1.0 as a limit and is usually 0.94 for a high magnification lens. The index of refraction of the medium is also limited, being 1.0 for air, 1.33 for water and 1.515 for the usual immersion oils. The product of the index of refraction and the sine of α is called the numerical

aperture (N.A.) of the lens. This will range from 1.25 for a high magnification (97x) oil immersion lens to less than 1.00 for a low power lens. The wavelength of the light used is limited to the visible spectrum. Thus the shortest visible wavelength will be at the violet end of the spectrum and of the order of 400 millimicrons. Substituting these values in the Abbé equation shows that the theoretical limit of resolution for any optical lens must be approximately $200m\mu$ ($0.2 \mu m$). In order to attain this, however, the full numerical aperture of the lens must be utilized, and this is possible only with a condenser lens having a high numerical aperture and either Kohler or critical illumination. In addition to this the objective lens must be of high quality and corrected for chromatic aberrations for three colors. Such a lens is called an apochromatic objective.

The quality of the ocular is somewhat less important. The limit of resolution of the eye is usually taken to be approximately 0.1 mm. If the finest detail in the specimen is magnified to 0.1 mm, it will be discernible to the eye. Therefore, the finest detail resolvable by the objective lens ($0.2 \mu m$) has to be magnified only 500 times in order to be visible. If the high-dry objective (usually 46x) were used, a 10x ocular would accomplish this since the overall magnification would be 46×10 or 460. Certain refinements which are available in oculars such as wide field, flat field (for photographic purposes), high eyepoint (for people who wear glasses) and higher magnifications (15-20x) may be desirable and convenient even though they may contribute little to actual improvement of the image.

Preparation of Specimens

Given a satisfactory optical system, the specimen must be suitably prepared for observation and measurement. The sample may have been obtained in the same manner as described in Chapter 13 for dust counting, with either the midjet impinger or a membrane-filter. In either case the sample would be prepared in the same manner in the Dunn cell or the haemocytometer or by using the proper immersion fluid to render the membrane-filter transparent. There is no need to relate the sample used for size analysis to any particular volume of air, and it is often convenient, therefore, to collect separate samples for size analysis in order to obtain a greater number of particles. Occasionally, one may be working with a bulk sample of material, and in this case great care must be taken to spread a representative sample uniformly on a microscope slide in such a manner that bias is not introduced by selectively retaining the small particles on the glass surface. It must be remembered that the collection of the sample resulted in the concentration of the particles either on a surface or in a liquid and thus may have resulted in agglomeration or other change from the airborne state. It may, therefore, be necessary to subject the particles to a deagglomeration procedure such as insonation in an ultrasonic generator prior to the preparation of the final specimen. In general it is felt that collection

on the membrane filter causes less change from the airborne state than other methods.

Reticles and Calibration

When the specimen has been properly prepared on the microscope slide it must be focused in the field of the microscope. Actual measurement then consists of superimposing on the field a suitable scale, reticle or measuring device. The first device that was used intensively for this purpose was the Filar micrometer. It is, in fact, a substitute eye piece which superimposes on the field a scale comprised of 100 units. Part of this scale is a movable verticle cross-hair which is controlled by a micrometer screw thread connected to a drum dial. The circumference of the drum dial is divided into 100 units and can be read to 0.1 unit by means of a vernier. One complete rotation of the drum dial (100 units) moves the cross-hair one division of the field scale. In practice the cross-hair must be moved in one direction until it just touches one boundary of the particle to be measured. A reading of the drum dial is taken and the traverse continued until the other side of the particle is reached. The difference between the two drum dial readings gives the Feret's diameter of the particle in units. A minimum of 200 particles are measured in this manner.

The Filar micrometer, however, is a tedious instrument to use. The measurement of Feret's diameter obtained with this instrument is less representative as the particles depart from isometric. For these reasons reticles which are more easily used have come into favor.

The most common of these is the Porton reticle which is named after the research group in England that was responsible for its design. It consists of a photographically reduced and reproduced transparent grid which is mounted exactly in the focal plane of either the Hygens or the Ramsden ocular. The grid is thus superimposed on the field of the microscope. A picture of this grid superimposed on a dust specimen is shown in Figure 14-4. It consists of a large rectangle one half of which is divided into six smaller rectangles. Along the top and bottom of the rectangle are a series of circles or dots of increasing size. The diameter of each dot is larger than the previous one by the square-root of two. Thus the diameter of any circle in Porton-units is given by:

$$d = \sqrt{2^n}$$

where n is the number of the circle. The height of the large rectangle is 100 units and its length is 200 units. Either the length or height can be calibrated against a stage micrometer to determine the value of one Porton unit in micrometers. Measurements are made by comparing the size of the particles with the circles to find the circle that would completely enclose the particle. This can be done visually and without superimposing the circle on the particle by moving the stage of the microscope. Therefore, all particles contained in the area defined by the six smaller rectangles can be sized before moving on to a new field. This tends to minimize the possible bias of sizing only the larger particles. There is, of course, a natural tendency to equate projected areas of the particles

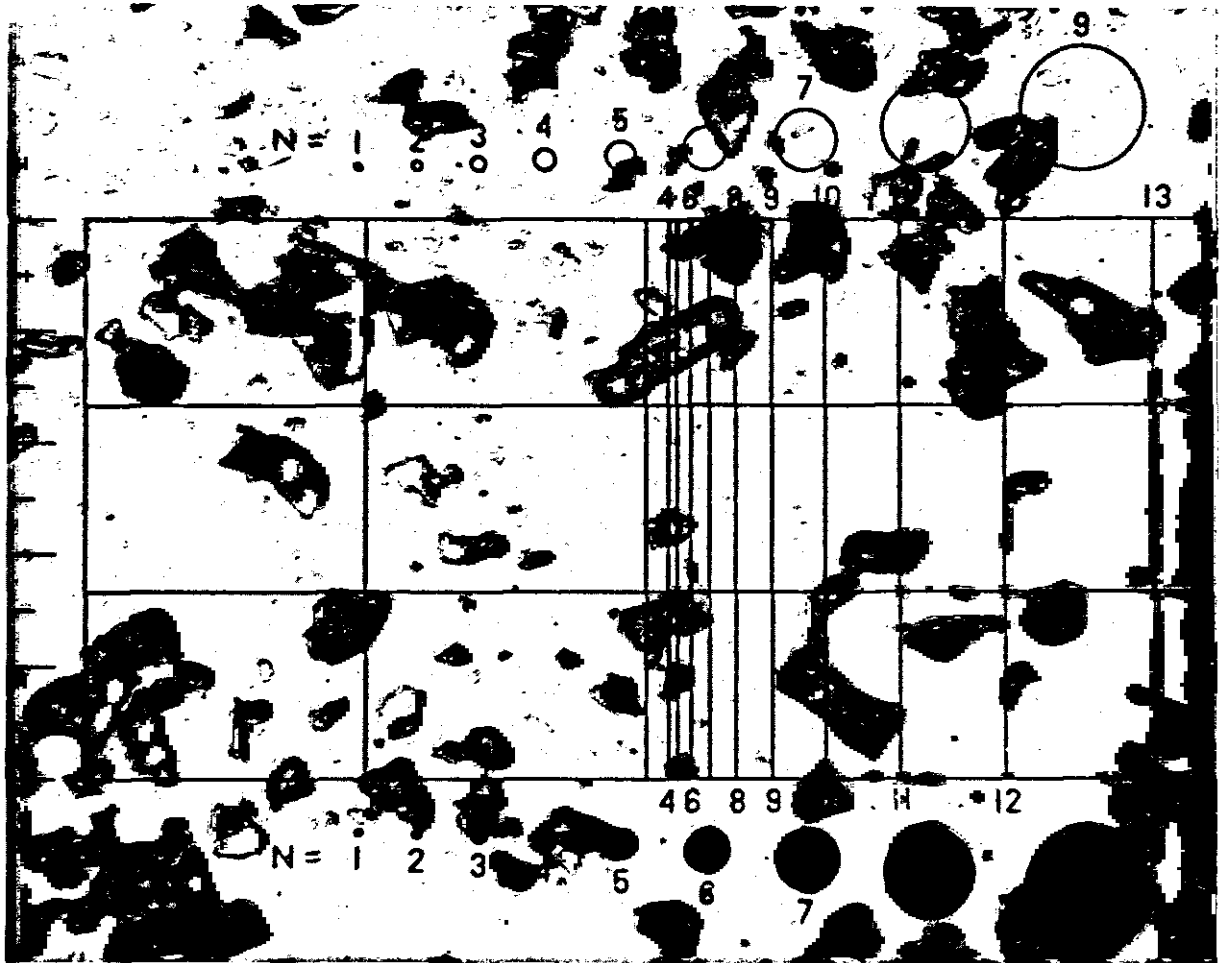


Figure 14-4. The Porton Reticle Superimposed on a Dust Field

and circles. In many cases this projected area diameter is more desirable than Feret's diameter. The entire analysis can be done by one operator and only one reading is required for each measurement.

The calibration of any reticle placed in the optical system consists of comparing that reticle to a stage micrometer substituted for the actual specimen and using exactly the same optics that are used for measurement. Thus one cannot calibrate the optical system using the 10x objective and then switch to the 46x or oil immersion objective to size the particles. Nor can a calibration be transferred from one microscope to another even if similar lenses are used. The tube length of the microscope on older models can sometimes be adjusted to make the calibration result in even numbers. It is good practice, therefore, to include the calibration data with each size analysis and also, if possible, a photo-micrograph superimposing the reticle directly on the image of the stage micrometer so that the reader can see for himself that the calibration is at least approximately correct.

RELATED TECHNIQUES

Although the standard method for particle-size analysis with the optical microscope is usually adequate to describe the implication to health of airborne particles, there may be special situations which require the application of more sophisticated techniques. Smoke and fume particles may well lie below the limit of resolution of the optical system. Continuous monitoring using automated instrumentation and an immediate readout may be desired. It is appropriate therefore to describe a few of the techniques which may be useful in research or specialized field application.

The Electron Microscope⁴

Because of the short wavelength associated with a beam of electrons, the theoretical limit of resolution of the electron microscope is extremely small. In practice resolution between 10 and 20 angstrom units is readily attainable. Physically the electron microscope is quite analogous to the optical microscope. It consists of a heated filament which is the source of electrons, a condenser lens, a mechanical stage, an objective lens, a projector lens and a fluorescent screen which converts the

electron image into visible light. Electrons, having both mass and charge, have a short path length or penetrating power through any medium, and a high vacuum is necessary if they are to travel the length of the microscope column. Since the specimen must be placed in the vacuum, only dry non-volatile materials can be examined. These must be extremely thin (0.1μ or less) and be supported on a thin film of low density material. Classically, films of collodion or Formvar (R) approximately 100 \AA thick are used to support the specimen. These films in turn are supported on 200 mesh grids of copper or stainless steel $\frac{1}{8}$ in. in diameter.

Preparation of the specimen consists of transferring the airborne particles which may have been collected by a technique described in Chapter 13 to a previously prepared film and grid. Because of the high magnification of the electron microscope and consequently the small field to be observed, the preparation of the specimen without introducing bias is more critical than in the case of optical microscopy. The particular technique will depend on the method that was used to collect the sample. If the dust sample was collected in water by impingement, a drop of the particulate suspension may be placed on the grid and allowed to evaporate to dryness. If a bulk sample of insoluble dust is to be examined, a dilute suspension of the particles in distilled water may be prepared. Insonation by ultrasonic energy is often useful to deagglomerate the particles. If the sample has been collected on the membrane filter, it may be transferred to a grid by placing a small piece of the filter face down on a Formvar (R) grid and removing the filter media by solution in ethyl acetate as described by Fraser.⁵ Airborne dusts or fumes may be deposited directly on the filmed grids by electrostatic or thermal precipitation. In each case, however, the size distribution may be altered.⁶ Shadow-casting, the technique of evaporating a thin film of metal on the specimen from a low angle, can be used effectively to enhance the detail and increase the contrast of any of the above preparations.

Impaction Devices

Impingement implies the collection of particles in a liquid medium. Impaction, on the other hand, describes the deposition of particles on a dry (or adhesive coated) surface. If air moving at high velocity is forced to change direction abruptly by an obstacle, particles entrained in the air may be unable to follow the air stream and, due to their momentum, may collide with the barrier. If in a single instrument air is drawn through a series of orifices of decreasing size, the velocities attained will increase as the cross-sectional area of the orifice decreases. With increasing velocity, smaller particles will be forced to collide with an obstacle such as a microscope slide placed in the path of the jet. Only large particles will be deposited on the first stage of this device while smaller particles will deposit on subsequent stages. Such a device is called a "cascade impactor" and is used to collect particles in various size fractions. It should be noted that the range of sizes collected on each stage depends on the density and shape of the particles as well as the diameter and therefore

represents the aerodynamic behavior of the particles. The number or weight of particles collected on each stage can be determined by counting, using an optical microscope, by weighing or by chemical analysis. If the density of the dust is known and a size-distribution is obtained for each stage, a relationship can be calculated which will permit one to predict what size of particles will be deposited on each stage for dusts of different densities. For subsequent analyses it is only necessary to determine the mass of material collected on each stage in order to describe the particle-size distribution. The volume flow of air through the device must of course, be kept constant. Because of the varieties of sizes, shapes and densities of airborne particulates inertial impactors are usually calibrated with reference to a standard material. If this standard consists of spherical particles having a density of 1 gm/cc (polystyrene latex balls), then in subsequent analyses particles of irregular shapes and varying densities will be classified according to their aerodynamic equivalence to these unit density spherical particles.

A recent innovation has been the Anderson sampler which is a multi-orifice cascade impactor. A number of orifices of the same size are arranged in concentric circles on each stage. Orifice diameters decrease for each succeeding stage and the diameters of the circles in which they are arranged are staggered on alternating plates; thus the orifice plate serves as the collecting plate for the preceding stage. This design has a number of advantages over single jet impactors. The multiple jets permit large air flows and the collection of larger samples. The plate construction can be quite thin and light-weight permitting more sensitive weighing. The instrument has fewer parts and each time the plates are cleaned the jets are also cleaned. The orifices are circular and therefore the machining can be more precise and the calculations simpler. There is a minimum size of particle which can be collected by inertial impaction. This is the smallest particle that can be collected when the air passing through the jet reaches sonic velocity. This maximum velocity limits the collection of particles by this technique to those larger than a few tenths of a micrometer in diameter. It may be desirable to follow the cascade impactor with a membrane filter or an electrostatic precipitator to collect smaller particles.

Centrifugal Collectors

Centrifugal classifiers or cyclone separators have been used commercially for many years to provide aerodynamically sized fractions of bulk materials. In sampling technology they are generally used as pre-filters to eliminate particles larger than the respirable size. In a few instances the technique has been used to provide information concerning the size of airborne particles.

When an air stream containing dust is forced to follow a circular path, the particles experience a centrifugal force which tends to move them across the stream lines toward the outer wall of the vessel or duct. The centrifugal force increases as the radius of curvature decreases. In the cyclone collector the air stream is introduced tan-

gentially into the widest section of a cone and forced to follow a spiral path of decreasing radius of curvature to the apex of the cone. Thus the centrifugal force increases to a maximum at which point all particles larger than a minimum size will intersect the wall of the cone and be collected. The minimum size that will be collected depends on the dimensions of the cone, the inlet velocity of the air and the distance that the particle must travel perpendicular to the direction of the air flow in order to reach the side. The greatest efficiency will be provided by a long narrow cone operating at high air velocity.⁷ For any given cyclone the minimum size can be increased or decreased by varying the air velocity. Goetz designed an aerosol spectrometer which passed the air in a narrow channel between two concentric rotating cones so that the larger particles were eliminated at the larger end and smaller ones were deposited near the apex. By examining the surface of the outer cone and measuring the distance between the point of inlet and point of deposition, and knowing the speed of rotation and therefore the centrifugal force, he was able to calculate the aerodynamic size of the particle. This instrument was particularly useful in investigating the effect of air, temperature and humidity on the size of particles.

Light Scattering

In the search for automated techniques, instruments which can detect light reflected or scattered from the surface of airborne particles have been developed. A major advantage of such a technique is that the particles need not be collected but are examined in their airborne state. These instruments may respond to light scattered by all particles contained in a fixed volume or the light from individual particles. While the former are sensitive to changes in the number of particles, they are of little use in determining the size of the particles since many small particles may scatter the same amount of light as a few larger ones. Since the light from a discrete particle is reflected from its surface, it can be related to its size. This, however, is not a simple relationship since light may also be diffracted by the edge of the particle or adsorbed a specific wavelength by colored particles. This is further complicated when the particle-size approaches the wavelength of the light. Thus the intensity of light scattered depends on the angle of observation relative to the direction of the incident beam, the greatest intensity usually being observed in the forward direction or looking back toward the light source. The original theory of light scattering was described by Rayleigh for large particles and by Mie for small particles approaching the wavelength of light.⁸ Mathematical functions and tables have been constructed to describe the light scattered at various angles by transparent isotropic spheres. This is, of course, most useful, but one has only to consider the effect of particle shape ranging from flat platelets to long fibers to imagine the complexity of the practical situation. In spite of this, light-scattering devices can be calibrated empirically for a particular dust with a standard chemical or optical method and can be extremely useful for

routine monitoring of clean rooms, animal inhalation chambers, certain industrial processes and testing of filter penetration.

Measurement of Electrical Charge

Airborne particles undergo a continuous bombardment of approximately 10^9 collisions per second by the molecules which comprise the air. If a portion of these molecules are electrically charged ions, this charge will be transferred to the particles and if the ions are unipolar the particles assume this polarity. Due to the coulombic force of repulsion between like charges this charge will be distributed on the surface of the particles. The first ions which approach the neutral surface experience no repulsive force but as the total charge on the particle increases additional ions approaching the surface must overcome a force of repulsion if contact is to be made with the surface. It is apparent that there will be a maximum number of charges that a particle can accept for a given concentration and energy of the ions in its environment. This maximum will be a function of the surface area of the particle.

A charged particle which finds itself in an electrostatic field between two plates will migrate toward the plate of opposite polarity. The velocity that it attains will depend on the field strength as well as the charge to mass ratio of the particle. Since the ratio of the surface to the mass is greatest for small particles, this will also be true for the charge to mass ratio. Small particles will therefore have a greater mobility in the electrical field than larger ones.

In recent years instruments have been developed to take advantage of the phenomena to classify particles according to their size.⁹ The airborne particles are first subjected to a dense concentration of unipolar ions. Maximum charging of the particles can usually be attained in a few milliseconds. They are then passed between a series of plates each of which subjects the particles to an electrostatic field of increasing strength. Thus the free ions will be eliminated by the first field while small charged particles will be collected by the next, and larger particles by subsequent plates. A sensitive electrometer connected to each of the plates can measure the electrical current collected at each stage. Thus the fraction of the current flowing in each stage becomes a measure of the number of particles of each size that comprise the overall particle-size distribution.

The major advantage of the charge measuring technique is its ability to cope with the total range of particle sizes from air ions to large dust particles and its great sensitivity for the smallest particles. The equipment, however, is extremely complicated and expensive, and it is not now feasible to use it as a field instrument.

SUMMARY

Information concerning the distribution of airborne particles can be obtained by means of a variety of methods and techniques which measure any one of several physical properties of the particles. The interpretation of the results from measuring different physical properties may be quite different and not necessarily comparable.

It is most important, therefore, that the sampling device, the measurement technique, and the parameter measured be chosen with careful consideration of the application to be made of the data. It is often true that as the sophistication of the instrumentation increases, the actual parameters measured become more obscure. The industrial hygienist should be thoroughly familiar with the basic concepts and the relatively simple techniques that can be used for estimating the size of airborne particles, since these provide a basis for standardization of automated equipment and a solution to problems when such equipment is not available.

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Periodic Publications

1. Journal of the American Industrial Hygiene Assoc.
2. Journal of the Air Pollution Control Assoc.
3. Staub
4. British J. Applied Physics
5. Environmental Science and Technology
6. Review of Scientific Instruments
7. Health Physics
8. British Journal of Industrial Medicine
9. Annals of Occupational Hygiene
10. Journal of Colloid Science

SAMPLING AND ANALYSIS OF GASES AND VAPORS

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and

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INTRODUCTION

This chapter deals principally with manual methods of sampling and analysis of industrial atmospheres for gaseous and vaporous contaminants (see Chapter 10 for a discussion of the "General Principles in Evaluating the Occupational Environment" and Chapter 16 for the discussion on "Direct Reading Instruments for Determining Concentrations of Aerosols, Gases and Vapors").

For industrial hygiene purposes, a substance is considered to be a gas if this is its normal physical state at room temperature and atmospheric pressure; it is called a vapor if, under the environmental conditions, a conversion of its liquid or solid form to the gaseous state results from its vapor pressure affecting its volatilization or sublimation into the atmosphere of the container, the process equipment, or the workroom. In this chapter the term "gaseous" is used therefore in a general sense in discussing gases or vapors.

Basic Sampling Techniques

There are two basic methods for the collection of gaseous samples. The first involves the use of a gas collecting device, such as an evacuated flask or bottle, to obtain a definite volume of an air-gas mixture at a known temperature and pressure. This type of sample is called a "grab" or "instantaneous" sample as it is collected almost instantaneously, i.e., usually within a few seconds to 1-2 minutes maximum, and is thus representative of the atmospheric conditions at the sampling site at a given point in time. This method is used when the atmospheric analyses are limited to such gross contaminants as mine gases, sewer gases, carbon dioxide and carbon monoxide (above 0.2 percent) and other situations where the concentrations of contaminants are in the percentage range. However, with the increased sensitivity of modern gas chromatographic, infrared and other analytical techniques, instantaneous sampling of ever lower concentrations of atmospheric contaminants is becoming more feasible. The collectors are resealed immediately after sampling to prevent any losses of the sample by diffusion.

The second method for the collection of gaseous samples involves the passage of a known volume of air through an absorbing or adsorbing medium to remove the desired contaminants from the sampled atmosphere. This technique provides a sample of the atmosphere over a recorded time period and is termed "integrated sampling." The contaminant which is removed from the air stream becomes concentrated in/on the collecting me-

dium; the sampling period is chosen to permit the collection of a sufficient quantity of the contaminant for the subsequent analyses.

Sampling Criteria

Whereas airborne particulate substances are readily scrubbed or filtered from sampled air streams due to their larger physical dimensions and to the operation of agglomerative, gravitational or inertial effects, gases and vapors form true solutions in the atmosphere and thus require either sampling of the total atmosphere using a gas collector or the use of a more vigorous scrubbing technique to separate the gas or vapor from the surrounding air molecules. Selected sampling reagents which react chemically with contaminants in the air stream can improve the collection efficiencies of the sampling procedures. In devising an integrated sampling scheme, it is essential to consider the following basic requirements:

1. Provide an acceptable efficiency of collection for the contaminant(s) involved;
2. Maintain this efficiency at a rate of air flow which can provide sufficient sample for the intended analytical procedure(s) in a reasonable and acceptable period of time;
3. Retain the collected gas or vapor in a chemical form which is stable during transport to the laboratory or other analytical site;
4. Provide the sample in a form which is suitable for the analytical procedure(s);
5. Require minimal manipulation in the field;
6. Avoid the use of corrosive or otherwise hazardous sampling media if possible.

Whereas most of these criteria are self-explanatory, some elaboration on the first and second is desirable. It is extremely important that the collection efficiency of a sampling system be known, either from published, well-documented data, as summarized in Table 15-1 for a variety of common contaminants found in industrial atmospheres, or as a result of an independent evaluation as an essential part of planning a future survey. In making such an evaluation, known concentrations of gases and vapors must be prepared (see Chapter 12) and used in a dynamic or static test system to determine the efficiency of the proposed sampling device. The efficiency must be defined in terms of such variables as the type of scrubber, porosity of frits used in the scrubber, size of scrubber, the height, volume, nature, and temperature of the collecting medium, rate of air flow, stability of the sample during collection, losses by adsorption on the walls of the probe, connecting

TABLE 15-1
Collection and Analysis of Gases and Vapors

Gas or Vapor	Sampler	Sorption Medium	Air Flow (L/m)	Minimum Sample (L)	Collection Efficiency	Analysis	Interferences	Ref.
Ammonia	Midget Impinger	25 ml 0.1N Sulfuric Acid	1-3	10	+ 95	Nessler Reagent	—	(13)
	Petri Bubbler	10 ml of above	1-3	10	+ 95	" "	—	
Benzene	Glass Bead Column	5 ml Nitroting Acid	0.25	3-5	+ 95	Butanone Method	Other Aromatic Hydrocarbons	(15)
Carbon Dioxide	Fritted Bubbler	10 ml 0.1 N Barium Hydroxide	1	10-15	60-80	Titra- with 0.05N Oxalic Acid	Other Acids	(13)
Ethyl Benzene	Fritted Bubbler or Midget Impinger	15 ml Spectrograde Isooctane " "	1	20	+ 90	Alcohol Extraction, Ultraviolet Analysis	Other Aromatic Hydrocarbons	(26)
Formaldehyde	Fritted Bubbler	1% 10 ml Sodium Bisulfite	1-3	25	+ 95	Liberated Sulfite Titrated, 0.01 N Iodine	Methyl Ketones	(13)
Hydrochloric Acid	Fritted Bubbler	0.005 N Sodium Hydroxide	10	100	+ 95	Titration 0.01 N Silver Nitrate	Other Chlorides	(13)
Hydrogen Sulfide	Midget Impinger	15 ml 5% Cadmium Sulfate	1-2	20	+ 95	Add 0.05 N Iodine, 6N Sulfuric, back titrate 0.01 N Sodium Thiosulfate	Mercaptans, Carbon Disulfide, Organic Sulfur Compounds	(13)
Lead, Tetraethyl, Tetramethyl	Dreschel Type Scrubber	100 ml 0.1M Iodine Monochloride in 0.3N Hydrochloric Acid	1.8-2.9	50-75	100	Dithizone	Bismuth, Thallium, Stannous Tin	(27)
Mercury, Diethyl and Dimethyl	Midget Impinger	15 ml of above	1.9	50-75	91-95	Same as Above	Same as Above	
	Midget Impinger	10 ml 0.1M Iodine Monochloride in .3 N Hydrochloric Acid	1-1.5	100	91-100	Dithizone	Copper	(28)
Nickel Carbonyl	Midget Impinger	15 ml 3% Hydrochloric Acid	2.8	50-90	+ 90	Complex with alpha-Furildioxime	—	(29)

TABLE 15-1 (cont'd)
Collection and Analysis of Gases and Vapors

Gas or Vapor	Sampler	Sorption Medium	Air Flow (L/m)	Minimum Sample (L)	Collection Efficiency	Analysis	Interferences	Ref.
Nitrogen Dioxide	Fritted Bubbler (60-70 micron pore size)	20 - 30 ml Saltzman Reagent*	0.4	Sample until color appears Probably 10 ml of Air	94-99	Reacts with Absorbing Solution	Ozone in 5 fold excess Peroxyacyl Nitrate	(30)
Ozone	Midget Impinger	1% Potassium Iodide in IN Potassium Hydroxide	1	25	+95	Measure Color of Iodine Liberated	Other oxidizing agents	(31)
Phosphine	Fritted Bubbler	15 ml 0.5% Silver Diethyl Dithiocarbamate in Pyridine	0.5	5	86	Complexes with Absorbing Solution	Arsine, Stibine, Hydrogen Sulfide	(32)
Styrene	Fritted Midget Impinger	15 ml Spectrograde Isooctane	1	20	+90	Ultraviolet Analysis	Other Aromatic Hydrocarbons	(26)
Sulfur Dioxide	Midget Impinger, Fritted Rubber	10 ml Sodium Tetrachloromercurate	2-3	2	99	Reaction of Dichlorosulfite-mercurate and Formaldehyde-para-rosaniline	Nitrogen [#] Dioxide, Hydrogen ^{**} Sulfide	(33)
Toluene Diisocyanate	Midget Impinger	15 ml Marcali Solution	1	25	95	Diazotization and Coupling Reaction	Materials containing Reactive Hydrogen attached to Oxygen (phenol) Certain other Diamines	(12)
Vinyl Acetate	Fritted Midget Impinger and simple Midget Impinger in Series	Toluene	1.5	15	+99 (84 with fritted bubbler only)	Gas Chromatography	Other Substances with same retention time on Column	(34)

* 5 gram sulfanilic
140 ml glacial acetic acid
20 ml of 0.1% aqueous N-(1-naphthyl) ethylene diamine

Add sulfamic acid after sampling.
** Filter or centrifuge any precipitate.

tubing or collecting device which may necessitate a rinsing with a special reagent to remove the adsorbate which must then be added to the collected portion in the sampling device.

The collection of sufficient sample for the intended method of analysis is a matter which must be discussed by the field and laboratory personnel jointly when the survey plans are made. The field men must discuss as fully as possible with the chemists the nature of the processes involved in the survey so they may select the best combination of sampling and analytical methods to meet the sensitivity requirements of the analytical method, minimize the effects of potential interferences and complete each sampling within a time period which is consistent with the cyclic nature of processing operations or with the exposure conditions (see Chapter 10).

INSTANTANEOUS OR GRAB SAMPLING

Numerous types of devices are used in instantaneous or "grab" sampling to obtain a definite volume of air within a gas collector. These include vacuum flasks, vacuum bottles, gas- or liquid-displacement type collectors, metallic collectors, glass bottles, syringes and plastic bags. Air samples must be collected with these devices at a known temperature and pressure to permit the reporting of the analyzed components in terms of standard conditions, normally 25°C and 760 mm of mercury for industrial hygiene purposes.

Grab samples are collected usually where gross components of gases in air such as methane, carbon monoxide, oxygen, and carbon dioxide are to be analyzed. The samplers should not be used for collecting reactive gases such as hydrogen sulfide, oxides of nitrogen and sulfur dioxide since there may be a reaction with dust particles, moisture, wax sealing compound or glass which would alter the composition of the sample. It is preferable when reactive substances are collected in grab samples that the analyses be made directly in the field.

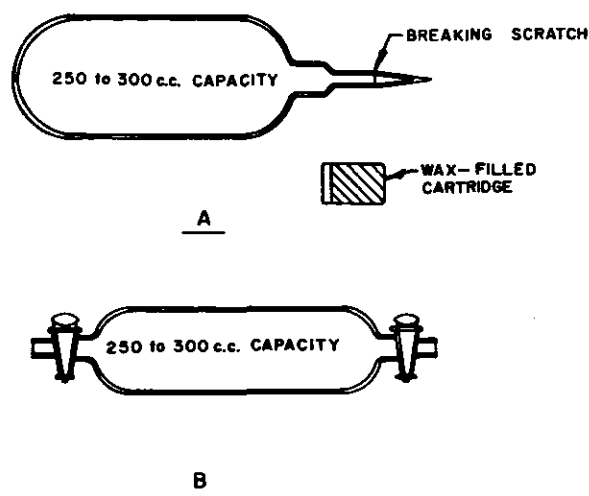
Grab samples are not limited to sampling gross amounts of gases or vapor. The introduction of highly sensitive and sophisticated instrumentation, including infrared spectrophotometry and gas chromatography, has extended the applications of grab sampling to low levels of contaminants.¹ In areas where the atmosphere remains constant the grab sample will be representative of the average as well as the momentary concentration of the components and thus it may truly represent an integrated equivalent. Where the atmospheric composition varies, peaks and valleys of contamination will be observed, and numerous samples must be taken to determine the average concentration of a specific component. The chief advantage of grab sampling methods is that their collection efficiency is normally considered to be 100 percent; there must, of course, be no losses due to leakage or chemical reaction preceding analysis.

Evacuated flasks are heavy-walled glass containers, usually of 250 or 300, but frequently of 500 or 1000, milliliter capacity (Figure 15-1A) from which 99.97 percent or more of the air has

been removed by a heavy duty vacuum pump. The internal pressure after the evacuation is practically zero. The neck is sealed by heating and drawing during the final stages of evacuation. These units are simple to use since no metering devices or pressure measurements are required. The pressure of the sample is taken as the barometric pressure reading at the site. After the sample has been collected by breaking the heat-sealed end, the flask is resealed with a ball of wax and transported to the laboratory for analysis.

A variation of this procedure with evacuated flasks is to add a liquid absorbent to the flask before it is evacuated and sealed to preserve the sample in a desirable form following collection.

Partially evacuated containers or vacuum bottles are prepared with a suction pump just before sampling is performed although frequently they are evacuated in the laboratory the day before a field visit. No attempt is made to bring the internal pressure to zero, but temperature readings and pressure measurements with a manometer are recorded after the evacuation, and again after the sample has been collected. This type of collector may include heavy-walled glass bottles, metal or heavy plastic containers with tubing connectors which are closed with screw clamps or stopcocks. The volume of air or gas taken into the bottle may be computed as described later in this chapter.



Sampling and Analysis of Mine Atmosphere, Miner's Circular 34. U.S. Dept. of Interior, 1948.

Figure 15-1. Grab Sample Bottles (A) Evacuated Flask (B) Gas or Liquid Displacement Type

Gas or liquid displacement collectors include 250-300 ml glass bulbs (Figure 15-1B) fitted with end tubes which can be closed with greased stopcocks or with rubber tubing and screw clamps. They are used widely in collecting samples containing O₂, CO₂, CO, N₂, and H₂ or other combustible gases for analysis by an Orsat or similar analyzer. Other devices operating on the liquid displacement principle include aspirator bottles

of various sizes which have exit openings at the bottom of the bottles through which the liquid is drained during sampling.

In applying the gas displacement technique, the samplers are purged conveniently with a bulb aspirator, hand pump, small vacuum pump or other suitable source of suction. Satisfactory purging is achieved by drawing a minimum of ten air changes of the test atmosphere through the gas collector.

The collectors mentioned in the gas displacement section can also be filled by liquid displacement. The most frequently employed liquid is water. In sampling, liquid in the container is drained or poured out slowly in the test area and replaced by air to be sampled. Application of this method is limited to those gases which are insoluble in and non-reactive with the displaced liquid. The solubility problem can be minimized by using mercury or water conditioned with the gas to be collected. Mercury, however, must be used with caution since it may create an exposure problem if handled carelessly.

Flexible plastic bags²⁻⁷ are used to collect air and breath samples containing organic and inorganic vapors and gases in concentrations ranging from parts per billion to more than 10 percent by volume in air and also to prepare known concentrations of gases and vapors for equipment calibration.⁸ The bags are easily inflated without stretching to their full volume using rubber squeeze bulbs or small hand pumps. They are available commercially in a variety of sizes, up to 9 cubic feet, but they may also be made in the laboratory. They are manufactured from several plastic materials including Saran, Scotchpak, Aluminized Scotchpak, Mylar, Aluminized Mylar, Teflon, Kel-F, Polyethylene and Polyester. The bag materials are from 1 to 5 mils in thickness and may be purchased in 100-foot or longer rolls of large sheets which may be cut to the desired size. Some, such as Mylar, may be sealed with a hot iron using a Mylar tape around the edges. Others, such as FEP Teflon, require high temperature and controlled pressure in sealing. Certain plastics, including Mylar and Scotchpak, may be laminated with aluminum which seals the pores and reduces the permeability of the inner walls to sample gases and the outer walls to moisture. Sampling ports may consist of a sampling tube molded into the fabricated bag and provided with a closing device or a clamp-on air valve. The 6- and 12-liter size are suitable for many industrial hygiene samples to be analyzed by infrared spectrophotometry using a 10-meter gas cell. Plastic bags have the advantages of being light, nonbreakable and inexpensive, and they permit the entire sample to be withdrawn without the difficulty associated with dilution by replacement air as is the case with rigid containers.

Plastic bags, however, must be used with caution since generalization of recovery characteristics of a given plastic cannot be extended to a broad range of gases and vapors. Important factors to be considered in using these collectors are: absorption and diffusion characteristics of the plastic material, concentration of the gas or vapor,

and reactive characteristics of the gas or vapor with moisture and with other constituents in the sample. A valuable summary of information sources on the storage properties of gases and vapors in plastic containers has been provided by Schuette⁹ and Nelson.¹⁰

The bags must be leak tested and preconditioned for 24 hours to the chemical vapors to be tested before they are used for sampling. Preconditioning consists of flushing the bag three to six times with the test gas, the number of refills depending on the nature of the bag material and the gas. In some cases it is recommended that the final refill remain in the bag overnight prior to the use of the bag for sampling. Such preconditioning is usually helpful in minimizing the rate of decay of a collected gas except for nitrogen dioxide. At the sampling site the air to be sampled is allowed to stand in the bag for several minutes, if possible, before removal and subsequent refilling of the bag with a sample. Once collected, the interval between sampling and analysis should be minimal.

Hypodermic syringes of 10- to 50-milliliter volume have also been used successfully for air sampling. These units are available usually in glass, but the disposable plastic type have also been used successfully. Ten milliliter Plastipak¹¹ syringes have been shown to have excellent retention properties for methane, hydrogen and other gases in normal mine air, but some loss of carbon dioxide was observed over a storage period of a week. The advantages of these units are cost, convenience and ease of use.

INTEGRATED SAMPLING

Integrated (or "continuous") sampling of the workroom atmosphere must be performed when the composition of the air is not uniform, the sensitivity requirements of the method of analysis necessitates sampling over a minimal (10-30 minutes) finite period, or when compliance or non-compliance with an 8-hour time-weighted average air standard must be established. Thus, the professional observations and judgment of the industrial hygienist are called upon in devising the strategy for the procurement of representative samples to meet the requirements of an environmental survey of the workplace.

Sampling Pumps

An integrated air sampling method requires a relatively constant source of suction as an air moving device. A vacuum line, if available, may be satisfactory. The most practical source, however, is an electrically powered pump or blower for prolonged periods of sampling. These come in various sizes and types and must be chosen for the sampling devices with which they will be used.

If electricity is not available or if flammable vapors present a fire hazard, aspirator bulbs, hand pumps, a portable unit operated by means of compressed gas (Freon; Unijet Sampler) or battery-operated pumps (activate outside the area to avoid a spark) are suitable for sampling at rates up to 2-3 liters per minute. For higher sampling requirements, ejectors using compressed air or a

water aspirator may be employed.

An air aspirator is usable where the pressure is constant. When compressed air or batteries are to be used as the driving force for a pump, the length of the sampling period is important in relation to the supply of compressed air or the life of the rechargeable battery. These units must not be allowed to run unattended and periodic checks on the air flow must be made.

Measurement of Air Flow

Air volume may be measured directly by means of an aspirator bottle, or by dry or wet test meters, but these units are used primarily in the laboratory for calibration purposes.

The common practice in the field is to sample for a measured period of time at a constant, known rate of air flow. Direct measurements are made with rate meters such as rotameters and orifice or capillary flowmeters. These units are small and convenient to use, but at very low rates of flow their accuracy decreases. The sampling period must be timed carefully with a stop watch.

Many pumps have inlet vacuum gauges or outlet pressure gauges attached. These gauges, upon proper calibration with a calibrated wet or dry gas meter, can be used to determine the flow-rate through the pump. The gauge may be calibrated in terms of cubic feet per minute or liters per minute. If the sample absorber does not have enough resistance to produce a pressure drop, a simple procedure is to introduce a capillary tube or other resistance into the train behind the sampling unit.

Sampling Trains

Samplers are always used in assembly with an air moving device (source of suction), and an air metering unit. These are the basic essentials. Frequently, however, the sampling train may consist of a filter, probe, absorber (or adsorber), flowmeter, flow regulator and air mover. The filter is included to remove any particulate matter that may interfere in the analysis. It should be ascertained that it does not also remove the gaseous contaminant of interest. The probe or sampling line is extended beyond the sampler to reach a desired location. It also must be checked to determine that it does not collect a portion of the sample. The meter which follows the sampler indicates the flow-rate of air passing through the system. The flow regulator controls the air flow. Finally at the end of the train the air mover provides the driving force.

Collection Efficiency of Samplers

Several methods of testing the efficiency of an absorbing, or adsorbing, device are available. One or more of these methods should be employed for periodic evaluation of individual units, in particular fritted bubblers whose porosities are subject to change from the effects of sampling corrosive atmospheric contaminants.

A recommended test system is a gas tight chamber or tank in which known concentrations of a given contaminant can be prepared. Absorbers are attached to sampling ports and operated under simulated field conditions to determine their collection efficiencies.

Frequently the relative efficiency of a single

absorber can be estimated by placing another in series with it. Any leakage is carried over into the second collector. The absence of any carry-over is not in itself an absolute indication of the efficiency of the test absorber since it may be possible that the contaminant is not stopped effectively by either absorber. Analysis of the two legs of a U-tube containing silica gel used in sampling a contaminant is a useful check on the collection efficiency of the first leg of the tube.

Another valuable technique is the operation of the test absorber in parallel or in series with a different type of collector having a known high collection efficiency (an absolute collector if one is available) for the contaminant of interest. By running the test absorber at different rates of flow the maximum permissible rate of flow for the device can be ascertained.

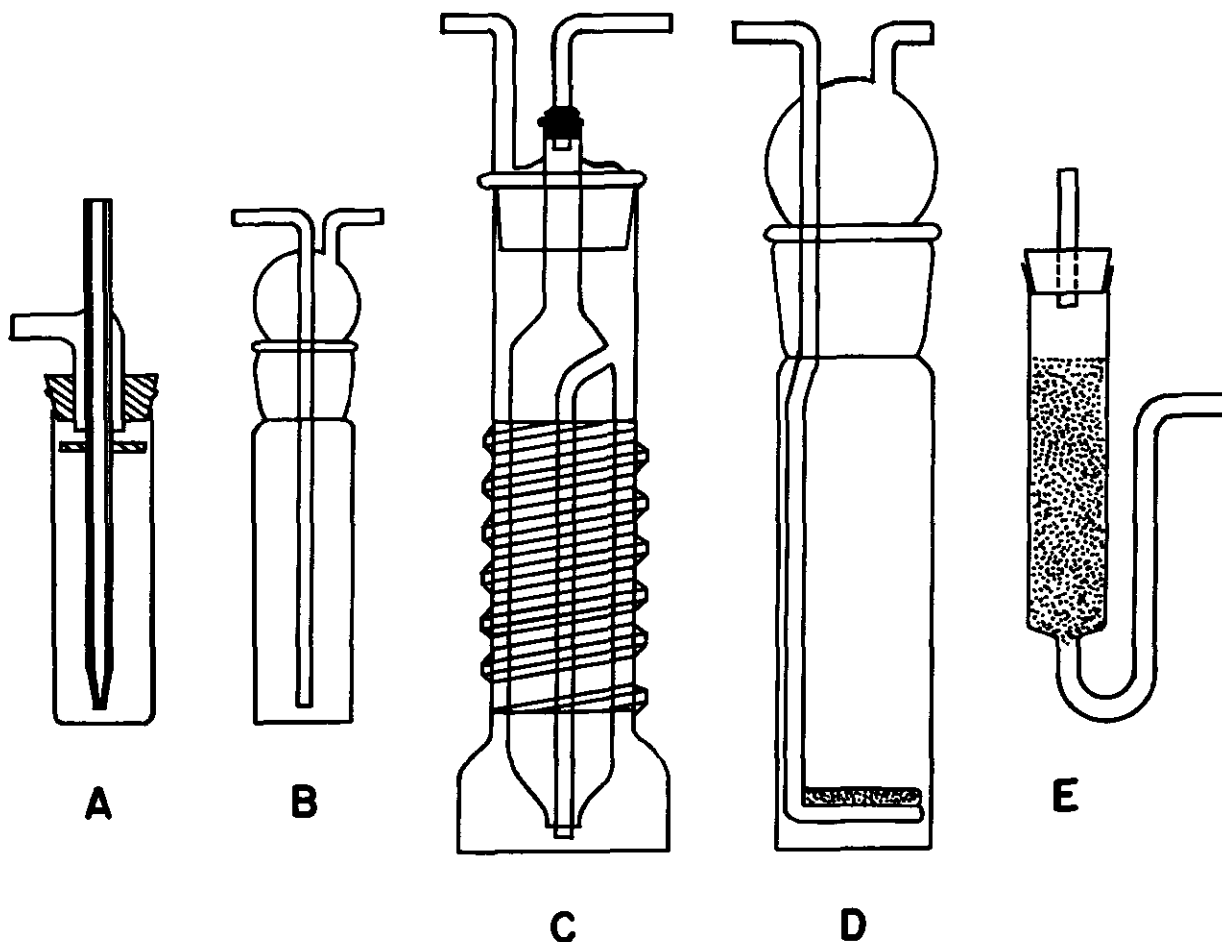
Discussion of Variable Factors Influencing Efficiency of Collection

A high collection efficiency is achieved when a chemically reactive sampling medium is used at a sufficiently slow rate to collect a contaminant with which it reacts to form a nonvolatile product. Such is the case in neutralization reactions of caustic scrubbing solutions with acid gases such as HF, HCl, SO₂, and nitrous fumes and the hydrolysis of toluene diisocyanate in Marcali Solution.¹² Other examples are given in Table 15-1 where collection efficiencies of 95 percent are reported generally for this type of sampling system. Long-term sampling may thus be conducted provided an excess of the collecting reagent is maintained.

Gases and vapors can also be collected satisfactorily in liquids that are not reactive if the contaminant is readily soluble in the medium. Thus, methanol and formaldehyde may be absorbed readily in water and esters in alcohol. The vapor pressure of these contaminants is lowered by the solvent effect of the absorbing liquid.

A discussion of the theoretical and practical aspects of absorbing vapors in non-reacting liquids is given by Elkins.¹³ It is emphasized that the variable which determines the efficiency of collection in a given system is the ratio of the volume of sampled air to the volume of the collecting liquid. The concentration of vapor in the air actually has no effect on the collection efficiency of non-reacting absorbing media. Other factors to be considered are: the degree of contact between the gas or vapor being sampled and the absorbent, duration of contact of the contaminant with the absorbent, rates of diffusion of gas and liquid phases, degree of solubility of the contaminant in the absorbent, and volatility of the contaminant.

The collection efficiency (the ratio of the amount of contaminant retained by the absorbing medium to that entering it) need not be 100 percent as long as it is known, constant and reproducible. The minimal acceptable collection performance in a sampling system is usually 90 percent, but higher efficiency is certainly desirable. When the efficiency falls below the acceptable minimum, sampling may be carried out at a lower rate, or at a reduced temperature by immersing



American Society for Testing and Materials: Tentative Methods of Sampling Atmospheres for Analyses of Gases and Vapors. Philadelphia, July 24, 1956.

Figure 15-2. Absorbers: A and B simple Gas Washing, C Helical Absorber, D Fritted Bubbler, E Glass Bead Column

the absorber in a cold bath to reduce the volatility of both the solute and solvent. It is often necessary to use two or more absorbers in series. Two bubblers in series have been shown to maintain a 95 percent efficiency of collection using water or isopropyl alcohol solvents with a sevenfold¹³ increase in the volume of sampled air (see Table 15-2). A fivefold bubbler system was proposed for the collection of organic chlorides.¹⁴

There are four basic types of absorbers employed for the collection of gases and vapors, classified as follows: simple gas washing bottles, spiral and helical absorbers, fritted bubblers and glass-bead columns. The function of these absorbers is to provide sufficient contact between the sampled air and the liquid surface to provide complete absorption of the gaseous contaminant. In general, the lower the sampling rate, the more complete is the absorption. See Figure 15-2 and Table 15-3.

Simple gas washing bottles include Drechsel types and standard Greenburg-Smith and midget impingers. In these devices the air is bubbled

through the liquid absorber without special effort to secure intimate mixing of air and liquid. The length of travel of the gas through the collecting medium is equivalent to the height of the absorbing liquid. These scrubbers are suitable for gases and vapors that are readily soluble in or react with the absorbing liquid. One or two units may be enough for efficient collection, but in some cases several in series may be required to attain the efficiency of a single fritted glass bubbler. Advantages of these devices are their simplicity in construction, ease of rinsing (for removing particulates), and the small volume of liquid required (with the exception of the Greenburg-Smith impinger).

The chief advantage of spiral and helical absorbers over simple gas washing bottles is that they provide a longer contact path between the sampled air and the absorbing solution. The sample is forced to travel a spiral or helical path through the liquid five to ten times that in the simpler units. Friedrichs and Milligan gas washing bottles are examples of this type of device.

TABLE 15-2

*The Effect of Two Bubblers in Series on Collection Efficiency of Non-Reactive Liquids

Vapor	Solvent	Maximum Air Volume in Liters for 95% Recovery	
		1 bubbler (10ml)	2 Bubblers (10 ml each)
Acetone	Water	0.8	5.4
Methanol	"	9.0	62.
n-Butanol	"	10.0	68.
Chloroform	Isopropanol	0.8	5.4
Carbon Tetrachloride	" "	0.5	3.4
Methyl Chloroform	" "	0.5	3.4
Trichloroethylene	" "	0.9	6.2

*Courtesy HB Elkins, Ph.D.

In fritted glass bubblers air passes through porous glass plates, and enters the liquid in the form of small bubbles. The size of the air bubbles depends on the nature of the liquid and the diameter of the orifices from which they emerge. Frits are classified as fine, coarse, or extra coarse, depending on the number of openings per unit area. The extra coarse frit is used when a more rapid flow is desired. The heavier froth generated by some liquids increases the time of contact of gas and liquid. These devices are more efficient collectors than the simple gas washing bottles and can be used for the majority of gases and vapors which are soluble in or react rapidly with the reagent. Rates of flow between 0.5 and 1.0 liter per minute are used. These absorbers are relatively sturdy, but the fritted glass is difficult to rinse out when used for contaminants which form a precipitate with the reagent, e.g., H_2S with $CdCl_2$. In

TABLE 15-3

Sampling and Absorbent Capacity of Absorbers

Type of Absorber	Absorbent Capacity (ml)	Sample Rate ml/min.
Simple gas washing bottles (Figure 15-2 A and B)	5-100	5-3000
Spiral and Helical (Figure 15-2 C)	10-100	40-500
Fritted Bubblers (Figure 15-2 D)	1-100	500-100,000
Glass-bead Column (Figure 15-2 E)	5-50	500-2000

ASTM Tentative Methods of Sampling Atmospheres for Analysis of Gases and Vapors. July 24, 1956, Philadelphia, Penna.

these cases a simple gas washing bottle should be used.

Packed glass-bead columns are used for special situations where a concentrated solution is needed. Glass pearl beads are wetted with the absorbing solution and provide a large surface area for the collection of a sample. It is of historical interest to note that the absorption of benzene and other aromatic hydrocarbon vapors in nitrating acid has been performed with this type of absorber.¹⁵ It is especially useful when a viscous liquid is required. The rate of sampling is low, 0.25 to 0.5 liter of air per minute.

When it is desired to collect insoluble or non-reactive vapors, an adsorption technique is frequently the method of choice. Activated charcoal and silica gel, 6 to 20 mesh, are common adsorbents. Esters, acetates and other soluble compounds are sampled regularly on these adsorbents. Solid adsorbents require less manipulative care than do liquid absorbents, can provide high collection efficiencies and, with improved adsorption tube design and a better definition of desorption requirements, are becoming increasingly popular in industrial hygiene surveys.

Activated charcoal is an excellent adsorbent for most vapors boiling above 0°C, moderately effective for low-boiling gaseous substances, between -100°C and 0°C, such as ammonia, formaldehyde, and hydrogen sulfide, particularly if the carbon bed is refrigerated, but a poor collector of hydrogen, nitrogen and gases having boiling points below -150°C. Its retentivity for sorbed vapor is twice that of alumina and several times that of silica gel. Because of its non-polar characteristics, organic gases and vapors are adsorbed in preference to atmospheric moisture, and sampling can be performed for long periods of time.

Numerous investigators have been directing their efforts to the study of the optimal conditions for the sampling of organic solvent vapors by adsorption on activated charcoal and the subsequent desorption of the collected sample components for analysis in the laboratory. Fraust and Hermann have developed valuable breakthrough data on aliphatic acetates in their evaluation of the effects of mass flowrates and four separate mesh sizes of Pittsburgh Activated Carbon Company Type BPL activated carbon.¹⁶ Working with 4-6, 8-12, 16-20 and 30-40 mesh sizes and using 5-in., 5 mm sampling tubes containing 0.5 gm of activated carbon, these investigators have shown that, with the exception of the 4-6 mesh carbon, typical breakthrough curves consist of two segments: (a) a plateau region of almost constant efficiency and (b) an S-curve portion where the efficiency drops to zero with continued sampling. The 4-6 mesh carbon proved to be a relatively inefficient absorber as it showed no plateau except at the lowest mass flowrate of 0.002 mM ethyl acetate per minute. The other mesh sizes each showed a plateau of high-efficiency adsorption that was independent of mass flow until breakthrough time. The 8-12 mesh adsorbent provided a definite plateau at 96% efficiency but butyl acetate sampled at a mass rate of 0.0204 mM/min for a period of approximately 45 min. In the experimental

system used in this study, the 0.0204 mM/min flowrate was maintained by sampling a 500 ppm concentration of the ester at 1.0 liter/min. The time periods shown for the plateau regions with butyl acetate varied approximately from several minutes with a flowrate of 0.0409 mM/min to about 550 min at the lowest of the eight flowrates evaluated, i.e., 0.0020 mM/min.

The 16-20 and 30-40 mesh carbon each provided a plateau at 98% efficiency with amyl and butyl acetates separately. Again, the duration of the plateau varied with the mass flowrate; however, the sharp distinction between the plateau and S-curve sections should facilitate the selection of the upper limit of sampling time for anticipated concentrations of the esters.

Fraust and Hermann found that the times required for breakthrough and for the collection efficiency to drop to 50% are nearly inversely proportional to the mass flowrate expressed on a molar basis but that the adsorption process is not affected significantly by differences in the molecular weight. Other investigators have reported on the optimal conditions for sampling organic vapors in the atmosphere with activated charcoal followed by desorption with carbon disulfide and gas chromatographic analysis of the sample components.¹⁷⁻¹⁸ Their procedures are based upon the method of Otterson and Guy.¹⁹ Reid and Halpin¹⁷ obtained average recoveries of mostly 90-100% in sampling a test chamber containing known concentrations of halogenated and aromatic hydrocarbons using Darco 12-20 mesh activated charcoal in 0.6 gm quantities in a 5-in., 6-mm i.d. tube, followed by desorption with 3 ml carbon disulfide and gas chromatographic analysis of an aliquot portion of the resulting solution. The method was applied to concentrations of the separately vaporized compounds equivalent to one-half, one, and two times the respective threshold limit values. The sampling rate was 2 liters/min in tubes packed to a prescribed pressure drop.

White et al.¹⁸ have shown that the first two of four 1-in. sections of 180 mg each of activated charcoal supported in a 6-in., 4-mm i.d. tube adsorbed vapor concentrations of fourteen organic solvents completely at two times the TLV levels and that the overall recoveries were equivalent to those obtained by desorption of the corresponding liquid state of each compound with 1 ml of carbon disulfide. These investigators conducted experimental desorption studies with the single compounds and with multiple combinations of halogenated hydrocarbons, aromatic hydrocarbons, pyridine, ethanol, isooctane, 2-butanone and ethyl ether. They concluded that a mixture of seven or fourteen of the compounds evaluated did not affect significantly the desorption efficiency for any one of the substances. The sampling rates ranged 0.5-2 liters/min with no apparent effect on overall efficiency. The 1-in. sections of charcoal reportedly have a saturation limit of 28-30 mg of a single solvent and 28-45 mg of the total group of fourteen solvents. In the case of butyl acetate, for example, a saturation limit of 30 mg/10 liters of air sampled (3000 mg/m³) is more than four times the 1970 threshold limit value of 710 mg/m³ for

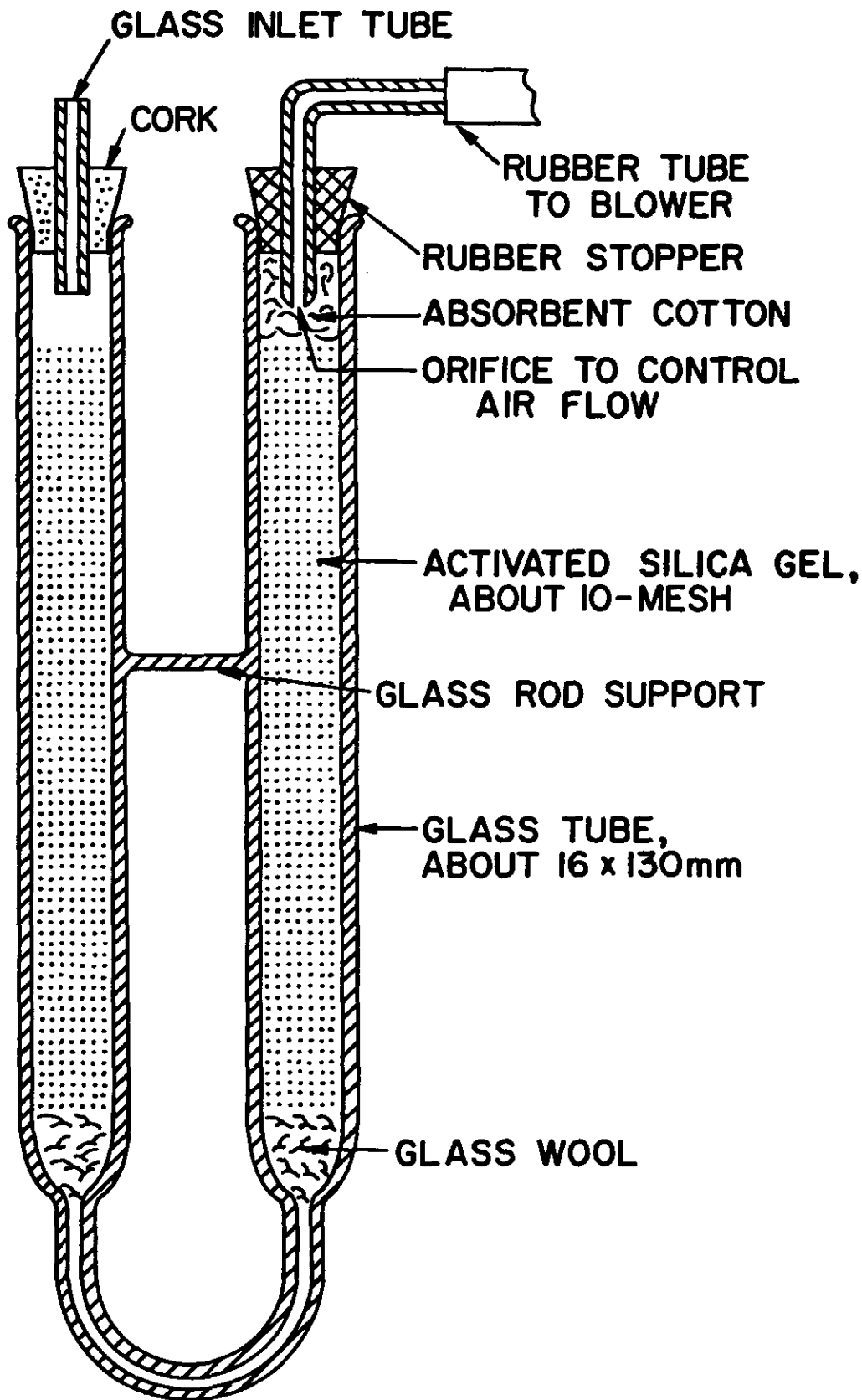
this ester, thus providing a comfortable margin of active adsorption sites when sampling at the TLV level.

Van Houten and Lee have reported their experiences in the use of 4-oz French Square bottles for the collection of atmospheric samples of solvent vapors for gas chromatographic analysis.¹ These bottles are filled by purging with an aspirator bulb fitted with two one-way valves. The bottles are capped quickly using a screw cap containing a 1/16 in. hole and provided with a set of four gaskets, one rubber and three Type 18 Saran, to prevent leakage of the collected sample. Aliquot portions of the sample are withdrawn through the port, using a calibrated syringe, and injected into the gas chromatograph for analysis. The authors have tested the effects of repetitive temperature changes over the 0-175°F range for a period of 7 days. The samples showed no appreciable loss from this treatment which was calculated to produce a pressure change equivalent to an altitude of 10,000 feet, considered as the effective altitude of the cargo compartment of commercial airliners. They concluded that the containers were suitable for shipping samples by air.

Silica gel (see U-tube, Figure 15-3) has been used widely as an adsorbent for gaseous contaminants in air samples. Because of its polar character it tends to attract polar or readily polarizable substances preferentially. The general order of decreasing polarizability or attraction is given as water, alcohols, aldehydes, ketones, esters, aromatic compounds, olefins and paraffins. (The polarity of chlorinated hydrocarbons is to a great extent determined by their structure.) Organic solvents are relatively non-polar in comparison with water, which is strongly adsorbed on silica gel; such compounds will be displaced by water in the entering air stream. Consequently, the volume of air samples collected under humid conditions may need to be restricted. Despite this limitation silica gel is a very useful adsorbent. It has been shown experimentally that, under conditions of 90 percent humidity, relatively heavy concentrations of benzene, toluene, and trichloroethylene could be adsorbed quantitatively from air passed through a tube charged with 10 grams of silica gel at the rate of 2.5 liters per minute for periods up to 20 minutes. Losses from the first to the second leg of a U-tube charged with silica gel was less when the humidity of the air was low.

Silica gel has been used for halogenated hydrocarbons²⁰⁻²² and nitrogen dioxide²³ and a wide range of organic solvents. The collection efficiency of the adsorbent can be increased by introducing a drying agent into the train.²⁴ Other factors that affect the collection efficiency include the volatility of vapor, mesh size of silica gel, rate of airflow and temperature.

Desorption of organic vapor is usually complete after the exposed gel has stood overnight in a correctly chosen solvent although, for many organic substances, the required elution period is much shorter. The lower molecular weight ketones are completely removed in an hour with water, benzene is eluted with isopropyl alcohol in about the same period whereas toluene and xylene



Elkins HB: The Chemistry of Industrial Toxicology, 2nd Edition. New York, John Wiley & Sons, p. 280.

Figure 15-3. Silica Gel Adsorber

are desorbed more slowly.

Other desorbing agents mentioned in the literature for silica gel are acetone and dimethylsulfoxide. The latter²¹ has been found particularly useful if the analysis is performed by gas chromatography. The retention time of this solvent is considerably greater than that of many common organic compounds. Poor recoveries were obtained with carbon disulfide; the addition of water after an initial contact period of two hours improved the desorption of toluene, xylene and certain halogenated hydrocarbons. Non-polar solvents are unsuitable for displacing vapors of aromatic hydrocarbons. Aliphatic hydrocarbons, for example, will not displace benzene.

The use of microcolumns of silica gel has been recommended for reducing bulkiness and cost of mailing sampling equipment.²⁵ Glass columns containing 500 mg of 42/80 mesh silica gel are prepared in three sections, and air is sampled at the low rate of 60 milliliters of air per minute. The presence of water and other polar substances may cause non-polar substances like benzene, cyclohexane, and toluene to migrate to a different section of the column. It was found necessary to analyze each section (by ultraviolet spectrophotometry) after elution with 5 milliliters of alcohol. Collection efficiency may be determined by the extent of migration of the adsorbate. Most laboratories now use gas chromatographic methods to analyze the eluates from solid adsorbents.

In condensation methods vapors or gases are separated from sampled air by passing the air through a coil immersed in a cooling medium, dry

ice and acetone, liquid air or liquid nitrogen. The device is not considered to be a portable field technique ordinarily. It may be necessary in certain cases to use this method where the gas or vapor may be altered by collecting in liquid or where it is difficult to collect by other techniques. Nitrogen dioxide and mercury vapor have been collected by this method prior to the development of more modern procedures. A feature of this method is that the contaminating material is obtained in a concentrated form. The partial pressure of the vapor can be measured when the system is brought back to room temperature.

ANALYSIS OF GASES AND VAPOR

A complete listing of methods of gas and vapor analysis is not intended, but a few of the commonly employed procedures are mentioned in Tables 15-1 and 15-4. Details of the analyses are found in the literature cited; additional procedures are found in the recommended publications listed in the reference section.

APPENDIX I

The direct measurement of the volume of an instantaneous (grab) sample of an atmosphere must be corrected to standard conditions of temperature and pressure in order to calculate the absolute quantity of matter which is to be determined. An understanding of the fundamental gas laws and their application is essential for this purpose. Examples of their applications are presented in this appendix.

TABLE 15-4
Gases and Vapors Collected on Solid Adsorbents and Their Analysis

Gas or Vapor	Sampler	Sorption Medium	Air Flow (L/m)	Adequate Sample (L)	Collection Efficiency	Analysis	Ref.
Wide range of organic vapors	Straight tube, 5 inches long, 6mm diameter	0.5 grams 12 x 20 mesh Activated Charcoal	0.1 to 1	2-10	*	Desorb with carbon disulfide, Inject into chromatograph	16-19
Wide range of organic vapors	U Tube	10 grams 8-16 mesh Silica Gel	3-5	25	*	Extract with alcohol, water, acetone for ultraviolet analysis or with dimethylsulfoxide for chromatography	20-25
Nitrogen dioxide	U Tube	10 grams 8-16 mesh Silica Gel	3-5	10-30	+90	Desorb with 50 ml sulfuric acid-peroxide solution *	13

* Depends on nature of solvent vapor, amount of adsorbent, sampling time and size of sample. For many organic vapors a sample of 25 liters will not leak into second arm of U tube.

* 1 ml concentrated Sulfuric Acid and 6 drops 30% hydrogen peroxide to 200 ml of water.

CALCULATIONS

Application of Gas Laws

At 0° C (273°K) and 760 mm pressure a gram molecular weight of any perfect gas will occupy a volume of 22.414 liters. If we ignore deviations from ideal behavior, oxygen of this volume would weigh 32 grams and nitrogen 28 grams, their molecular weights respectively. If there is a change in temperature and pressure the molar volumes of these gases will be altered. According to the laws of Boyle and Charles the change in molar volume will be inversely proportional to its pressure and directly proportional to its absolute temperature (°C+273).

In order for the actual measured volumes of gases and gas air mixtures to have meaning, they must be corrected to standard conditions of temperature and pressure (STP), 0° C (273°K) and 760 mm of mercury pressure.

From a consideration of the laws of Charles and Boyle is derived the equation:

$$V_{STP} = V_{\text{meas.}} \times \frac{P_{\text{bar.}}}{760} \times \frac{273}{273 + t^{\circ}C}$$

A correction for the presence of water vapor is made by subtracting the partial pressure of the water vapor in the air from the barometric pressure:

$$V_{STP} = V_{\text{meas.}} \times \frac{P_{\text{bar.}} - P_w}{760} \times \frac{273}{273 + t^{\circ}C}$$

t° C = temperature
at which
the sample
was taken.

If this formula is applied to a grab sample in a 12-liter volume bottle taken at 22°C at a barometric pressure of 760 mm, and a partial pressure of water vapor at 22°C of 19.8 mm, $V_{STP} = 10.8$ liters.

If an analysis of the grab sample showed it contained 5 mg of carbon tetrachloride, then:

$$\text{PPM} = \frac{\frac{\text{g}}{\text{MW}} \times 22.414}{V_{STP}} \times 10^6 = \frac{0.005 \times 22.414}{10.8} \times 10^6 = 67$$

MW = molecular weight of carbon tetrachloride
22.414 = molar volume (liters) of carbon tetrachloride at standard conditions of temperature and pressure (STP)

If the sample was taken in a partially evacuated flask, and a manometer reading showed that 365.1 mm of pressure remained in the flask, the formula for the corrected volume is:

$$V_{STP} = V_{\text{meas.}} \times \frac{P_{\text{bar.}} - P_w - P_p}{760} \times \frac{273}{273 + t^{\circ}C}$$

$$V_{STP} = 5.5$$

$$\text{PPM} = 132$$

Conversion Formulas

$$\text{mg per liter} \times 1000 = \text{mg per cubic meter}$$

$$\text{mg per liter} \times 28.32 = \text{mg per cubic foot}$$

$$\text{mg per cubic foot} \times 35.314 = \text{mg per cubic meter}$$

The common practice among industrial hygienists is to assume that air samples taken in normal factory air are at 25°C and 760 mm of mercury pressure. One gram molecular weight of a gas occupies 24.45 liters under these conditions. PPM (parts per million of a contaminant) may then be calculated from an air sample with the following simplified version of the expression given earlier:

$$\text{PPM} = \frac{24,450 \times \text{mg per liter}}{\text{molecular weight (contaminant)}} \times \frac{\text{mg per liter} = \text{mg of contaminant in one liter of air sample collected}}{\text{mg per liter}}$$

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DIRECT READING INSTRUMENTS FOR DETERMINING CONCENTRATIONS OF AEROSOLS, GASES AND VAPORS

Robert G. Keenan

INTRODUCTION

This chapter deals with direct reading instruments which may be portable devices or fixed-site monitors; it does not include those instruments which have been designed primarily for use in the laboratory.

Direct reading instruments are used for on-site evaluations for a number of reasons, including:

1. To find the sources of emission of hazardous substances on the spot;
2. To ascertain if select OSHA air standards are being exceeded;
3. To check the performance of control equipment;
4. As continuous monitors at fixed locations,
 - a. To trigger an alarm system in the event of a breakdown in a process control which could result in the accidental release of copious amounts of harmful substances to the workroom atmosphere;
 - b. To obtain permanent recorded documentation of the concentrations of a contaminant in the atmospheric environment for future use in epidemiological and other types of occupational studies, in legal actions, to inform employees as to their exposure, and for information required for improved design of control measures.

Such on-site evaluations of the atmospheric concentrations of hazardous substances make possible the immediate assessment of undesirable exposures and enable the industrial hygienist to make an immediate correction (including a shutdown) of an operation, in accordance with his judgment of the seriousness of a situation, without permitting further risk of injury to the workers. It cannot be over-emphasized that great caution must be employed in the use of direct reading instruments and in the interpretation of their results. Many of these instruments are nonspecific and the industrial hygienist may find it necessary before recommending any action to make certain of his on-site findings by supplemental sampling and laboratory analyses to characterize fully the chemical nature of the contaminants in a workroom area and to develop the supporting quantitative data with more specific methods of greater accuracy. Such precautions become the more mandatory if the industrial hygienist has not had extensive experience with the particular process

area in question or when the possibilities of a change in the process or in the substitution of chemical substances may have occurred. The last possibility must always be foremost in the minds of industrial hygienists.

Calibration

The calibration of any direct reading instrument is an absolute necessity if the data are to have any meaning. Considering this to be axiomatic, we must also recognize that the frequency of calibration is dependent upon the type of instrument as well as individual instruments within any one class. It is well known that certain classes of instruments, because of their design and complexity, require more frequent calibration than others. It is also recognized that peculiar "quirks" in an individual instrument produce greater variations in its response and general performance, thus requiring a greater amount of attention and more frequent calibration than other instruments of the same design. Direct personal experience with a given instrument serves as the best guide in this matter.

Another unknown factor which can be evaluated only by experience is the variability of sampling locations. For example, when locating a particular fixed-station monitor at a specific site, consideration must be given to such problems as the presence of interfering chemical substances, the corrosive nature of contaminants, vibration, voltage fluctuations and other disturbing influences which may affect the response of the instrument.

Finally, the required accuracy of the measurements must be determined initially. Obviously, if an accuracy of ± 3 percent is needed, more frequent calibration must be made than if ± 25 percent accuracy is adequate in the solution of a particular problem.

Properties of Aerosols

An aerosol is an airborne solid or liquid substance. Aerosol particles normally present in ambient air have been dispersed as a result of nature's or man's activities. The latter source is of greatest concern to environmental control specialists. Aerosols are generated by fire, erosion, sublimation, condensation and the abrading action of friction on minerals, metallurgical materials, organic and other inorganic substances in construction, manufacturing, mining, agriculture, transportation and other gainful pursuits.

Aerosols are classified conveniently as dusts, fumes, smokes, mists and fogs according to their physical nature, their particle size, and their

method of generation. Dusts range from 1 to 150 μm in diameter; they are produced mechanically by grinding and other abrasive actions occurring in natural and commercial operations.

Fumes are particulate substances whose diameters range from 0.2 to 1 μm ; they are produced by such processes as combustion, distillation, calcination, condensation, sublimation, and chemical reactions. They form true colloidal systems in air. Examples are such substances as heated metals or metallic oxides, ammonium chloride, hot asphalt and volatilized polynuclear hydrocarbons from coking operations.

Smokes are colloidal systems whose particle sizes range from 0.3 to 0.5 μm in diameter. They are produced by the incomplete combustion of carbonaceous materials such as coal, oil, tobacco, and wood.

Mists and fogs cover a wide range of particle sizes and are considered to be primarily liquid; they may consist of liquids, such as water vapor, condensed on the surfaces of submicroscopic particles of dust or gaseous ions.

Mineral, vegetable and animal fibers constitute a unique situation insofar as exposures are concerned. Inhalation of asbestos fibers up to 200 μm in length has been reported.^{1,2} Microscopic procedures are used to assist in the identification of, and to determine, the atmospheric concentration of fibrous materials.

Properties of Gases and Vapors

Gases and vapors are "elastic fluids," so-called because they take the shape and volume of their containers. A fluid is generally termed a gas if its temperature is very far removed from that required for liquefaction; it is called a vapor if its temperature is close to that of liquefaction. In the field of occupational health, a substance is considered a gas if this is its normal physical state at room temperature and atmospheric pressure. It is considered a vapor if, under the existing environmental conditions, conversion of its liquid or solid form to the gaseous state results from its vapor pressure affecting its volatilization or sublimation into the atmosphere of the container, which may be the process equipment or the workroom. Our chief interest in distinguishing between gases and vapors lies in our need to assess the potential occupational hazards associated with the use of specific chemical agents, an assessment which requires a knowledge of the physical and chemical properties of these substances (see Chapter 15).

Characteristics of Direct Reading Instruments

Direct reading instruments for atmospheric contaminants are classified as those devices which provide an immediate indication of the concentration of aerosols, gases, or vapors by a dial reading, a strip chart recording, a tape printout or a color change on an impregnated paper or in an indicator tube. These devices, when properly calibrated and when used with full cognizance of their performance characteristics and limitations, can be extremely helpful to industrial hygienists who are engaged in on-site evaluations of potentially hazardous conditions. There are many types of

instruments which depend on certain physical or chemical principles for their operation. They are discussed later in this chapter.

The advantages of direct reading instruments include:

1. Immediate estimations of the concentration of a contaminant, permitting on-site evaluations;
2. Provision of permanent 24-hour records of contaminant concentrations using continuous monitors;
3. Attachment of alarm system to instrument to warn workers of build-up of hazardous situations;
4. Reduction of number of manual tests;
5. Reduction of number of laboratory analyses;
6. Provision of more convincing evidence for presentation at hearings and litigation proceedings;
7. Reduced cost of obtaining individual results.

The disadvantages of different types of direct reading instruments may include some of the following:

1. High initial cost of instrumentation;
2. Need of frequent calibration;
3. Lack of adequate calibration facilities;
4. Lack of portability;
5. Lack of specificity.

DIRECT READING PHYSICAL INSTRUMENTS

The physical properties of aerosols, gases, and vapors are used in the design of direct reading physical instruments for quantitative estimations of these types of contaminants in the atmosphere. The principles upon which these instruments are based are presented in the following discussion.

Operating Principles

Aerosol Photometry (Light Scattering). The principle of aerosol photometry is the generation of an electrical pulse by a photocell which detects the light scattered by a particle. A pulse height analyzer estimates the effective particle diameter. The number of electronic pulses is related to the number of particles counted per unit flowrate of the sampled gaseous medium. Calibrations may be made using a reference standard such as polystyrene spheres whose diameters and refractive index are known although the aerosol under study is the reference of choice because of the unique effects of shape factor, angle of scatter, and refractive index, as well as particle size. Whereas certain commercial instruments are designed to give a size analysis based upon the above principles, there are others which use a forward light scattering principle to provide an integrated measurement of total particle concentration in a large illuminated volume. The latter are used in monitoring particulate concentrations in experimental rooms and exposure chambers.

Aerosol photometry can usually provide only an approximate analysis of particulate classified according to particle size in plant surveys because

of the impracticality of calibrating the instrument with each type of particulate suspension which is to be measured. The great variations in shape, size, degrees of agglomeration and refractive indices of the mixture of chemical components in a given dust or fume suspension make such a calibration exceedingly difficult. Whereas aerosol photometry can, therefore, provide an indication of the particulate concentration in the different particle size ranges of interest, it is still necessary to perform size distribution analyses by microsieveing and microscopic procedures for greatest accuracy.

Chemiluminescence. Chemiluminescence is a phenomenon which occurs with certain chemical reactions. The process provides a distinctly colored glow which accompanies such reactions as the oxidation of certain decaying wood, of luciferin in fireflies and of yellow phosphorus. Recently, analytical advantage of this phenomenon is taken in the reaction of ozone with such other gases as ethylene and nitric oxide for the measurement of ozone or nitrogen oxides in ambient atmospheres.

The chemiluminescent principle has been incorporated into continuous ambient air monitors which are selective for ozone or for $\text{NO} - \text{NO}_x$. Measurements of ozone at concentrations extending from 0.001 to 1 ppm in ambient atmospheres are based upon the photometric (photomultiplier tube) detection of the chemiluminescence produced by the flameless gas phase reaction of the ozone in the air sample stream with ethylene gas whose flow from a bottled supply is regulated through a calibrated capillary tubing to the reactor chamber.

Similarly, NO measurements from 0.01 to 5,000 ppm are based upon the chemiluminescent reaction of NO and ozone to produce NO_2 and $\text{O}_2 + h\nu$. The ozone is produced from bottled oxygen by an in-line ozone generator. Monitoring of NO_x is accomplished by means of an NO_2 to NO catalytic converter which operates in a bypass line on a timed sequence basis. Thus, NO_2 measurements can be obtained by difference.

The selectivity of these instruments is enhanced by the use of narrow-band optical filters to provide negligible interference effects from other atmospheric contaminants. Although designed for ambient air studies, these instruments may be used advantageously as fixed-station monitors of in-plant atmospheres.

Colorimetry (see Photometry)

Combustion. A combustible gas or vapor mixture is passed over a filament heated above the ignition temperature of the substance of analytical interest. If the filament is part of a bridge circuit, the resulting heat of combustion changes the resistance of the filament, and the measurement of the imbalance is related to the concentration of the gas or vapor in the sample mixture. The method is basically nonspecific, but it may be made more selective by choosing appropriate filament temperatures for individual gases or vapors or by using an oxidation catalyst for a desired reaction such as Hopcalite for carbon monoxide.

Combustible gas indicators must be calibrated

in the laboratory for their response to the anticipated individual test gases and vapors, such as benzene, toluene, hexane (for hydrocarbons in general), carbon monoxide, acetone, and styrene. These instruments are definitely portable and they are valuable survey meters in the industrial hygienist's collection of field instruments. Readings are in terms of 0-1000 ppm or 0-1.0 Lower Explosive Limit (LEL). However, it is essential to recognize that industrial atmospheres rarely contain one gaseous contaminant and that these indicators will respond to all the combustible gases present. Hence, supplementary sampling and analytical techniques should be used for a complete definition of hazardous environmental conditions.

Conductivity, Electrical. A gas-air mixture is drawn through an aqueous solution. Those gases which form electrolytes produce a change in the electroconductivity as a summation of the effects of all ions thus produced. Hence, the method is nonspecific. If the concentrations of all other ionizable gases are either constant or insignificant, then the resulting changes in conductivity may be related to the gaseous substance of interest. Temperature control is extremely critical in conductance measurements; if thermostated units are not used, then electrical compensation must enter into the measurements to allow for the 2% per degree C conductivity temperature coefficient average for many gases.

The electrical conductivity method has found its greatest application in the continuous monitoring of sulfur dioxide in ambient atmospheres. However, a lightweight portable analyzer which uses a peroxide absorber to convert SO_2 to H_2SO_4 is now available; this battery operated instrument can provide within one minute an integrated reading of the SO_2 concentration over the 0-1 ppm range. A larger portable model which may be operated off a 12-volt automobile battery is also available for the higher concentration ranges of SO_2 encountered in field sampling.

Conductivity, Thermal. The specific heat of conductance of a gas or vapor is a measure of its concentration in a carrier gas such as air, argon, helium, hydrogen, or nitrogen. However, thermal conductivity measurements are nonspecific and the method finds its greatest usefulness in estimating the concentration of the separately eluted components from a gas chromatographic column. The method operates by virtue of the loss of heat from a hot filament to a single component of a flowing gas stream, the loss being registered as a decrease in electrical resistance measured by a Wheatstone bridge circuit. The applications of this method are limited mostly to binary gas mixtures and are based upon the electrical unbalance produced in the bridge circuit by the difference in the filament resistances of the sample and reference gases passed through the separate cavities in the thermal conductivity cell.

Coulometry. Coulometry is the precise measurement of the quantity of electricity passing through a solution during an electrochemical reaction. The substance of analytical interest is oxidized or reduced at one electrode in a primary coulometric

analysis or it may react stoichiometrically (in a secondary coulometric analysis) with one of the electrolytic products. The method is capable of a high degree of precision. It is used in the automatic monitoring of part per billion to part per million concentrations of reactive inorganic gases present in ambient atmospheres; air samples are drawn through the electrolytic cell in which the reactant is generated in controlled quantities to meet the concentration requirements.

The method is basically nonspecific; it is made more selective for specific atmospheric oxidants by adjusting the concentration, pH and composition of the electrolyte used in the reaction. In certain instances a chemical filter or a selective membrane is used to remove serious interferents from the sampled gas stream. Both portable and fixed monitor types of instruments, based upon this principle, are used to monitor ozone, nitrogen dioxide and sulfur dioxide concentrations.

Flame Ionization. The hydrogen flame ionization detector (FID) is a stainless steel burner in which hydrogen is mixed with the sample gas stream in the base of the unit; combustion air or oxygen is fed axially and diffused around the jet through which the hydrogen — gas mixture flows to the cathode tip where ignition occurs. A loop of platinum serves as the collector electrode which is set about 6 mm above the tip of the burner. The current carried across the electrode gap is proportional to the number of ions generated during the burning of the sample; the detector responds to all organic compounds, except formic acid, but its response is greatest with hydrocarbons and diminishes with increasing substitution of other elements: notably oxygen, sulfur and chlorine. Its low noise level of 10^{-12} amperes provides a high sensitivity of detection and it is capable of the wide linear dynamic range of 10^7 . Its usefulness is enhanced by its insensitivity to water, the permanent gases and most inorganic compounds thus simplifying the analysis of aqueous solutions and atmospheric samples. It is used to great advantage in both laboratory and field models of gas chromatographs as well as in hydrocarbon analyzers which are set up as fixed station monitors of ambient atmospheres in the laboratory or field.

Hydrocarbon analyzers, operating with an FID detector, are carbon counters; their response to a given quantity of a typical C_n hydrocarbon is six times to that of methane, at a fixed flowrate of the sample stream. Thus, the instrumental characteristics such as sensitivity, are usually given as methane equivalent. In addition to hydrocarbons, these analyzers respond to alcohols, aldehydes, amines and other compounds which will produce an ionized carbon atom in the hydrogen flame. The electronic stability of at least one model is within 1 percent over 24 hours of operation; this instrument is equipped with electronic span calibration to improve the accuracy of the data.

Gas Chromatography. Gas chromatography is a physical process for separating the components of complex mixtures and is now being used profitably as a portable technique for in-plant studies. A gas chromatograph consists of (1) a carrier gas sup-

ply complete with a pressure regulator and flow meter, (2) an injection system for the introduction of a gas or vaporizable sample into a port at the front end of the separation column, (3) a stainless steel, copper or glass separation column containing a stationary phase consisting of an inert material, such as diatomaceous earth, used alone as in gas-solid chromatography (GSC) or as a support for a thin layer of a liquid substrate, such as silicone oils, in gas-liquid chromatography (GLC), (4) a heater and oven assembly to control the temperature of the column(s), injection port and detector unit, (5) a detector and (6) a recorder for the chromatograms produced during the separations. The separations are based upon the varied affinities of the sample components for the packing materials of a particular column, the rate of carrier gas flow and the operating temperature of the column. Improved separations are made possible by the use of temperature programming. The sample components, as a consequence of their varied affinities for a given column, are eluted sequentially and thus evoke separate responses by the detection system whose signal is amplified to produce a peak on the strip chart recorder. The height and area of the peak are proportional to the concentration of the eluted sample component. Calibrations are made using known mixtures of the pure substance in a gas-air mixture prepared in a 5- to 100-liter Saran bag or other suitable container. The time of retention on the column and supporting analytical techniques (infrared spectrophotometry, for example) are used in the identification of the individual peaks of a chromatogram. The method is capable of providing extremely clean-cut separations and is one of the most useful techniques in the field of organic analysis. It is sensitive to fractional part per million concentrations of organic substances. The most commonly used detectors include flame ionization, thermal conductivity and electron capture (see Chapter 21 on Gas Chromatography).

Rugged, battery operated, portable gas chromatographs have been refined to the point where they may now be considered practical for many field study applications. These instruments may now be obtained with a choice of thermistor-type thermal conductivity, flame ionization and electron capture detectors and, in some instances, the latter two types are interchangeable. Complete with gas sampling valve, rechargeable batteries, appropriate columns and self-contained supplies of gases, these chromatographs have much to offer to the industrial hygienist engaged in on-site analyses of trace quantities of organic compounds and the permanent gases. The gas lecture bottles provide 8 to 20 hours of operation dependent on the flowrates and must be recharged using high pressure gas regulators. The retention times of the compounds of analytical interest must be determined in the laboratory for a given type of column, as is true for the laboratory type chromatographs.

Photometry (Colorimetry). Photometry is the measurement of the relative radiant power of a beam of radiant energy, in the visible, ultraviolet or infrared region of the electromagnetic spectrum,

which has been attenuated as a result of passing through a solution, a gas-air mixture containing a substance such as mercury vapor, ozone or benzene vapor, a suspension of solid or liquid particulates in air or other gaseous medium, or a photographic image of a spectral line or an x-ray diffraction pattern on a photographic film or plate. Photometers used for the indicated types of applications contain (1) a lamp or other generating source of energy, (2) an optical filter arrangement to limit the bandwidth of the incident beam of radiation, (3) an optical system to collimate the filtered beam, which is then passed through (4) the sample system contained in a cuvette or gas cell to (5) a photocell, bolometer, thermocouple or pressure sensor type of detector where the signal is amplified and fed to a (6) readout meter or to a strip chart recorder.

The more sophisticated technique is termed spectrophotometry which makes use of prisms made of glass (visible region), quartz (ultraviolet), and sodium chloride or potassium bromide (infrared) or of diffraction gratings, instead of optical filters, to provide essentially monochromatic radiation as a "purer" source of energy. Spectrophotometers are used mostly in laboratories for highly specific and precise analytical determinations.

Most field type colorimetric analyzers have been designed to function as fixed-station monitors for the active gases such as oxides of nitrogen, sulfur dioxide, "total oxidant," ammonia, aldehydes, chlorine, hydrogen fluoride, and hydrogen sulfide. These instruments require frequent calibration with zero and span gases at the sampling site to assure the provisions of reliable data. However, built-in automated calibration systems, which standardize regularly zero and span controls against pure air and a calibrated optical filter, are now available from one source of colorimetric analyzers for the nitrogen oxides, sulfur dioxide and aldehydes. A further advantage is the 0-10 ppm working range of these instruments with the optional capability of extending the upper limit to 10,000 ppm.

Another recent advance is the provision of a portable, colorimetric analyzer for NO_2 - NO_x by another manufacturer. This instrument, which uses dual photometric cells, is designed for rugged field use, may be operated from a 12-volt automobile battery and operates over the 0-2.0 ppm range, with higher ranges available. It may also be used as a field monitor, if desired.

Polarography. Polarographic analysis is based on the electrolysis of a sample solution using an easily polarized microelectrode (the indicator electrode) and a large nonpolarizable reference electrode. In laboratory instruments the indicator electrode is a noble metal, usually a dropping mercury electrode for reduction reactions and a platinum electrode for oxidation reactions. The reference electrode may be a pool of mercury on the bottom of the electrolysis vessel or a saturated calomel electrode.

The method provides both qualitative and quantitative information. As the increasing voltage to the polarographic cell is applied at a steady

rate, the decomposition potentials of electroreducible (or electrooxidizable) ions are reached in turn. At the decomposition potential of a given ion, the current increases rapidly and then levels off to a limiting current thus producing an S-shaped curve or "wave." The value of the half-wave potential is characteristic of the discharged ion in a given electrolyte. The height of the wave, i.e., the rise in the current, is proportional to the concentration of the discharged ion species in the sample.

The method has been used largely for the analysis of metallic ions and organic species. Manufacturers of modern field instruments, however, are taking advantage of advanced, compact, long-lived polarographic sensors to provide continuous monitors for oxygen in such diversified environments as furnace atmospheres, flue gases, auto exhausts, space vehicles, manholes and physiology test chambers.

These portable instruments may be easily calibrated for gaseous oxygen by exposing the sensor to ambient air and adjusting the calibration pot to provide a meter reading of 20.9 on the 0-25 percent scale. These instruments provide a rapid response to changes in the concentration of oxygen and should prove valuable to the industrial hygienist who may encounter oxygen deficient atmospheres during his surveys.

Radioactivity. Radioactive substances emit three principal types of radiation, viz. alpha (α), beta (β), and gamma (γ). Radioactive particles and gases may be monitored manually or automatically in gas streams, in ambient atmospheres, in process water or in solid process materials or products by means of ionization chambers, scintillation detectors or Geiger-Mueller counters. Choice of detectors for alpha, beta-gamma or alpha-beta-gamma monitors is determined by the isotopes of interest. Electronic recorders are available for graphic presentation of monitoring data.

Portable lightweight air monitors for gamma, beta-gamma, and alpha-beta-gamma radiation are available with interchangeable probes to survey work areas for the different types of radiation encountered. One such instrument thus provides the capability of measuring alpha and weak beta radiation using one probe and gamma radiation up to 10 or 60 mr per hour with the others. Other portable survey meters include the "Cutie Pie" with ranges of 50, 500, and 5000 mr per hour and a fast neutron survey meter designed with tissue equivalent response in making health hazard surveys in the range of 0.2 to 14 MEV around reactors and neutron generators.

A summary of the operating characteristics of the current (1972) commercially available direct reading physical instruments is presented in Table 16-1. The information provided in this table is based upon that given in the manufacturers' literature; in certain instances, e.g., repeatability, a range of values may represent either the specifications given by more than one source of supply or different applications of an operating principle to the estimation of multiple chemical entities. In other cases, the information has not been provided

TABLE 16-1
Direct Reading Physical Instruments

Principle of Operation	Applications & Remarks	Code*	Range	Repeatability (Precision)	Sensitivity	Response Time
Aerosol Photometry	Measures, records and controls particulates continuously in areas requiring sensitive detection of aerosol levels; detection of 0.05 to 40 μm diameter particles. Computer interface equipment is available.	A & B	10^{-3} to 10^2 μg per liter	Not given	10^{-3} μg per liter (for 0.3 μm DOP)	Not given
Chemiluminescence	Measurement of NO in ambient air selectivity and NO ₂ after conversion to NO by hot catalyst. Specific measurement of O ₃ . No atmospheric interferences.	B	0 to 10,000 ppm	± 0.5 to $\pm 3\%$	Varies: 0.1 ppb to 0.1 ppm	ca 0.7 sec NO Mode and 1 sec NO _x mode; Longer period when switching ranges
Colorimetry	Measurement and separate recording of NO ₂ -NO _x , SO ₂ , total oxidants, H ₂ S, HF, NH ₃ , Cl ₂ and aldehydes in ambient air.	A & B	ppb & ppm	± 1 to $\pm 5\%$	0.01 ppm (NO ₂ , SO ₂)	30 sec. to 90% of full scale
Combustion	Detects and analyzes combustible gases in terms of percent LEL on graduated scale. Available with alarm set at 1/3 LEL.	A	ppm to 100%	—	ppm	<30 sec.
Conductivity, Electrical	Records SO ₂ concentrations in ambient air. Some operate off a 12-volt car battery. Operate unattended for periods up to 30 days.	A & B	0 to 2 ppm	$<\pm 1\%$ to $\pm 10\%$	0.01 ppm	1 to 15 sec. (lag)
Coulometry	Continuous monitoring of NO, NO ₂ , O ₃ and SO ₂ in ambient air. Provided with strip chart recorders. Some require attention only once a month.	A & B	Selective: 0 to 1.0 ppm overall, or to 100 ppm (optional)	$\pm 4\%$ of full scale	varies: 4 to 100 ppb dependent on instrument range setting.	<10 min. to 90% of full scale.
Flame Ionization (with gas chromatograph)	Continuous determination & recording of methane, total hydrocarbons and carbon monoxide in air. Catalytic conversion of CO to CH ₄ . Operates up to 3 days unattended.	B	Selective: 0 to 1 ppm; 0 to 100 ppm	$\pm 1\%$ of full scale	Not given	5 min. (cycle time)
Same as above	Separate model for continuous monitoring of SO ₂ , H ₂ S and total sulfur in air. Unattended operation up to 3 days.	B	0-20 ppm	$\pm 4\%$ of full scale	0.005 ppm (H ₂ S); 0.01 ppm (SO ₂)	5 min. (cycle time)
Flame Ionization (Hydrocarbon Analyzer)	Continuous monitoring of total hydrocarbons in ambient air; potentiometric or optional current outputs compatible with any recorder. Electronic stability from 32° to 110°F.	B	0 to 1 ppm as CH ₄ ; X1, X10, X100, X1000 with continuous span adjustment	$\pm 1\%$ of full scale	1 ppm to 2% full scale as CH ₄ ; 4 ppm to 10% as mixed fuel.	<0.5 sec. to 90% of full scale

TABLE 16-1 (Continued)

Principle of Operation	Applications & Remarks	Code*	Range	Repeatability (Precision)	Sensitivity	Response Time
Gas Chromatograph, Portable	On site determination of fixed gases, solvent vapors, nitro and halogenated compounds and light hydrocarbons. Instruments available with choice of flame ionization, electron capture or thermal conductivity detectors and appropriate columns for desired analyses. Rechargeable batteries.	A	Depends on detector	Not given	<1 ppb (SF ₆) with electron capture detector; <1 ppm (HC's)	—
Infrared Analyzer (Photometry)	Continuous determination of a given component in a gaseous or liquid stream by measuring amount of infrared energy absorbed by component of interest using pressure sensor technique. Wide variety of applications include CO, CO ₂ , Freons, hydrocarbons, nitrous oxide, NH ₃ , SO ₂ , and water vapor.	B	From ppm to 100% depending on application	±1% of full scale	0.5% of full scale	0.5 sec. to 90% of full scale
Photometry, Ultraviolet (tuned to 253.7 mμ)	Direct readout of mercury vapor; calibration filter is built into the meter. Other gases or vapors which interfere include acetone, aniline, benzene, ozone and others which absorb radiation at 253.7 mμ.	A	0.005 to 0.1 and 0.03 to 1 mg/m ³	±10% of meter reading or ± minimum scale division, whichever is larger	0.005 mg/m ³	Not given
Photometry, Visible (Narrow-centered 394 mμ band pass)	Continuous monitoring of SO ₂ , SO ₃ , H ₂ S, mercaptans and total sulfur compounds in ambient air. Operates more than 3 days unattended.	B	1 to 3,000 ppm (with air flow dilution)	±2%	0.01 to 10 ppm	<30 sec. to 90% of full scale.
Particle Counting (Near Forward Scattering)	Reads and prints directly particle concentrations at 1 of 3 preset time intervals of 100, 1000 or 10,000 seconds, corresponding to 0.01, 0.1 and 1 cubic foot of sampled air.	B	Preset (by selector switch) Particle Size Ranges: 0.3, 0.5, 1.0, 2.0, 3.0, 5.0, and 10.0 μm. Counts up to 10 ⁷ particles per cu. ft. (35 × 10 ³ /liter)	±0.05% (probability of coincidence)	—	Not given
Polarography	Monitor gaseous oxygen in flue gases, auto exhausts, hazardous environments and in food storage atmospheres and dissolved oxygen in wastewater samples. Battery operated, portable, sample temperature 32° to 110°F, up to 95% relative humidity. Potentiometric recorder output. Maximum distance between sensor and amplifier is 1000 feet.	A	0-5 and 0-25%	±1% of reading at constant sample temperature	Not given	20 sec. to 90% of full scale

TABLE 16-1 (Continued)

Principle of Operation	Applications & Remarks	Code*	Range	Repeat-ability (Precision)	Sensitivity	Response Time
Radio-activity	Continuous monitoring of ambient gamma and x-radiation by measurement of ion chamber currents, averaging or integrating over a constant recycling time interval, sample temperature limits 32°F to 120°F; 0 to 95% relative humidity (weatherproof detector); up to 1,000 feet remote sensing capability. Recorder and computer outputs. Complete with alert, scram and failure alarm systems. All solid-state circuitry.	B	0.1 to 10 ⁷ mR/hr.	±10% (Decade Accuracy)	—	<1 sec.
Radio-activity	Continuous monitoring of beta or gamma emitting radioactive materials within gaseous or liquid effluents; either a thin wall Geiger-Mueller tube or a gamma scintillation crystal detector is selected depending on the isotope of interest; gaseous effluent flow — 4 cfm; effluent sample temperature limits 32°F to 120°F using scintillation detector and —65°F to 165°F using G-M detector. Complete with high radiation, alert and failure alarms.	B	10 to 10 ⁶ cpm	±2% full scale (rate meter accuracy)	<10 ⁻⁷ μCi of I-131 per cc of air and 10 ⁻⁷ μCi of Cs-137 per cc of water using a scintillation detector	0.2 sec. at 10 ⁶ cpm (rate-meter)
Radio-activity	Continuous monitoring of radioactive airborne particulates collected on a filter tape transport system; rate of air flow — 10 SCFM; scintillation and G-M detectors, optional but a beta sensitive plastic scintillator is provided to reduce shielding requirements and offer greater sensitivity. Air sample temperature limits 32°F to 120°F; weight 550 pounds. Complete with high and low flow alarm and a filter failure alarm.	B	10 to 10 ⁶ cpm	±2% of full-scale (rate-meter accuracy)	10 ⁻¹² μ Ci of Cs-137 per cc of air using a scintillation detector	0.2 sec. at 10 ⁶ cpm (rate-meter)

* Code: A-Portable Instruments; B-Fixed Monitor or "Transportable" Instruments.

Taken from Draeger Detector Tube Handbook, Draegerwerk. Lübeck, West Germany, 1970, pp. 33-71.

in a manufacturer's list of specifications for an instrument and this has been so noted in Table 16-1. The material presented under "Applications and Remarks" provides information on the individual substances which may be analyzed directly by the stipulated technique along with specified interferences and other important considerations. This tabulation is not an official certified list; it is intended as a useful guide in selecting direct read-

ing physical instruments on the basis of desired operating parameters.

DIRECT READING COLORIMETRIC DEVICES

Operating Principles

Direct-reading colorimetric devices utilize the chemical properties of an atmospheric contaminant for the reaction of that substance with a

color-producing reagent. Reagents used in detector kits may be in either a liquid or a solid phase or provided in the form of chemically treated papers. The liquid and solid reagents are generally supported in sampling devices through which a measured amount of contaminated air is drawn. On the other hand, chemically treated papers are usually exposed to the atmosphere and the reaction time noted for a color change to occur.

Liquid Reagents. Liquid reagents may be supplied in sealed ampoules or in tubes for field use. Such preparations are provided in a concentrated or a solid form for easy dilution or dissolution at the sampling site. Representative of this type of reagent are the ortho-tolidine and the Griess-Iso-vay kits for chlorine and nitrogen dioxide, respectively. Although the glassware needed for these applications may be somewhat inconvenient to transport to the field, methods based on the use of liquid reagents are more accurate than those which use solid reactants. This is due to the inherently greater reproducibility and accuracy of color measurements made in a liquid system.

Chemically Treated Papers. Papers impregnated with chemical reagents have found wide applications for many years for the detection of toxic substances in air. Examples include the use of mercuric bromide papers for the detection of arsine, lead acetate for hydrogen sulfide, and a freshly impregnated mixture of o-tolidine and cupric acetate for hydrogen cyanide. When a specific paper is exposed to an atmosphere containing the contaminant in question, the observed time of reaction provides an indication of the concentration of that substance. Thus, in the case of hydrogen cyanide a 5-second response time by the o-tolidine-cupric acetate paper is indicative of a concentration of 10 ppm of HCN in the tested atmosphere.

Similarly, sensitive detector crayons have been devised for the preparation of a reagent smear on a test paper whose response to a specific toxic substance in a suspect atmosphere may then be timed to obtain an estimation of the atmospheric concentration of a contaminant. Crayons for phosgene, hydrogen cyanide, cyanogen chloride, and Lewisite (ethyl dichloroarsine) have been formulated for this purpose.³

Colorimetric Indicator Tubes. Colorimetric indicating tubes containing solid reagent chemicals provide compact direct-reading devices, which are convenient to use for the detection and semiquantitative estimation of gases and vapors in atmospheric environments. There are tubes for nearly two hundred atmospheric contaminants on the market, and seven U.S. companies manufacture and/or distribute these devices currently in this country.⁴ Whereas it is true that the operating procedures for these tubes are simple, rapid and convenient, there are distinct limitations and potential errors inherent in this method of assessing atmospheric concentrations of toxic gases and vapors. Therefore, dangerously misleading results may be obtained with these devices unless they are used under the supervision of an adequately trained industrial hygienist who (1) enforces rig-

idly (a) the periodic (as required) calibration of individual batches of each specific type of tube for its response to known concentrations of the contaminant and (b) the refrigerated storage of all tubes to minimize their rate of deterioration; (2) informs his staff of the physical and chemical nature and extent of interferences to which a given type of tube is subject and limits the tube's usage accordingly; and (3) stipulates how and when other independent sampling and analytical procedures will be employed to derive needed quantitative data.

Colorimetric indicating tubes are filled with a solid granular material, such as silica gel or aluminum oxide, which has been impregnated with an appropriate chemical reagent. The ends of the glass tubes are sealed during manufacture. When a tube is to be used, its end tips are broken off, the tube is placed in the manufacturer's holder, and the recommended volume of air is drawn through the tube by means of the air moving device provided by the manufacturer. This device may be one of several types such as a positive displacement pump, a simple squeeze bulb, or a small electrically operated pump with an attached flow meter. Each air moving device must be calibrated after each usage or after sampling 100 tubes as an arbitrary rule or more often if there are reasons to suspect changes due to effects of a corrosive action from contaminants in tested atmospheres. An acceptable pump should be correct to within $\pm 5\%$ by volume; with use, its flow characteristics may change. It should also be checked for leakage and plugging of the inlet after every 10 samples.

In most cases, a fixed volume of air is drawn through the detector tube although, with some systems, varied amounts of air may be sampled. The operator compares either an absolute length-of-stain produced in the column of the indicator gel or a ratio of the length-of-stain to the total gel length against a calibration chart to obtain an indication of the atmospheric concentration of the contaminant that reacted with the reagent. In another type of tube, a progressive change in color intensity is compared with a chart of color tints in making the estimation. In a third type of detector, the volume of sampled air which is required to produce an immediate color change is noted; it is intended that this air volume should be inversely proportional to the concentration of the atmospheric contaminant. The remainder of this chapter is devoted to the direct-reading, colorimetric indicating detector tube systems because of the widespread use of these devices.

Detector Tube Characteristics

Reagents and Interferences. Complete information on the formulations of the chemical reagents used in the manufacture of the commercial devices is not available owing to the understandably competitive nature of this enterprise. However, there is sufficient knowledge of the chemical nature of certain solid reactants commonly used for this purpose to provide the limited information on chemical reactants, products, color changes, and stated interferences given in Table

TABLE 16-2
Select List of Detecting Reactions in
Colorimetric Indicating Tubes*

Test Gas or Vapor	Reagents in			Product(s)	Color Change	Stated Interferences
	Pre-cleanse Layer	Ampoule or Conversion Layer	Indicating Layer			
Acetone	None	None	2, 4-Dinitrophenylhydrazine	A hydrazone	Pale Yellow to Yellow	Other ketones and aldehydes, alcohols, esters
Acrylonitrile	None	(1) Chromate (VI) Compound	(2) Mercuric chloride (3) Methyl red	(1) Hydrogen cyanide (2) Hydrogen chloride (3) Red form of indicator	Yellow to red	HCl, HCN, organic CN compounds, aromatic solvents
Alcohol	Drying agent	None	Chromate (VI) compound	Chromic (III) compound	Yellow to green	Other oxygenated compounds
Ammonia	None	None	(1) Acid (2) Bromophenol blue	(1) Ammonium salt (2) Blue form of indicator	Orange to dark blue	Amines, Hydrazines
Aniline	None	(1) Furfural	(2) Acid	(1) Schiff base (2) Dianiline derivative	White to red	Ammonia
Arsine	Copper compound (to retain reduced S compounds, H ₂ Se, NH ₃ , and HCl)	None	Gold compound	Colloidal gold	White to weak violet grey	Phosphine, stibine
Benzene	Acid and aldehyde (to retain other aromatics)	None	(1) Formaldehyde (2) Sulfuric acid	(1) Diphenylmethane (2) p-Quinoid compound	White to brown	None affect the indication
Carbon Dioxide	None	None	(1) Hydrazine (2) Crystal violet	(1) Carbonic Acid Monohydrazide (2) Blue form of indicator	White to blue	None affect the indication
Carbon Disulfide	Copper compound (to retain H ₂ S)	None	(1) Copper compound (2) Amine	Copper Dialkyldithiocarbamate	Pale blue to yellowish green	None affect the indication (except H ₂ S)
Carbon Monoxide	Chromate (VI) compound (to retain H ₂ S, C ₆ H ₆ , petroleum compounds)	None	(1) Iodine pentoxide (2) Selenium dioxide (3) Fuming sulfuric acid	Iodine (and carbon dioxide)	White to brownish green	Acetylene and easily cleaved halogenated hydrocarbons

TABLE 16-2 (Continued)
 Select List of Detecting Reactions in
 Colorimetric Indicating Tubes*

Test Gas or Vapor	Reagents in			Product(s)	Color Change	Stated Interferences
	Pre-cleanse Layer	Ampoule or Conversion Layer	Indicating Layer			
Carbon Tetrachloride	None	(1) Fuming Sulfuric acid	(2) Dimethyl-amino-benzaldehyde (3) Dimethyl-aniline	(1) Phosgene (2) "Blue reaction product"	Yellow to blue	Fluorochloromethane compounds
Chlorine	Drying agent	None	o-Tolidine	"Yellow reaction product"	White to yellow	Bromine, chlorine dioxide; discoloration by nitrogen dioxide
Chloroprene	None	None	Permanganate	"Yellowish Brown Reaction Product"	Violet to yellowish brown	Other organic compounds with carbon-carbon double bonds
Cyanogen Chloride	None	(1) Pyridine (2) Water	(3) Barbituric acid	(1) & (2) Glutaconaldehyde cyanamide (3) "Pink Reaction Product"	White to pink	Cyanogen bromide
Ethyl acetate	Drying agent	None	Chromosulfuric acid	Chromic (III) compound	Orange to brown green	Easily oxidized organic compounds including other acetates
Formaldehyde	None	(1) Xylene vapor	(2) Sulfuric acid	(1) Dixyl methane (2) "Pink quinoid compound"	White to pink	Other aldehydes and styrene
Hydrazine	None	None	(1) Acid (2) Bromophenol blue	(1) Hydrazinium salt (2) Blue form of indicator	Yellow to blue	1,1-Dimethyl hydrazine, ammonia, amines
Hydrochloric Acid	Drying agent	None	Bromophenol blue	Yellow form of indicator	Blue to yellow	Chlorine; R.H. > 80%
Hydrocyanic Acid	Lead compound (to retain H ₂ S, HCl, SO ₂ , NO ₂ and NH ₃)	None	(1) Mercuric Chloride (2) Methyl red	(1) Hydrogen chloride (2) Red form of indicator	Yellow to red	None affect the indication (except those not retained in pre-cleanse layer)
Hydrogen fluoride	None	None	Zirconium-alizarin lake	Alizarin	Pale violet to pale yellow	High humidity
Hydrogen sulfide	None	None	Lead compound	Lead Sulfide	White to light brown	None affect the indication
Mercaptan	None	(2) Sulfur solution	(1) Copper compound	(1) Copper mercaptide (2) Yellowish brown copper compound	White to yellowish brown	Other mercaptans, hydrogen sulfide, ammonia, amines

TABLE 16-2 (Continued)
Select List of Detecting Reactions in
Colorimetric Indicating Tubes*

Test Gas or Vapor	Reagents in			Product(s)	Color Change	Stated Interferences
	Pre-cleanse Layer	Ampoule or Conversion Layer	Indicating Layer			
Methyl bromide	None	(1) Sulfur trioxide (2) Permanganate	(3) o-dianisidine	(1) & (2) Bromine (3) "Brown Reaction Product"	White to brown	Halogens, halides, halogenated hydrocarbons
Mono-styrene	Drying agent	None	Sulfuric acid	"Yellow Reaction Product"	White to yellow	Butadiene and other polymertending organic compounds
Nickel tetracarbonyl	None	(2) Dioxime	(1) Iodine	(1) Nickel iodide (2) Nickel dioxime complex	Pale brown to pink	Iron pentacarbonyl, hydrogen sulfide, sulfur dioxide
Nitrogen dioxide (NO ₂)	Drying agent	None	N,N'-diphenylbenzidine	"Bluish grey Reaction Product"	White to bluish grey	Ozone, chlorine
Nitrous fumes (NO + NO ₂)	None	(1) Chromium (VI) compound	(2) N,N'-diphenylbenzidine	(1) Nitrogen dioxide (2) "Bluish grey reaction product"	White to bluish grey	Ozone, chlorine
Ozone	None	None	Indigo	Isatine	Pale blue to white	Chlorine, nitrogen dioxide
Perchloroethylene	None	(1) Permanganate	(2) N,N'-diphenylbenzidine	(1) Chlorine (2) "Greyish blue Reaction Product"	White to greyish blue	Halogens, hydrogen halides, easily cleaved halogenated hydrocarbons, petroleum vapor
Phenol	None	(1) 2,6-dibromoquinone chlorimide	(2) Activated silica gel	(1) & (2) Indophenol dye	White to blue	Other aromatic hydroxy compounds, quinones; ammonia and amines discolor indicating layer
Phosgene	Drying agent	None	(1) Dimethylaminobenzaldehyde (2) Diethylaniline	Bluish green complex	Yellow to bluish green	Carbonyl bromide
Phosphine	Copper compound (to retain reduced sulfur compounds, NH ₃ , H ₂ S & H ₂ Se)	None	Gold compound	Colloidal gold	White to weak greyish violet	Arsine, stibine
Sulfur dioxide	Copper compound (to retain H ₂ S)	None	Iodine/Starch	Sulfuric acid	Blue to white	Nitrogen dioxide

TABLE 16-2 (Continued)
Select List of Detecting Reactions in
Colorimetric Indicating Tubes*

Test Gas or Vapor	Reagents in			Product(s)	Color Change	Stated Interferences
	Pre-cleanse Layer	Ampoule or Conversion Layer	Indicating Layer			
Toluene	Drying agent	None	(1) Iodine pentoxide (2) Dilute sulfuric acid	(1) & (2) Iodine	White to brown	Xylenes, benzene
Trichloroethane	None	(1) Sulfuric acid (2) Oxidizing agent	(3) o-dianisidine	(1) & (2) Chlorine (3) "Brownish red Reaction Product"	Pale grey to brownish red	Some other halogenated hydrocarbons; petroleum hydrocarbons & aromatic compounds >1000 ppm
Trichloroethylene	None	(1) Permanganate	(2) o-tolidine	(1) Chlorine (2) "Orange Reaction Product"	White to orange	Halogens, halides, easily cleaved halogenated hydrocarbons, petroleum distillate vapors
Vinyl chloride	None	None	Permanganate	Light brown manganese compound	Violet to light brown	Organic compounds with carbon-carbon double bond

* Taken from Draeger Detector Tube Handbook, Draegerwerk. Lübeck, West Germany, 1970, pp. 33-71.

16-2. From this table it is apparent that the lack of specificity encountered with certain detector tubes is due to the use of common reagents for numerous compounds. Thus, the use of a hexavalent chromium compound for the oxidation of a wide variety of organic substances with the production of a green chromic reaction product is a completely nonspecific procedure for these substances. This type of detector tube must be used with the realization that all readily oxidizable substances may affect the indication and efforts should therefore be taken to ascertain the chemical nature of the various associated contaminants in each exposure situation. Further, aromatic hydrocarbons, hydrides, halides, and chlorinated hydrocarbons provide other examples of class compounds for which single formulations in detector tube reactants may have been used. Such formulations limit the usefulness of these tubes in mixed exposure areas as the estimations are then based on the results of the reaction of a mixture of contaminants. Furthermore, errors of estimation may be positive or negative depending upon whether a stain is intensified (or lengthened) by the presence of a similarly reacting contaminant or bleached by a differing chemical contaminant present in the sampled air stream. This general situation has evoked a great deal of criticism of detector tube systems by the industrial hygiene profession which recognizes the need for improved devices of this type.

Efforts to overcome this cross sensitivity have been attempted by: a. Use of a pre-layer to remove certain known interferences from the air stream before they reach the indicating layer; and b. Use of a conversion layer to transform the desired gaseous substance to a different chemical compound which can then react with the indicating layer.

Examples of the incorporation of a pre-layer in the formulation of a tube include the Dräger Arsiné 0.05/a and the Benzene 0.05 tubes. The former uses a copper compound to retain in the pre-layer such interferences as hydrogen sulfide, hydrogen selenide, mercaptans, ammonia, and hydrogen chloride, but allows arsine to pass through to the indicating layer containing a gold compound with which the arsine reacts to yield a weak violet-gray color. The benzene 0.05 tube has an acid-aldehyde reagent to remove toluene, xylene and naphthalene; benzene passes on into the indicating layer where it produces a brown color from its reaction with formaldehyde and sulfuric acid.

Another difficulty arising from detector tube reagents is the catalyzed reaction of gaseous contaminants with one another due to the active contact surface provided by the column of chemicals in the detector tube. This phenomenon has been observed with sulfur dioxide and nitrogen dioxide when these gases are brought into closer molecular contact in detector tubes than that prevailing

in ambient atmospheres where their reaction rate with each other is generally low.

Quality Control. The rigid control of the purity of reagents, grain size of the gel, method of packing the tubes, moisture content of the gel, uniformity of tube diameter, and proper storage precautions is required for the optimal performance of any detector tube. The lack of such controls will lead to an inferior product whose use may produce disastrous results in the evaluation of health related problems. Thus, an incompletely responsive tube could cause a hazardous situation to remain uncorrected. Conversely, an overly reactive response may cause undue concern, wasted effort and needless expense for unwarranted corrections.

Failure of certain manufacturers to maintain a rigid control over manufacturing practices has been observed in the past. Although it has been established⁵ that an elevated moisture content above 20% will cause a rapid deterioration of the silica gel used in the potassium pallado-sulfite formulation for a carbon monoxide tube, one observer found during a visit to a detector tube manufacturing facility that there was a lapse of many hours following the packing but preceding the hermetical sealing of the tubes.⁶ Indeed, such a practice permits the entry of not only moisture but also other contaminating vaporous substances which might produce a deleterious effect on the reagent's future response to the analysis substance.

Another critical parameter is the tube diameter. Manufacturing variations in the internal diameter of the narrower tubes can produce appreciably different cross sectional areas. Saltzman has pointed out that this situation leads to calibration errors as high as 50 percent due to a varying volume of air sample per unit cross sectional area as compared with those provided under standard test conditions.⁷ At least one manufacturer minimizes the effect of this source of error by loading equal amounts of the indicating gel into each tube; the variations in cross sectional areas are then compensated by corresponding variations in the filled lengths of the tubes.⁸ The manufacturer provides calibration scales which permit the positioning of each tube in accordance with its filled length when measuring the length of stain and thus reduce the overall error of measurement of the gas concentration.

Variations in the grain size of the gel, in the purity of the reagents and the cleanliness of the air in the tube manufacturing facility can affect the properties of different batches of the indicating gel markedly. If not controlled carefully, these parameters can cause marked and unpredictable changes in the number of active centers on the solid surface of the gel and thus affect the reaction velocity of the indicating system.

The method of storage has a profound effect on the shelf life of an indicator tube. Deterioration of the tubes increases greatly at elevated temperatures and storage under refrigeration by both the manufacturer and the user is mandatory to realize a useful shelf life which may approximate

two years for some of the tubes. Multiple layer tubes may have a shorter shelf life due to diffusion of chemicals between layers. For these reasons a realistic expiration date for tubes stored under refrigeration should be stamped on each box of tubes by the manufacturer.

Calibration. Saltzman has presented an excellent treatment of the theory of indicator tube calibration where he has developed a basic mathematical analysis of the relationships between the variables which affect the length of stain, i.e., the concentration of test gas, volume of air sample, sampling flowrate, grain size of gel, tube diameter and other variables. This source should be consulted for a full appreciation of the complex interrelationships between the factors affecting the kinetics of indicator tube reactions. It is sufficient to point out in this chapter that the length of stain is proportional to the logarithm of the product of gas concentration and air sample volume as shown in the following equation:⁷

$$L/H = \ln(CV) + \ln(K/H)$$

where: L = the length of stain in centimeters,

C = the gas concentration in parts per million,

V = the air sample volume in cubic centimeters,

K = a constant for a given type of indicator tube and test gas,

H = a mass transfer proportionality factor having the dimensions of centimeters, and known as the height of a mass transfer unit.

If this mathematical model is correct for a given indicator tube, a linear plot of L versus the logarithm of the CV product, for a fixed constant flowrate, will yield a straight line with slope = H. The significance of this equation is the implication that it is important to control the flowrate, which may produce a greater effect on the length of stain than does the concentration of the test gas. Therefore, in the optimal design of an indicator tube it is desirable that the reaction rate be sufficiently rapid to permit the establishment of equilibrium between the indicating gel and the test gas and thus produce a stoichiometric relationship between the volume of stained indicating gel and the quantity of the absorbed test gas. Such equilibrium conditions may be assumed to exist when stain lengths are directly proportional to the volume of sampled air and are not affected by the sampling flowrate.⁷ With this situation a log-log plot of stain length versus concentration for a fixed sample volume may be prepared in the calibration of a given batch of tubes.

From the preceding discussion of the complexity of the heterogeneous phase kinetics of indicator tube reactions, the quality control problems associated with their manufacture and storage, and the difficulties posed by interfering substances, it is obvious that frequent, periodic calibration of these devices should be made by the user. Dynamic dilution systems for the reliable preparation of low concentrations of a test gas or vapor are recommended for this purpose (see

Chapter 12). Such calibrations should be performed before each use if there has been an appreciable period since the last calibration was performed.

Evaluation of Performance

As of January 1, 1972, the results of the evaluation of gas detector tubes for five substances had been published by the National Institute for Occupational Safety and Health.^{9, 10, 11, 12, 13}

The results are as follows:

Substance	No. of Manufactured Tubes Meeting Approval Criterion Within	
	± 25% at 95% C.L.*	± 50% at 95% C.L.
Benzene	None	3
Carbon Monoxide	None	8
Carbon Tetrachloride	None	None
Perchloroethylene	3	—
Sulfur Dioxide	4	—

*95% Confidence Level

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MEDICAL ASPECTS OF THE OCCUPATIONAL ENVIRONMENT

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THE PHYSICIAN, NURSE AND INDUSTRIAL HYGIENIST

(The Occupational Health Protection Team)

The Role of The Physician

Elucidation of Human Parameters of Response. The health of man in the working environment is the central theme of occupational health. While measurement of atmospheric concentrations of an environmental pollutant, per se, in the work place is of interest, it has little relevance to occupational health except in terms of what it means to man's health and well-being. Hence, measurements of environmental contamination must be evaluated in terms of their effects, or lack of them, upon humans. In order to elucidate the effects upon man of potentially deleterious physical or chemical agents found in the work place, the physician, as a specialist in human biology, must provide and interpret such "readouts" of human response. Only then can the main component of this "agent-host" interaction be defined. Only within such a frame of reference may the ultimate significance for man be ascertained of such quantifications of occupationally encountered biological, physical or chemical agents.

Promotion of Human Health. The physician's role in occupational health cannot be that of a mere passive interpreter of human response. He has a positive responsibility for utilizing his special expertise in conjunction with his societal status to actively promote health in industry. One aspect of this responsibility relates to occupationally-related disease and injury; the other to prevention, where feasible, of non-occupational health deterioration; e.g., diabetes or glaucoma detection. Regarding the former, the physician must be prepared to extend his capacities so as to detect early, even subclinical responses; in addition he must be unhesitating in his readiness to insist upon management's taking notice and acting upon his recommendations for amelioration and control of the working environment. In the industrial environment, the *ex cathedra* stance carries only limited impact as compared to the private practice physician-patient relationship. It is because of this reality that the physician requires all the available facts to buttress his opinion. Here the industrial hygienist with his quantitative evaluation of the situation provides the irreplaceable other portion of the equation, "man + agent = effect."

As to the physician's responsibility for prevention of the deleterious effects of non-occupational disease, here his duty parallels usual medical functions elsewhere. However, by virtue of the physician's place in the industrial setting, he has

several advantages over the practitioner in the private sector. This largely stems from his knowledge of human interactions in the work place; he is in a unique position to evaluate the social as well as the physical demands made upon the worker in industry. Thus, hypertensive cardiovascular disease is a process which is not purely biological; its course is affected by the transactions between the patient and his socio-economic environment. A not insignificant segment of this environment is constituted by that setting in which the worker spends approximately one-fourth his life span, i.e., the work place. Operationally, this gives the physician the opportunity to manipulate within limits the human environment within the work place so as to favorably influence the course of the employees' health and well-being.

The Role of the Nurse

The nurse is the "front line" worker in occupational medicine. It is the nurse whom the worker meets 90% of the time when he encounters the medical department. She must be ready to keep a highly "tuned" ear. Information bearing upon the work environment or the individual's health will be imparted to her long before it is transmitted to others. Therefore, as the eyes and ears of the medical department she must guard against "tuning out" worker complaints and statements. Given human tendencies for just such response after years of listening, both the physician and nurse must be constantly alert to prevent the development of a hardened, unsympathetic auditor. While suspending value judgments as regards the merit, — or lack of same, — of employee complaints is difficult, nevertheless all such information inputs contain some value, positive or otherwise. Workers perceive through the nurse the attitude toward them of the medical organization. If they conclude that their statements are consistently ignored, disputed or denied, soon this invaluable intelligence concerning the total work environment within the plant will disappear. From these facts stem the reality that the actions and treatment afforded by the industrial nurse will primarily determine the effectiveness of the medical department.

However, the nurse is not merely a passive reporter. While not implying that she is practicing psychiatry, nevertheless as a skillful listener she fulfills many of the requirements for promotion of mental hygiene. As a sympathetic auditor, she provides the opportunity for verbal ventilation, a significant part of the therapist-patient transaction.

Beyond even this role, the nurse is being given greater responsibilities in worker evaluation. Many more components of the pre-placement and periodic medical evaluation process are being relegated

by the physician to the nurse. While restrictions imposed by various of the Medical Practice Acts must be observed, nevertheless with the aid of new automated devices many of these examinations are being performed by the nurse. Execution of the amanuensis by use of appropriately designed printed forms can conserve significant portions of physician time. Indeed, it appears that given sympathetic listening, such historical portions of the medical examination can be more effectively performed by the nurse rather than the physician.

The Role of The Industrial Hygienist

As alluded to previously, the physician in private practice can frequently assume an authoritative relationship with the patient. However, in the world of business and industry decisions are usually made and action taken upon the basis of quantitative objective parameters. While by the use of clinical laboratory modalities the physician can provide many measurable descriptions of human response, such data may or may not be a reflection of work environment-induced biological change. For example, while anemia may result from chronic benzene absorption, it may also stem from non-occupational medical causes. Thus, in any determination of the reality of possible benzene exposure, it is necessary to know whether sufficient benzene was present in the work environment to cause the observed anemia. Only the industrial hygienist can provide this necessary environmental quantification. Without this information it should be readily apparent that the physician can only guess at causal relationships between the worker's condition and the work place. Such "guesses" are not considered, and should not be, sufficient basis for action by industrial management.

The Need for Coordination of the Work of the Medical Team with the Industrial Hygienist

Evaluation of the Host-Agent Interaction. It would be apparent from the foregoing that measurement of environmental parameters, while intellectually interesting, has little relevance in industry except in terms of its human health implications. It is equally clear that human biological response is usually non-specific in nature. It is only when these two components, environmental and biological, are interdigitated does reality emerge. Accordingly, both medical personnel and industrial hygienists have their contribution to make in elucidating this reality. Since the host-environment interaction is a dynamic ever-changing relationship, an on-going relationship must be developed and maintained between these two disciplines, medicine and industrial hygiene. From the results of such quantitatively validated investigations appropriate engineering and medical control programs are developed.

Evaluation of the Efficacy of Occupational Hazard Control Programs. In response to validated needs for industrial hazard control, engineering measures (e.g., ventilation, enclosure, etc.) are instituted. Despite the highest quality of engineering design and performance, because such measures are controlled, operated and maintained by men, human

imperfections impose themselves upon the efficacy of such controls.

While physical and chemical measurements of the effectiveness of such approaches to hazard control are useful, once more their relevance to the ends desired are man-oriented. Therefore, the adequacy of control performance must be measured in terms of human protection or its lack. Once more, the inputs of the biological scientist (the physician) and the physical scientist (the industrial hygienist) are required to round out the entire picture. Only by coordinating their inter-relating investigational data can these two contributors to industrial health control be effective. Since these interactions may be long-term as well as immediate, adequately coordinated record systems must be developed. Such systems must not only provide records of events, they must be so designed as to provide adequate and early signals of ongoing failures or inadequacies of control systems. Once more, coordination of medical and work environment data must be carefully built into such recording methods.

Detection of New or Potential Problems. Among the greatest challenges to occupational health is the delineation of new occupational hazards. Early warning systems for new health conditions arising out of the working environment have only infrequently been achieved before harm has been done. As quantitative environmental and biological indicators develop greater sensitivities, the potential for detection of a problem before human harm occurs becomes more feasible. With thousands of new chemical agents entering the industrial scene there is an increasing opportunity for development of new knowledge as well as for preventing human damage. Only by coordinating the activities of the medical and industrial hygiene components of the occupational health team will this potentiality be realized.

The Special Qualifications of the Physician Specialist in Industry

Preventive Medicine in Industry

1. Primary prevention

(a) Definition: This has been defined as the prevention of the occurrence of disease or disability arising from pathological processes. While its accomplishment in relationship to the usual chronic or degenerative disease process has been less than spectacular, the potentials for realization of the concept of primary prevention are uniquely feasible in the industrial setting.

(b) Applicability to environmentally induced disease: While the mechanisms responsible for the common degenerative disease processes (e.g., cancer, heart disease, diabetes) remain obscure, the etiologies of environmentally induced diseases are relatively accessible. Thus, if the etiological agents causing occupational diseases can be prevented from contacting the human host, a potentially pathologic process can be totally prevented. Within the limits of an adequate perspective, one cannot imply that certain biological variables, e.g., age, sex, nutritional status, do not affect the course of an agent-host interaction. These variables, and other poorly defined, genetically controlled factors,

will also affect the human response. But while the importance of these determinants of human response to environmentally encountered agents cannot be disregarded, the intrinsic potency of occupational chemical or physical agents can be prevented from being expressed. The knowledge that such agents are capable of inciting human damage upon absorption leads logically to design of measure directed toward prevention of this event. This in turn requires that the physician have the capability of *quantitatively* determining which level of contaminant presents no health hazard (*viz.*, the "no-effect" portion of the dose-response relationship) so that control design criteria can be developed.

Another potential method of primary prevention depends upon detection of special susceptibilities of individual workers to certain occupational hazards. Obvious examples, such as crane operators with inadequacies in their visual fields, come to mind. More subtle potential opportunities for prevention arise out of detection of inborn defects in certain metabolic processes, e.g., a "serum antitrypsin," activity defect which interferes with normal cleansing of the lungs, should preclude such workers' contact with pulmonary irritants.

(c) Limitations in primary prevention: One considerable limitation placed upon the efficacy of primary prevention stems from the fact that at present there are few existent physical or clinical laboratory indicators of special susceptibility to environmental agents. Thus, which worker, upon exposure to benzene, will develop a leukemic response cannot be adequately predicted; similarly, predictors of special susceptibility to low back injury are not existent.

2. Secondary Prevention

(a) Definition: By secondary prevention we refer to the precluding of progression of disease or disability resulting from some pathologic process.

(b) Work and disease acceleration: While the causation of the usual degenerative disease process rarely directly results from occupational exposure, there is sufficient reason to believe that certain work demands may unfavorably influence the course of common degenerative disorders. Thus, the requirement of the brittle diabetic for strict and regular dietary control makes rotating shift work difficult for such an individual. The anxiety, physical and mental strain associated with jobs requiring rapid, weighty decisions or excessive travel may aggravate coronary artery disease. Workers with chronic bronchitis hardly make fit candidates for jobs wherein there exists risks of exposure to pulmonary irritant gases and vapors. Since medical evaluation can detect such individuals, even though medical measures have not prevented the occurrence of such disease processes, exclusion from such risk can prevent acceleration or aggravation of those pathological processes.

(c) Limitations upon secondary prevention: As previously discussed, it is our inability to predict response or understand the inherent nature of many diseases which limits our ability to prevent disease. Similarly, in many cases which factors associated with work or a pathologic process may

accelerate or aggravate such conditions also remain obscure. Furthermore, peculiar to the problem of prevention at the secondary level is the fact that such activity is usually most productive when directed to an early stage of development. Accordingly, effectiveness here depends upon pre-existence indicators of minimal or subliminal disease; unfortunately our abilities in this regard are at present somewhat limited.

Understanding the Patho-physiology of Human Response to Environmental Change

1. Physiological principles

(a) Mechanism of human response: While previously discussed (see Chapter 6) extensively, some mention of the interplay of homeostatic mechanisms should be reviewed. Because the human organism lives within a dynamic ever-changing environment and receives a constant stream of external stimuli, the ability to adapt to such continuous change is a necessity of existence. In effect, this means that the body must be able to change the rate at which various activities were previously occurring.

While physiologically at the whole organ level of organization this is readily perceived, e.g., as a tachycardia in response to running, at the cellular level similar changes in rates of metabolic activities must occur. Similarly as with the previous example, until an optimal new rate which meets the new demand is achieved, activity may overshoot and then compensate by slackening in attempting ultimately to ascertain what the optimum might be. Thus oscillation about an optimum rate, i.e., the eventual new steady state, has been characterized as a "hunting phenomenon." This control system also has an information gathering component which reports all activity changes to control centers; the latter, in response to such information directs the activity to hasten or slacken. In turn, it is receptive to new information which assesses the result of the control center's previous directions. In effect, what we have described is a self-regulating dynamic system.

It should be emphasized that this system can meet new conditions within limits. Essentially, the rate at which it may function has finite limits, i.e., "rate limits," at all levels of biological organization. It is such "rate limits" at the cellular level which determine the response of the body to agents encountered at this level. Among the most prominent at this level of organization are the physical and chemical agents; these rate limits are at the heart of such encounters which constitute the science of toxicology.

2. Toxicologic principles

While these are described in more detail in Chapter 7, review of the dose-response relationship is especially pertinent to the role of medicine in industry. The physician clearly recognizes that the effectiveness of therapeutic agents are a function of the quantity of a medication given as well as the time period over which such agent is administered. However, for unknown reasons the same considerations are not usually applied to non-therapeutic elements, e.g., lead. In short, "poisons" are considered to be "poisonous" regardless of dose and time consideration. Regard-

less of such a viewpoint, the fact remains that the same dynamic principles of dose and time apply to *all* elements or compounds entering the bodily economy. That is, when the organism encounters a material in its internal milieu, as long as too much is not presented over too short a time period, i.e., the body's rate limit for handling such a compound is not exceeded, such a foreign material will have little if any effect. *For most practical purposes, this appears true regardless of the material.* That this must be the case is reflected in the fact that sophisticated analysis will find all 92 original elements in the body. It should, therefore, be apparent that the dose-response relationship (Chapter 7) is basic to an understanding of the effect of "foreign" elements or compounds in the body.

(a) Measurement of response or body loadings

The numerous methods utilized by the body to bind, transport or readily excrete a foreign element have been reviewed in Chapter 7. Thus detoxification mechanisms which depend upon the formation of polar conjugates, e.g., glucuronates, sulfates, also present an opportunity to measure the body's effectiveness in dealing with a chemical. Measurements of such or similar metabolites in various body excreta provide a readily utilized technique to both detect such responses as well as measuring any effectiveness of metabolic handling.

Similarly, certain non-polar solvents, because of their low solubility in blood (essentially an aqueous medium), readily diffuse from the lungs upon cessation of exposure. This too can be measured to gain insights into the amounts which have previously been taken up in the body. Following the breath concentration of such solvents as they leave the lungs over a time course permits even more exact estimates of such body loadings.

Other possible indirect measurements of body loadings may be elucidated by measurements of altered bodily functions induced by such foreign materials. For example, exposure to SO₂ will produce bronchial constriction; the increased airway resistance which ensues can be readily measured and the amount of effect determined.

While this last measurement can be derived from human experimental exposures, at least at relatively low concentrations, other metabolic insights frequently require analysis and extrapolation from animal data.

(b) Extrapolation from animal data

(1) Values

By loading animals with varying concentrations of toxic materials, both the threshold for effect as well as related excretory and metabolic handling rates can be ascertained. Data require the study of multiple species, since some of these animal species may not handle certain agents in a similar fashion as man; nevertheless, where sufficient data are collected such information *may* be applicable to setting levels which are not deleterious as well as determining the rates at which man might safely handle such material (see Chapter 8). By construction of appropriate curves describing lung excretion over time periods, it is possible to estimate from similar curves in exposed workers the quantity of a chemical they have absorbed;

thus the means of estimating risk as well as identifying the absorbed agent, can aid the occupational health team in determining its course of action for both treatment and prevention. That is, this latter end can be achieved since indications of overexposure suggest the failure of established control measures.

(2) Limitations

Unfortunately, the use of animal testing to predict human response has limitations arising from the fact that man is a higher and different mammal from species used for such test purposes. This problem in extrapolation from animals to man is exemplified by the fact that because of metabolic pathway differences, aromatic amines, e.g., beta naphthyl amine, which clearly produce urinary bladder tumors in man, have not such effect in rats, mice or other rodents. Likewise sensitization processes, e.g., to toluene diisocyanates, which occur in man, cannot be reproduced in animals. Accordingly, in view of such extrapolation problems negative results found after animal exposure to toxic chemicals is no guarantee of safety to man. Though this risk may be minimized by testing several different species, the results of such investigations must be applied to man with caution.

Understanding Manufacturing Processes

1 Periodic plant inspection

(a) As with production and management personnel, the physician in industry should be totally aware of everything that occurs in the plant from its roof to sub-basement. In order to place any human aberration in its occupational context he should be familiar with every step of every process in the plant. In order to attain such understanding, it is useful if plant tours be made with technical and production personnel who can explain any ramifications of any process, work station relationships, job requirements, material used or product produced within the plant. This may require an understanding of chemistry, physics or mechanics which such personnel can impart. The physician must be familiar with every job, its title (official or otherwise) and demands in order to visualize it when such are referred to by workers who come to the medical department. Since every industrial plant is a dynamic, organic entity, what occurs within the plant is subject to constant change. Accordingly, such tours should be frequent and regularly repeated.

(b) Plant tours can be of even more value to the physician if carried out with an industrial hygienist. Many of the health ramifications of materials and processes which are unknown to production or other plant technical personnel can be readily recognized and their significance estimated by industrial hygienists. For example, while the safety hazards of Stoddard solvent are self evident, the industrial hygienist should recognize and be prepared to answer the question of how much benzene may be present. Furthermore, by careful use of environmental measurement devices in the plant, he comes to be recognized as having a responsibility for protecting health. Such tours with the industrial hygienist, and especially working tours, serves to demonstrate to employees that

there is a serious team effort directed toward making the work place safe and healthy (see below).

The Position of the Physician in the Management-Labor Relationship

1. The honest broker

The physician, as a staff member of the management group, does not have executive responsibility (except in the medical department) within the plant hierarchy. As any other staff person, he is essentially an advisor, with management having the executive rights and responsibilities for action. Thus management need not heed the advice of any staff member, although if untoward results ensue it is the executive who is held responsible. While it is obvious to much of management that technical advice, e.g., engineering, marketing, etc., should be heeded, this occasionally may not be so apparent to management as regards medical questions. Since the executive is subject to multiple pressures and demands, frequently they may be inclined to "trade-off" long-term requirements to solve "short-term" needs. Thus, it can be seen that while production requirements make immediate demands on management, that on occasions when health or safety requirements might impede production, they might be induced to "short-cut" such inhibitions upon production.

While top management most frequently can see the long-term objective, the daily demands imposed upon middle or lower management more frequently leads them to such "short-term" observations. While this is yet another reason why the medical departments should report at the highest levels, this does not relieve them of the responsibility for vigorously presenting the rationale behind their judgments.

Most assuredly, the position and responsibility of the medical organization is to consistently promote all activities designed to protect employee health and welfare. This reinforces the fact that as a staff individual, given the responsibility for health and welfare, he should take a position based upon only these questions. While such health controls as are required to meet these demands may indeed intrude upon "short-term" production requirements, these latter requirements are clearly *not his responsibility*, and should not intrude upon professional judgments. Thus the medical department should be the "honest broker," always acting upon the basis of health need requirements. While this may make for some short-term problems for management, if such health and safety positions are soundly based they are more profitable for all concerned in the long-run. If such a consistent position is taken by the medical department, the trust of all — management and labor — will follow. If the medical department thus sincerely follows up all health and safety problems brought to their attention by employees, such a position of integrity is further re-inforced. Both the physician and the industrial hygienist have their responsibilities for equitable, fair and consistent evaluations based upon facts, uncolored by either the desires of management or labor.

2. The medical department and the confidence of labor and management — privileged communica-

tions. All information dealing with health and welfare matters should be treated carefully and within the context of a written management policy. Personal medical questions especially should be dealt with as privileged information. Thus the "need to know" should govern how information is handled, e.g., while personal medical details are not necessary for the ends of management, such information should only be made available in terms of management needs and comprehension. Therefore, *detailed* information describing the medical status of any individual is neither needed nor useful to management. The functional ability of a worker in terms of his ability to do a specific job is pertinent and necessary. Similarly the relationship of health hazards to production rather than the intimate medical details of the situation, are required by management.

MEDICAL APPROACHES TO CONTROL OF THE OCCUPATIONAL ENVIRONMENT

Medical Examination Procedure — A Re-Oriented of Medical Practices

The historical examination. While medical practitioners generally have been trained to reflexly think in terms of the diseased patient, in the industrial setting it becomes necessary for him to appreciate that he is dealing in the main with essentially healthy individuals. While the historical examination of any person should consider him in terms of deviation from normal, it is also important to evaluate the worker in terms of his functional, total health status. Accordingly, it becomes appropriate to carry out the medical history by use of self completion questionnaire. Thus, not only is greatest economy of physician time and cost achieved, it is possible for him to readily obtain an entire health inventory. This is in contrast to the usual situation wherein an individual consults a physician because of some health complaint, and the historical examination becomes oriented to elaboration of some specific pathologic process, affecting a specific organ system.

The physical examination. The same principle as elaborated above applies here also. Thus, investigations directed toward the whole person rather than toward a single organ system directs the physical examination. It should, therefore, be obvious that in dealing with the relatively HEALTHY person the physical examination should take another form. For example, in a cost-yield basis the relative cost of percussion and auscultation of the chests of large numbers of individuals is high in terms of the information obtained. Thus, for large numbers of persons it becomes less costly, for example, to obtain a chest X ray and a timed vital capacity determination rather than to laboriously perform a chest examination. This is especially true since essentially the same information is obtained. Thus any deviations obtained by such a "screening examination" can be followed up by the usual more elaborate examination procedures. Certainly, in view of the relatively few deviations expected in an essentially healthy population, such procedure has its obvious cost-effectiveness savings and yields.

Much of the physical as well as historical ex-

amination can be performed by paramedical personnel. With the rapid development of medical-electronic investigative techniques, increasingly more of the examination can be achieved by these means.

Use of the clinical laboratory for examination of ostensibly normal individuals. Our increasing capability to inexpensively and rapidly carry out clinical laboratory tests makes use of such determinations ever more fruitful. As automated laboratory procedures develop, the per unit cost decreases. In this fashion, a complete health profile can be more adequately and rapidly achieved. Problems arising out of the work environment may cause changes which can be detected by tests, such as multiphasic examination (i.e., medical, laboratory). This profile provides a useful baseline which aids in the detection of any possible subsequent health deviations. Should any physical or chemical agent produce health change, a health profile previously obtained has obvious comparison values for use in the control of health hazards.

Where small numbers of workers are involved, consideration should be given to the purchase of multiphasic laboratory services. The cost per worker for such services in this case will be far less expensive than the cost of setting up a laboratory. Accordingly, medical services for small plants should seriously investigate contract proposals and performance of such commercial laboratories.

The Pre-Placement and Pre-Employment Examination

Philosophy and Purposes. The basic purpose of the pre-placement examination is to determine the capability of the job applicant to perform a specific job for which he is to be hired. Thus such an evaluation is directed toward *capabilities, not disabilities*. While not all employees necessarily require testing of color perception, such evaluations become highly pertinent for workers for jobs requiring this adequacy; e.g., in color printing, color-coded electrical wiring, etc. While this theory applies in part, in reality many corporations recognize the point that they accept the *whole worker* with all his immediate health problems and possibly his long-term medical problems. This becomes especially pertinent as more and more of health and medical benefit costs are assumed through employer purchased health insurance. Accordingly, pre-placement examinations increasingly have become pre-employment examinations, so that total health evaluation becomes increasingly the rule.

Nevertheless, there is still required an evaluation of physical and psychological capabilities to perform a specific range of jobs. It therefore becomes necessary for the medical department to determine that a prospective employee does not have a pre-existing health problem that can be aggravated by his expected range of work duties. What has been previously stated regarding the use of electronic medical modalities and paramedical personnel applies equally here. However, it still remains the responsibility of the occupational health team to be fully cognizant of the job requirements and work environment so as to design

an appropriate examination regimen. This once more underlines the necessity for the occupational health group to be comprehensively knowledgeable concerning any and all jobs, their peculiarities or needs within the plant.

Values and limitations. While fitting the right man in the right job is the aim of these examinations, the limitations inherent in this procedure must be recognized. These largely stem from the limitations inherent in medical prognostication of special susceptibility or inherent biological risk. The inability to clearly determine which individual possesses an inherent weakness of the lower back immediately comes to mind. Certainly the present inability to clearly evaluate the state of psychological fitness of an individual to fit into a specific social and physical environment presents even more serious problems. Recognizing these inherent weaknesses makes even more apparent the need for periodic re-evaluation of workers.

Job restrictions and transmission of information to management. Once more, the executive is primarily interested in being informed of the job applicant's ability to do a job. Accordingly, all *medical information* derived from such examinations *should remain privileged information*, inaccessible to all but medical personnel. Management should be fully informed of job abilities; *why* limitations are necessary in terms of specific *medical* diagnoses is neither necessary to his needs nor pertinent. Management should be kept informed *through established channels* (usually through the personnel departments) largely in terms of fitness to do a certain job. If medical conditions require job limitations or restrictions, such restrictions upon activities should be clearly and simply stated; the medical details as to "why" should not be divulged.

The purpose of these job restrictions is to prevent deleterious effects upon the employee's health. Since each person undergoes dynamic changes with time, the medical department has a responsibility for following and re-evaluating the appropriateness of such restrictions as time passes. As regards the need for follow-up of individuals placed under job restrictions, plant tours will also serve to determine whether the persons with restrictions are performing in appropriate jobs. As for re-evaluation, this too requires periodic re-examination to determine the current appropriateness of work restrictions previously applied.

The Periodic Health Examination

Philosophy and purposes. As related to the working environment, present limitations in our knowledge of human response to environmental changes requires that the periodic re-evaluation of exposed workers be performed. Thus, early detection of health changes becomes the primary orientation of this examination. In addition, because of the inexorable course of aging, those responsible for health protection need detect such changes so that work conditions do not accelerate or aggravate the aging process.

Method of execution. General health maintenance: Too often the pathology oriented physician seeks only to elucidate the presence of disease. How-

ever, equally important is a careful evaluation of the individual's hygiene of living. Due consideration should be directed toward elaboration of life habits, e.g., smoking, diet, social interactions and mental health, sleep patterns, etc. Out of such a matrix of life habits and styles emerges a picture of the whole man, and the effects of his life style upon health and well being. While inquiry into medical status is appropriate and accepted, the physician in industry must carefully direct such evaluation of a personal nature along the same lines of action of the medical practitioner whose appropriate concern is the whole man. Only insofar as he is recognized as being *primarily* concerned with the employee's well being, this approach is proper. Otherwise, this all-encompassing approach may represent an encroachment by the employer upon a realm of employee's personal life which is wholly inappropriate. Obviously, the methods employed in these examinations should be consistent with the cost-yield considerations noted above.

Examination of workers exposed to occupational risk. Such examinations should be oriented toward medical and health evaluation procedures which delineate human responses to special environments. For example, workers handling defatting solvents should be carefully examined to determine that dermatoses do not ensue. Other examples of special occupational risks, e.g., potentially hepatotoxic solvent, pulmonary irritants, etc., will determine which clinical and laboratory examinations are required. Again, the health protection team must be completely familiar with the risk potentials of *all* jobs in the plant so as to intelligently design such examinations.

Since engineering controls may fail or personal protective devices may be inadequately utilized, such examinations of workers at special risk should be *regularly and periodically* carried out. Record and scheduling systems should be so designed that these examinations are not missed and so that the information gathered can be rapidly and rationally reviewed. This requires both careful organizational efforts and design of medical records.

Sources of information regarding occupational risks. The clinical literature in occupational medicine and industrial hygiene is a rich mine of information. Herein will usually be found, to varying degrees of adequacy, much information regarding human response to environmental agents. In addition, the literature concerning experimental investigation of these special risks also becomes essential (see suggested readings).

However, the occupational health team should be aware of the shortcomings inherent in that body of information. Newly encountered occupational chemicals may be associated with little available data concerning *clinical* effects. However, the experimental literature can contribute to an understanding of risk potentials. For example, while there is little clinical data concerning N-dimethylnitrosoamines, the experimental literature extensively documents that agent's potential for carcinogenesis in animals. Accordingly, that agent should be treated as a potential carcinogen in the work

place, despite an absence of such recorded effects on man.

The problems of extrapolation of data derived from animal experiments to man are self evident (see Chapter 7). Therefore, the experimental literature while potentially useful for health control requires that it be used with appropriate care. This makes even more important the need for careful periodic clinical evaluation being performed with due consideration of such animal data.

Other Examinations

Separation Examinations. If a worker has been exposed to some occupational hazard and is to be separated from employment, it is the employer's responsibility to ascertain his health status before such an event. While the legal responsibility of the employer ends only in part with discharge, any subsequent change may represent an aggravation or progression of a disease state incurred while at work. If a later status represents disease progression caused by work, the employer should be made aware of his legal and moral responsibility. If his future condition is unrelated to a work incurred condition, then equity demands that this ascertainment also be made.

It should be apparent that the role of the medical department is to accumulate and evaluate all health information so that the best medical opinion can be clearly and equitably applied to the matter in question.

THE ROLE OF THERAPY IN OCCUPATIONAL MEDICINE

For Occupational Disease

The Occupational Medical Practitioner as a Specialist. In the treatment of occupational disease of a non-surgical nature, the occupational medical practitioner should be prepared to provide definitive therapy. Certainly, in the area of clinical toxicology, such physicians more frequently encounter these problems, e.g., as in chemical plants, than do their fellow practitioners. Thus all ramifications (diagnosis, treatment and management) should be clearly within his competence. Should such medical problems arise, the occupational health specialist should be prepared to assume responsibility for all such cases, making use of appropriate medical or surgical consultants as the patient's complications may require.

The Use of Consultants

(1) Principles governing choice

Since the occupational medical specialist should know more about occupational diseases and the conditions of the work place, it follows that he should assume responsibility for medical management and direction of such occupationally caused problems. However, as noted above, should complications involving special organ systems arise, e.g., cardiovascular, respiratory, etc., it is appropriate that such specialists be consulted. Nevertheless, except for unusual reasons the responsibility should remain in the occupational medical specialist's hands. A close working relationship with such specialists should be developed in each case, as such physicians are invariably

non-cognizant of in-plant conditions or the effects of toxic or physical agents. While it becomes the occupational medical specialist's responsibility to cooperatively aid the outside specialist in becoming aware of those problems, the latter should not nevertheless abandon his primary responsibility.

In one case of surgical problems, it is axiomatic that the best specialist help is the least expensive in the long-term prospect as well as being the most effective. While full responsibility for surgical treatment and management should be in such specialist's hands, the occupational medical specialist still has an important role to play. Again, since he is the most knowledgeable regarding work requirements or opportunities for less demanding tasks, he is in the best position to guide the rehabilitation of the injured worker during the recovery phase. Close cooperation with physicians, utilizing both extra- and intra-mural (i.e., plant) facilities can lead to the most effective programs of rehabilitative therapy.

(2) Limitations

It should be pointed out that in many, if not most, jurisdictions the worker has the final and definitive choice of who should treat his occupational disease or injury. Thus, the occupational medical specialist must observe this legal right. However, if the work force has confidence in the medical capabilities and the probity of the plant physician, most often the worker will accept his ministrations. However, should he decide otherwise, the plant physician has an ethical responsibility for cooperating with and aiding the management of the outside physician.

Therapy of Non-Occupational Disease

Stated Positions. It has been the position of organized medicine that plant medical departments should not become involved in the treatment of non-work conditions. The only qualification of this position is related to treatment of minor conditions, e.g., headache, indigestion, of a non-recurring nature for which the patient would not ordinarily seek medical help. Except for making it medically possible for the worker to safely finish his work-shift, he was to refer other medical problems to the private practitioner.

Trends in Occupational Medicine Regarding Management of Non-Occupational Conditions. Because of increased medical care utilization, rising health expectations and modes of medical practice, the availability of primary medical care has become somewhat diminished. Accordingly, strict application of the foregoing principles have been tempered by present realities. Especially in areas where medical care resources are limited, the plant physician is seen as providing a scarce capability. As health care delivery systems become integrated, it would appear that the occupational health specialist will play a more active role within such systems.

In addition, since the employer assumes increasingly more financial responsibility for general medical care, he demands that medical care utilization become optimized. All of these forces cannot but help affect the present and future patterns of occupational health practice. While the form

such activity will take is unclear, given the present dynamism of this system, changes in such patterns of care are and will be occurring.

OPPORTUNITIES FOR RESEARCH IN THE PRACTICE OF OCCUPATIONAL HEALTH

Research in the Natural History of Disease. Use of Medical Records. At present, medical records in industry are largely oriented toward providing a data base for the several immediate responsibilities of the medical department. They are primarily directed toward providing the medical information necessary to adequate management of medical conditions. Except where they also provide health base lines needed for estimation of alteration due to environmental factors encountered in the work place or because of periodic health evaluation program needs, they are frequently ill-suited for long-range assessments.

In the past such records consisted of hand entries into medical forms. As such, ready assessments of large populations could not be achieved. Until the development of electronic tape and disc data storage systems, existent record systems inhibited worker-population studies. However, it is becoming increasingly possible to store and readily retrieve discrete data "bits" involving large numbers of workers. As such capabilities become increasingly more available, it should be possible to more readily use the masses of industrial health data presently unavailable. Given these capabilities, invaluable opportunities for the development of new medical knowledge will present themselves. Because working populations represent a useful cross-section of the active, non-hospitalized, the opportunity for delineation of the long-term, natural history of disease arises. In addition, study of the long-term effects of environmental stresses upon health should be accessible.

As an example of the former type information, industrial populations have been useful in developing new insights upon the effects of diabetes, hypertension and cardiovascular disease on long-term health status and productivity. Because such non-hospitalized populations can be studied, the misapprehensions derived from biased populations investigated in hospitals are avoided.

Elucidation of the Effects of Environmental Pollution upon Health

The Work Population as an Exposed Population. Because occupational exposures usually are more intensive than that incurred by the general population, working groups represent ideal study groups for the evaluation of such environmental effects. Relatively higher doses of common environmental pollutants (e.g., CO, SO₂) encountered in industry should, theoretically, accelerate the rate of development of deleterious health effects, if any, as compared to the rate of development possible because of lower doses in the community. Coupled with the advantage of the possibility of long-term observations is the fact that large numbers of exposed groups are concentrated in one area. Given adequate record systems the opportunities for epidemiological investigation are unparalleled.

The Use and Limitations of the Epidemiologic Method. The epidemiologic method depends upon

the systematic collection of information which makes possible the comparison of one population's behavior with that of another similar group. Thus one assumes that the variables determining, e.g., health status, are completely similar in all regards except for a specific variable acting on only one of these two groups.

Obviously, as many of these variables are operating upon *both* groups they must be defined, since *assumptions* of such comparability in all regards (except for the one under scrutiny in the group at risk) are unacceptable. Thus, data collection involves large numbers of variables, e.g., age, sex, activity and residence. These must be adjusted for in both groups. The use of industrial populations in this connection given adequate data collection, should be obvious. Especially pertinent is the opportunity for construction of a control group derived from a working population in order to estimate health or mortality experience. Such comparison groups are essentially the only group with which a working population at a special environmental risk can be compared.

Nevertheless, the use of industrial populations for delineation of occupational health risks presents some attendant problems. One of these relates to assessment of exposure to a risk, since frequent in-plant job turnover may make tracing individual work or exposure experience difficult, especially in certain occupations, e.g., chemical operations. In addition, workers who are no longer on the rolls are a source of loss to a population of some consequence. This follows since they may have left employment because of incurring the health consequence under study. While conclu-

sions indicating a *positive* association between work and some condition might only lead, at worst, to underestimation of risk, the significance of absence of an association becomes severely compromised because of such losses. This points up the obvious need for careful, painstaking follow-up of those separated from the groups under study. However, *carefully* performed multi-corporation or industry-wide studies, e.g., of mortality, have succeeded in providing valuable medical knowledge.¹ Studies of morbidity have been less satisfactory, yet present a considerable potential source of valuable medical information.

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SEPARATIONS PROCESSES IN ANALYTICAL CHEMISTRY*Henry Freiser, Ph.D.***INTRODUCTION**

Industrial hygiene chemistry is an extremely demanding branch of analytical chemistry. Whereas many areas of applied chemical analysis are self-limiting, e.g., gas, mineral or metallurgical analyses, the field of industrial hygiene chemistry covers the tremendous breadth of the thousands of chemical substances encountered in man's working environment. This complexity is compounded further by the need to separate, characterize and determine quantitatively trace quantities of these organic and inorganic substances in the presence of overwhelming quantities of bulk materials containing chemical interferences. The successful application of *all* modern physical and chemical methods of analysis to the detection and determination of these individual chemical entities requires in many instances, the preliminary separation and concentration of an analytically desired constituent from the bulk diluents and interfering elements present in biological tissues and fluids, complex mixtures of aerosols or industrial process materials and finished products. The daily solution of these problems requires a full understanding of the basic principles of the separation processes which must be applied to these sample systems to obtain the accurate analytical data needed for the valid and complete assessment of environmental conditions and their effects on the health of the worker.

This chapter provides a basic theoretical treatment of two of the most powerful techniques used in inorganic separations; i.e., solvent extraction and ion exchange chromatography. These methods have provided the foundation of numerous analytical procedures used in the industrial hygiene laboratory. The solvent extraction technique has been used widely for rapid, clean-cut separations of trace level quantities of analytically desired elements and compounds (dithionates, dithiocarbamates and 8-quinolinates of the heavy metals, phenolic compounds and ferric chloride, as examples) from biological and environmental sample materials. Ion exchange chromatography has proved to be extremely valuable in separating fractional part per million concentrations of interfering chemical elements from one another to increase the specificity, accuracy and sensitivity of their final method of estimation in diverse industrial hygiene samples.

CLASSIFICATION OF SEPARATION PROCESSES

Although great strides have been made in the development of highly selective analytical methods, the analytical chemist is called upon to deal

with samples that are increasingly complex. As a result, inclusion of separation steps might be necessary even with highly discriminatory instrumental methods such as neutron activation or atomic absorption analysis. Furthermore, separation of a component of interest from the sample medium may also serve to concentrate it, which would effectively increase the sensitivity of the analytical method ultimately employed.

One of the most powerful approaches to separations involves using pairs of phases in which the component of interest transfers from one to the other in a manner that differentiates it from interferences. It is useful to classify phase separation processes according to (a) the state of the phase pair involved (solid, liquid or gas), (b) whether the phase is in bulk or spread thin as on a surface and (c) the means of contacting the phase pair: (i) batch, (ii) multistage (iii) countercurrent.

Bulk and "thin" phases can be distinguished in that by the latter is meant a spreading of the phase involved over a relatively large surface area. Thus, both distillation and gas-liquid chromatography (GLC) are separations involving gas-liquid phase pairs but in the latter, the liquid phase is spread out as a thin layer on a largely inert solid supporting material. Similarly, solvent extraction and liquid partition chromatography (either paper or column) involve a liquid-liquid phase pair but in the latter, one of the liquid phases is present as a supported thin layer. In these two examples cited, the mode of contacting the phases can also be different. In a simple distillation process, a batch of the mixture is placed in the boiler and the distillate contains the more volatile components. In contrast, with GLC, the gas mixture moves countercurrently to the immobilized liquid layer ensuring that the increasingly depleted mobile gas phase encounters a fresh clean portion of the immobilized liquid phase. In countercurrent processes, a large number of equilibration (or approximate equilibration) steps occur. It is possible to carry out separations involving bulk phase pairs with countercurrent contacting. Thus, fractional distillation, in which a packed distillation column and reflux head are used, involves countercurrent contacting.

This chapter is devoted to the description of the principles and practices of two-phase separation processes, solvent extraction and ion exchange, which are important in dealing with complex aqueous mixtures. Elsewhere in this syllabus (Chapter 21) several forms of chromatography are also covered.

SOLVENT EXTRACTION

General Principles and Terminology

Solvent extraction is a process in which a solute of interest transfers from one solvent into a second which is essentially immiscible with the first. Because the extent of such transfer for various solutes can be varied individually from negligible to essentially total extraction, through control of the experimental conditions this process provides the basis for many excellent separations.

Fundamentally, all solvent extraction procedures can be described in terms of three aspects, or steps:

First, the distribution of the solute, called the extractable complex or species, between the two immiscible solvents. This step can be described quantitatively by Nernst's Distribution Law which states: The ratio of the concentrations of a solute distributing between two essentially immiscible solvents at constant temperatures is a constant, provided that the solute is not involved in chemical interactions in either solvent phase, or

$$K_{D_A} = \frac{[A]_o}{[A]} \quad (1)$$

where A is a solute distributing between an organic solvent in which the molar concentration of A is expressed as $[A]_o$ and an aqueous phase as A without subscript. The constant K_D is called the *distribution constant*.

Second, chemical transformations to produce an extractable species are of primary importance in solvent extraction processes inasmuch as most of the substances of interest, particularly metal ions, are not usually encountered in a form that can be extracted into an organic solvent. This second aspect of extraction concerns the chemical interactions in the aqueous phase or formation of the extractable complex.

Third, chemical interactions in the organic phase may be necessary, such as self-association or mixed ligand complex formation. Such chemical interactions do not negate the validity of the Nernst distribution law, but obviously the extraction cannot be described quantitatively by such a simple equation. For this purpose it is necessary to know how each of the contributing reactions affects the extent of extraction and this is discussed in the following sections.

The extent of extraction may be described in terms of the *distribution ratio* as follows:

$$D_A = \frac{C_{A(o)}}{C_A} \quad (2)$$

where D is the distribution ratio, $C_{A(o)}$ and C_A correspond to the total analytical concentration of component A in whatever form it is present in the organic (o) and aqueous (A) phase, respectively. If the substance does not enter any chemical reactions in either phase, then D_A reduces to K_{D_A} . (K = distribution constant)

Another important way of expressing extent of extraction is by the *Fraction Extracted*

$$F_A = \frac{C_{A(o)} V_o}{C_{A(o)} V_o + C_A V} = \frac{D_A R_V}{D_A R_V + 1} \quad (3)$$

where F = fraction extracted, V_o and V are the respective volumes of the organic (o) and aqueous

phases, R_V is the phase volume ratio, V_o/V (others as in equation 2). The *percentage extraction* is simply 100F.

Equation (3) demonstrates the possibility of increasing the extent of extraction with a given D value by increasing the phase volume ratio. If instead of a single batch extraction, a second or third extraction is carried out on the same aqueous solution by successive portions of organic solvent such that R_V remains the same, the additional fractions extracted are $F(1-F)$ and $F(1-F)^2$, respectively. The fractions remaining in the aqueous phase following n successive extractions is $(1-F)^{n-1}$.

Separation Factor:

If two substances A and B are present in a solution in an initial concentration ratio, C_A/C_B , then upon extraction their concentration ratio in the organic phase would be $C_A F_A / C_B F_B$, where F_A and F_B are the corresponding fractions extracted. The ratio F_A/F_B , which is the factor by which the initial concentration ratio is changed by the separation, is a measure of separation. A corollary measure of separation which represents the change in the ratio of concentrations remaining in the aqueous phase is $(1-F_A)/(1-F_B)$.

Two substances whose distribution ratios differ by a constant factor will be separated most efficiently if the product, $D_A D_B$, is unity. As an illustration of this principle, consider the case of a pair of substances whose distribution ratios are 10^3 and 10^1 respectively. If these substances were present in equal quantity, then a single extraction would remove 99.9% of the first and 90% of the second. A much more efficient extraction would be obtainable if, using the same factor of 100 between the distribution ratios, the two distribution ratios were 10^{+1} and 10^{-1} . In this case respective fractions extracted would be 90% and 10%.

Classification of Extraction Systems

The following classification refers essentially to inorganic systems, particularly those involving metal ions. There are, of course, many organic compounds which are extracted without any significant chemical reaction such as alcohols, ethers and carboxyl compounds. Systematic changes in the extraction of such compounds by various solvents can be related to molecular weight, hydrogen bonding and less specific interactions.

Chemical reactions are at the very heart of metal ion extractions. Most metal salts are soluble in water, but not in organic solvents, particularly of the hydrocarbon and chlorinated hydrocarbon types. This results not only from the high dielectric constant of water but, more importantly, from its ability to coordinate with the ions, especially the metal ion, so that the hydrated salt more nearly resembles the solvent. To form an extractable metal complex it is necessary to replace the coordinated water from around the metal ion by groups, or ligands, that will form an uncharged species that will be compatible with a low dielectric constant organic solvent.

Formation of an extractable metal species can be accomplished in a great variety of ways which makes a classification of extractions based on this very useful, particularly as a guide to the under-

standing of the thousands of different extractions systems now in use.

The formation of an uncharged species that is extractable by the relatively non-polar organic solvent can involve

1. Simple (monodentate) coordination alone, as with GeCl_4 ,
2. Heteropoly acids, a class of coordination complexes in which the central ion is complex rather than monatomic, as with phosphomolybdic acid, $\text{H}_3\text{PO}_4 \cdot 12\text{MoO}_3$,
3. Chelation (polydentate coordination) alone, as with Al (8-quinolinolate)₃,
4. Ion-association alone, as with Cs^+ , $(\text{C}_6\text{H}_5)_4\text{B}^-$ or
5. Combinations of the above, such as:
 - a. Simple coordination and ion-association — e.g., (“Onium”⁺), FeCl_4^- , [“Onium” stands for one of the following cation types, hydrated hydronium ion, $(\text{H}_3\text{O})_3\text{O}^+$, a rather labile cation requiring stabilization by solvation with an oxygen-containing solvent, a substituted ammonium ion, $\text{R}_n\text{NH}^+_{(4-n)}$ where R is an alkyl or aralkyl group and N may vary from 1 to 3, a sub-

stituted phosphonium ion R_4P^+ , stibonium ion R_4Sb^+ , sulfonium ion and other ions of this sort, including the important category of cationic dyes such as Rhodamine B].

- b. Chelation and ion-association with either positively or negatively charged metal chelates — e.g., $\text{Cu}(2,9\text{-dimethyl-1,10-phenanthroline})_2^+ \cdot \text{ClO}_4^-$ or 3 ($n\text{-C}_4\text{H}_9\text{NH}_3^+$) Co (Nitroso R Salt)₃⁻³ — and, finally,
- c. Simple coordination and chelation — e.g., $\text{Zn}(\text{oxinate})_2 \cdot \text{pyridine}$. This category is of significance for chelates that are coordinatively unsaturated — i.e., those with a monoprotic bidentate reagent in which the coordination number of the metal is greater than twice its valence.

An examination of the foregoing material and of Table 18-1 serves to underline the close relationship between inorganic and analytical chemistry employed in the principles and practice of metal extraction systems. A thorough understanding of analytical solvent extraction of metals requires a deep appreciation of many branches of coordination chemistry.

Table 18-1 Metal Extraction Systems
PRIMARY SYSTEMS

I. Simple (Monodentate) Coordination Systems

1. Certain halide systems — e.g., HgCl_2 , GeCl_4
2. Certain nitrate systems — e.g., $(\text{UO}_2^+)(\text{TBP})_2(\text{NO}_3^-)_2$

II. Heteropoly Acid Systems — e.g., $\text{H}_3\text{PO}_4 \cdot 12\text{MoO}_3$

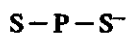
III. Chelate Systems

A. Bidentate chelating agents

a) 4-Membered ring systems

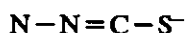
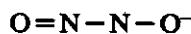
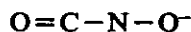
1. Disubstituted dithiocarbamates — e.g., Na^+ , $(\text{C}_2\text{H}_5)_2\text{NCSS}^-$ or $(\text{C}_6\text{H}_5\text{CH}_2)_2\text{NCSS}^-$ Xanthates — e.g., Na^+ , $\text{C}_2\text{H}_5\text{OCSS}^-$
2. Dithiophosphoric acids — e.g., diethyldithiophosphoric acid
3. Arsinic and arsonic acids — e.g., benzenearsonic acid

Reactive Grouping



b) 5-Membered ring systems

1. *N*-Acyl hydroxylamines — e.g., *N*-benzoylphenylhydroxylamine (BPHA) or benzohydroxamic acid
2. *N*-nitroso-*N*-arylhydroxylamines — e.g., Cupferron, (*N*-nitrosophenyl-hydroxylamine) or neocupferron, (*N*-nitrosophthalhydroxylamine)
3. α -Dioximes — e.g., Dimethylgloxime, cyclohexane-dionedioxime (Nioxime)
4. Diaryldithiocarbazonates — e.g., Dithizone, (diphenyldithiocarbazonate)
5. 8-Quinolinols — e.g., Oxine, (8-quinolinol), Methyloxine, (2-methyl-8-quinolinol)



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6. Quinoline-S-thiols, dithioamides — e.g., thio-oxine, (quinoline-8-thiol) N, N'-didodecylthiooxamide $N=C-C-S^-$
7. Quinoline-S-selenol $N=C-C-Se^-$
8. O-Dihydroxybenzenes — e.g., catechol, phenylfluorone, rhodizonic acid $\text{^-}O-C=C-O\text{^-}$
9. o-Dimercaptobenzenes — e.g., toluene-3, 4-dithiol $\text{^-}S-C=C-S\text{^-}$
10. Thionalid (thioglycolic- β -aminophthalide) $O-C-C-S\text{^-}$

c) 6-Membered ring systems

1. β -Diketones — e.g., Acetylacetone, TTA (thenoyltrifluoroacetone) dibenzoyl ethane, Morin, quercetin, quinalizarin $O=C-C=C-O\text{^-}$
2. o-Nitrosophenols — e.g., 1-nitroso-2-naphthol $O=N-C=C-O\text{^-}$
3. o-Hydroxyloximes — e.g., salicyladoxime $N=C-C=C-O\text{^-}$

d) Larger ring systems

1. Mono or dialkyl-phosphoric or -phosphonic acids $O=P-OHO=P-O\text{^-}$

B. Polydentate chelating systems

1. Pyridylazonaphthol (PAN) and pyridylazoresorcinol (PAR) $N=C-N=N-C=C-O\text{^-}$
2. o, o' Dihydroxyazobenzenes — e.g., 2, 2'-dihydroxy-5'-isopropyl 1-4-methyl-4-nitroazobenzene $O-C=C-N=N-C=C-O\text{^-}$
3. N, N'-(Disalicylidene) ethylenediimine (also S analog) $\text{^-}O-C=C-N=C-C=N-C=C-O\text{^-}$
4. Glyoxal bis(2-hydroxyanil) (also S analog) $\text{^-}O-C=C-N=C-C=N-C=C-O\text{^-}$

IV. Simple Ion Association Systems

A. Metal in cation

1. Inorganic anions — e.g., Cs^+ , I_3^- or PF_6^-
2. Tetraphenylboride anion
3. Dipicrylamine anion
4. Alkylphenolate anion
5. Carboxylate and perfluorocarboxylate anions

MIXED SYSTEMS

V. Ion Association and Simple Coordination Systems

A. Metal in cation

1. Oxygen solvents — e.g., alcohols, ketones, esters, ethers — e.g., $[(UO_2)(ROH)_6]^{+2}$, $2NO_3^-$
2. Neutral phosphorus compounds, phosphates, phosphonates, phosphinates, phosphine oxides, and sulfides

B. Metal in anion (paired with "onium" ion)

1. Halides — e.g., $FeCl_4^-$
2. Thiocyanates — e.g., $Co(CNS)_4^{-2}$
3. Oxyanions — e.g., MnO_4^-

VI. Ion Association and Chelation Systems

A. Cationic chelates

1. Phenanthrolines and polypyridyls — e.g., $Cu(I)$ (2, 9-dimethylphenanthroline) $_2^+$
2. Tetraalkyl methylenediphosphonates — e.g., $(RO)_2P-CH_2-P(OR)_2$

B. Anionic chelates

1. Sulfonated chelating agents

- 1-Nitroso-2-naphthol — e.g., Co (III) (nitroso R salt)₂⁻²
- 8-Quinolinol — e.g., Fe(III) (7-iodo 8-quinolinol-5 sulfonate)₂⁻²

VII. Chelation and Simple Coordination Systems — e.g., Th(TTA)₄ · TBP, Ca (TTA)₂ · (TOPO)₂

GENERAL EXPERIMENTAL TECHNIQUES

Methods of Extraction:

(1) Batch Extraction

When experimental conditions can be adjusted so that the fraction extracted is 0.99 or higher ($DR_v > 100$) then a single or batch extraction suffices to transfer the bulk of the desired sub-

stance to the organic phase. Most situations in analytical extraction fall into this category. The usual apparatus for a batch extraction is a separatory funnel such as the Squibb pear-shaped type. (For additional special types of funnels see reference (1).)

Even when the DR_v of the desired substance is as low as 10, carrying out batch extraction twice will transfer 99% of the material to the organic phase.

If one chooses as a desirable criterion of separation of a pair of substances that one be at least 99% extracted and the other no more than 1%, then it can be seen that $D_1 R_v > 100$ and $D_2 R_v < 0.01$.

(2) Continuous Extraction

For substances whose DR_v values are relatively small, even multiple batch extraction cannot conveniently or economically (too much organic solvent required) be used. Continuous extraction using volatile solvents can be carried out in an apparatus in which the solvent distilled from an extract collection flask is condensed, contacted with the aqueous phase and returned continuously to the extract collection flask. Continuous extraction apparatus for solvents that may be either heavier or lighter than water is shown in Figures 18-1 and 18-2.

(3) Countercurrent Distribution (CCD)

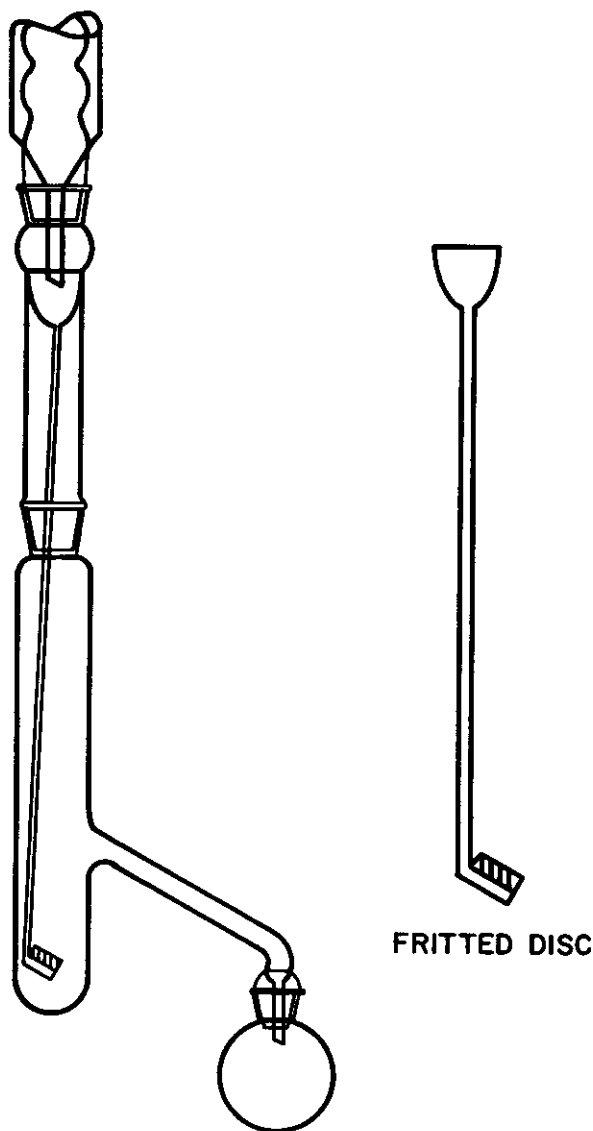
A special multiple-contact extraction is needed to bring about separation of two substances whose D values are very similar even under optimum conditions. In principle, countercurrent distribution could be carried out in a series of separatory funnels, each containing an identical lower phase. The mixture is introduced into the first portion of upper phase in the first funnel. After equilibration, the upper phase is transferred to the second funnel and a new portion of upper phase (devoid of sample) is introduced into the first funnel. After both funnels are equilibrated the upper phase of each is moved on to the next funnel and a fresh portion of upper phase is again added to the first funnel. This process is repeated as many times as necessary collecting the upper phases as "elution fractions."

With automated CCD equipment several hundred transfers can be accomplished conveniently which permit the separation of two solutes whose D_1/D_2 is less than two.

The relation of the distribution ratio, D , of a solute in a CCD process to the concentration in the various separatory funnels or stages can be shown to be given by the binomial expansion:

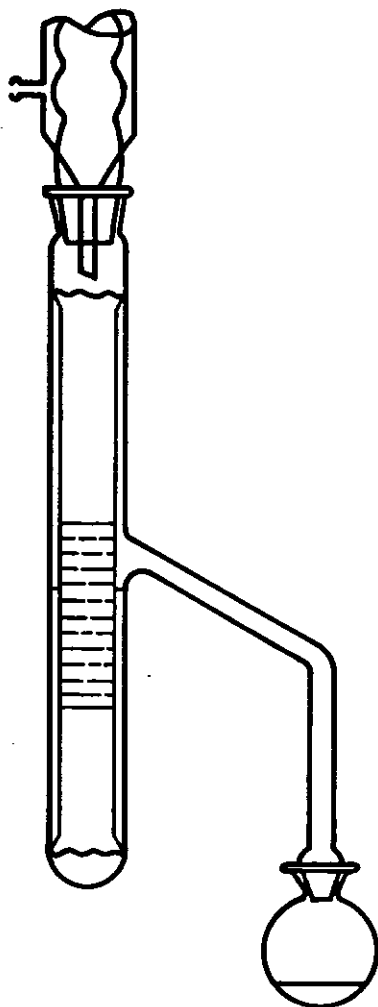
$$[F + (1-F)]^n = 1 \quad (4)$$

where F , the fraction extracted, is $DR_v / 1 + DR_v$, as shown in (3), and n is the number of stages in the CCD process.



Morrison GH, Freiser H: Solvent Extraction in Analytic Chemistry. New York, John Wiley & Sons, 1957, p. 23.

Figure 18-1. Continuous Extractor for Use with a Solvent Lighter Than Water.



Morrison GH, Freiser H: Solvent Extraction in Analytical Chemistry. New York, John Wiley & Sons, 1957, p. 23.

Figure 18-2. Continuous Extractor for Use with a Solvent Heavier Than Water

The fraction $T_{n,r}$ of the solute present in the r th stage for n transfers can be calculated from

$$T = \frac{n!}{r!(n-r)!} \frac{(DR_v)^r}{(1+DR_v)^n} \quad (5)$$

A modification of CCD useful for laboratory purposes involves the use of a small number of separatory funnels (e.g., three) together with a larger number of transfers of upper phase portions (e.g., eight) and collecting the first upper phase portions as the product fraction. This means it would be possible to separate quantitatively a substance with a D of 10 from one whose D is 0.1.

Experimental Techniques:

(1) Introduction

Selection of a particular extraction method from the large number of methods available involves consideration of the behavior of interferences that might be present as well as that of the substance of interest. Another factor of importance is the means to be employed in the analytical determination of the species in question.

Some of the chelate systems, e.g., dithizone, are colored sufficiently to provide the basis of a spectrophotometric determination. If the extract is to be aspirated into the flame of an atomic absorption apparatus, however, a dithizone solution would not be as desirable as a non-benzenoid reagent because of its behavior in the flame.

The problem is simplified greatly by the existence of abundant literature which permits the selection of a method on the basis of similarity or even matching of separation problems. Although even those experienced in extraction methods generally proceed in a new problem by following published precedents, a better understanding of the design of an extraction procedure can benefit from the careful study upon which previous work is based.

(2) Choice of Solvent

Solvents differ in polarity, density and ability to participate in complex formation. Generally it is more convenient to use a solvent denser than water when the element of interest is being extracted and a less dense solvent when interferences are extracted away from the element of interest.

Ion association complexes in which one of the ions is strongly solvated, such as the hydrated hydronium ion, $O(H_2O)_3^+$, as in the extraction of chloride complexes from HCl solutions (e.g., H^+ , $FeCl_4^-$), can be extracted most effectively with oxygen-containing solvents such as alcohols, esters, ketones and ethers. Similarly, with coordinatively unsaturated chelates; i.e., in which the coordination number of the metal ion is greater than twice its oxidation state, such as $ZnOx_2$ (where Ox refers to the 8-hydroxyquinolate anion), use of an oxygen-containing solvent will increase extractability significantly over that obtainable with hydrocarbon and chlorinated hydrocarbons.

On the other hand, ion association complexes involving quaternary ammonium, phosphonium or arsonium ions, and chelates that are saturated coordinatively may be readily extracted in hydrocarbons as well as in oxygenated solvents. In such cases, the principle of "like dissolves like," as expressed by the Hildebrand "solubility parameter," δ , (defined as the heat of vaporization of one cc of a liquid) offers a guide to extractability. Simply expressed, in the absence of specific chemical interactions, a substance will be more extractable in a solvent whose δ value most closely matches its own. Thus, 8-hydroxyquinoline ($\delta=10$) is more extractable into benzene ($\delta=9.2$) than CCl_4 ($\delta=8.6$) than heptane ($\delta=7.4$). The absence of δ values for many extractable species hampers the full applicability of this principle.

It must not be assumed that the best solvent to use is always that which gives the highest extractability because a poorer solvent is often more selective.

(3) Stripping and Backwashing

Occasionally it is of advantage to remove the extracted solute from the organic phase as part of the analytical procedure. This process, called stripping, may be accomplished by shaking the organic phase with a fresh portion of aqueous

solution containing acids or other reagents which will decompose the extractable complex.

Backwashing is the technique of contacting the organic extract with a fresh aqueous phase. The combined organic phase, containing almost all the desired element and some of the impurities (extracted to a smaller extent), is shaken with small portions of a fresh aqueous phase containing the same reagent concentrations initially present. Under these conditions, most of the desired element remains in the organic phase whereas the bulk of the impurities are back-extracted (back-washed) into the aqueous phase because of their lower distribution ratios.

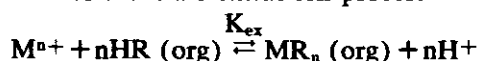
(4) Treatment of Emulsions

Rapid reappearance of a sharp phase boundary after shaking two immiscible liquids depends on the avoidance of emulsion formation. Tendency to form emulsions decreases with increasing interfacial tension. With liquids of relatively high mutual solubility or in the presence of surfactants, the interfacial tension is low and the tendency to form emulsions correspondingly high. Also of importance in avoiding emulsions is the use of solvents of low viscosity and whose densities are significantly different from water. With systems that tend to form emulsions, repeated inversion of the phases rather than vigorous shaking is helpful. In an extreme case, use of a continuous extractor rather than a separatory funnel is often successful. Tendency to emulsion formation can be reduced by addition of neutral salts or an anti-emulsion agent.

Important Experimental Variables

(1) Chelate Experimental Variables

As seen from Table 18-1, many chelating extractants are weak acids and can be represented as HR. For a chelate extraction process



the extent of extraction is described by the expression

$$D_M = \frac{C_{M(o)}}{C_M} = \frac{K_f K_{DC} K_a^n [HR]_o^n}{K_{DR}^n [H^+]^n} \alpha_M = K_{ex} \frac{[HR]_o^n}{[H^+]^n} \alpha_M \quad (6)$$

where K_f is the formation constant of the metal chelate MR_n , K_a the acid dissociation constant of the chelating agent HR, K_{DR} and K_{DC} the distribution constants of reagent and chelate, respectively. The combination of constants in equation (6) is called the overall extraction constant, K_{ex} . Representative values of K_{ex} are listed in Table 18-2.

Equation (6) shows that the value of D increases with the concentration of the reagent in the organic phase and decreases with the hydrogen ion concentration in the aqueous phase. From this we see the importance of pH control in chelate extractions. Inasmuch as the extractions of different metal ions with a given reagent are characterized by different extraction constants, the extraction curves (%E vs pH) will be similar but displaced in pH. Figure 18-3 shows a typical set of extraction curves for various metal dithizonates. It will be noted that, while the curves of all of the

divalent metal ions are parallel, those for Ag(I) and Tl(I) are less steep, as a result of n in equation (6) being 1. From the curve we can conclude that at pH 2, Hg(II) is 100% extracted; Ag, Cu, Bi are fractionally extracted, and the other ions listed not extracted at all. It would be simple to separate Hg(II) from Sn(II), Pb, Zn, Tl(I) and Cd in a mixture by extracting with dithizone at pH 2 but difficult to separate it from Ag, Cu and Bi. Since Bi is only 10% extracted at this pH, backwashing several times with fresh aqueous (pH 2) portions would quantitatively remove Bi (90% of remaining amount each time) from the extract without appreciably affecting the extracted Hg.

Table 18-2 Extraction Constants, K_{ex} , and $pH_{1/2}$ Values of Selected Metal Chelate Systems

Metal Ion	Extractant			
	8-Quinolinol 0.10M CHCl ₃		Dithizone 10 ⁻⁴ M CCl ₄	
	log K_{ex}	$pH_{1/2}$	log K_{ex}	$pH_{1/2}$
Ag ⁺	—	6.5	7.18	—3.2
Al ³⁺	-5.22	2.87	Not extracted	
Ca ²⁺	-17.9	10.4	Not extracted	
Cd ²⁺	—	4.65	2.14	2.9
Cu ²⁺	1.77	1.51	10.53	-1.3
Fe ³⁺	4.11	1.00	Not extracted	
Pb ²⁺	-8.04	5.04	0.44	3.8
Zn ²⁺	—	3.30	2.3	2.8

One useful way to condense extraction information from curves such as in Figure 18-3 or from expressions such as equation (6) is to specify the $pH_{1/2}$ (called "pH one half") value for the metal ion obtained with a particular concentration of the reagent. The $pH_{1/2}$ is the value of the pH at which half the metal is extracted. Thus from Figure 18-3, the $pH_{1/2}$ values for the dithizonates are 0.3 for Hg, 1.0 for Ag, 1.9 for Cu, 2.5 for Bi, 4.7 for Sn, 7.4 for Pb, 8.5 for Zn, 9.7 for Tl and 11.6 for Cd. For a single batch extraction, a minimum of three units difference in $pH_{1/2}$ is required to permit the quantitative separation of two metal ions, although as mentioned above the technique of backwashing can reduce this requirement.

The factor α_M in equation (6) which represents the fraction of the total metal concentration in the aqueous phase that is in the form of the simple hydrated metal ion, points to the importance of masking agents in improving selectivity of extraction. Masking agents are auxiliary complexing agents which form charged water-soluble complexes whose effectiveness in inhibiting other reactions (e.g., extraction) of metal ions increase with the formation constants of the masking complex, the concentration of the masking agent, and, for the many masking agents which are bases, with the pH. A number of representative values are listed in Table 18-3.

As an illustration of masking let us consider a mixture of Ag⁺ and Cu²⁺ from which we wish to extract Ag⁺ selectively. As can be seen from Figure 18-3, Ag⁺ can be extracted quantitatively

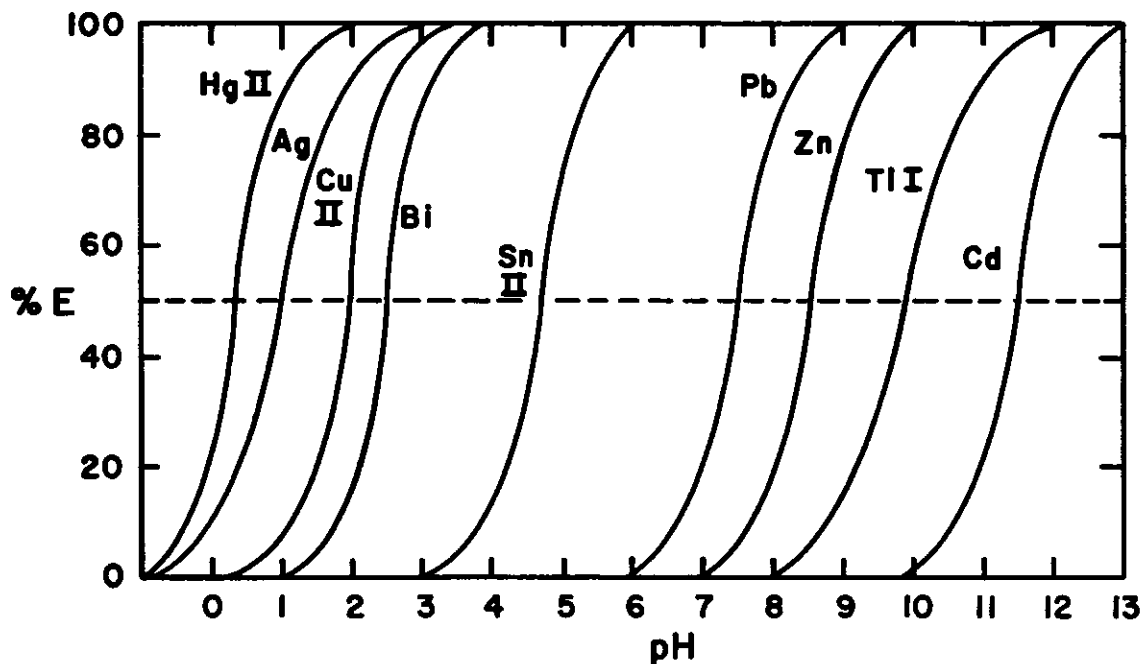


Figure 18-3. Qualitative Extration Curves for Metal Dithizonates

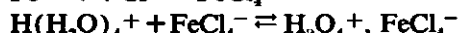
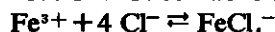
at pH 3 but without any masking agent present, Cu^{2+} is also appreciably extracted. In the presence of 0.1M EDTA, the value of $\log \alpha_{\text{Cu}} = -6.6$ (estimated from Table 18-3) which would displace the extraction curve of copper dithizonate to the right increasing $\text{pH}_{1/2}$ by 3.3 units [according to equation 6]. Since the value of $\log \alpha_{\text{Ag}}$ under these conditions is about -0.2 , EDTA has little effect on the extraction curve of Ag dithizonate. Hence, in the presence of 0.1M EDTA at pH 3, Ag^+ will be selectively extracted from Cu^{2+} . Similarly the use of cyanide as masking agent will permit the selective extraction of Al^{3+} , which does not form a CN^- complex, by 8-hydroxyquinoline in the presence of such transition metal ions as Cu, Fe, as well as Ag which form strong cyanide complexes. Other examples of successful masking can be predicted with the help of Table 18-3. We will return to the use of masking in the discussion of ion exchange separations.

Kinetic factors may be important in all types of extraction, but since they are observed most frequently with chelate extraction systems, they will be discussed here. Generally, extraction equilibrium can be achieved in one or two minutes of normal shaking because mass transfer rates are reasonably rapid. Occasionally it is observed, particularly with some chelates, that the formation of an extractable complex or the dissociation of a masking complex is slow enough to affect the course of the extraction. For example, most substitution reactions of Cr^{3+} are very slow, so that although Cr^{3+} forms stable chelates it is rarely extracted in the usual chelate extraction proce-

dure. Less dramatic but of analytical utility is the significant difference in the speed of formation of other metal dithizonates which makes it possible to separate Hg^{2+} from Cu^{2+} and Zn^{2+} from Ni^{2+} by limiting the shaking periods to one minute.

(2) Ion Association Extraction Systems

As with chelate systems, ion association extraction equilibria involve a number of contributing reactions. For example, for the extraction of Fe^{3+} out of HCl solutions into ether:



From these equations, the importance of chloride and acid can be seen. About 6M HCl is required for optimum iron extraction. Ether, as an oxygen containing solvent, is needed to stabilize the H_3O_4^+ ion. If $(\text{C}_4\text{H}_9)_4\text{N}^+$ is used, then the iron can be extracted out of a much less acidic solution (provided that the chloride concentration was about 6M) and, more significantly it would be possible to use benzene, CCl_4 or CHCl_3 as well as oxygen-containing solvents for the extraction.

In many ion association extraction systems, high electrolyte concentrations are found effective in increasing the extent of extraction. The addition of such salts, referred to as salting-out agents, serves two purposes. The first, and more obvious, is to aid in the direct formation of the complex by the mass action effect. That is, the formation of a chloro or nitrate complex, for instance, is promoted by increasing the concentration of Cl^-

Table 18-3 Values of Masking Factor
[-log α_M from Equation (6)]
For Representative Metal Ions and 0.1M
Masking Agents at Various pH Values

	pH =	2	5	8	10
Ag	EDTA	0	0.5	3.7	5.5
	NH ₃	0	0.1	4.6	7.2
	CN ⁻	4.7	10.7	16.7	19.0
Al (no masking NH ₃ or CN ⁻)					
	EDTA	1.8	8.2	14.5	18.3
	OH ⁻	0	0.4	9.3	17.3
	F ⁻	10.0	14.5	14.5	17.3
Ca (no masking NH ₃ or CN ⁻)					
	EDTA	0	3.2	7.1	8.9
	Citrate	0	1.8	2.5	2.5
Cd	EDTA	1.8	7.9	12.2	14.0
	NH ₃	0	0	2.3	6.7
	CN ⁻	0	0.7	10.1	14.5
Cu (II)					
	EDTA	4.6	10.7	15.0	16.8
	NH ₃	0	0	3.6	8.2
Fe (III)					
	EDTA	10.3	17.2	22.0	26.4
	OH ⁻	0	3.7	9.7	13.7
	F ⁻	5.7	8.9	9.8	13.7
Pb (no masking NH ₃ or CN ⁻)					
	EDTA	4.2	10.2	14.4	16.2
	OH ⁻	0	0	0.5	2.7
	Citrate	1.0	4.2	4.2	5.3
Zn	EDTA	2.8	8.8	12.9	14.7
	NH ₃	0	0	0.4	0.7
	CN ⁻	0	0	7.5	12.3

or NO₃⁻. Second, as the salt concentration increases, the concentration of "free", i.e., uncomplexed, water decreases because the ions require a certain amount of water for hydration. Because Li⁺ is more strongly hydrated than K⁺, LiNO₃ is a much better salting-out agent than KNO₃ for nitrate extraction systems even though equimolar solutions supply the same nitrate concentration.

Metal Extraction Systems

In this section the application of a few representative extractants are described in periodic array. Elements extractable as diethyldithiocarbamates are shown in Figure 18-4. The number under each element represents the lowest pH at which it will be extracted. Because the reagent is non-aromatic, solutions of its chelates can burn with a smokeless flame so this reagent is widely used as a separation or preconcentration step preparatory to atomic absorption spectrometry.

The application of dithizone is shown in Figure 18-5. Because of the highly conjugated reagent, the chelates are all highly colored in the visible range, which provides the basis of sensitive spectrophotometric determinations.

Extractions with 8-quinolinol (8-hydroxyquinoline, oxine) are described in Figure 18-6. These chelates also are used in spectrophotometric and fluorimetric determinations.

The extraction of metal ions from hydrochloric acid into ethyl ether is shown in Figure 18-7.

Outline of Illustrative Extraction Procedures

In this section several extraction procedures will be outlined as a means of illustrating the application of principles discussed above. Naturally for a working method, more detailed procedures in the references should be consulted. Precautions

Sodium Diethyldithiocarbamate

H	$(C_2H_5)_2N-C \begin{matrix} \nearrow S \\ \searrow S^- \end{matrix}, Na^+$																He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	A
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
				3	0	6.5	0	6	6	1	3	3			3		
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
				~5	3					3	3	3	5		-0.7		
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
					1	-1					3	3	-0.2	1			
Fa	Ra	Ac															
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	E	Fm	Mv	102	103	
					6.5		3										

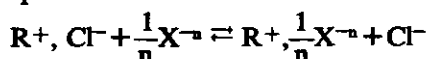
Morrison GH, Freiser H: Solvent extractions in radiochemical separations. Ann. Rev. of Nuclear Sci., vol. 9, 1959.

Figure 18-4. Elements Extractable with Sodium Diethyldithiocarbamate. The number under an element symbol indicates the pH value at which the element can be completely extracted.

$$K_{IX} = K_H^{M^{1/n}} \frac{[M^{n+}]_R^{1/n} [H^+]}{[M^{n+}]^{1/n} [H^+]_R} \quad (7)$$

where brackets signify concentrations in the aqueous and resin (subscript R) phases. It is convenient to use milliequivalents per gram of resin to describe resin concentrations and milliequivalents per milliliter (Normality) for solution concentrations. It should be noted that K_{IX} is expressed in terms of concentrations rather than the more rigorously correct activities. This is not only more practical but, because the resin phase is equivalent to an extremely concentrated electrolyte solution (e.g., about 5-6 molar in NaCl) activity, coefficients are difficult to evaluate accurately. Representative values of K_{IX} for cation exchange are listed in Table 18-4.

Similarly, the equilibrium of an anion exchange process



can be expressed by

$$K_{IX} = K_{Cl}^{X^{1/n}} = \frac{[X^{-n}]_R^{1/n} [Cl^-]}{[X^{-n}]^{1/n} [Cl^-]_R} \quad (8)$$

The extent of cation exchange may be expressed by a distribution ratio, D_M , which like equation (2) for extraction, is the ratio of total metal concentration in the resin phase, $C_{M(R)}$, (meq/g), to the total metal concentration in the aqueous phase, C_M (normality)

$$D_M = \frac{C_{M(R)}}{C_M} \quad (9)$$

Usually the metal ion in the resin phase is uncomplexed and can be represented as $[M^{n+}]_R$ but in the aqueous phase the frequent use of complexing agents suggests the use of the same masking factor that is incorporated in equation (6). Hence, equation (8) becomes

$$D_M = \frac{[M^{n+}]_R}{[M^{n+}]^{1/n} \alpha_M} \quad (10)$$

A major difference between masking in ion exchange and solvent extraction is the requirement that the masking complex for the metal cation be anionic, because cationic metal complexes (e.g., $M(NH_3)_6^{2+}$ or $M(\text{phenanthroline})_3^{2+}$) are also strongly absorbed on the resin.

If the resin is initially in the H^+ form the distribution ratio may be related to the exchange constant by the following equation [note analogy to (6)]

$$D_M = \frac{[M^+]_R}{[M^{n+}]} \cdot \alpha_M = \left[K_H^{M^{1/n}} \frac{[H^+]_R}{[H^+]} \right]^n \cdot \alpha_M \quad (11)$$

When the exchanged ion is present in small quantities, the resin loading, i.e. the $[H^+]_R$, remains substantially constant so that D_M is inversely proportional to $[H^+]^n$ which signifies the importance of dilution on the extent of exchange, particularly as the charge (n) of the metal ion increases.

Another important means of describing the extent of exchange is F , the fraction exchanged, which is given by (note resemblance to equation (3))

$$F = \frac{C_{M(R)} \cdot W}{C_{M(R)} \cdot W + C_M \cdot V} = \frac{D_M(W/V)}{D_M(W/V) + 1} \quad (12)$$

where W is the weight of the resin in grams and V , the volume of the aqueous phase in milliliters. The fraction of metal remaining in solution is $1-F$ or $[D_M(W/V) + 1]^{-1}$.

Properties of Ion Exchange Materials

Typical commercial cation exchange resins of the strong acid type are Dowex 50 and Amberlite IR-120, while Amberlite IRC 50 is weakly acidic. The strong acid types can function throughout the pH range but Amberlite IRC 50 must be used at a pH of 7 or higher.

Commercial anion exchange resins of the strong base type include Dowex 1, Dowex 2, Amberlite IRA-400 which can be used throughout the pH range but the weakly basic resins such as Dowex 3 or Amberlite IR-4B must be used at pH 7 or below.

The exchange capacities for the strong acid and base resins is of the order of 3-5 meq/g dry resin whereas that of the weak acid and base resins is about 10 meq/g.

These ion exchange resins are available with different degrees of crosslinking which affects both the hardness of the resin beads and their selectivity. Typically the resin is about 8% crosslinked with divinylbenzene (denoted in the listing of the resin as Dowex 50-X8), but at higher crosslinking a significant drop of exchange of larger ions imparts a greater ion size selectivity to the resin. This can be seen from Table 18-4 by the insensi-

Table 18-4 Concentration Exchange Constants, $K_H^{M^{1/n}}$, For Some Metal Ions on Dowex 50 Resins of Different Extents of Crosslinking (Measured in Terms of Percent Divinylbenzene (DVB)).

	4% DVB	8% DVB	16% DVB
Li ⁺	0.76	0.79	0.68
Na ⁺	1.20	1.56	1.61
NH ₄ ⁺	1.44	2.01	2.27
K ⁺	1.72	2.28	3.06
Ag ⁺	3.58	6.70	15.6
Mg ²⁺	0.99	1.15	1.10
Zn ²⁺	1.05	1.21	1.18
Co ²⁺	1.08	1.31	1.19
Cu ²⁺	1.10	1.35	1.40
Cd ²⁺	1.13	1.36	1.55
Pb ²⁺	2.20	3.46	5.65
Ni ²⁺	1.16	1.37	1.27
Ca ²⁺	1.39	1.80	2.28
Sr ²⁺	1.57	2.27	3.16
Ba ²⁺	2.50	4.02	6.52
Cr ³⁺	1.6	2.0	2.5
Ce ³⁺	1.9	2.8	4.1
La ³⁺	1.9	2.8	4.1

From O.D. Bonner et al., J. Phys. Chem., 61, 326 (1957) and 62, 250 (1968).

Table 18-5 Concentration Exchange Constants, $K_{Cl}^{X/1/n}$ For Some Anions on Dowex 1 and Dowex 2.

Ion	Dowex 1	Dowex 2
OH ⁻	0.09	0.65
F ⁻	0.09	0.13
Br ⁻	2.8	2.3
I ⁻	8.7	7.3
CN ⁻	1.6	1.3
NO ₃ ⁻	3.8	3.3
CNS ⁻	—	18.5
ClO ₂ ⁻	—	32
H ₂ PO ₄ ⁻	0.25	0.34
HCO ₃ ⁻	0.32	0.53
HSO ₃ ⁻	1.3	1.3
HSO ₄ ⁻	4.1	6.1
SO ₄ ⁻	2.55	0.55
HCOO ⁻	0.22	0.22
CH ₃ COO ⁻	0.17	0.18

From O.D. Bonner et al., J. Phys. Chem., 61, 326 (1957) and 62, 250 (1968).

tivity of a small ion such as Li⁺ to degree of crosslinking, whereas for a large ion such as K⁺ or Ag⁺, the $K_{H^+}^{M^+}$ changes significantly. The effect is not as dramatic with the more highly charged ions but may still be observed with Ba²⁺ and Pb²⁺.

General Experimental Techniques

Two means of employing ion exchange resins are the batch technique, in which a portion of the resin is added to the solution to selectively remove an ion of interest, and column techniques which may involve either "column filtration" or chromatography. Both column techniques can serve to separate ions too similar to permit use of the batch technique; chromatography is both more powerful and more inconvenient than column filtration. The following typical values of the extent of removal by a batch ion exchange using a Dowex 50 x 8 resin are illustrative. (These values could be derived from equations (11) and (12)).

(1) For 1 g of resin in the H form equilibrated with 100 ml 0.1 M HCl which is 0.02M in Ca, Sr, or Ba to be 97%, 98%, and 99.3% removal, respectively. If only trace levels of the metal ions were present, the percent removal would be 98.8%, 99.3%, 99.8% of these metal ions. Hence, when resin loading is kept low the exchange is more efficient.

(2) The effect of ionic charge may be seen from the value of NH₄ remaining in solution = 4% when a gram of resin is equilibrated with 40 ml of 0.01M NH₄Cl. The corresponding Mg is 0.01% if 40 ml of 0.005M Mg Cl₂ is used.

(3) The effect of the concentration of the counter ion may be seen from a comparison of the 0.01% Mg remaining in solution mentioned in (b) where the aqueous phase would then be 0.01M in HCl and the value of 4% Mg remaining if the aqueous phase were 0.1M in HCl at equilibrium.

With the help of values in Tables 18-4 and 18-5 and equations (11) and (12), one can calculate the feasibility of separating various pairs of ions. For example, from equation (12) for removal of 99% of a metal ion M₁, (assuming a V/W value of 25:1) a value of D_{M₁}, of at least 2500 is needed. Under similar experimental conditions a D_{M₂} of 0.25 or less for a second metal ion, of which 99% or more will remain in the aqueous solution.

For metal ions of the same charge, it is evident from the similarity of values of K_{ix} as well as the form of equation (11) that, unless great variation in α_M for the pair of ions can be achieved, quantitative separation of the ions using a simple batch process is hopeless. A number of interesting and useful batch separations can be carried out, however, by adjusting conditions to obtain sufficiently different values of the masking factor, α_M, of the pair of metal ions.

For example, a mixture of Ca²⁺ and Cu²⁺ at concentrations of 10⁻³M or lower can be separated using Dowex 50-X8 in the Na- form by adding 0.1M EDTA and adjusting the pH suitably. In the absence of EDTA the distribution values are D^{Ca} = 40,000 and D^{Cu} = 25,000, so that both metal ions would be quantitatively removed from solution. From Table 18-3 we can estimate that at pH 3, α_{Ca} is between 1 and 0.1 but α_{Cu} is 10^{-6.0}. Hence under these conditions Ca²⁺ (D_{Ca} > 4000) will be quantitatively taken up by the resin while Cu²⁺ (D_{Cu} ~ 0.008) will remain entirely in solution (as Cu-EDTA complex).

When differences in D_M values for a pair of ions cannot be made large enough to permit use of a batch technique, an ion exchange column must be used. Although column chromatographic methods represent the ultimate separation efficiency these are rather complicated, requiring either close attention or automatic fraction collectors. The technique of column filtration, however, offers both speed and simplicity while providing significantly greater separating efficiency than the batch process.

In preparation of an ion exchange column for analytical use several precautions should be observed. The resin, usually about 8% crosslinked and about 50-100 mesh, is slurried in water in a beaker. After allowing the mixture to stand for a few minutes to settle the large particles, the turbid supernatant liquid is poured off. This process is repeated a few times in order to remove the fine particles which would otherwise clog the column. The resin is slurried again with water and poured into a tube which is provided with a plug of glass wool or sintered glass disk (coarse porosity) on which the ion exchange bed will rest. Because air bubbles in the column interfere with the flow of liquids through the tube and can lower column efficiency drastically, the meniscus of the liquid must never be allowed to fall below the top of the column. This, as well as the desired flowrate, is controlled by a stopcock or pinchclamp at the bottom of the tube.

All columns should be conditioned prior to general use to remove impurities. For both strong cation and anion exchange resins, conditioning is

carried out by passing through the column, in succession, about 3-4 bed volumes each of 1M NaOH, 1M HCl, water, 95% ethanol and water for two to three cycles. The conditioning ends with either NaOH or HCl depending whether the cation exchange resin is to be used in either the Na- or H-form (for the anion exchange resin this is either the -OH or Cl-form), and then rinsed with water until a qualitative test (with a suitable indicator) verifies completeness of rinsing.

Regeneration of the column after some use is necessary in order to avoid leakage of exchanged ions into the effluent. This can be carried out by passing either HCl (from 1-3M) for cation exchange resins or NaOH (1-3M) until tests of the effluent reveals the completeness of ion removal. If a particularly strongly held metal ion is on the cation exchange column, a complexing agent like ammonium citrate or EDTA can be used effectively in the regenerative solution.

It is useful to keep in mind that the theory of ion exchange column chromatography behavior is almost identical with that of other chromatographic systems. The concentration profile of a particular ion moving down the column under the influence of a solvent (eluent) resembles a Gaussian (bell shaped) curve. When enough eluent has been added, the ionic component will emerge. The elution volume corresponding to the peak (maximum concentration) of the curve is described by the relation

$$V_{\max} = D_M \cdot W \quad (13)$$

where D_M is the distribution ratio of the ion under the conditions of the elution and W is the weight of the resin in the column. The peak concentration, C_{\max} , is given by the equation

$$C_{\max} = \frac{(\text{meq}) \times \left(\frac{N}{2\pi}\right)^{1/2}}{V_{\max}} \quad (14)$$

where (meq) is the number of meq of the ion on the column and N is the number of theoretical plates. Since V_{\max} and N are both linearly related to W and hence to column length at constant column width, the value of C_{\max} is inversely proportional to the square root of column length. The width in milliliters of an elution band (i.e., the concentration-volume profile of an eluted ion) is proportional to the square root of the column length. Hence, the relative width of a particular elution band decreases with the square root of column length.

Column filtration is a process involving separation of two ions on an ion exchange column by passing a given (reasonable) volume of an eluent through the column to quantitatively remove one of the ions but essentially none of the other.

Two ions can be successfully separated by column filtration provided that the D value for the ion retained on the column is at least 100 (compared to at least 2500 for batch) while the D for the ion washing through the column may be three or smaller (0.25 for batch). Even such large differences in D are unusual for metal ions of the same charge unless α_M values can be modified by suitable masking agents. If the ratio of DM_1/DM_2 is below 30, column filtration may not

be used and a full-fledged chromatographic procedure must be used.

Outline of Illustrative Ion Exchange Procedures

As in the corresponding section on extraction, several ion exchange procedures will be outlined to illustrate the principles and indicate the range of applications.

(a) Non-Chromatographic Applications

The determination of phosphate is simplified and improved by the removal of cations. Passing an acidified solution of the sample through a cation exchanger (H- form) removes all interfering cations. Analogously, phosphate interferes with the determination of a number of cations. For example, the atomic absorption determination of Ca^{2+} is preferably carried out after removing phosphate by passing the sample through an anion exchanger (Cl- form).

Fluoride can be separated from all interfering cations prior to determination with the F^- selective electrode.

Sodium or potassium can be determined in the presence of transition metal ions such as Ni^{2-} , Cu^{2+} , Co^{2+} , Fe^{3+} , V^{4+} by passing the mixture through a column of Dowex 2 in the citrate form which will remove interfering metals as anionic citrate complexes. Utilization of column filtration with an anion exchanger in the CyDTA form, permits the separation of Ca and Mg from Al^{3+} , Cu^{2+} , Fe^{3+} , Mn^{2+} , and Zn^{2+} .

A series of several concentrations of HCl can be used to wash the metal ions of the NH_4OH group successively through an anion exchange column in the chloride form. With 9M HCl, Ni^{2+} will come through, with 4M HCl, Co^{2+} ; with 1M HCl, Fe^{3+} , and finally using water, Zn^{2+} will wash through. This order is a consequence of the increasing stability ($Ni^{2+}-Zn^{2+}$) of the chloroanionic complexes of these ions.

(b) Chromatographic Applications

As differences in D value decrease, separations naturally become more difficult. This implies longer columns, slower flowrates, more carefully controlled conditions and almost continuous monitoring of the column effluent or automated fraction collectors. One of the most promising new developments in liquid chromatography of all types (adsorption, partition, etc., as well as ion exchange) is that involving exceptionally long and narrow columns through which the eluent is forced under very high pressure. This renders practical the use of columns of very great separating efficiency (large number of theoretical plates) in procedures which give sharply defined bands without excessively long run times. High pressure liquid chromatography should make it possible to extend the present scope of application of ion exchange (as well as other types) chromatography to almost any organic or inorganic electrolyte mixture.

Suggestions for Further Reading

Samuelson (1) is the classic text on ion exchange and its application to analytical chemistry. Ringbom (3) is responsible for the excellent treatment of the role of complexation in improving ion exchange separations.

A wealth of references to current develop-

ments is to be found in the biennial ion exchange review in *Analytical Chemistry* (4).

- (1) O. Samuelson, "Ion Exchange Separations in Analytical Chemistry," Second Ed., John Wiley & Sons, New York (1963).
- (2) W. Rieman and H. Walton, "Ion Exchange in Analytical Chemistry," Pergamon Press, Oxford (1970).
- (3) A. Ringbom, "Complexation in Analytical Chemistry," John Wiley & Sons, New York (1963).
- (4) H. Walton, *Analytical Chemistry*, 42, 86R (1970).

Other Separation Processes

Although it is impossible in this brief chapter to do more than simply mention other methods of separation, it might be of some value to point these out as having useful application and high potential in problems of environmental analysis.

Liquid-liquid partition chromatography which is based on the selective distribution of solutes between two liquids: an immobilized liquid spread thin on a largely inert solid support in contact with a mobile eluent liquid with which the immobilized liquid may or may not be miscible. This process which can be carried out on either a column or paper and can best be understood as a modified multistage countercurrent solvent extraction process. Many of the recently published methods for separating inorganic ions, particularly those of so-called *reverse phase partition* (the immobilized phase is organic — the eluent is aqueous) are direct adaptations of extraction systems.

Thin layer chromatography analogous to paper but makes use of noncellulosic materials, e.g., silica, alumina, which are capable of being heated (for activation of substrate or development reactions) to much higher temperatures. TLC is more often the two dimensional analog of column adsorption chromatography (but not exclusively so) in which the immobilized phase is a solid of high surface area.

Exclusion chromatography is a separation process based on the relative size of adsorbate molecules and adsorbent pores or channels. Molecular sieve materials such as the inorganic zeolites and the organic gels are used successfully as column packing materials for chromatographic fractionation of both relatively small and large molecular weight mixtures. Zeolites are open silicate networks with highly uniform pore sizes that can be available in diameters from 4.2Å to about 9.0Å. For example, molecular sieve 4Å will adsorb molecules whose diameter is under 4Å (H₂O, CO₂, H₂S, SO₂, and hydrocarbons containing one or two carbon atoms) but will exclude all others. Type 5A sieve will adsorb straight chain hydrocarbons and derivatives up to about fourteen carbon atoms but will exclude all branched chain and cyclic compounds. Because of their silicate

character, zeolite sieves will exhibit a strong preference for polar over non-polar molecules of equal size. Zeolite sieves are frequently used in gas-solid chromatography.

Gel permeation chromatography which may utilize either hydrophilic gels like Bio-Gel (a polyacrylamide) or Sephadex (a cross-linked dextran) or hydrophobic gels such as Styragel (a sponge-like cross-linked polystyrene), are generally used as a column packing in liquid chromatography. This technique is particularly useful for size separation of high molecular weight mixtures such as protein and polymeric fractions, although a mixture of mono-, di- and tri-saccharide can be easily separated (Sephadex).

A number of separation processes are based on the differential migration of charged species in solution when subjected to an electric field gradient. Of particular interest is electrophoresis carried out on a supporting medium of filter paper, cellulose acetate, or gel layer which is soaked in a buffered electrolyte and subjected to a d.c. voltage with electrodes placed at each end of the paper (or gel). A sample of the material to be separated breaks up into zones because of the differential migration rate influenced by the charge, size and shape of the species. Greater variation in behavior of inorganic ions and, hence, improvement in separation can be brought about by variation of pH, oxidation state, and the ability to form complexes.

Interposing a thin perm-selective membrane between two solutions forms the basis of *dialysis* and, with the addition of an electric field gradient, *electrodialysis* which have been used for separations used more for recovery and purification than analysis per se. Nevertheless, as a means of removing interferences, such methods can be of value.

Fractional distillation is a separation process for liquid mixtures based on differences in volatility. By the addition of a non-volatile component that can interact with the volatile components in a differential manner, (called extractive distillation) such volatility differences can be increased.

Zone refining involves countercurrent fractional recrystallization by moving a narrow band heater slowly along a column of the solid material. The small melted zone contains most of the impurities so that the cooled recrystallized material becomes significantly purer, while the impurities concentrate at one end of the column. The process can be repeated several times. This technique could be useful in concentrating trace level impurities.

Thermal diffusion, which does not involve phase separation, can be used to separate gas or liquid mixtures by virtue of the concentration gradient produced in a homogenous fluid mixture to which a temperature gradient is applied. Thermal diffusion is a sufficiently powerful technique to permit separation of the gaseous isotopes of helium, of chlorine, and of C¹³H₄ from C¹²H₄, as well as the components of liquid hydrocarbon mixtures.

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2. BLACK, R. J., E. L. DURRUM and G. ZWEIG, *Manual of Paper Chromatography and Paper Electrophoresis*, Academic Press, New York (1958).
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CHAPTER 19
SPECTROPHOTOMETRY

H. E. Bumsted

INTRODUCTION

The electromagnetic spectrum of energy extends from the gamma rays emitted by radioactive elements with wavelengths of less than 0.1 nanometer to radio waves with a wavelength greater than 250 millimeters. However, this chapter will deal only with a very small section of this spectrum, namely the ultraviolet (185 to 380 nanometers), the visible (380 to 800 nanometers) and the infrared (0.8 to 50 micrometers). A schematic diagram is shown in Figure 19-1.

The terms used in spectrophotometry are gradually changing, and unless one is familiar with the old and new forms, confusion may result. The new and old terms are shown in Table 19-1.

Table 19-1.
Terms in Common Usage in Spectrophotometry

<i>New</i>	<i>Old</i>	<i>Value</i>
Nanometer	Angstrom, A	10 ⁻¹⁰ meter
Micrometer	Millimicron	10 ⁻⁹ meter
Millimeter	Micron	10 ⁻⁶ meter
Nanogram	Milligram	10 ⁻⁹ gram
Microgram	Gamma	10 ⁻⁶ gram
Milligram		10 ⁻³ gram

Visible light can be divided into the six principal colors as shown in Table 19-2. These are the principal colors seen when white light is diffracted into its primary colors by a prism or diffraction grating. Various shades and tones of these colors are possible. When visible light is absorbed by a compound, there are resulting energy changes involving the valence electrons.

The ultraviolet portion of the spectrum is that portion of the sun's energy which causes sunburn and similar skin damage. The absorption of ultraviolet energy causes energy changes involving the ionization of atoms and molecules.

Infrared radiation is the portion of the spec-

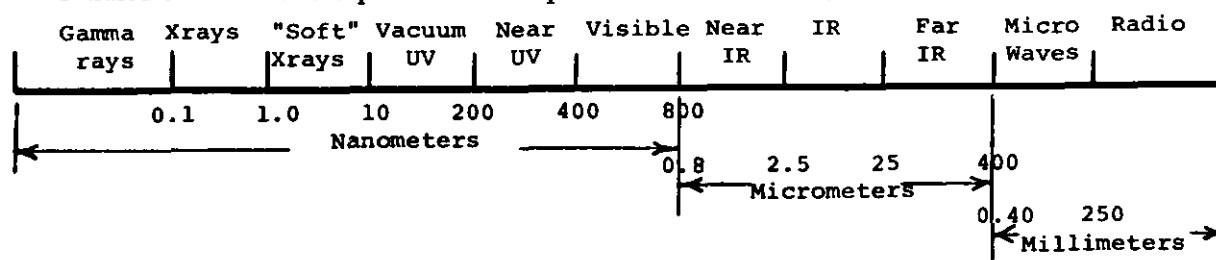


Figure 19-1. Schematic Diagram of Electromagnetic Spectrum. Note that the wavelength scale is not linear.

Table 19-2.
Principal and Complementary Colors

<i>Transmitted Color</i>	<i>Wavelength (nm)</i>	<i>Complementary Colors</i>
Violet	380-435	Yellowish Green
Blue	435-480	Yellow
Green	500-560	Purple
Yellow	580-595	Blue
Orange	595-650	Greenish Blue
Red	650-780	Bluish Green

trum associated with the generation of heat. Absorption of infrared energy results in molecular vibrations, such as bending or stretching of the interatomic bonds, and molecular rotation. The type of vibration is dependent on the wavelength of the incident radiation.

When certain types of molecules absorb ultraviolet energy, energy in the ultraviolet or visible regions is emitted as the excess energy is released. This is called fluorescence and is a valuable tool for the chemist in identifying and quantitating such compounds.

The absorption of energy by solutions follows two basic laws. The Bouguer (1729), or Lambert (1760), law states that when a beam of plane-parallel monochromatic light enters an absorbing medium at right angles to the plane surfaces of the medium, the rate of decrease in intensity with the length of the light path through the absorbing medium is proportional to the intensity of the beam. Mathematically this can be expressed as

$$I = I_0 e^{-Kb}$$

where

I = Unabsorbed Intensity

I₀ = Incident Intensity

K = Constant

b = Cell Thickness (light path length)

Bernard's (1852), or Beer's (1852), law

states that the intensity of the energy decreases exponentially with the increase in concentration. Mathematically this can be written as

$$2.303 \log \frac{I_0}{I} = K' C$$

Where C is the concentration of the absorbing material.

Combination of these two laws forms the basic law of spectrophotometry. It takes the form of:

$$\log \frac{I_0}{I} = a b c$$

where —a— is the absorptivity, a constant dependent upon the wavelength of the radiation and the nature of the absorbing material, whose concentration —c— is expressed in grams per liter. The product of the absorptivity and the molecular weight of the absorbing substance is called the "molar absorptivity" (ϵ).

Absorbance A is the product of the absorptivity, the optical pathlength and the concentration; i.e.,

$$A = a b c$$

The absorbance of a 1-cm layer of a solution containing 1 percent by weight of the absorbing solute is represented by the term $A \frac{1\%}{\text{cm}}$. The term "transmittance %" is the percent of the incident light passing through the absorbing solution and is related to the concentration exponentially. Thus, when the transmittance is plotted against concentration on semi-logarithmic graph paper a straight line should result if the system follows Beer's law.

Absorbance is directly related to concentration and can be plotted against concentration on linear coordinate graph paper. When such a plot gives a straight line the system follows Beer's law.

Most dilute systems will follow Beer's law over a limited range of concentration. Beer's law requires monochromatic radiation. However, most spectrophotometers and all filter photometers employ a finite group of light frequencies. The wider the band of the radiation, the greater will be the deviations from Beer's law. Temperature changes, ionization of the solute, stray light and changes in the pH of the solute, may cause deviations from Beer's law.

While it is desirable to have the analytical system follow Beer's law, it is not essential if a good reproducible calibration curve can be prepared.

VISIBLE LIGHT SPECTROPHOTOMETRY

Introduction

Analytical methods utilizing the visible section of the electromagnetic spectrum are of great importance. Most methods for the determination of metals in trace concentrations involve the production of a colored complex with some organic reagent. To be of value for analytical purposes the color-producing reaction should have the following characteristics:

1. Reagent and the color complex should be stable.
2. The reaction should be stoichiometric.

3. The color development should be rapid and color should resist fading.
4. The reaction should be specific for the element to be determined.
5. The reaction should show no more than minor variation with pH, temperature and other factors.
6. The color complex should be soluble in a solvent which is transparent in the area of spectral absorbance of the complex.
7. The color complex should have a sharp absorbance band.

Methods of color development generally fall into the following categories:

1. redox methods
2. complex formation
3. diazo and coupling reactions
4. condensations and addition
5. salt formation
6. chromophoric changes in valence
7. substitution.

Color procedures used may be classed as either single or mixed color. In the single color procedure, the color producing reagent is either colorless or the excess reagent is removed from the solution by suitable extractions. An example of this is the color complex formed with hexavalent chromium by *s*-diphenylcarbazide. Here the reagents are colorless but react with hexavalent chromium to produce a red complex. Oxidation of manganese to permanganate is another example of a single color method. The absorbance spectrum of the permanganate ion is shown in Figure 19-2. This ion shows a strong absorbance at 525 nanometers.

The determination of lead with dithizone (diphenylthiocarbazone) is an example of the mixed color technique. Dithizone dissolved in chloroform has a bright green color with a maximum absorbance at 625 nanometers as shown in Figure 19-3. In this figure Curve 1 is the absorbance spectrum of the dithizone solution which has been used to extract the reagent blank. It shows a zero absorbance or 100 percent transmittance at 610 nanometers and an absorbance at 515 nanometers which is due to traces of lead in the reagents. Curve 2 is the spectrum of the dithizone after extracting a solution containing 10 micrograms of lead. The increase in absorbance at 515 nanometers is evident. Figure 19-4 illustrates the change in absorbance as the lead dithizonate increases from 0.0 to 3.0 micrograms per ml of chloroform. The absorbance is set at 0.0 with the reagent blank. This will correct for any lead in the reagents. Then the absorbance is measured for the three standard solutions. It is evident that the standards follow Beer's law.

As a general rule, the complementary color is used to measure any colored complex. For example, if the solution to be measured is red, green light should be used.

When any colored reaction is used, it is advisable to determine the absorbance spectrum of the reaction product with the spectrophotometer to be used for the analysis. From this spectrum the proper wavelength to be used for the pro-

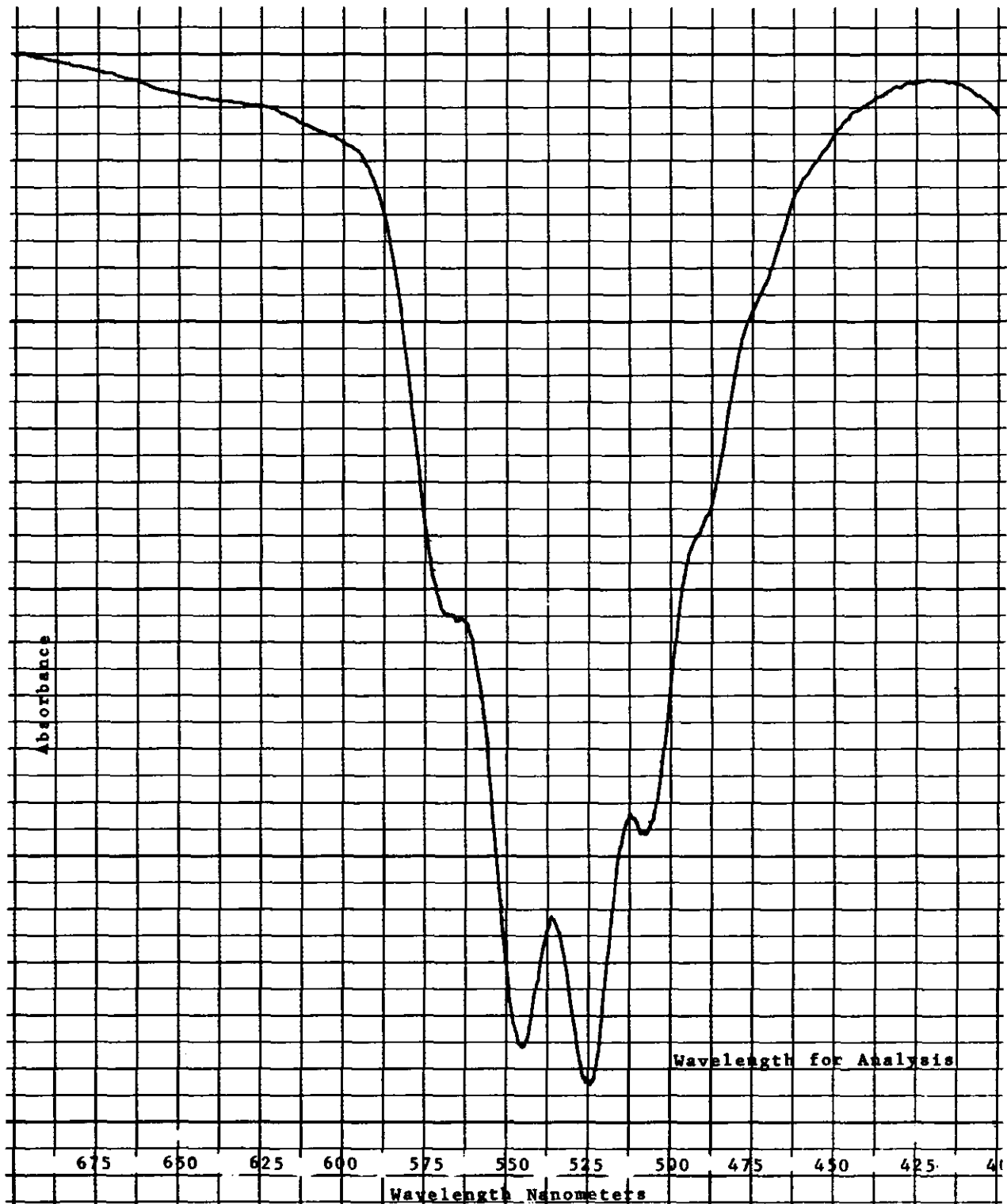


Figure 19-2. Visible Absorbance Spectrum of Permanganate Ion in Water.

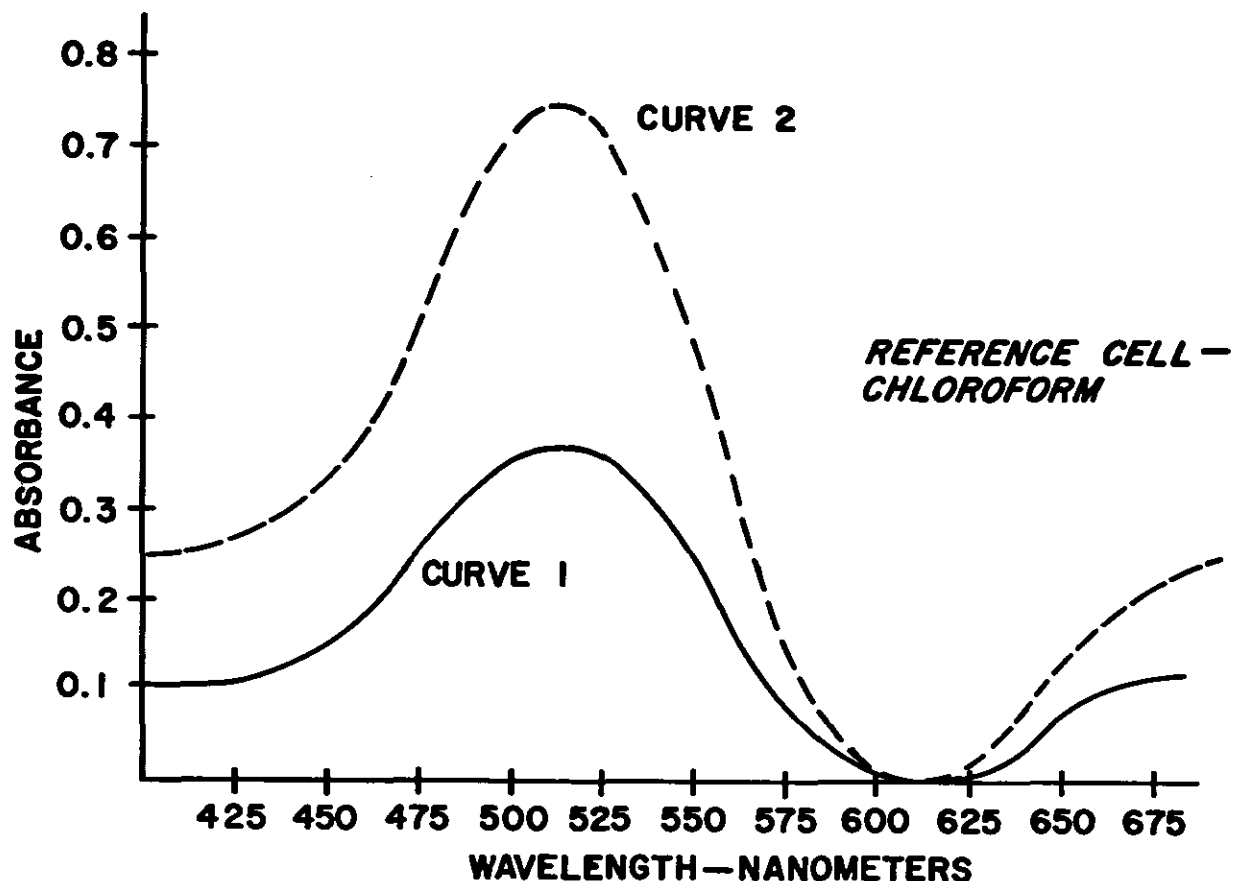


Figure 19-3. Absorption Spectra of Dithizone and Lead Dithizonate in Chloroform.

cedure will be evident and any instrumental variation or shifts in the wavelength scale of the particular instrument will be corrected.

In some instances, it is possible to utilize the bleaching effect of some ion on a colored organo-metallic complex to measure the concentration of the ion of interest. An example of this is the bleaching effect of fluoride ion on thorium or zirconium alizarin lakes. In this case, the loss of color of the lake is directly proportional to the amount of fluoride present.

While many color-producing reactions are available, some ions of interest do not form colored complexes that are suitable for analytical procedures. Frequently it is possible to produce a suspension of a finely divided uniformly sized precipitate. When a beam of light is passed through such a suspension, energy is lost due to light scattering. Under proper conditions this loss is proportional to the amount of precipitate. This analytical technique is called nephelometry. Such procedures require very rigid control of all conditions such as temperature, pH and concentrations of reagents to produce uniform size precipitates or reproducible results cannot be obtained. Procedures for the determination of chloride, as silver chloride, and sulfate, as barium sulfate, are examples of the application of this technique.

Instrumentation

The first techniques of spectrophotometry involved the direct comparisons of colors produced in unknown solutions with those of standards prepared under similar conditions. Observations were made with the naked eye using a common light source. Such techniques can still be used to obtain a rough estimate of the concentration. From this beginning, Nessler tubes developed. The color reaction is carried out in both a series of standards and unknowns. The solutions are placed in a series of long flat-bottom tubes and diluted so that the column of solution is either 10 or 20 centimeters in depth. After mixing, the color of the unknowns is matched against the standards. The unknown solutions can be bracketed between two standards and a rough approximation of the concentration can be made.

The Duboscq colorimeter developed from this technique. Light illumination from a common light source is passed up through the bottom of a pair of matched cups, through the solution and through a matched set of glass plungers. A prism system brings the light beams to a common axis. Light from each cup illuminates one-half of the viewed field. The intensities of the two halves of the viewed field are matched visually by raising or lowering the plunger in one cup. The depth is

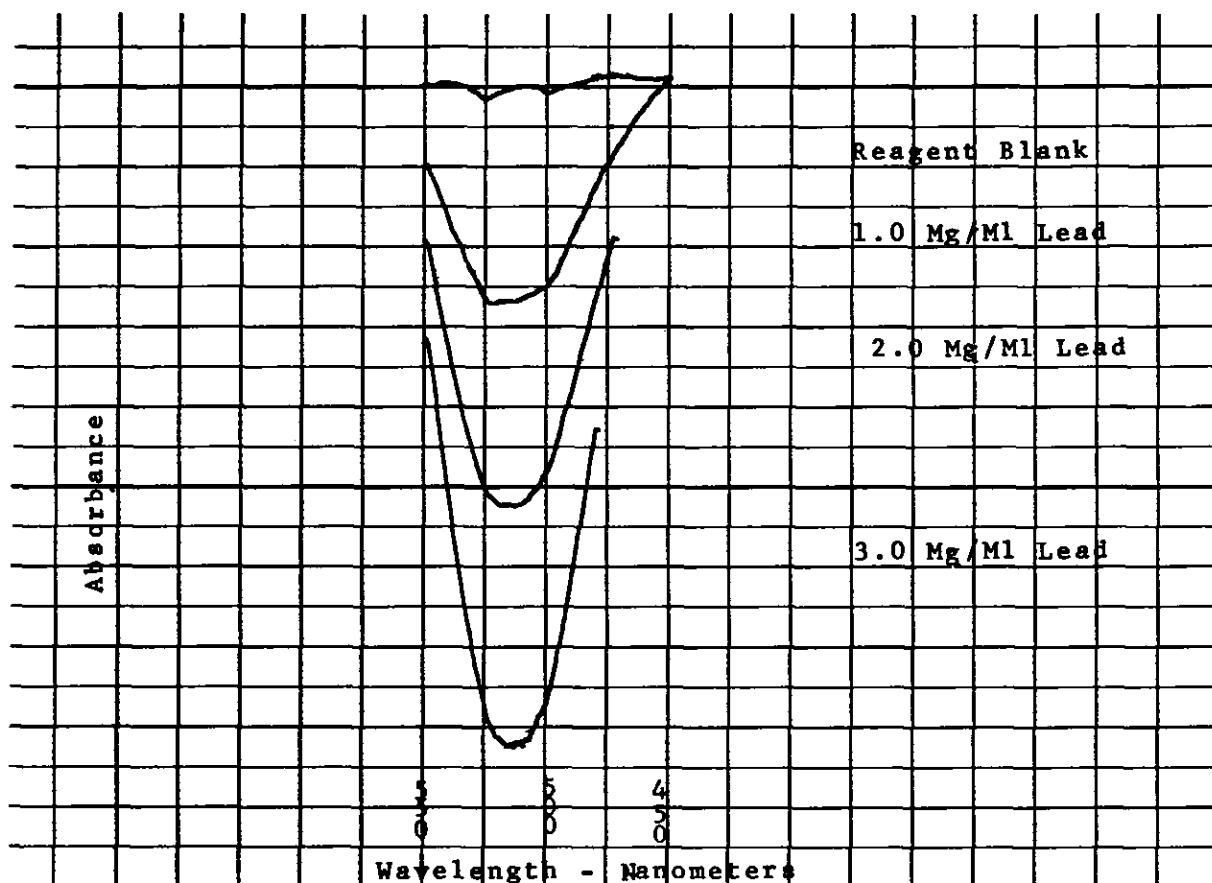


Figure 19-4. Absorption Spectra of Lead Dithizonate.

measured on a scale. From previously prepared calibration curves it is possible to estimate the concentration. The ability of the eye to match intensities varies with wavelength and intensity. The eye is best at about 500 nanometers and under the best conditions can be accurate to within 1 or 2 percent.

Another version of this technique is the wedge comparator. The light beam is split into two segments. One passes through the standard solution and one through the unknown. A neutral wedge of glass is moved into the exit beam of the standard solution to attenuate the light intensity until it matches the unknown.

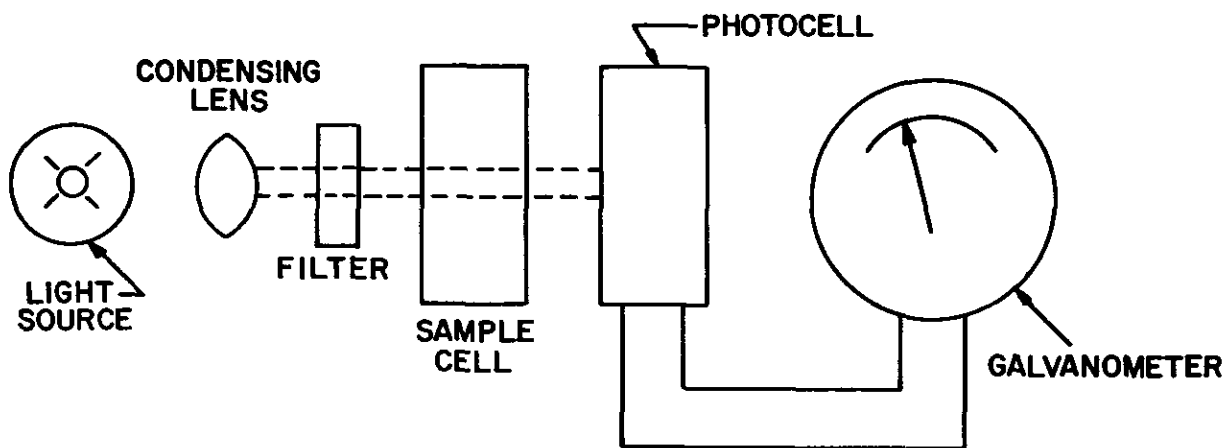
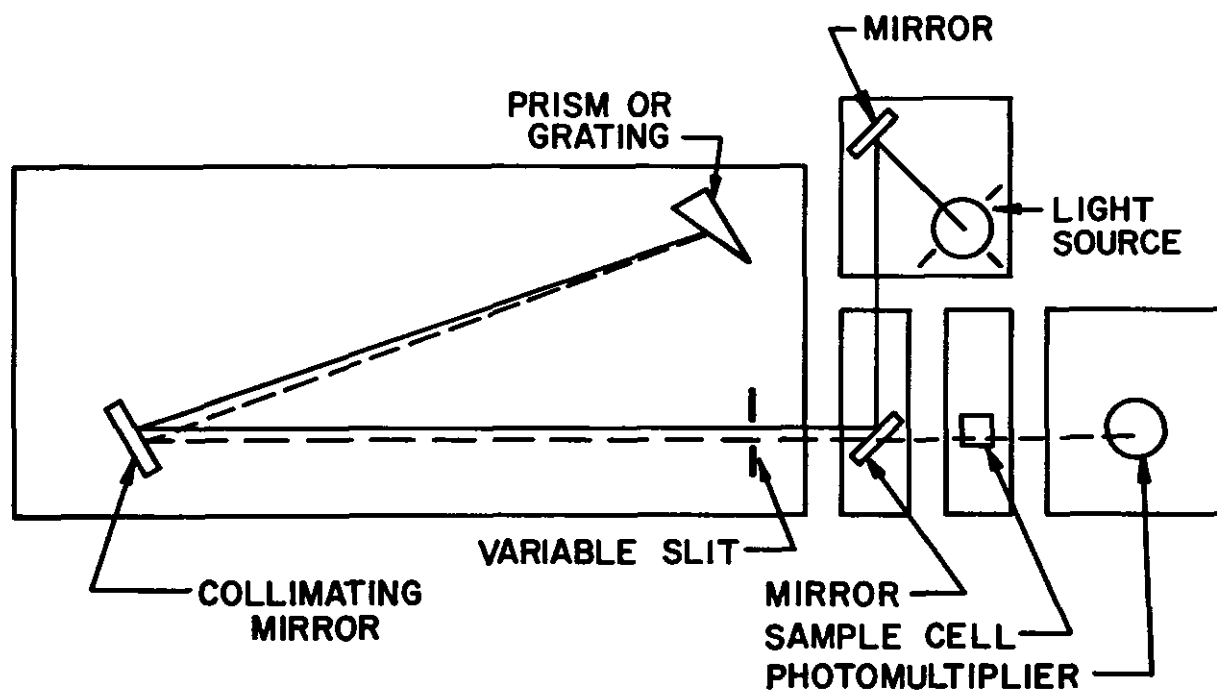


Figure 19-5. Schematic Diagram of Filter Photometer.

The next instrumental development was the single-beam photometer. The basic design of this type of instrument is shown in Figure 19-5. The light from the source passes through a filter, through the solution, and strikes a photocell. With the solvent in the light path and the proper filter in position the light intensity is adjusted to give a reading of 100 on the scale. Next the standards are inserted and the scale readings are recorded. Then the unknown solutions are inserted and read. The intensity of the light source can be adjusted either by a rheostat in series with the light source or a diaphragm in the light path.

To eliminate errors due to variations in the light source with time, the double-beam photom-

eter was developed. In this instrument the filtered light is separated into two beams. One beam is reflected to a reference photocell. The remaining beam passes through the solution to be measured and strikes a second photocell. The net output of the two photocells, connected in opposition, is balanced by a variable resistor to give a zero reading on a galvanometer for the blank solution. The standards and unknowns are inserted into the beam and the deflections of the galvanometer are read; from the calibration curve the concentrations of the unknown can be determined. Filters available for these instruments were generally wide band-pass filters and lacked the narrow spectral band width required by Beer's Law.



Beckman Instruments, Inc.: Bulletin 134-D. Fullerton, California.

Figure 19-6. Schematic Diagram of Prism or Grating Spectrophotometer.

The next development was the prism or grating single-beam spectrophotometer. The basic instrumental design is shown in Figure 19-6. In this instrument light from the source is refracted by a prism or diffracted by a grating into its spectrum. A series of adjustable exit slits limits the wavelengths striking the sample. This spectrophotometer has a narrow band-pass which improves the conformity to Beer's Law. The position of the grating or the prism is set to the proper wavelength and the blank is inserted in the beam. After balancing the instrument with the shutter closed, the shutter is opened and the meter set to 100 percent transmittance or 0 absorbance by adjustment of the slit width and the sensitivity control. The standards are inserted in the beam and the absorbance determined for each concentration. The absorbance of the unknowns can be measured and the concentration determined from the calibration curve.

The light-measuring devices used in this type of instrument are either photocells or photomultiplier tubes. Generally two photocells are available to cover the entire spectral range. These instruments are much more expensive than photometers but give greater accuracy and reproducibility as well as monochromatic character of the light used in the analysis.

A more recent development has been the ratio-recording spectrophotometer. In this instrument the light beam from the source is refracted by a prism and strikes a rotating segmented disc. One half of the disc is open allowing the beam to pass through a reference cell and eventually strike a detector. The other half of the disc is a mirror that reflects the light through the sample cell to the detector. The detector system produces a reading which is the ratio of the two beams. Such instruments eliminate all variations due to voltage or electronic fluctuations. Any of the newer in-

struments can be coupled to a recorder to give a permanent record of the results.

Applications

Visible spectrophotometry has many uses in the analyses needed in environmental control work. Several examples are discussed.

1. Biological Analysis.

Frequently, the measurement of some ion in a biological specimen is the best indicator of an exposure. The analysis of blood or urine for lead is an excellent means of evaluation of the worker's exposure. The blood or urine is ashed, the ash dissolved and extracted with a chloroform solution of dithizone at pH of 9.5. The lead reacts with the dithizone to form lead dithizonate. The lead dithizonate in the dithizone-chloroform solution is determined at 510 nanometers. By proper control of pH and use of complexing agents it is possible to eliminate interferences from other metallic ions.

The determination of manganese in urine is a useful measure of the exposure of workers to manganese. The urine is ashed and the manganese is oxidized to permanganate ion. The color of permanganate can be measured at 525 nanometers.

The determination of mercury in urine has taken on increased importance with the recent emphasis on mercury pollution. The urine is ashed under a reflux condenser, extracted with dithizone in carbon tetrachloride. The dithizone mercury solution is further extracted with 9N ammonium hydroxide twice to remove the unreacted dithizone leaving the single color of the mercury dithizonate. This is measured at a wavelength of 475 nanometers.

Many other ions of interest in environmental control work may be determined by spectrophotometric procedures.

2. Air Sample and Sample Analysis.

Lead can be determined in air samples by dithizone after ashing and solution of the sample. Under proper conditions the reaction is specific.

Several methods are available for the determination of iron. Under proper conditions, iron as ferric chloride in 28 percent hydrochloric acid can be measured directly at 460 nanometers. This method is not specific, for other colored metals in solution may affect the results. Specific reagents such as dipyriddy and ortho-phenanthroline are available for the determination of iron in trace quantities.

As mentioned earlier, manganese can be oxidized to permanganate ion whose concentration can be measured at 525 nanometers. While the reaction is specific for manganese, the presence of easily oxidized materials can reduce the permanganate ion and seriously affect the results.

Arsenic can be vaporized as arsine and absorbed in a solution of silver diethyldithiocarbamate in chloroform solution. The color produced is measured at 560 nanometers and the arsenic content determined from a calibration curve.

Chromium, in the hexavalent state, can be complexed with *s*-diphenylcarbazide and read at 540 nanometers. The reaction under the proper conditions is specific.

Aldehydes after absorption in sodium bisulfite solution can be determined using Schiff's reagent. The reaction is not specific for any one aldehyde in the presence of other aldehydes. The measurement is made at 560 nanometers.

Sulfates as barium sulfate, or chloride as silver chloride may be measured by nephelometric techniques under carefully controlled conditions. All reagents, except the precipitating agent, are added and the solution diluted to volume. The absorbance is measured at 500 nanometers. The precipitating agent is then added and the precipitate allowed to form for a specific time period. The absorbance is again measured at the same wavelength. The difference in absorbance is a measure of the sulfate or chloride ion.

ULTRAVIOLET SPECTROPHOTOMETRY

Many compounds containing specific types of chemical bonds will absorb ultraviolet light strongly at very specific wavelengths. The ultraviolet spectrum from 210 to 380 nanometers is of most interest since the ultraviolet spectrophotometers in use are not capable of operation below 210 nanometers. Some compounds of environmental interest, such as ketones, aldehydes, esters and organic acids absorb below this point.

However, many other compounds of great interest do absorb ultraviolet light above 210 nanometers. In general, all aromatic compounds such as benzene, toluene, and xylene have strong absorbing bands. The absorbance spectra of benzene and toluene vapors are shown in Figure 19-7. The spectra of these two compounds show many relatively intense absorption bands with good resolution. While these two compounds are homologs, their spectra are quite different. Figure 19-8 gives the spectra of different concentrations of benzene dissolved in cyclohexane. While the resolution is not as good as that observed in the vapor state, it is still sufficient to identify the compound. Even at a concentration as low as 0.20 milligram per milliliter appreciable absorption occurs at 254.6 nanometers. Phenolic type compounds also exhibit strong absorbance bands in the ultraviolet region.

Some inorganic materials show strong absorbances in the ultraviolet range. Iodine absorbs strongly at 352 and 440 nanometers. Nitrates and nitrites absorb at 270 and 225 nanometers, respectively.

One of the prime requirements for analytical work in this section of the spectrum is a solvent that is relatively transparent to ultraviolet light. A solvent must have a cutoff point well below the absorbing band to be measured. The cutoff point in the ultraviolet region is the wavelength at which the absorbance of a 10-mm path length approaches unity with water as the reference. Table 19-3 gives the cutoff wavelengths for many of the more common solvents.

Generally the solvents of greatest use are methanol, ethanol, isopropanol, isooctane, cyclohexane, sulfuric acid and water. Since absolute ethanol is distilled with benzene, it usually contains traces of benzene which make it unsatisfactory as a solvent.

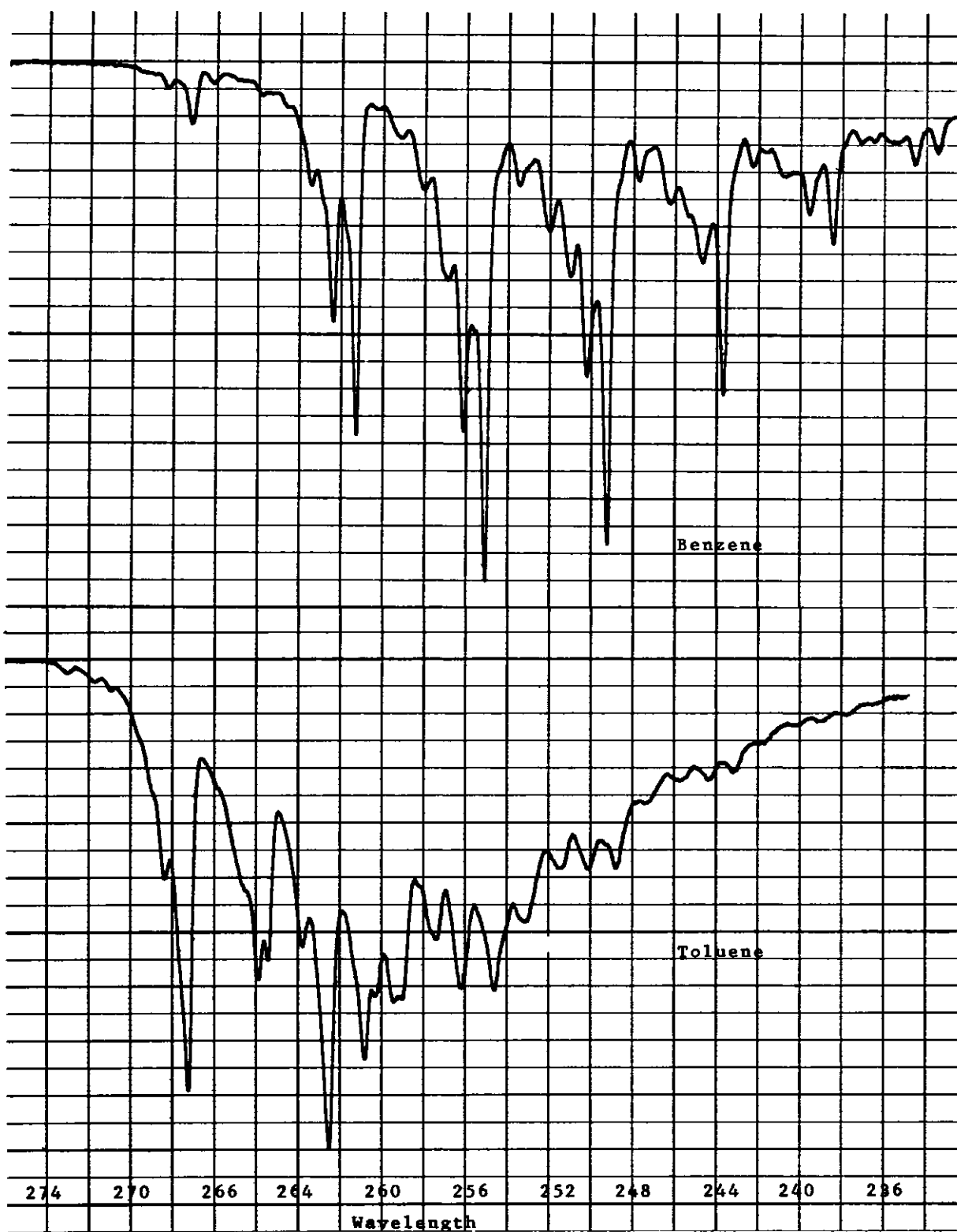


Figure 19-7. Ultraviolet Spectra of Benzene and Toluene Vapor.

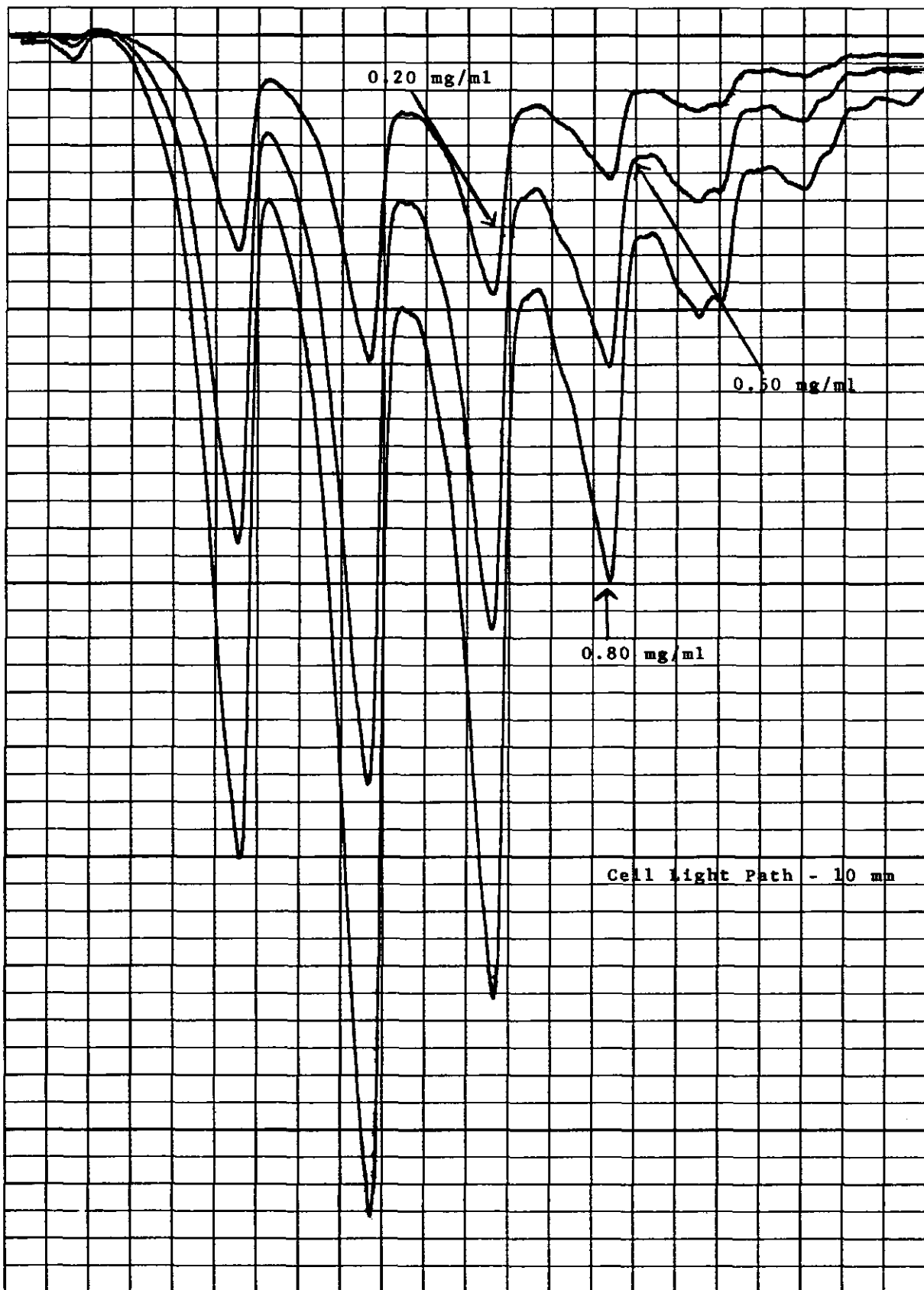


Figure 19-8. Ultraviolet Spectra of Benzene in Cyclohexane.

Table 19-3. Ultraviolet Cutoff Wavelength, Nanometers

Solvent	Grade	
	Reagent	Spectrographic
Acetone	327	330
Benzene	279	280
N-butanol	268	210
Carbon tetrachloride	263	265
Chloroform	245	245
Cyclohexane	210	
Ethanol	219	
Isooctane	220	210
Isopropanol	218	210
Methanol	218	210
Methylethyl ketone	327	
Nitric Acid — 6N	334	
Sulfuric Acid — 6N	215	
Trichloroethylene	287	
Tetrachloroethylene	292	290
Toluene	285	285
Water	212	

"Ultraviolet spectrophotometric and Fluorescence Data", J. A. Houghton and George Lee. *Am. Ind. Hyg. J.* Vol. 22, No. 4, page 296, 301, 1961.

When the material of interest does not absorb in the ultraviolet region, it is sometimes possible to couple it with an absorbing compound to give an absorbing complex.

The sensitivity of ultraviolet methods is much greater than that found with either visible or infrared methods. Frequently, it is necessary to dilute an absorbing compound to the range of 1 microgram per milliliter to read the absorbance. A solution of styrene in cyclohexane as a concentration of 2 micrograms per milliliter gives an absorbance of 0.300 at a wavelength of 247 nanometers.

Much information can be obtained from the absorbance spectrum. If the system is essentially transparent in the region from 210 to 800 nanometers, it contains no conjugated unsaturated or benzenoid system, no aldehyde or keto groups, no nitro group and no bromine or iodine. When absorbance bands do appear, their wavelength will give some indication as to the identity of the group causing the absorbance. Several tables of chromophoric groups and their wavelengths have been published and can be used for identification.¹

Instrumentation

Many types of ultraviolet spectrophotometers are available. They can be generally classed as single or double beam with either a prism or grating for the refraction or diffraction, respectively, of the spectrum. In the single-beam instruments, the unit is balanced against the solvent to read zero absorbance, then the sample is moved into the beam and the absorbance measured. Several of the visible range spectrophotometers can be

converted to ultraviolet spectrophotometers by a suitable attachment.

In some double-beam instruments the beam is chopped by a rotating disc containing an open and a mirrored segment. The beam is sent through the sample cell and then through the reference cell. In other instruments the beam is split and sent through both the reference and the sample cells.

Initially, with the solvent in both the sample and the reference light paths the instrument is adjusted to give a zero absorbance at the wavelength to be used. When the sample is placed in the sample beam, the absorbance due to the cells and the solvent is cancelled and the instrument measures the absorbance of the solute only. An example of a double beam instrument is shown in Figure 19-9.

The single-beam instruments are much lower in price than the double-beam instruments. While it is not necessary to have a recording instrument, it is very convenient to have a recorded spectrum produced by the instrument. If not, the spectrum must be determined by a point-to-point scan and plotting of the points. This is a time-consuming operation.

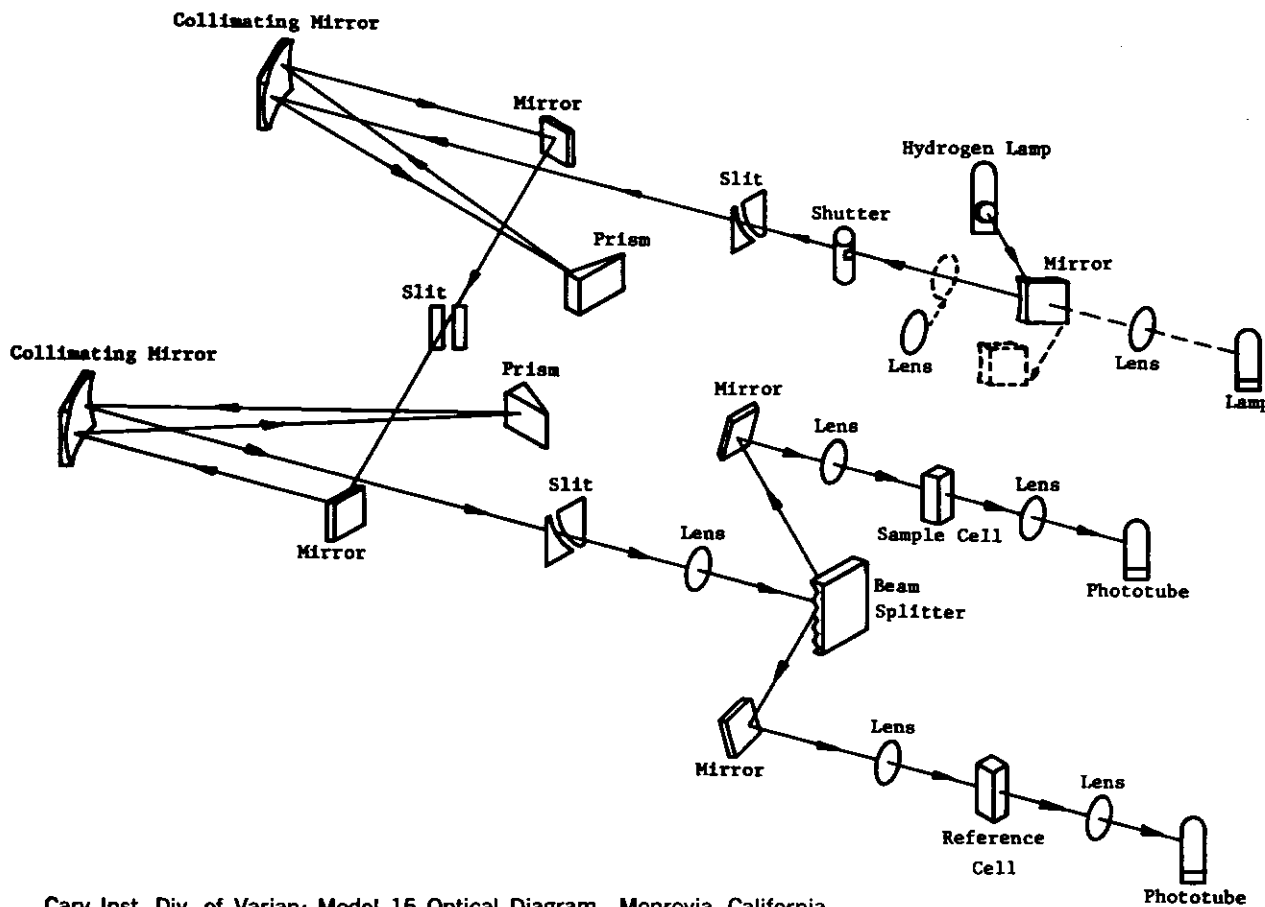
In ultraviolet spectrophotometry the cells used must be transparent to ultraviolet light. This requires that the cells usually be constructed of pure silica because the ordinary glass cells used in visible work absorb much of the ultraviolet. Silica cells are expensive and must be handled with care to prevent scratching and etching. Light sources used are generally either hydrogen, deuterium or xenon lamps. These sources all require special power supplies and in many cases auxiliary cooling systems. Many types of detector tubes may be used. All these tubes have their specific properties. In the less expensive instruments the 1P21 phototube is used as the detector. More expensive photomultiplier tubes are available which are more sensitive in specific regions.

In summary the ultraviolet spectrophotometer is a valuable tool for both the qualitative and quantitative analyses required in environmental work. It offers many possibilities for the analysis of air pollutants. At times it may be the only method available for the analysis of trace amounts of organic pollutants.

Applications

While it is not possible to discuss all the possible determinations that can be made with ultraviolet light, a few will be briefly discussed to illustrate possible procedures. If long-path gas cells are available for the spectrophotometer, it is possible to determine benzene, toluene or xylene directly in air samples. A standard curve is first prepared in the ppm (parts per million) range using the absorbance measurements obtained with known concentrations of the aromatic hydrocarbon vapor at the wavelength giving the maximum absorbance. The absorbance of the air samples are then determined under the same conditions. From the calibration curve prepared earlier it is possible to estimate the concentration of the aromatic hydrocarbon, directly in the air sample.

Where a suitable gas handling system or gas



Cary Inst. Div. of Varian: Model 15 Optical Diagram. Monrovia, California.

Figure 19-9. Schematic Diagram of Double Beam Spectrophotometer.

cells are not available, it is possible to absorb the aromatic hydrocarbon in a transparent solvent and determine it in this solvent as was shown earlier in Figure 19-8 of this section. Calibration curves must be prepared to compensate for incomplete absorption in the solvent.

It is possible to determine phenols and cresols in dilute sodium hydroxide solutions directly in the absorbing solution. The phenolic-type compounds are absorbed in a dilute caustic solution and after dilution the absorbance is measured at the wavelength of maximum absorbance. From previously prepared calibration curves the amount of phenolic compounds can be determined. It must be emphasized that it is not possible to identify the specific phenolic compound present. The results will give only total phenolic content.

The use of the ultraviolet spectrophotometer for the identification of polynuclear aromatic hydrocarbons was developed by Sawicki.² Benzene extracts of air samples are dissolved in a chlorinated solvent and passed through a chromatographic column. Specific sections of the column are extracted with a suitable solvent and the ultraviolet spectrum is determined. The polynuclear aromatic hydrocarbons can be identified and quantitated by the ultraviolet spectra using previously prepared calibration curves. More recent work has utilized the trapping of gas chromatographic peaks and the identification and quantitation of the

material present by ultraviolet spectrophotometry.

With all the recent emphasis on mercury pollution, the ultraviolet absorbance spectrum of mercury vapor has been utilized for the quantitative determination of this element. Mercury strongly absorbs ultraviolet light of wavelength of 253.6 nanometers. Many direct reading instruments are available for the determination of mercury in air. Recent development of the mercury meter for water analysis also utilizes this property. The sample is ashed with potassium permanganate, sulfuric and nitric acids and reduced to elemental mercury with stannous chloride. The mercury is vaporized from the liquid by a stream of filtered air and passed through a cell and the absorbance of 253.6 nanometer ultraviolet light is measured. From previously prepared calibration curves the mercury content of the sample can be determined. It should be emphasized that any organic compound that absorbs at this wavelength and can be vaporized along with the mercury vapor into the gas cell will be determined as mercury and will cause high results. Acetone, for example, can cause serious interference in the determination of mercury.

While the above examples are only a few of the possibilities for the use of ultraviolet spectrometry, experience in the technique will open up many other uses. It is a powerful tool for the solution of many analytical problems.

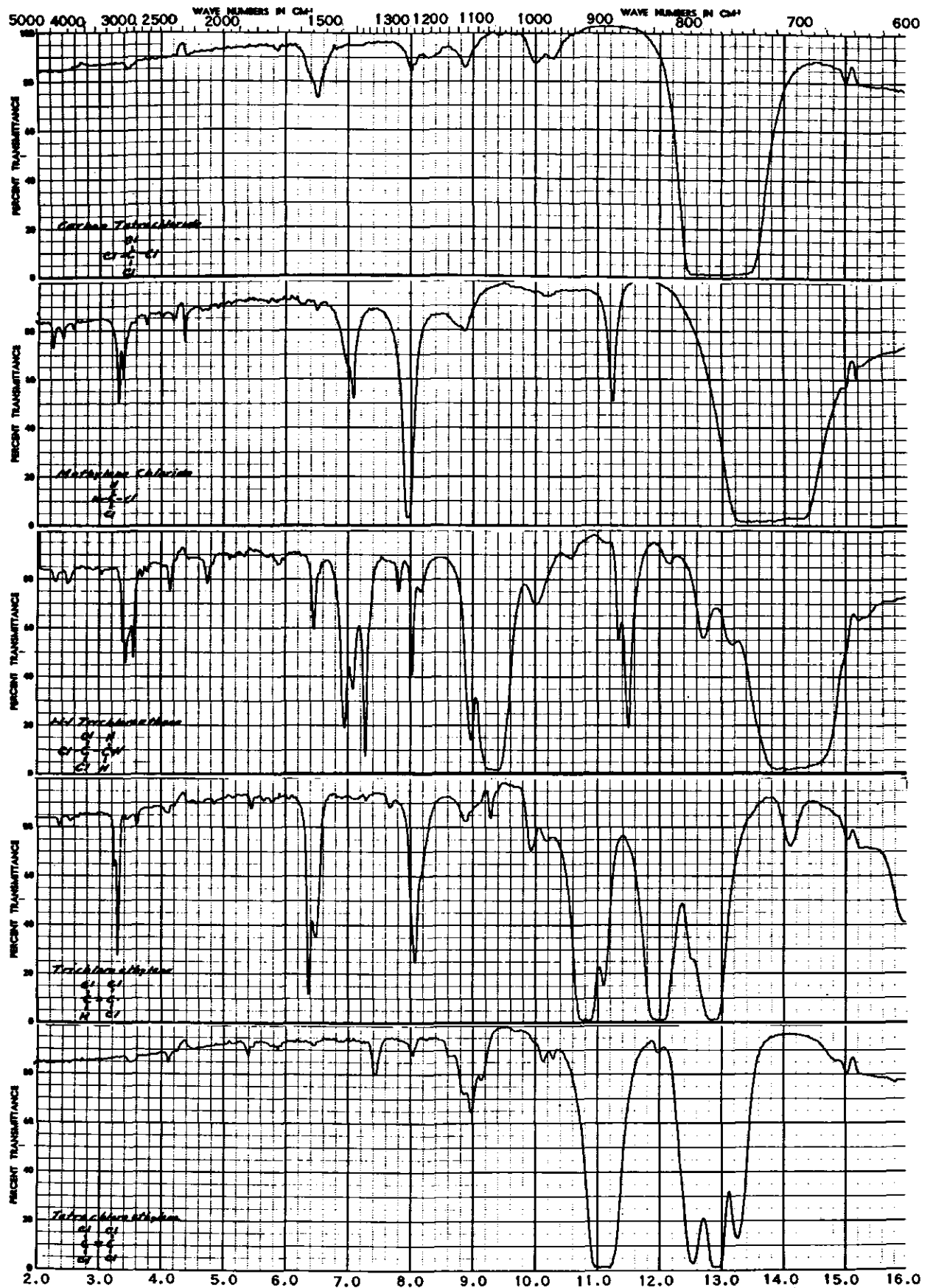


Figure 19-10. Infrared Spectra of Chlorinated Hydrocarbons — Wavelength in Micrometers.

INFRARED SPECTROPHOTOMETRY

Introduction

The section of the electromagnetic spectrum extending from 0.8 to 200 micrometers is classed as the infrared region. However, most of the analytical uses of this energy fall in the range of 0.8 to 50 micrometers, which can be explored with commercially available instruments. Absorption of energy in this section of the spectrum results from the vibrational-rotational stretching and bending modes in the molecule. The infrared absorption spectrum of a compound can be characterized as a fingerprint of that compound. The absorbance bands are so definite that it is possible to identify stereoisomers from their spectra. It is possible to define the structure of complex molecules, such as penicillin, from study of its infrared spectrum.

The infrared region is divided into three primary sections, the rock salt (sodium chloride) or fundamental region from 2 to 16 micrometers, the potassium bromide region from 10 to 25 micrometers and the cesium iodide region from 10 to 38 micrometers. These regions are so named because of the material used for the prisms and cell windows. Silica and glass cannot be used in infrared equipment since they absorb any energy with a wavelength above 4 micrometers.

Much valuable information can be gained from the absorbance bands found in the fundamental region. This section is usually divided into the "group frequency" region from 2.5 to 8 micrometers and the "fingerprint region" 8 to 16 micrometers.

In the group frequency region the principal absorption bands are primarily due to vibration of units consisting of only two atoms of the molecule, units which are more or less dependent only on the functional group giving the absorption and not on the complete molecule structure. Structural influences may cause small shifts in absorption bands from their normal position.

In the region from 2.5 to 4.0 micrometers the absorption is due to hydrogen stretching vibrations with elements of mass of less than 20. The center range from 4 to 6.5 micrometers is termed the unsaturated region. Primarily, triple bonds cause absorption from 4.0 to 5.0 micrometers. Double bonds frequently absorb in the region from 5.0 to 6.5 micrometers. Careful study of the absorption bands can help to identify and distinguish between C=O, C=C, C=N, and N=O bonds.

Absorptions in the region from 8.0 to 16.0 micrometers are single-bond stretching frequencies and bending vibrations of poly-atomic systems involving motions of bonds linking a substituent group to the remainder of the molecule. This is the fingerprint region. While too many absorption bands appear in this region to allow for specific identification it is possible to determine much information about the molecule. Ortho, meta and para substitutions are easily identified.

Chlorinated molecules absorb strongly in this region. Figure 19-10 shows the infrared spectra of five of the chlorinated hydrocarbons. Carbon tetrachloride and tetrachloroethylene show a complete absence of any absorption below 6 microm-

eters. As hydrogen is added to the molecule the bands at 3.3, 3.4, and 3.6 micrometers appear in the spectra. The intense absorption bands above 11 micrometers are typical of chlorinated compounds. From these spectra it is quite evident that there is little problem identifying the specific compound present. Generally for liquid work the light path is relatively short. These spectra were prepared using a cell with a light path of 0.25 mm.

Inorganic molecules also have characteristic absorption bands in the rock salt region. The inorganic material is generally ground to a very small particle size in a clear mineral oil and a mull prepared or it can be dispersed in potassium bromide powder and pressed into a pellet. As will be discussed later, methods are available to determine small amounts of alpha quartz in respirable dust by the pellet technique.

Some of the specific absorption bands of interest in environmental control work are shown in Table 19-4. Many more complete tabulations of absorption bands are available in the literature. One of the most useful is the COLTHUP chart.³ From the data in Table 19-4 it is evident that the bands tend to overlap in some areas. For example the esters, acids, ketones and aldehydes all show strong absorption bands in the same region. Bands in the fingerprint region may make it possible to identify the particular type of compound present.

Table 19-4. Specific Infrared Absorption Bands

Grouping	Absorption Band Micrometers
Alkanes, CH ₃ -C, -CH ₂ =	3.35 to 3.65
Alkenes CH=CH ₂	3.25 to 3.45
Alkyne C=C	3.05 to 3.25
Aromatic Hydrocarbons	3.25 to 3.35
Aromatic (Subst, benzenes)	6.15 to 6.35
Alcoholic (OH)	2.80 to 3.10
Acids (COOH)	5.75 to 6.00
Aldehydes (COH)	5.60 to 5.90
Ketones (C=O)	5.60 to 5.90
Esters (COOR)	5.75 to 6.00
Chlorinated (C-Cl)	12.80 to 15.50

It should be pointed out that while infrared is a very valuable analytical tool it does have its deficiencies. The sensitivity of infrared methods is much less than that for the ultraviolet methods.

As an example, in the determination of mineral oil using the 3 micrometer bands, the minimum concentration that can be determined with conventional cells is 1 milligram per milliliter of solvent.

Water and lower molecular weight alcohols cannot be used as solvents as they damage the cell windows. Moisture condensation on cell windows will also cause severe damage to the cell windows. In addition, water absorbs infrared energy strongly.

A solvent, to be of value in infrared work, should have as few absorption bands as possible and none in the region of interest. No organic solvent is completely transparent to infrared radiation. Carbon disulfide and carbon tetrachloride

are the common solvents. Carbon tetrachloride absorbs strongly from 12.5 to 13.5 micrometers while carbon disulfide absorbs strongly at 4.5 and 6.5 micrometers. Tetrachloroethylene is transparent except in the region from 10 to 16 micrometers. The high-boiling liquid Freons also are useful as solvents. The solvent may influence the spectrum of the solute. Particular care should be exercised in the selection of a solvent for compounds which are susceptible to hydrogen bonding effects. All solvents must be free of water.

Instrumentation

Basically, an infrared spectrophotometer consists of a source to produce the radiation, a monochromator to disperse the radiation, a sample compartment, a detector and a recorder. The equipment may be classified as either a single- or a double-beam system. In the single-beam system the beam passes through a single sample cell and to the detector. In this system it is necessary to determine the spectrum of the solvent, the combined spectrum of the solvent-solute mixture and then subtract the spectra to determine the net spectrum of the solute.

In the double-beam system the incident beam is chopped and sent alternately through the sample cell and then through the reference cell. The beams are then brought to the same detector. The detector balances the signal it receives from both cells by driving a comb in and out of the reference beam to alter the intensity of the reference beam to equal that of the sample beam. The position of the comb is transmitted to the recorder. An example of a double beam instrument is shown in Figure 19-11.

The source in most infrared spectrophotometers is either a Nernst glower or a Globar. The Nernst glower consists of a mixture of zirconium and yttrium oxides which is formed into a hollow rod 2 millimeters in diameter and 30 millimeters long. The surface temperature is between 1500° and 2000°C. The glower furnishes a wide range of infrared wavelengths, with maximum emission at 1.4 micrometers. A secondary heating source is necessary to light the glower since it is non-conducting when cold. It must be protected from drafts but still must be ventilated to remove the vaporized oxides and binders from the glower.

The Globar source is a solid rod of sintered silicon carbide. It is self-starting and is heated to 1300° to 1700°C. Maximum intensity occurs at 1.9 micrometers. Although it is less intense than the Nernst glower, it is more suitable for work beyond 15 micrometers, since its radiant energy output decreases less rapidly with increasing wavelength.

The monochromator is generally a Littrow mount. The beam from the collimating mirror is focused on the entrance slit. Either a grating or a prism may be used to disperse the incident beam. The prisms are made from single crystals of either sodium chloride or potassium bromide, depending upon the required working range of the instrument.

The grating provides better dispersion and thus better resolution but is usable over only a limited range. Two gratings are generally used to cover

the entire range of the instrument so that each is used only in the first order.

The detectors are of a thermal type. Photoconductors are not applicable except in the near infrared region. A special type thermocouple is the most widely used. Quartz fibers are used to support a blackened gold foil receiver less than one micron in thickness to which is fastened the hot junction made by welding two different semiconductors together at one end. The semiconductors must have a high thermoelectric efficiency. The cold junction is maintained at a constant temperature and kept darkened. The pair is housed in an evacuated steel casing with a potassium bromide or cesium iodide window.

A second type of thermal detector is the bolometer. It produces an electrical signal as the result of a change in resistance of a metallic conductor with temperature as the infrared energy is absorbed.

Cells for infrared use consist of polished, optically flat discs of sodium chloride or potassium bromide separated by an amalgamated lead spacer and held liquid-tight by a holder. Liquid cell path lengths range usually from 0.1 mm down so that only a thin layer of the sample is exposed to the beam. Gas cells with path lengths of 1 meter are available for analysis of air pollutants. Infrared cells are very expensive and must be protected from any contact with moisture either in the sample or by exterior condensation to prevent etching of the crystals.

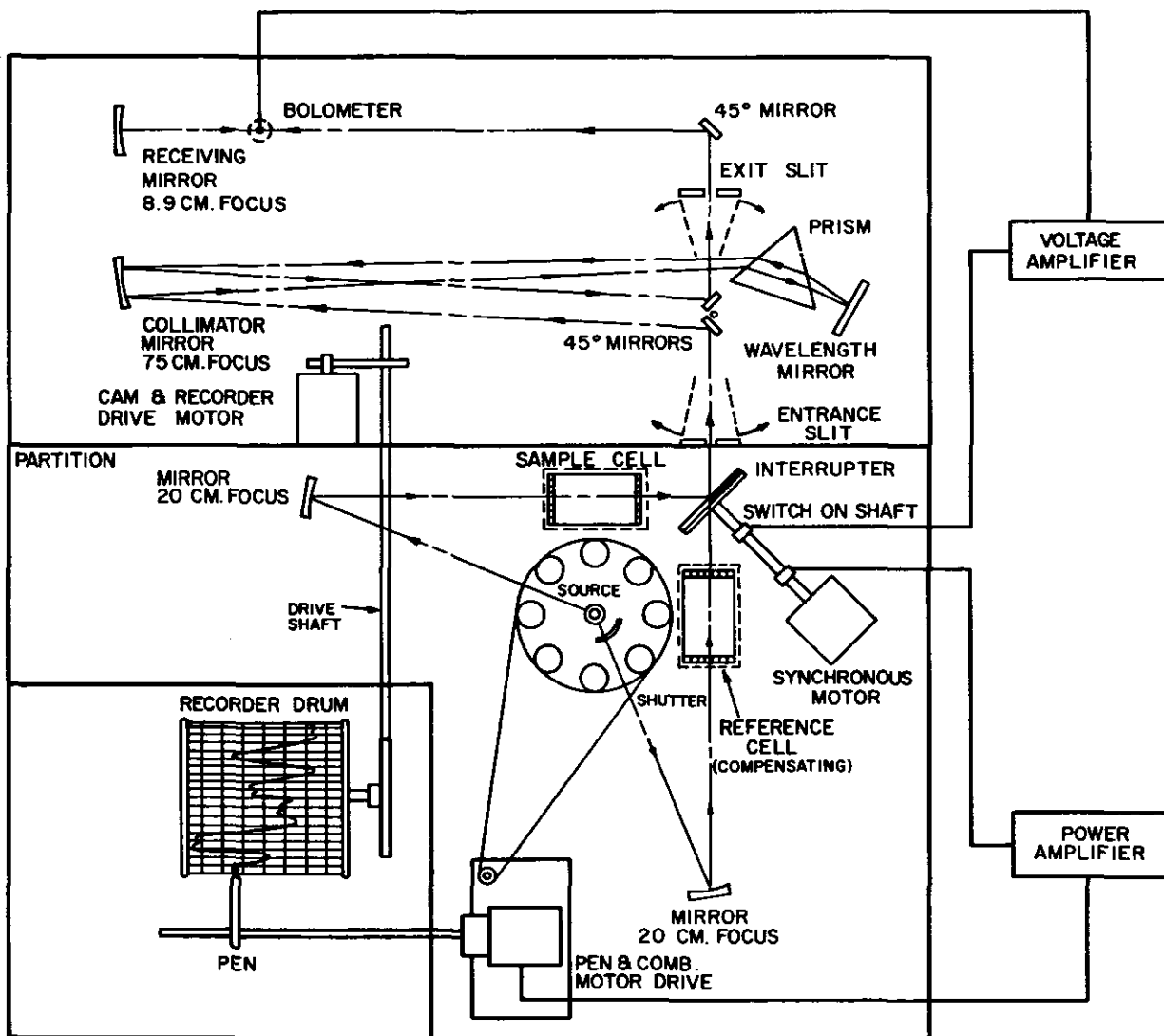
The potassium bromide pellet technique was developed to handle materials that could not be dissolved in a suitable solvent. The material to be examined is reduced to a fine powder, dispersed in high-purity potassium bromide powder and formed into a pellet under high pressure. The pellet is placed in the cell compartment and the spectrum determined. Instruments to be used for pellet analysis should be equipped with a beam condensing system to concentrate the incident beam to a small size. Using the condensing system the pellet size can be kept small and the dilution of the sample by the potassium bromide is reduced.

Applications

The use of infrared spectrophotometers in environmental control analysis has been quite limited in the past probably due to the cost of the equipment and a limited knowledge of its possibilities. It is extremely valuable for the qualitative and quantitative analysis of solvents. With experience in the technique, simple solvent mixtures can be analyzed qualitatively from one spectrum. An estimate of the quantitative analysis can usually be made from the same spectrum. A known synthetic can be prepared at the approximate concentration and its spectrum determined. By comparing the spectra of the unknown and known mixtures it is possible to get an estimate of the actual concentration.

For complex solvents, it is usually advisable to fractionate the mixture and examine the fractions by infrared analysis.

The determination of airborne mineral oil on filters used to collect particulate material is pos-



Baird Associates: Bulletin XXXIII. Cambridge, Massachusetts.

Figure 19-11. Schematic Diagram of a Double Beam Infrared Spectrophotometer.

sible using infrared. The oil is first extracted from the filter with ether or hexane. The solvent is allowed to evaporate at room temperature. The oil is then redissolved in a known volume of carbon tetrachloride. The absorbance of the sample is determined over the range of 3 to 4 micrometers. The mineral oil content is calculated from a previously prepared calibration curve, using a comparable oil.

The fixed gases such as carbon monoxide, sulfur dioxide and ammonia can be determined directly in air by use of gas cells with a one meter light path. The gases have definite spectra and can easily be identified. The technique requires relatively large volume air samples.

One recent development is the determination of alpha quartz in respirable air samples as is required by both the Coal Mine Safety and Health Act and the Occupational Safety and Health Act. The dust sample and filter are ashed or the dust removed from the filter by ultrasonic means and ashed. The ashed sample is mixed with potassium bromide and formed into a pellet under high pressure. The infrared absorbance is measured at 13.1 micrometers. Using a previously prepared calibration curve, the alpha quartz content is then determined. Under carefully controlled conditions it is possible to measure 10 micrograms of quartz by this technique.

FLUORESCENCE SPECTROPHOTOMETRY

Introduction

Use of the fluorescence properties of certain compounds as an analytical tool has become important in the environmental control field only in the last few years. The analysis of beryllium in particulate material collected in air samples is based on the fluorescence of a beryllium morin complex. Later work on the polynuclear aromatic hydrocarbons has developed additional interest in this technique.

Fluorescence spectrometry is a highly sensitive analytical tool which can be used to measure concentrations as low as 10^{-8} to 10^{-10} grams per milliliter. Few colorimetric procedures are of value at concentrations below 10^{-7} grams per milliliter.

Fluorescence is essentially an electronic phenomenon and is primarily concerned with light of wavelengths in the region of 200 to 800 nanometers. When light in this region strikes some compounds they absorb energy at specific wavelengths which are characteristic of the compound. This is called the absorption spectrum of the compound. As a result of this absorption of energy, some of the molecules are raised from the ground state to a higher energy level called a singlet or excited state. Since this excited state is unstable, the molecule tends to return to the ground state by emitting the absorbed energy as fluorescence. As some of the released energy is lost by other means, the energy released as fluorescence is always less than the absorbed energy. Therefore, the wavelength of the fluorescence is longer than that of the absorbed energy. The absorption and release of energy as fluorescence takes place in 10^{-8} seconds.

In some instances the absorbed energy may be released in two steps. First a small amount of energy is lost, allowing the molecule to reach the triplet or metastable state. It then returns to the ground state by releasing energy slowly. The energy lost from the triplet to the ground state is called phosphorescence. As in fluorescence, the energy lost by phosphorescence is less than the total absorbed energy and thus, the wavelength of the phosphorescence is longer than that of the absorbed energy. Since the energy release is slower, phosphorescence is more persistent than fluorescence.

Not all organic compounds exhibit fluorescence. In general, the compounds which fluoresce are aromatic or contain conjugated double bonds (i.e., alternating single and double bonds). Those compounds containing electrons which undergo energy transformations readily should fluoresce. Any radical, which when added to the molecule increases the freedom of these electrons, will enhance the fluorescence. Conversely, any radical which tends to restrict the electrons' ability to absorb energy will decrease the fluorescence.

Two different spectra are generally shown for compounds showing fluorescence. The excitation spectrum is obtained by measuring the variation in intensity of a strong emission wavelength as the wavelength of the excitation energy is changed. Conversely, when the wavelength and intensity are measured over the emission range using a

strong excitation wavelength, an emission spectrum is obtained.

The effects of substitution upon fluorescence can be illustrated with benzene, aniline and nitrobenzene. In dilute solutions, aniline is 40 to 50 times more fluorescent than benzene whereas nitrobenzene does not fluoresce. The $-NH_2$ group increases the freedom of the electrons while the $-NO_2$ group tends to decrease the freedom.

Many factors may affect the intensity of fluorescence. Among the more important are instrumental parameters, concentration, solvent, pH, temperature and the stability of the compound to light. Instrumental slit widths and light intensity can affect the intensity and all instrumental parameters must be kept constant during any set of determinations.

Concentration plays a very important role in the intensity of emitted light. Generally the fluorescence is viewed at right angles to the incident light. The fluorescence emitted must pass through the cell and some is reabsorbed by the solution. The higher the concentration of the compound, the greater the energy which is reabsorbed and lost. Consequently, a linear relationship between concentration and fluorescence exists only in a very dilute solution.

Solvents used in fluorescence measurements may affect the results radically. Many solvents may contain impurities which will fluoresce and need extensive purification to make them usable. Solvents such as water, simple alcohols, ether or hexane can be used. The fluorescence wavelength may shift rather widely as the solvent is varied.

Ionization of the fluorescing compound may change or eliminate fluorescence. Thus, pH may become an important factor in any measurement. Aqueous buffer solutions are frequently used to control pH.

Fluorescence intensity tends to increase as the temperature is lowered and decreases as the temperature is raised. The fluorescence may change by as much as 5 percent per degree of temperature change.

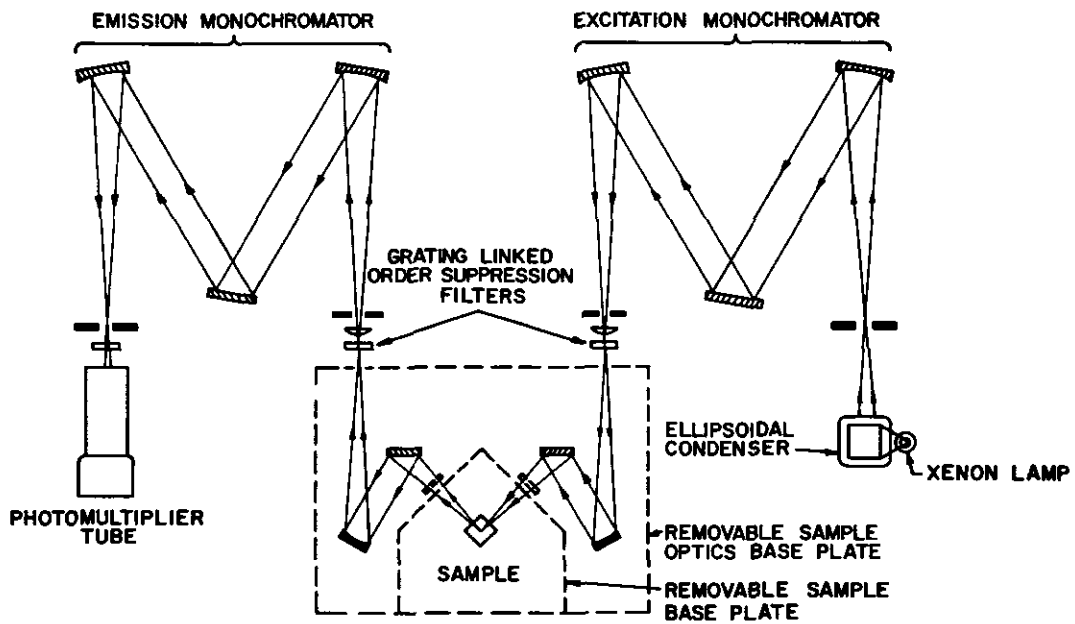
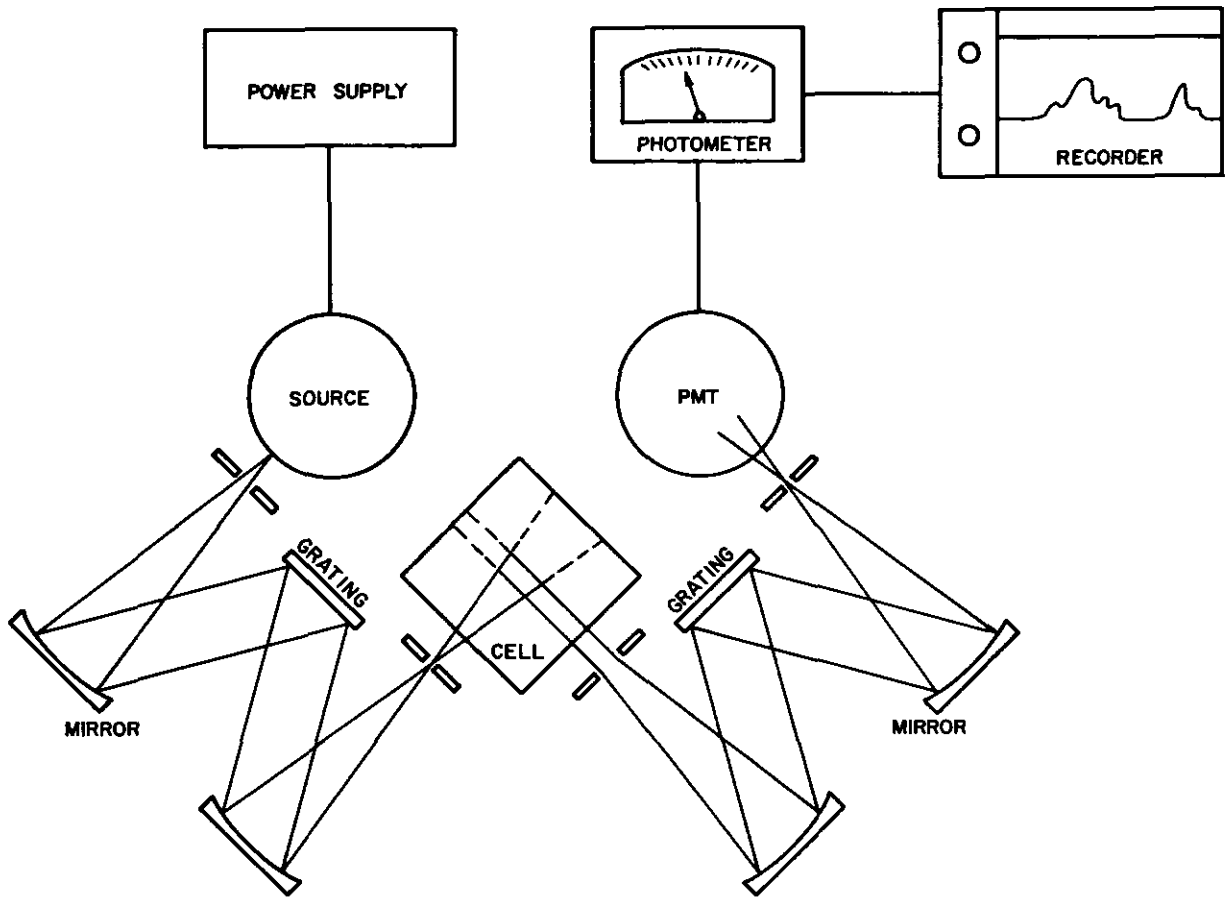
Some compounds tend to decompose under the influence of ultraviolet light. Thus, as the concentration of the solute decreases the intensity of fluorescence decreases, except in those cases where the decomposition products may fluoresce.

Quenching is the term applied to the loss of fluorescence. As mentioned earlier, the compound itself may cause concentration quenching. Some compounds can reduce or eliminate fluorescence. Quenching can be caused by inner filter effects, energy degradation, chemical change, absorption and/or intersystem transfer.

It should be pointed out that all glassware must be kept very clean. Many detergents fluoresce and should not be used to clean cuvettes (sample cells). Chromic acid absorbs ultraviolet light and should not be used for cleaning glassware for fluorescent procedures. Concentrated nitric acid is frequently used to clean cuvettes.

Instrumentation

There are several types of instruments available on the market. Many of the UV-visible light spectrophotometers have fluorescence attachments.



American Instruments Co.: Bulletins 2392H and 2423-1. Silver Springs, Maryland.

Figure 19-12. Schematic Diagram of Two Types of Spectrofluorometers.

In these the excitation is caused by the entire spectrum of the ultraviolet region. The emitted radiation is measured at a right angle to the incident beam. The emitted radiation is analyzed by filters, gratings or prisms. With these instruments the excitation spectrum cannot be determined. These units are generally suitable for routine analysis.

The second general type of instrumentation involves units with two monochromators. With these spectrophotofluorometers a specific wavelength can be used for excitation and the fluorescence spectrum can be determined. Since both the excitation and emission spectra are valuable for identification purposes, these systems are very valuable for the identification of unknown samples. These instruments can be either direct reading or equipped with a recorder.

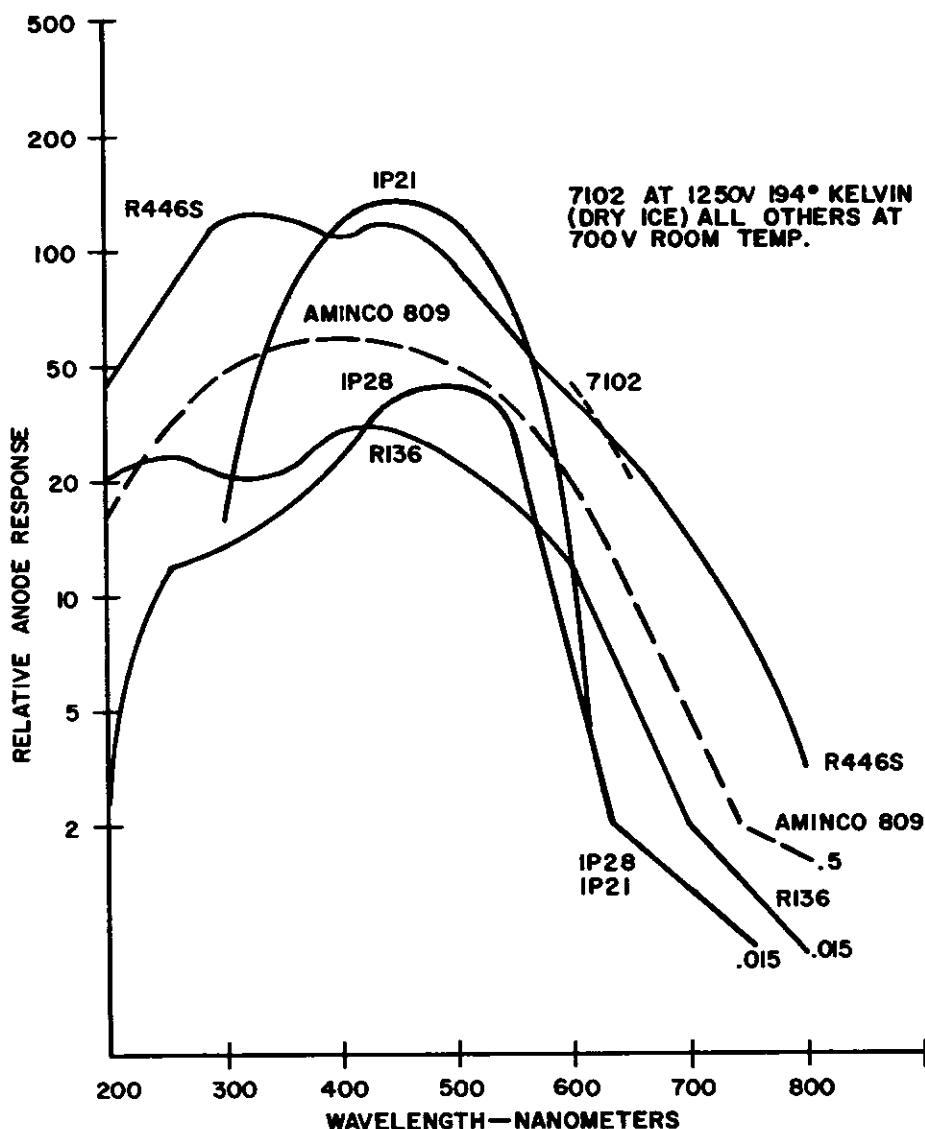
Schematic diagrams of two different spectrophotofluorometers are shown in Figure 19-12.

The light source is an important part of any spectrophotofluorometer. The xenon-arc lamp is commonly used. It produces a continuous spectrum from 200 to 800 nanometers and has a greater intensity in the ultraviolet region than does the tungsten lamp. The xenon-arc lamp produces large amounts of ozone and should be locally exhausted to remove the toxic gas.

Mercury lamps give a discontinuous spectrum consisting of high intensity lines at 365, 405, 436 and 546 nanometers. If the compound to be studied is excited in this region, the mercury lamp is very satisfactory. It is not satisfactory for studying compounds excited by other wavelengths.

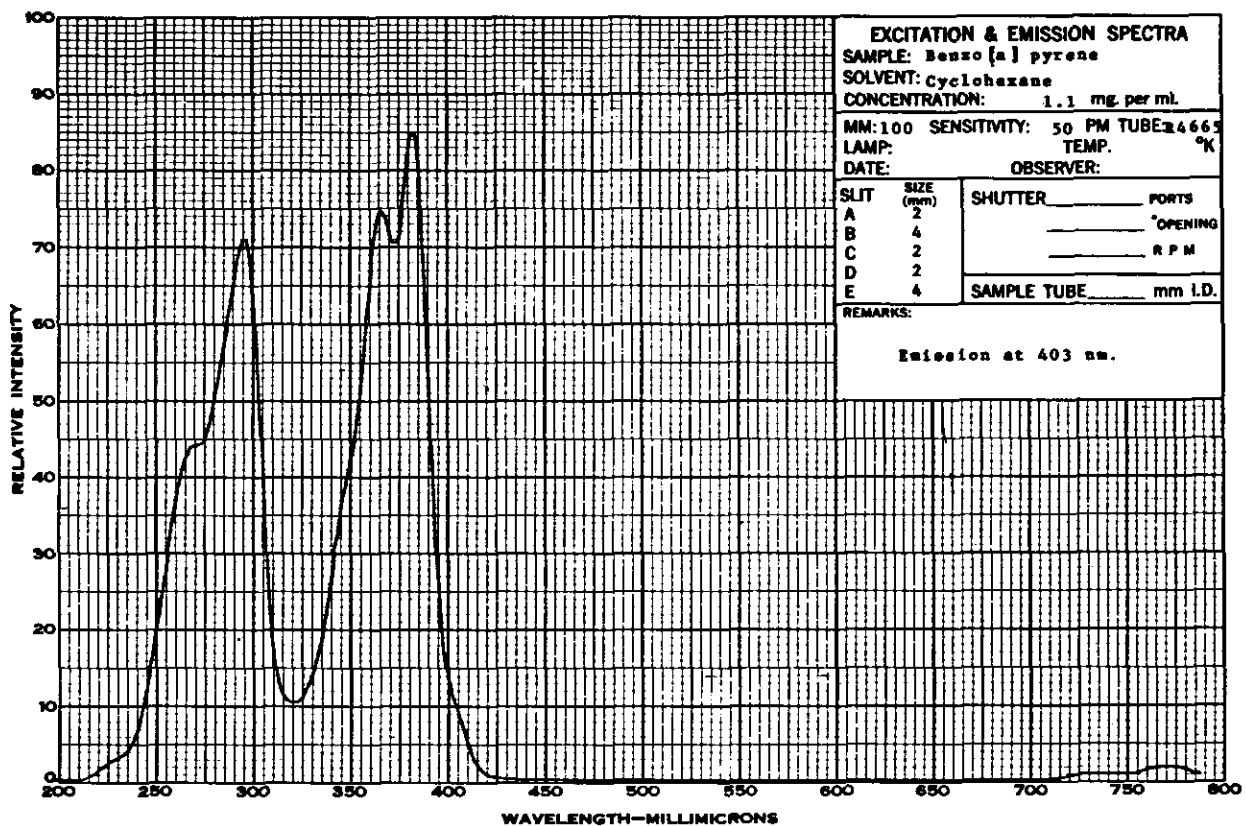
The cells used are of either glass or silica. If the exciting wavelength is above 320 nanometers the cheaper glass cells can be used. Below this wavelength silica cells are required. All cells should be checked for fluorescence.

The detectors are photomultiplier tubes. Since



American Instrument Co.: Aminco Lab. News 26 (182):8, 1970.

Figure 19-13. Spectral Response of Some Photomultiplier Tubes.



Tracing made at U.S. Steel Research.

Figure 19-14. Excitation Spectrum of Benzo (a) Pyrene.

the spectral response of the tube varies from type to type, consideration should be given to specifying a tube with the maximum response in the region of interest. Figure 19-13 shows the spectral response of several tubes. The 446 S gives the greatest response over the widest range but is the most expensive.

Applications

The use of fluorescence in environmental control has developed only in the last few years. Its use will probably increase rapidly as new organic compounds are added to the hazardous chemicals list and permissible levels are promulgated.

The analysis of airborne particulate material for beryllium is one example of fluorescence analysis. Under proper conditions beryllium can be reacted with morin to produce a compound with strongly fluorescent properties. This reaction has been the basis for many published methods for the determination of microgram quantities of beryllium.

As interest in the polynuclear aromatic hydrocarbon content of the effluent from combustion processes has increased, the use of the spectrophotofluorometer has increased rapidly. Most of these compounds have specific excitation and emission spectra, and very minute quantities of these compounds can be determined in complex mixtures after separation by column chromatography, gas chromatography or thin layer chroma-

tography. Procedures for the quantitative measurement of such compounds as benzo (a) pyrene directly from thin layer chromatograph plates have been published. The excitation and emission spectra of benzo (a) pyrene are shown in Figures 19-14 and 19-15. These spectra are specific for this compound.

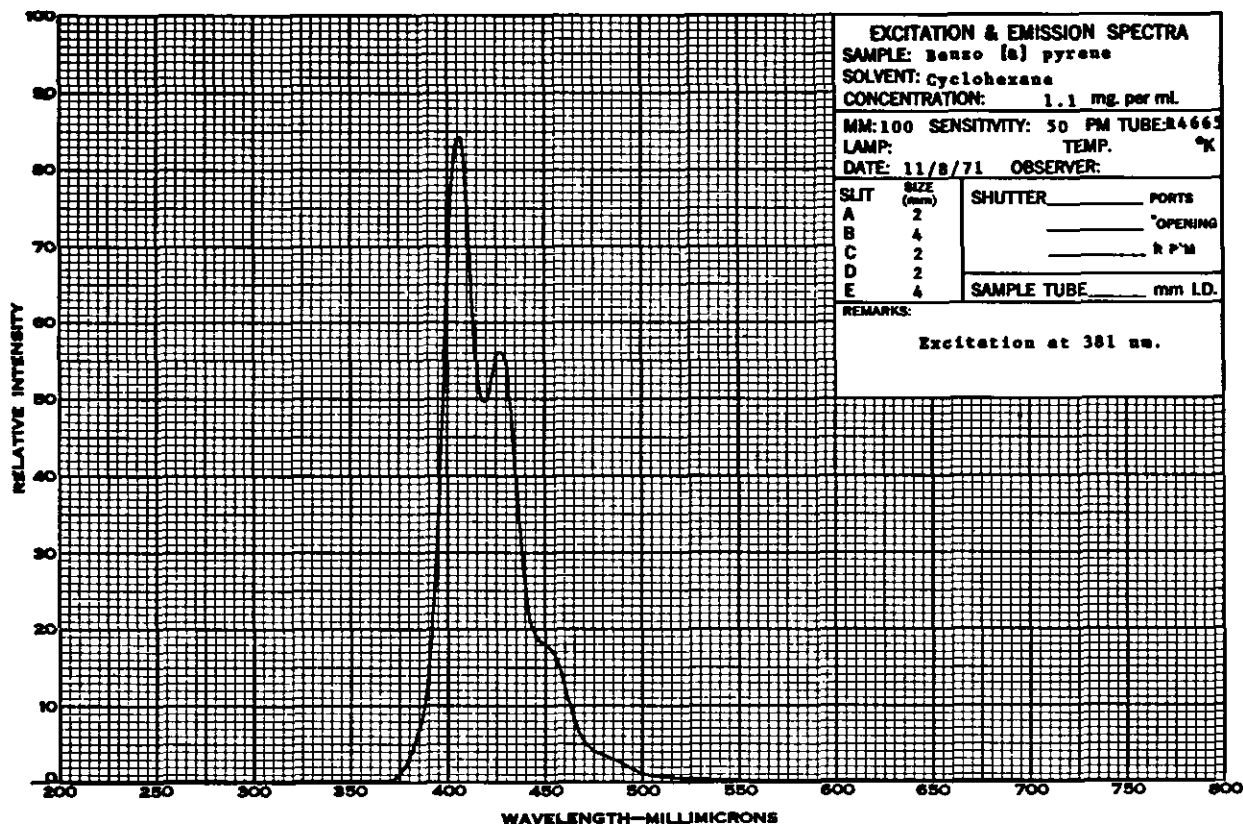
The extended use of these fluorescent techniques is expected to lead to a greater number of analytical methods in this phase of spectrophotometry.

ATOMIC ABSORPTION SPECTROPHOTOMETRY

Introduction

The basic principle of atomic absorption has been known for over one hundred and fifty years, but its application to analytical chemistry started with the work of Walsh, first published in 1955. Since that time the field has developed rapidly, producing new and improved instrumentation and many new and improved analytical techniques.

The basic principle of atomic absorption can be considered to be the inverse of that of the emission method of analysis. In the thermal excitation of atomic vapor, only a small proportion of the atoms are raised to an energy state where they emit characteristic radiation of specific wavelengths. This property is the basis of emission spectrography. Atomic absorption utilizes



Tracing made at U.S. Steel Research.

Figure 19-15. Emission Spectrum of Benzo (a) Pyrene.

the ability of the remaining atoms, which are in the ground state, to absorb energy at specific wavelengths as this energy passes through the atomic cloud.

At the temperature of a gas-air or gas-oxygen flame, a few atoms are excited but the remainder are in the ground or unexcited state. Thus, because of the higher population of ground state atoms, it would be advantageous, from the analytical viewpoint, to measure the ground state atoms. While it is possible to measure the absorption of a continuum at any specific wavelength, the width of the absorption line at the temperatures of 2000°

to 3000°K is of the order of 0.002Å and a spectrometer with a very high resolving power would be required. With the advent of the hollow cathode lamp it has become possible to produce a source emitting specific wavelengths. Thus, a lamp with a lead cathode will produce radiation of specific wavelengths characteristic of lead. If the physical properties of the metal prevent its use as the cathode, a salt of that metal may be packed in a cathode made of some other suitable metal.

The formation of an atomic vapor cloud requires (1) the dispersion of the solution in the form of small droplets, (2) evaporation of the solvent to form dry particulate material in the flame, (3) the decomposition of the salt or oxide, and (4) the formation of the atomic cloud.

Much information has been published on the detection limits of atomic absorption techniques. The detection limits should be used only as a general guide, as they will vary from instrument to instrument. The data in Table 19-5 will give some estimate of the detection limits of the technique for various elements. The detection limit is generally defined as the concentration in aqueous solution which will produce a signal that is twice the standard deviation of the random noise or baseline signal.

“Sensitivity” is another term often employed in the atomic absorption literature. It refers to the concentration in aqueous solution which will generate a signal of 1 percent absorption or 0.0044 absorbance units. The sensitivity will vary from instrument to instrument as it is a function of the lamp, burner head and the nebulizer.

As with other analytical systems, chemical interferences may occur for many elements in atomic absorption. A chemical interference may be defined as any reaction which affects the analyte or element to be determined. Any cation or anion present in the sample which will form compounds with the analyte that are not easily dissociated will reduce the absorption. Aluminum, phosphate, titanium and silica interfere with the determination of alkaline earth metals. Setting all parameters such as burner type, oxidant, fuel, flame temper-

Table 19-5. Detection Limits (ug/ml)

Element	D.L.	Element	D.L.	Element	D.L.
Ag	0.002	Ho(a)	0.1	Ru	0.3
Al(a)	0.03	In	0.05	Sb	0.1
As(b)	0.1	Ir	2.	Sc(a)	0.1
Au	0.02	K	0.005	Se(b)	0.1
B(a)	2.5	La(a)	2.	Si(a)	0.08
Ba(a)	0.02	Li	0.0006	Sm(a)	2.
Be(a)	0.001	Lu(a)	3.	Sn(c)	0.02
Bi	0.04	Mg	0.0001	Sr(a)	0.01
Ca	0.001	Mn	0.002	Ta(a)	2.
Cd	0.001	Mo(a)	0.03	Tb(a)	3.
Co	0.01	Na	0.002	Tc	0.9
Cr	0.003	Nb(a)	1.	Te	0.09
Cs	0.05	Nd(a)	2.	Ti(a)	0.09
Cu	0.002	Ni	0.01	Tl	0.03
Dy(a)	0.2	Os(a)	0.5	Tm(a)	0.2
Er	0.1	P(a)	100.	U(a)	30.
Eu	0.04	Pb	0.02	V(a)	0.06
Fe	0.01	Pd	0.02	W(a)	3.
Ga	0.1	Pr(a)	10.	Y(a)	0.3
Gd(a)	4.	Pt	0.1	Yb(a)	0.04
Ge(a)	1.	Rb	0.005	Zn	0.002
Hf(a)	8.	Re(a)	1.	Zr(a)	5.
Hg	0.5	Rh	0.03		

(a) Nitrous oxide-acetylene flame used.

(b) Argon-hydrogen-entrained air flame used.

(c) Air-hydrogen flame used.

Taken from Analytical Methods for Atomic Absorption Spectrophotometry

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ature, flame region and sample medium at the optimal values will reduce this interference. The addition of releasing or chelating agents to the sample will also reduce this interference. Lanthanum is used as a releasing agent and EDTA (ethylenediamine tetraacetic acid) is a common chelating agent.

Use of an organic solvent to extract the analyte from its solution will concentrate the analyte and improve the sensitivity and detection limit. Ammonium pyrrolidine dithiocarbamate (APDC), diethylammonium diethyldithiocarbamate (DDDC), thenoyltrifluoroacetone (TTA) and dithizone are used extensively as chelating agents. They can be made fairly selective by control of pH and the use of masking agents. Methyl isobutyl ketone (MIBK) is the most common organic extractant because it produces a stable flame. MIBK is somewhat soluble in acid aqueous solutions which makes the accurate control of the solvent volume difficult. A mixture of MIBK-cyclohexane (3:1) does not have as great a solubility in aqueous solutions and yet is reported to have as good extractive powers as MIBK. Also the MIBK can be saturated with an aqueous solution at the same pH as the sample solution to control this problem. If the standards are treated in exactly the same

manner as the samples, the solubility effect will be cancelled. Carbon tetrachloride or chloroform can be used, but the enhancement is less than that with MIBK and their combustion produces phosgene which is very toxic. Benzene and kerosene produce a smoky luminous flame and thus are not satisfactory.

While burners are the most common source of the vapor cloud, some new methods of forming the cloud have been developed for specific determinations. Flameless atomic absorption has been used to determine mercury, by the reduction of the mercury ions to elemental mercury and vaporization of the mercury in a gas stream into a gas cell substituted for the burner. Carbon rod and tantalum strips, electrically heated, to vaporize the sample have been developed. These special techniques will be discussed later.

Figure 19-16 is a modified atomic chart illustrating the elements that can be determined by atomic absorption methods at this time. Some elements can be determined by either flame photometry or atomic absorption, while others can be determined by one or the other technique.

Instrumentation

As discussed in the preceding section, the basic instrument consists of a light source, a burner or other producer of a ground-state vapor cloud, a monochromator and a detector. The basic equipment is shown in Figure 19-17. Many modifications of this basic design are available commercially. Single and double-beam spectrophotometers have been developed and each has specific advantages and disadvantages. Single-beam instruments require very stable electronic variations. In some types of double-beam instruments the beam is chopped so that part of the beam bypasses the burner. The detector balances the two beams to produce a signal. Other double-beam units pass two beams of light directly through the flame. The double-beam principle is used to eliminate instrumental variations.

The choice of the proper type of commercial instrumentation is a complex problem and is beyond the scope of this chapter. Either system is adequate for most of the determinations required of an environmental control laboratory. Personal preference of the user enters into the choice.




At the present time there are hollow cathode lamps to cover approximately 70 elements. These are available as single element lamps. The current requirements vary from 5 to 40 milliamperes. To reduce the number of lamps required some lamps are made with multiple element cathodes. The cathodes may contain from two to six elements in a single lamp.

The type of monochromator used varies from manufacturer to manufacturer and each is designed to give adequate performance with the remaining components of the system. Generally 0.25 to 0.5 meter monochromators are used. The shorter lightpath units have less energy loss in the system thus producing higher signals while the longer light-path gives better resolution.

A photomultiplier tube is generally used as the detector. Because the detection limit is di-

PERIOD	GROUP																	
	IA	IIA	IIIB	IVB	VB	VIB	VIIIB	VIII B			IB	IIB	IIIA	IVA	VA	VIA	VIIA	O
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	A
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Ac															

LANTH. IIIB	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
ACTINIDES	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	E	Fm	Mv	No	Lw

	ELEMENTS ANALYZED BY FLAME PHOTOMETRY
	ELEMENTS ANALYZED BY ATOMIC ABSORPTION
	ELEMENTS ANALYZED BY BOTH METHODS

Jarrell Ash Div., Fisher Scientific Co.: Bulletin No. 6B (Elements Suitable for Analysis by Atomic Absorption and Flame Photometry). Waltham, Massachusetts.

Figure 19-16. Elements Suitable for Analysis by Atomic Absorption and Flame Photometry.

rectly affected by the stability of the measuring circuit, the phototube, power supply, amplifier and readout system must be sensitive and stable. Some of the phototubes and their spectral range are shown in Table 19-6. It should be pointed out that while a tube can respond over the entire range, its response will vary widely. The spectral response of the tube to the region of interest will dictate the choice of the tube.

A small galvanometer or meter is supplied with the instrument to indicate the absorbance. The addition of a recorder or digital readout system greatly facilitates the handling of the data. Some of the higher priced models now have digital readout and averaging circuits built into the instrument.

Applications

The atomic absorption spectrophotometer offers a very sensitive method of analysis for many of the metals of interest in environmental control analysis. The sensitivity is sufficient to determine the metallic elements in particulate material collected on air filters.

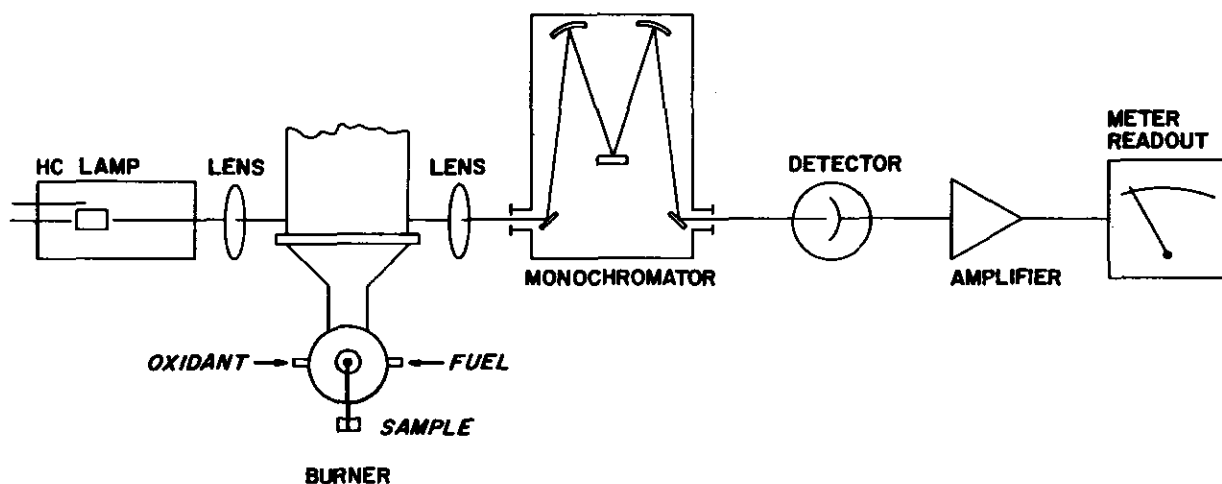
Several attachments for the atomic absorption spectrophotometer have been developed for the

Table 19-6. Photomultiplier Tubes and Their Spectral Ranges

Tube	Range — Å
106	1600 to 6500
1P21	3000 to 6000
1P28	2000 to 6500
6217	3300 to 8000
1102	4000 to 10000
6256	1650 to 6700
9558 Q	1650 to 8500
118	3200 to 10000
6291	3200 to 6000

Source: Atomic Absorption Spectroscopy
ASTM Technical Publication #443
Page 26.

determination of mercury in particulate material, water sewage, and biological specimens. The material to be analyzed is ashed to convert all mercury to the inorganic form. The mercury ion is reduced to metallic mercury. Air or some other fixed gas is bubbled through the solution, vapor-



Jarrell Ash, Div., Fisher Scientific Co.: Bulletin 160A. Waltham, Massachusetts, p. 5.

Figure 19-17. Schematic Diagram of a Basic Atomic Absorption Spectrophotometer.

izing the metallic mercury and carrying it to a sample cell mounted in the light-path in place of the burner. The absorption of light of a wavelength of 253.7 nanometers is measured. The mercury content is determined from a calibration curve prepared under identical conditions.

The use of atomic absorption for the determination of lead in biological specimens has been studied and many procedures have been published. The analysis of urine directly for lead has been unsuccessful with commercial instruments due to the heavy salt concentrations. The large amount of solids in the urine causes clogging of the nebulizer and variations in the atomization rate and the presence of large amounts of sodium causes interference. The detection limit for lead is approximately the same concentration as that found in normal urines.

Extraction of the urine or blood, after ashing, with APDC in methylisobutyl ketone has been reported. Co-precipitation of the lead with bismuth and solution of the precipitate has also been suggested.

Several modifications of equipment have been suggested for the analysis of urine or blood for lead directly. The tantalum boat has been suggested. An acidified solution of the urine or blood is placed in the boat, the boat is advanced to the edge of the flame to dry the sample. Then the boat is placed directly in the flame to ash the sample and vaporize the lead. The Delves cup procedure for blood has been suggested. The blood sample (0.1 ml) is placed in a small nickel cup and dried at the edge of the flame. After drying, the cup is pushed into the flame directly under a nickel tube. The lead is vaporized and passes into the tube where it can be held in the light-path for a longer period of time to enhance the sensitivity.

The tantalum strip or carbon rod furnace has been suggested as a technique for the analysis of

blood. A few microliters of blood are placed in a depression in the tantalum strip or in a cavity in the carbon rod. An electrical current is passed through the strip or the rod to dry the blood. The current is then increased to vaporize the lead.

In its present state of development atomic absorption spectrophotometry is a very valuable tool for an environmental control laboratory.

SUMMARY

Spectrophotometry is a valuable tool for the solution of many of the analytical problems of an environmental health laboratory. This chapter has presented a discussion of the principles of the techniques of spectrophotometry and their application to this type of analysis. The methods were presented as illustrations of the principles, and specific details can be found in any of the standard texts on analytical chemistry. The actual choice of the method will depend upon the equipment available in the laboratory, and the type of sample submitted for analysis.

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EMISSION SPECTROSCOPY

C. L. Grant

INTRODUCTION

Emission spectroscopy is that method of analysis that depends on the fact that energized atoms, ions, and molecules emit electromagnetic radiation when they lose energy. The characteristic line spectra emitted in flames, arcs, sparks, and related sources are highly specific for each element. Further, spectral line intensities are functionally related to element concentrations in the excitation source. Thus, when samples are introduced to these sources, both qualitative and quantitative analyses can be accomplished.

As a survey method, probably no other analytical technique provides so much information for a given amount of effort. A wide variety of sample types and forms can be analyzed, usually with a minimal amount of pretreatment. Up to 70 elements may be detected and estimated simultaneously, although procedures of this breadth are not generally attempted. The detection capability varies widely with elements, but it is generally best for the lower atomic number elements. Absolute detection limits are often below 10 nanograms which makes the technique quite useful for the analysis of small samples; i.e., one milligram or less. When sample size is not limiting, large spectrographs with high resolution readily provide detection capabilities as low as a few parts per million; and, in ideal cases, the limits may be as low as a few parts per billion.

In view of the above, it is not surprising that some of the earliest applications of emission spectroscopy were in the field of occupational health. Industrial workers are exposed to many substances containing toxic elements. Some elements tend to accumulate in body tissues and, therefore, very low concentrations of these elements in drinking water and/or air can be hazardous. For the safety of workers, it is necessary to monitor concentrations of toxic elements in the working environment and in body samples such as blood, urine and feces. The enormity of this analytical problem requires techniques of broad scope, high selectivity and detection capability, and adequate precision and accuracy. Emission spectroscopy is such a technique.

PRINCIPLES

Atomic line spectra are produced when energy is added to atoms in the ground state in an amount sufficient to cause some electrons to move from their normal energy levels to higher energy levels. In this form, the atom is said to be "excited." When the electrons return to their normal energy levels, they release energy stepwise in the form of radiation. Each step accounts for a definite

amount of energy. The radiation produced has specific frequencies corresponding to the energies associated with the various steps, as indicated by the relationship $E = h\nu$.

where: E = energy of the radiation (photon)
 h = Planck's constant
 ν = frequency of radiation

An element is characterized by as many different spectra as the atom has electrons. Lines originating from the electron transitions of the neutral atom are called arc lines, whereas those from the singly ionized atom are called the first spark spectra. Although greater degrees of ionization do occur to a limited extent in conventional spectroscopic sources, the lines originating from neutral atoms and singly ionized atoms are the ones of major analytical interest.

The number of spectral lines produced for any element depends on the atomic structure. Elements with comparatively few valence electrons produce relatively simple spectra (e.g., alkalis and alkaline earth metals). In contrast, an element such as uranium produces thousands of discrete lines, none of which are very intense. The spectrographic determination of elements with very complex spectra is less attractive than for elements with simple spectra. This is due to possible incomplete resolution of lines of very similar wavelengths and also because elements with very complex, less intense spectra exhibit only fair detection limits.

While all the elements can be excited, gaseous elements, bromine and iodine are only infrequently determined this way. These elements can occasionally be determined with conventional excitation procedures by measuring the band spectrum of a compound such as calcium fluoride. However, this approach is not widely used. Carbon, phosphorus, and sulfur have their most sensitive

lines below 2000\AA and, therefore, require the availability of a vacuum spectrograph to overcome air absorption. Fortunately, most elements that are readily studied by optical emission spectroscopy produce useful lines between 2000 and 8000\AA . In this wavelength region, simple optical, photographic and electronic equipment can be used to isolate and record spectral lines.

Qualitative analysis by emission spectroscopy is based on the fact that the atomic structure for each element is different. Therefore, a unique set of spectral lines is produced for each element; and these lines serve as a fingerprint. Line identification is usually accomplished by comparison of lines in the unknown spectrum with lines in a

series of standard spectra prepared from pure elements.

Quantitative analysis is based on the fact that the intensity of a spectral line depends on the amount of parent element present in the excitation source. When the spectra are photographically recorded, relative intensities are estimated by measuring the optical density with a densitometer. Density values are then converted to relative intensities by means of an emulsion calibration curve relating these two variables for the particular emulsion involved, at the wavelength of interest. Alternately, line intensity can be recorded photoelectrically, thereby eliminating many of the errors inherent in photographic procedures.

SYSTEM COMPONENTS

Analysis by optical emission spectroscopy involves four main steps: 1) vaporization and excitation, 2) resolution of emitted radiation into constituent wavelengths, 3) recording spectral lines, and 4) interpretation.

Vaporization and Excitation

The total radiation output of a spectroscopic source is dependent on the aggregate of the processes of volatilization and excitation. Often, a clear distinction between these two processes is not made, probably because both are occurring simultaneously in most sources. For optimum reproducibility in the production of spectra, it is important to know which process is most important in a particular situation so that it may be properly controlled. The comprehensive treatise by Boumans¹ is an excellent source of information on this topic.

Vaporization can be accomplished by thermal means as exemplified by flames, direct current arcs, ohmic heating and laser evaporation. The commonly used high voltage spark discharge promotes vaporization by bombardment with positive ions and high velocity electrons. Of course, the vaporization process is seldom entirely thermal or entirely bombardment; and, therefore, no sharp separation between these sources should be assumed.

Flames. When a solution is aspirated into a flame in the form of minute droplets, desolvation occurs leaving small residue particles. Decomposition and vaporization of these particles produce a vapor containing atoms and molecules which are then excited via inelastic collisions with high velocity molecules liberated by chemical reaction between the fuel gases. Since the energy available in a flame is relatively limited, the spectra obtained are quite simple. As a consequence, spectral interferences are uncommon, thereby making it possible to employ comparatively inexpensive spectrometers of low dispersion.

Because of the comparatively low temperature of common flames such as air-acetylene, this source was traditionally considered suitable only for the determination of easily vaporized and excited elements such as the alkalis and alkaline earths. However, Fassel et al.^{2,3} showed that many elements that tend to form stable oxides in normal stoichiometric flames can be dissociated to produce analytically useful atomic populations in

a fuel rich oxygen-acetylene flame. Pickett and Koirtzohann⁴ reported the successful use of the nitrous oxide-acetylene flame for the emission determination of many elements previously considered to be too refractory for analysis by this method. The development of a system for studying desolvation and vaporization processes of single droplets by Hieftje and Malmstadt⁵ gives further promise for the development of optimized systems of flame vaporization and excitation. These developments coupled with the comparative simplicity of spectra produced by flame excitation and the inherent reproducibility of flames for quantitative work, suggest a bright future for flames in the field of environmental analysis.

Arcs. The direct current arc is usually considered to be the most sensitive source for trace element analysis by emission spectroscopy. One reason for this high detection capability resides in the fact that comparatively large samples (100 milligrams or more) can be employed. Most of the current in this type of discharge is carried by the electrons which impact on the anode and quickly elevate it to very high temperatures. This promotes rapid sample vaporization with an attendant high concentration of atoms in the analytical gap.

Typically, nonconducting powders, solution residues, and similar samples are placed in the crater of a supporting graphite or carbon electrode. Three typical electrode geometries for direct current arc analyses are shown in Figure 20-1

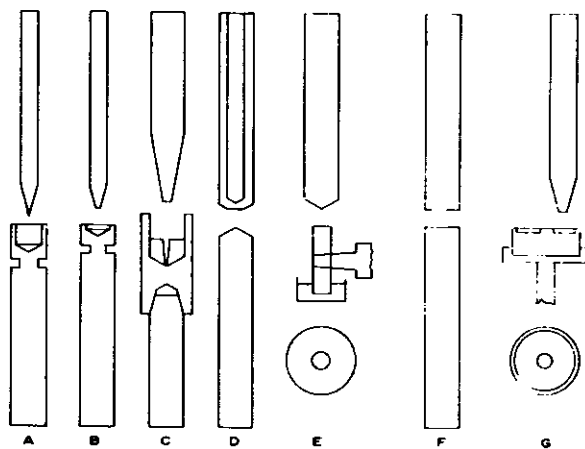


Figure 20-1. Some Typical Electrode Geometries.

(A), (B) and (C). Many other electrode shapes have been employed in direct current arc work.⁶ These variations in electrode configuration influence volatilization rates of elements and related aspects of the volatilization-excitation process. The choice of graphite and carbon as materials of construction for electrodes is based on the fact that (1) they are electrically conductive, readily manufactured in high purity, and easily shaped and (2) the carbon vapor produced during use does not depress the excitation characteristics of

the arc since the ionization potential of carbon is greater than that of most elements determined by this method.

One of the major objections to the use of the direct current arc is its tendency toward poor reproducibility in quantitative analysis. If we remember that the sample-containing crater is analogous to a miniature distillation pot, any fixation of the arc at one or a few spots on the anode results in temperature gradients that will promote selective volatilization of the sample. This type of behavior is generally nonreproducible from one burn to the next. The use of "spectroscopic buffers," extensively discussed by Boumans,¹ can greatly improve this situation if the buffer is carefully selected. Such buffers are usually compounds containing elements having low ionization potentials which tend to reduce the effective excitation temperature of the arc plasma and increase the population of neutral atoms. Using various buffers in a free-burning 10-ampere direct current arc in air at atmospheric pressure, Boumans reported a range of temperatures from 5,000 to 6,200°K.

Many of the objectionable features of the direct current arc can be reduced by directing an annular stream of gas upwards around the sample as it is arced. This system, first proposed by Stallwood,⁷ reduces arc wander. In addition, it has a tendency to reduce selective volatilization, thus oftentimes improving both precision and accuracy. If an inert gas is employed, the cyanogen bands are eliminated, thereby opening up a region of the spectrum which contains a number of sensitive lines.

Although we frequently go to great lengths to eliminate selective volatilization, sometimes it is possible to take advantage of this phenomena. In this approach, the shutter of the spectrograph is opened only while elements of interest are in the analytical gap. With the overall exposure level reduced, very large samples may be used; and this may produce a significant gain in detection capability. Many examples of this procedure have been described by Ahrens and Taylor.⁸

Occasionally, the addition of certain compounds to the sample can be used to induce chemical reactions which will either promote or reduce selective volatilization. One of the best known examples of this procedure is the carrier-distillation method first described by Scribner and Mullin.⁹ A comparatively large sample (100 mg.) is mixed with a carrier such as gallium oxide or silver chloride and then packed into a deep-cratered electrode of the type shown in Figure 20-1 (C). Many investigators also like to put a vent hole in the center of the sample to permit a smooth evolution of gases after the arc is struck. The electrode geometry is especially chosen to reduce heat loss from the sample-containing anode. Volatile impurities are transported into the excitation zone with the carrier while the refractory matrix is left behind.

Spark Discharges. Spark discharges are those in which the energy flow between the electrodes varies in a cyclic fashion, usually with a change of polarity each time the energy flow drops to zero. Because the discharge is being constantly

reignited, there is improved random sampling of electrode surfaces. Consequently, this discharge is generally considered to provide better precision but less sensitivity than arc discharges. The poorer sensitivity compared to a direct current arc is largely because the electrodes remain relatively cool, and considerably less sample is consumed. Despite this restriction, spark discharges have been employed with increasing frequency for trace analysis due to their excellent reproducibility. A comprehensive review of the characteristics of spark discharges was published by Walters and Malmstadt.¹⁰

The most extensive application of spark discharges is for the analysis of metals as self-electrodes. However, powders have been analyzed by blending and compressing with graphite to form conductive briquets. Solutions have been analyzed by a variety of innovative procedures. In the porous cup technique developed by Feldman,¹¹ a solution slowly percolates through the porous bottom of a hollow electrode [Figure 20-1 (D)]. As the liquid sample seeps through the porous bottom of the electrode, the spark discharge vaporizes and excites the residue to produce an emission spectrum. Another very versatile solution method involves the use of a rotating graphite disc that dips into the solution to be analyzed and transports fresh solution on its periphery into the spark excitation zone [Figure 20-1 (E)].

For very small samples, some solution methods are impractical because of the volume of sample required for analysis. In such situations, residues from the evaporation of these solutions can be analyzed. One of the best known solution residue methods is the copper-spark technique of Fred, Nachtrieb, and Tomkins.¹² A hydrochloric acid solution containing a very small amount of sample (<0.2 mg) is applied to the end of high purity copper rods and dried. The copper rods are then mounted, and the sample is subjected to spark excitation. Excellent detection capabilities are realized with this procedure; but, of course, copper cannot be determined and solvents that react with copper cannot be used. In an attempt to circumvent this limitation, Morris and Pink¹³ employed flat-topped graphite electrodes [Figure 20-1 (F)] which had been treated with Apiezon-N grease to render them impervious to solutions. This procedure, called the graphite-spark technique, has exhibited detection capabilities in the nanogram range for several elements. A variation of this approach employs the rotating "platrode" developed by Rozsa and Zeeb¹⁴ in which a graphite disc is substituted as the bottom electrode so that solution volumes up to 0.5 ml can be evaporated [Figure 20-1 (G)].

Plasmas. The plasma jet, sometimes called the gas-stabilized direct current arc, is an excitation source which has been used advantageously for the analysis of solutions.¹⁵⁻¹⁶ In this procedure, the solution is aspirated into a chamber by an inert gas under pressure and then swept through a small orifice into a direct current arc discharge. When the gas flow is increased through the orifice, the electrical conductivity of the jet rises, resulting in a high temperature at the core of the discharge.

The special advantages of this system are the excellent detection capability and the high degree of reproducibility. Precision values are generally much improved over conventional direct current arc excitation.

Another plasma excitation system of special interest is the induction-coupled plasma. In the system described by Dickinson and Fassel,¹⁷ the solution is converted into an aerosol by an ultrasonic generator. A condenser system is employed to desolvate the aerosol particles which are then introduced to the center of a donut-shaped argon plasma in a clear quartz tube. Power is supplied by a high frequency generator operating at 30 MHz. With this system, solutions were introduced at a rate of 0.3 ml/min. For many elements, detection capabilities were in the nanogram/ml range. Since the temperature of this source is on the order of 10,000°K, even the most refractory species are dissociated; and chemical interferences from matrix elements should be drastically reduced. The induction-coupled plasma deserves considerable attention in future methodological development.

Another very unique and potentially useful plasma source has been described by Kleinmann and Svoboda.¹⁸ In this system, the sample is evaporated from a graphite disc which is resistively heated. The evolved vapors are excited by a low voltage, high frequency, induction-coupled discharge in argon. Moderately good detection capabilities were obtained. Since the ideal of separating vaporization and excitation is attained in this source, there is an excellent opportunity to control interferences from elements which make up the bulk of a sample.

Laser Excitation. The analysis of very small areas of samples can be accomplished by emission spectroscopy using a laser to vaporize the sample. This system, first described by Brech and Cross,¹⁹ employs a high intensity pulsed laser beam focused on a spot that may be as small as 10 microns in diameter. With biological and geological specimens, it provides a means of gaining much greater insight into compositional variations than can be attained by bulk analytical systems.

A major problem with the system is the difficulty in obtaining precise quantitative results. Reasons for this difficulty relate to problems in controlling the laser output energy, and the fact that it is extremely difficult to prepare standards for the establishment of calibration curves. Recently, however, Scott and Strasheim²⁰ have described the use of a Q-switched neodymium laser without an auxiliary excitation system. They obtained promising results in the analysis of aluminum alloys with relative standard deviations in the range of 2% to 4%. Clearly, the ultimate potentialities of laser excitation for emission spectrographic analysis have not been realized.

Resolution of Emitted Radiation. Prisms and diffraction gratings are used to resolve the emitted light from a spectroscopic source into its component wavelengths. A variety of commercial instruments are available with differing geometric arrangements of the necessary optical components. For additional details, the interested reader can

consult the recent text by Slavin.²¹ Only a few points of special interest in the analysis of industrial hygiene samples will be considered here.

One of the most important properties of a spectrograph is dispersion, usually expressed as the

reciprocal linear dispersion in Å/mm. According to Mitchell,²² "It is in general not the elements to be determined, but the source to be used and the composition of the material to be examined, insofar as its major constituents are concerned, which decide the instrument to be used." When the number of lines produced by the major component is large, the reciprocal linear dispersion of the spectrograph must be small so that lines from the matrix material will not interfere with lines of elements to be determined. Fortunately, the major elements in most biological samples yield relatively simple spectra; and so, a spectrograph of only moderate dispersion is adequate. Of course, the industrial hygienist also encounters samples whose major components yield very complex spectra. For example, a plant processing heavy metals could yield dust samples which would produce extremely complex spectra requiring a large instrument with small reciprocal linear dispersion.

Detection capability can be a very important consideration in the analysis of typical industrial hygiene samples. In those cases where sample size is not limited, dispersion is the most critical factor governing detection limits. In a large spectrograph with low reciprocal linear dispersion, a given amount of background radiation is spread over a large area while the line remains unaffected. Jarrell²³ emphasized that this increase in line-to-background ratio occurs only up to the critical dispersion, i.e., the point at which the slit and line widths are equal.

When the industrial hygienist is interested in analyzing extremely small samples, the absolute quantity of an element is more important than its relative concentration. Mitteldorf²⁴ has emphasized that the critical consideration here is the speed of the spectrograph (approximately defined as light yield). Thus, we would normally use a small spectrograph of high speed (typically f/10) for micro samples. In contrast, a large spectrograph with optical speed on the order of f/30 might be employed where sample size is not limiting.

Recording Spectral Lines. Spectral lines are recorded either photographically on films and plates or photoelectrically. Emulsions of widely varying speed and resolving power are available to photograph the various wavelength regions of interest. When the investigator wishes to determine elements over a wide concentration range with moderate precision and accuracy, an emulsion of moderate contrast and high speed is selected. For precise quantitative analysis, an emulsion of high contrast is usually preferred.

Direct photoelectric recording of spectral line intensities is considerably more precise than photographic recording and is, therefore, often used for quantitative work. However, direct readers are expensive and sometimes lack the flexibility required for survey analyses. There-

fore, it is unlikely that photographic recording will become obsolete in the immediate future.

Quantitative Measurements. In order to do quantitative analysis by emission spectroscopy, it is necessary to estimate the intensity of spectral lines. When lines are recorded photographically, their optical densities can be measured by a microphotometer. In this system, a narrow slit of light is scanned through the spectral line. A photoelectric detector records the decrease in light transmission associated with the blackening on the photographic plate. The photoelectric detector output is recorded as optical density of the spectral line.

Next, optical densities must be translated into relative intensities by means of an emulsion calibration curve. To prepare an emulsion calibration curve, a variety of procedures are used including the use of rotating step sectors and filters with known light transmittances. Several accepted calibration procedures have been carefully described along with worked examples in ASTM Designation E 116.²⁵

For high volume repetitive quantitative determinations, direct reading spectrometers are generally employed to reduce the manual effort required. Photoelectric detectors are mounted behind exit slits located in the proper positions to record selected spectral lines. Calculation procedures have also been automated by using computers to handle data reduction.^{26,27} Even when spectra are recorded photographically, data reduction can be greatly facilitated via computer handling. Besides speeding up computations, errors are minimized, and precision is frequently improved.

SCOPE

Sample Types

Considering the variety of excitation sources which have been devised, it should be clear that emission spectroscopy provides the capability for detecting traces of most elements in solids, liquids, or gaseous samples. Solid metal specimens can be analyzed directly as self-electrodes, or they may be converted to other forms such as solutions. Inorganic powders can be directly analyzed; or they, too, may be converted to solution form. Solid specimens which contain large amounts of organic matter are usually either wet digested or dry ashed prior to analysis. Otherwise, the rapid combustion of organics may cause vaporization losses and inefficient excitation of the elements to be determined. Despite this fact, some methods have been devised for the direct analysis of organic solids and fluids without ashing. A wide variety of solutions such as natural water and acid digests of samples can be analyzed either by direct solution aspiration or by analysis of the solution residues. Gaseous samples can be analyzed by excitation in hollow cathode discharge tubes or in flowing systems. In short, the diversity of sample types that can be analyzed by emission spectroscopy is one of the great strengths of the method.

Sensitivity

Throughout much of the literature, the terms, sensitivity and detection limit, have been used interchangeably. In this discussion, sensitivity is

defined as the ability to discern a small change in concentration of analyte at some specified concentration. Thus, sensitivity is directly correlated with the slope of the analytical curve relating line intensity to analyte concentration. Sensitivity is also inversely related to the reproducibility of line intensity measurement. For high sensitivity, we require a large slope for the analytical curve and a small value for the standard deviation of line intensity.

It should be apparent from the foregoing sections that sensitivity is controlled by a multiplicity of factors in the total analytical procedure. Sample treatments such as selective preconcentration can improve sensitivity. Choice of excitation source, the fundamental properties of the spectrograph and the extent to which its performance is optimized, choice of detector, and the method of data manipulation all affect sensitivity.

Concentration Ranges

Although there is no hard and fast rule which precludes using emission spectroscopy for the determination of high concentrations of elements, the most advantageous concentration range lies below 10 percent. In fact, the preponderance of applications deal with determinations between 1 percent and the limit of detection.

Limit of detection is defined here as the smallest quantity or concentration of analyte that can be detected "with certainty." Apparently, then, limit of detection is merely a special case of sensitivity which depends on an ability to distinguish a difference in line intensity for a small increment of analyte in comparison to the blank signal. Thus, the limit of detection is inversely correlated with sensitivity. The limit of detection also depends on the definition of "with certainty." Although it is widely accepted that a statistical definition should be used, there is little agreement on the proper confidence level. To assume that a single value for the confidence level is correct seems naive. It is much more realistic to allow each investigator to choose a probability level that suits the particular requirements of the problem at hand.

Some specific procedures necessary to achieve improved detection limits have been discussed by DeKalb et al.²⁸ for both photographic and photoelectric sensors. It must be emphasized, however, that many of these detection limits are reported for ideal situations in which there is no matrix interference or other limiting characteristic. In addition, many different definitions of the detection limit have been employed by various investigators, thereby making direct comparisons very difficult. It should also be remembered that limits of detection do not represent concentrations that can be determined with the same quantitative precision and accuracy expected for higher concentrations. In general, the lower limits for good quantitative precision are approximately 10 times the detection limits.

While much can be accomplished through the selection of optimum instrumental conditions, sensitivity and detection limits can also be enhanced by sample preparation procedures that provide an enrichment of the analyte. Some

typical procedures are described in Chapter 18 of this syllabus. Aside from the extra effort required in sample preparation, a major precaution with enrichment procedures is the possible introduction of impurities from chemical reagents which obscure the true pattern of variation present in the original samples.

Precision and Accuracy

Precision is defined here as the extent of agreement of a series of measurements with their average, frequently measured by the standard deviation. It is essential to express the conditions under which the data have been obtained. Commonly, precision is expressed as the percent relative standard deviation (sometimes called coefficient of variation).

If we accept that a realistic value for the precision of a total analytical method applied to a given material should include components from the sampling step, the sample preparation step, and the measurement step, then the difficulty in making general statements for different methods is obvious. Nonetheless, it is generally conceded that the precision of emission spectroscopic techniques is superior to chemical methods at very low concentrations and inferior to chemical methods at concentrations much above 1 percent.

Usually, methods that employ solutions for the final intensity measurement give better precision than direct methods with solids. One reason for this difference is that larger samples are usually employed for solution methods. Under ideal conditions, percent relative standard deviations of $\pm 1\%$ can be obtained with solutions except when impurity concentrations approach their detection limits. Good reproducibility is also attained for the analysis of metals as self-electrodes. With the direct excitation of powdered solids, sample heterogeneity becomes more important; and percent relative standard deviations of ± 5 to 10% are more typical. For survey procedures which cannot be optimized for each element determined, percent relative standard deviations of $\pm 25\%$ or larger might be considered acceptable.

Accuracy is defined as a quantitative measure of the variability associated with the relating of an analytical result with what is assumed to be the true value. Strictly speaking, accuracy can never be exactly measured because true values are never known. However, when primary standards are available, the accuracy can be specified within acceptable limits.

Since quantitative emission spectroscopy requires the establishment of an analytical calibration curve based on standard samples, the accuracy is limited by the quality of the available standards. The precision of a method is sometimes thought to be an estimate of accuracy. However, a method can easily yield very precise but highly inaccurate results if systematic error is present. For example, a common misconception is that synthetic solution standards obviate the need for primary standards in the analysis of miscellaneous materials which can be converted to solution form. Unfortunately, this concept overlooks all of the systematic errors that can occur while converting

samples to solutions.²⁹ The recent activity of the National Bureau of Standards in the preparation of standard reference materials certified for trace amounts of different elements in matrices such as orchard leaves, beef liver, and serum will be of tremendous help to the emission spectroscopist concerned with the accuracy of his procedures.³⁰

STEPS OF A QUANTITATIVE METHOD

The first step in any quantitative analysis by emission spectroscopy is to clearly define the problem by designating the elements to be determined and the expected concentration ranges. Any special aspects of the sample such as its major element composition, its quantity, and its physical form should also be noted. Reference standards are required which are similar, both chemically and physically, to the samples to be analyzed. For example, if we wish to determine the concentration of several trace metals in water residues in which the matrix is a mixture of calcium, potassium, magnesium, and sodium salts, we normally require standards with a matrix of these same salts to match volatilization-excitation behavior. It may even be necessary to alter the ratios of the salts in the standards to match particular water samples. Lacking standards of similar physical and chemical composition, the samples must be modified to correspond with standards that are available. This may entail conversion to solutions, inorganic powders, or some related operation.

Once the physical form of samples and standards has been decided and the analytical requirements specified, it should be possible to make an optimum choice of the excitation system, assuming that several are available. Similarly, we should attempt to insure that the spectrograph will provide sufficient resolving power and adequate speed for the detection and estimation of the elements to be determined. This means that we must be able to locate lines of the analyte elements which are free from interferences by lines of the matrix elements. Further, these lines must be sufficiently sensitive to provide measurable optical densities down to the concentration levels required by the analysis.

In prior discussions, we have inferred that quantitative analysis involves only the construction of an analytical calibration curve relating intensity of the line of an element to be determined to the known amount of that element in a series of standards. However, because of the multitude of factors that affect the total amount of light emitted by a given weight of an element, this direct approach has usually not provided adequate precision and accuracy. To circumvent this difficulty, the principle of internal standardization is employed. In this procedure, concentration of the element to be determined is measured in terms of the ratio of the intensity of the analysis line to the intensity of a "homologous" line of another element present in fixed concentration in all samples and standards. The internal standard element may be a major component of the matrix which is present in invariant concentration. Alternatively, it may be an element which is absent in the sam-

ples and which has been added in constant amount from an external source. In this manner, uncontrollable fluctuations such as variations in excitation efficiency that affect both lines to a similar extent will not alter the intensity ratio between the lines. Unfortunately, it is usually impossible to find line pairs whose intensity ratios are completely insensitive to changes in chemical and physical composition of the sample. However, the literature provides references to many line pairs which are sufficiently insensitive to extraneous influences to permit excellent precision in quantitative work.

After preparation of samples and standards, they are excited in random order and recorded on a photographic plate or photoelectrically. If the lines are recorded photographically, their optical densities are measured and converted to relative intensities by means of an emulsion calibration curve. The intensity ratios of analytical lines relative to the selected internal standard lines are calculated and plotted on log-log paper versus the respective concentrations of the elements in the standards. Intensity ratios for the unknown concentrations in the samples are then read from these calibration curves.

Analytical calibration curves must be frequently checked. Day-to-day variations in atmospheric conditions will exert sufficient influence on excitation processes and photographic emulsions to cause significant curve shifts. The extent to which an investigator must check for curve shifts and recalibrate is partially dependent on the required precision and accuracy of the analyses being performed. For a summary of recommendations, the ASTM Designation E305-67 titled "Establishing and Controlling Spectrochemical Analytical Curves" should be consulted.³¹

APPLICATIONS IN INDUSTRIAL HYGIENE

Analysis of Biological Tissues and Fluids

The work of Tipton and Stewart³² is a typical example of a dry ash-direct current arc excitation procedure for surveying trace element contents of biological tissues and fluids. Samples of food, urine, and feces are dried and ashed at 550°C after treatment with double distilled sulfuric acid. This treatment produces a clean ash of mixed sulfates and oxides. The ash is combined with a graphite buffer containing 2,000 parts per million of palladium which serves as the internal standard. Synthetic standards of similar composition are prepared from inorganic materials. The elements Ag, Al, B, Ba, Be, Cr, Co, Cu, Fe, Mn, Mo, Ni, Pb, Sn, Sr, Ti, V, Zn, and Zr are determined at concentrations down to 1 part per million or less in a few cases with typical percent relative standard deviations on the order of $\pm 10\%$.

A typical procedure employing wet ashing of biological fluids prior to spectroscopic analysis is described by Niedermeier et al.³³ In this procedure, 2 ml of blood serum are digested with high purity nitric and perchloric acid. A battery of samples is treated simultaneously using a number of digestion tubes in a constant temperature block which can be maintained at 130°C. After ashing, the excess acid is evaporated; and the residue is

dissolved in ammonium chloride solution which serves as a spectroscopic buffer. An aliquot of the solution is transferred to a graphite electrode and evaporated to dryness in a vacuum desiccator. Synthetic standards are prepared in a matrix solution with composition closely approximating that of normal human blood serum. Excitation is accomplished by a 10-ampere direct current arc. Selected lines of Cu, Fe, Al, Ba, Mn, Ni, Cs, Sn, Sr, Cr, Zn, Pb, Mo and Cd are monitored with a direct reading emission spectrometer. Data analysis is accomplished by an IBM 7040 computer.

For rapid survey purposes, the procedure described by Bedrosian et al.³⁴ is especially attractive because ashing of the sample is not required. Materials such as animal tissue, blood serum, stool, bone, and plant leaves are dried. Twenty-five mg of samples are blended with graphite containing lutetium and yttrium as internal standards. The blended mixture is formed into a 3/16 inch diameter pellet using a small hand press. The pellet is placed in a graphite electrode, and a 1 mm diameter vent hole is placed in the center of the pellet. Electrodes are mounted in a Stallwood jet, and a gas mixture of 20% oxygen and 80% helium is used while the samples are excited by a 25-ampere direct current arc. They detected 26 elements in these various matrices at 1 part per million or less. Quantitation is accomplished using standards containing known concentrations of the trace metals in a matrix of p-nitrobenzene-azo-resorcinol which serves to simulate the organic matrix of samples being analyzed. The authors reported percent relative standard deviations of $\pm 15\%$ or less.

Water Samples

The determination of trace metals in natural waters is of great interest from a toxicological point of view. An excellent survey procedure for the determination of 19 minor elements in water has been described by Kopp and Kroner.³⁵ In this procedure water samples are filtered through a 0.45-micron membrane filter. Total dissolved solids are determined, and a volume of sample is selected to contain 100 mg of solids when concentrated to 5 ml. A portion of this concentrate is placed in a porcelain combustion boat and analyzed in triplicate using a rotating disc electrode and high voltage spark excitation. Standard solutions for construction of the analytical calibration curves are prepared using known amounts of the elements to be determined in a matrix of sodium, potassium, calcium and magnesium in proportions approximating the average composition of U. S. waters. Line intensities are recorded photoelectrically, and background is used as an internal standard. The concentration range is from 0.01 to 100 parts per million in the concentrated solution. Thus, the lower limits for the original samples depend on the degree of concentration employed to get 100 mg of dissolved solids. Precision expressed as the percent relative standard deviation was on the order of $\pm 5\%$. Recoveries from known additions varied from 80% to 113%.

Analysis of Air Samples

Not all spectrochemical analytical procedures are devised to determine multiple elements simul-

taneously. For example, O'Neil³⁶ described a procedure for the determination of beryllium in airborne dust. A high volume air sampler is used, and the sample is collected on Whatman No. 41 filter paper. The filter is ignited in a platinum crucible, and the ash weighed and mixed in definite proportions with an internal standard (lutetium) and graphite. The mixture is excited in an 11-ampere direct current arc and burned to completion. The author reported being able to detect 0.1 nanogram of beryllium in an electrode. Acceptable precision and accuracy was reported.

Of course, procedures have also been described for determining a large number of trace elements in air particulates. For example, the procedure by Keenan and Byers³⁷ permits the determination of 20 elements collected on paper filters.

SUMMARY

Emission spectroscopy provides an effective analytical technique as both a survey method and as a quantitative analysis tool. The applicability of this technique is being continually extended in the industrial hygiene field.

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GAS CHROMATOGRAPHY*Lial W. Brewer***INTRODUCTION**

Chromatography is a collective term for separations of mixtures based on the partition of substances between two immiscible heterogeneous phases, one of which is a stationary or fixed phase with a large surface area, and the other a moving or mobile phase which flows over the first phase. Gas chromatography is the most recent branch of chromatography and includes all the chromatographic processes in which the substance to be analyzed occurs in the gaseous or vapor state or can be converted into such a state.

Development

Although the first records of gas chromatography go back hundreds of years,¹ its true history began during World War II when a large industrial chemical company instituted a crash program for its development.² The first published work appeared in the early 1950's based on the successful experiments by James and Martin,³ following an earlier suggestion made by Martin and Synge in 1941.⁴ In the years between 1952 and 1956 the early apparatus and initial methods of application were developed. In 1956 the first commercial instruments appeared on the market, and since that time there has been a spectacularly rapid and widespread development in theory, techniques and applications of gas chromatography. Today, it is one of the most widely applied and versatile analytical tools available in basic and applied research and in quality control.

Applications

The success of gas chromatography is due to its simplicity of operation, high separation power and speed. The technique is capable of separating and measuring nanogram amounts of substances. In general, gas chromatography is suitable for analysis of substances with vapor pressures of at least 10 millimeters of mercury at the temperature of the column. Because the gas chromatograph separates, detects, qualifies and quantitates the individual components of a volatilized sample in a single step, it is an indispensable tool in every branch of chemistry. The wide choice of column packings, detectors and temperature controls allows versatile applications not only to the field of chemistry but also biology, medicine, industrial research and control, environmental health and scientific studies of the structure of chemical compounds, chemical reactions, partition coefficients, heats of solution and many others.

Specific separations and measurements accomplished by the use of gas chromatography in the medical-biochemical field include saturated and unsaturated fatty acids in low concentration, posi-

tional and configurational isomers of unsaturated fatty acids, straight-chain and branched-chain fatty acids, sterols and steroids, alkaloids, amino acids, urinary aromatic acids, bile acids, vitamins, blood gases, and toxic trace components in air, water, food and pesticides.

Recent developments in the field of toxicology enable the fractionation and determination of such substances as steroids, lipids, barbiturates, drugs and blood alcohol.⁵ The limited size of samples available and the low concentration of substances present in the field of toxicology make it a valuable tool for the complete characterization and analysis of mixtures of toxic substances. The progressive development of pyrolysis has led to the separation and identification of polymers and non-volatile substances. Advances have also been made in the miniaturization of gas chromatographic equipment. For example, a very small gas chromatograph-mass spectrometer was sent on one of the moon shots to separate and identify atmospheric components automatically. The aerospace⁶ and nuclear submarine fields⁷ have also used gas chromatographs to check air quality in working and sleeping environments for personnel. Gas chromatography has been used recently in the remote sampling and analysis of tunnel atmosphere after nuclear testing at the Nevada Test Site.⁸

In the field of industrial hygiene the chromatograph has been used to identify and quantitate solvent exposures by the analysis of breath samples. When toxic organic substances have either no recognized biological metabolite or one whose excretion cannot be correlated with atmospheric concentrations of the initial substance, it is difficult to evaluate the effects of exposures; however, breath analysis by a gas chromatographic procedure may be developed for certain organic solvents found to be expired after exposure at predictable rates. In addition, many industrial hygiene departments operate product identification programs which require the complete analysis of proprietary products. Additives to many commercial products can appreciably increase the toxic properties of less hazardous materials. An example is the addition of carbon tetrachloride to typewriter cleaner, which normally contains only trichloroethylene. Another example is the addition of benzene to gasoline for an increased performance efficiency. Before the development of gas chromatography tedious procedures involving fractional distillation and determination of physical constants were required for detection of such additives.

The analysis of solvents for changes in formulations is performed frequently in the industrial hygiene laboratory. The regular product may be analyzed and comparative chromatograms prepared for other batches at specific times to check for any alteration of the product. Furthermore, many solvents of unknown composition (trade name given without compositional information or, in other cases, a lost label or marking) can be analyzed for complete identification and determination of components. In-plant air samples containing solvent vapors can be chromatographed, avoiding the tedious chemical separation methods. Chlorinated hydrocarbons, for example, can be readily assayed in mixtures and each component identified whereas only total chlorinated hydrocarbons can be determined chemically. This is extremely important since each compound has a different Threshold Limit Value and tolerance level.

There is almost no type of vaporous compound whose analysis by gas chromatographic methods has not been described in the literature. A partial list of pertinent references is included at the end of this chapter.

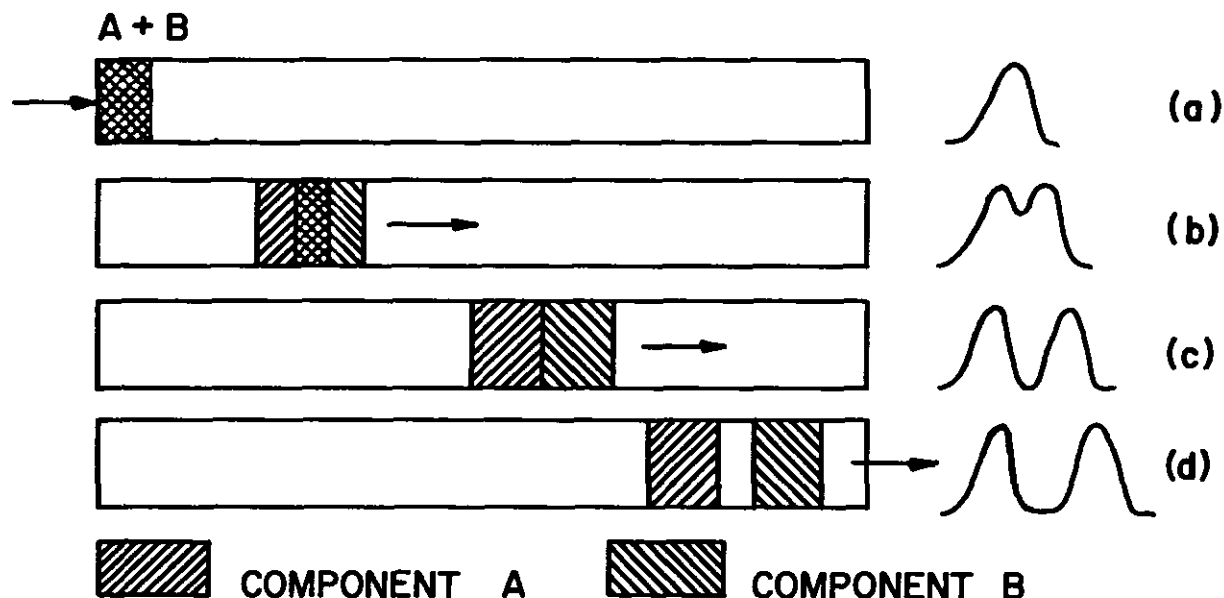
THEORETICAL ASPECTS OF GAS CHROMATOGRAPHY

Principle

Gas chromatography can be compared analytically to fractional distillation; however, it is a much more efficient type of separation technique. A good distillation column may have 100-200 theoretical plates, whereas a chromatographic column may separate components with 1000 to 500,000 theoretical plates. Basically, gas chromatography consists of the partition of compounds

between two phases. One phase is a fixed or stationary phase. This phase may be either a solid, as in adsorption chromatography, or a liquid held by a solid, as in partition chromatography. The second phase is mobile and is generally referred to as the moving phase. This phase may be a gas, liquid, vapor, or volatile solid. There are two principles of separation based on the previously noted difference in the nature of the stationary phase: (1) gas-solid chromatography (GSC) in which the moving phase is a gas and the stationary phase is an active solid such as alumina, charcoal, silica gel, molecular sieves, or the newer plastic granules (e.g., Poropak[®]); (2) gas-liquid chromatography (GLC) in which the moving phase is a gas and the stationary phase is a liquid distributed on an inert solid support. GLC is used for the separation of a variety of compounds, generally organics, while GSC is used for the separation of gases.

The principle of operation involves the introduction of small amounts of a gaseous or liquid sample solution containing nanogram amounts of analytically desired gaseous or vaporizable components which are carried under controlled temperature conditions by an inert carrier gas into a column containing the stationary phase. Phase equilibria occur between the sample components, the mobile phase and the stationary phase; the components are separated, due to differences in absorption, solubility and chemical bonding, into distinct bands (or zones) of molecules. These fractions move through the column at different rates and emerge as separated components, as shown in Figure 21-1. The carrier gas emerging from the column passes through a detector which produces a signal proportional to the quantity



Szepesy L: Gas Chromatography. Chemical Rubber Company Press, 1970, p. 14.

Figure 21-1. Separation of Components Into Bands of Molecules Which Move Through Column at Different Rates.

of each component. The detector response is amplified and shown on the recorder as a peak. The chromatogram that is obtained is a plot of time versus the intensity of a series of peaks representing the eluted components in the carrier stream. The length of time required for each of the peaks to appear on the chart is the retention time and is characteristic for each of the substances present under a given set of chromatographic conditions. The retention time, therefore, identifies the substance, and the area of the peak is a quantitative measurement which is proportional to the amount of each fraction present.

A proper selection of injection port, column, and detector temperatures, column materials, and the detector determines the effectiveness of the chromatographic separations of the components of each type of sample.

Basic Design

There are many commercial models of gas chromatographs available today, with considerable variation in design and arrangement of components. The latest trend in design is the modular concept, consisting of a simple addition of component parts with different functions. Starting with the basic unit, the performance of the apparatus can be expanded by addition of other units, depending on the type of analysis to be done. Gas chromatography may also be combined with other chromatographic, spectrometric and chemical methods of analysis by collecting the separated components from the gas chromatograph and incorporating other equipment into the system, either directly or indirectly. The recent coupling of computers with gas chromatographs allows completely automatic operation along with the storage and processing of data for estimation of the concentrations of the sample components.

The basic design of the apparatus consists of: (1) carrier gas system, (2) sample injector, (3) column, (4) thermostat, (5) detector and (6) recorder. Figures 21-2 and 21-3 show schematic

diagrams, respectively, of single and dual column assemblies, respectively. A general discussion of the components, with a brief explanation of the parameters pertinent to different applications of gas chromatography, is presented for the selection of proper instrumentation.

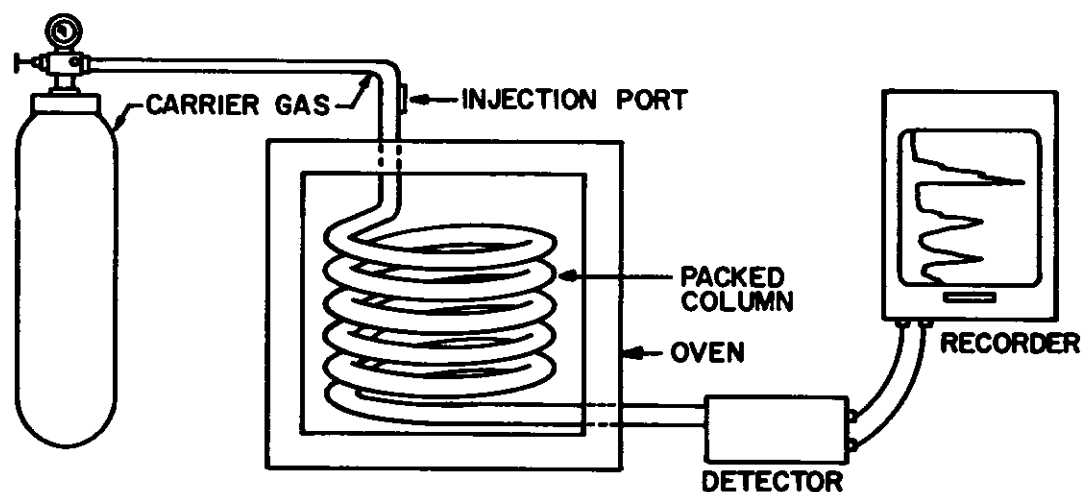
COMPONENTS OF THE GAS CHROMATOGRAPH

Carrier Gas System

The carrier gas is the mobile phase used to transport the sample through the column at a selected steady rate. To ensure constant and reproducible conditions, the system is composed of a gas cylinder, pressure and/or flow control, manometer, flow meter and pre-heater.

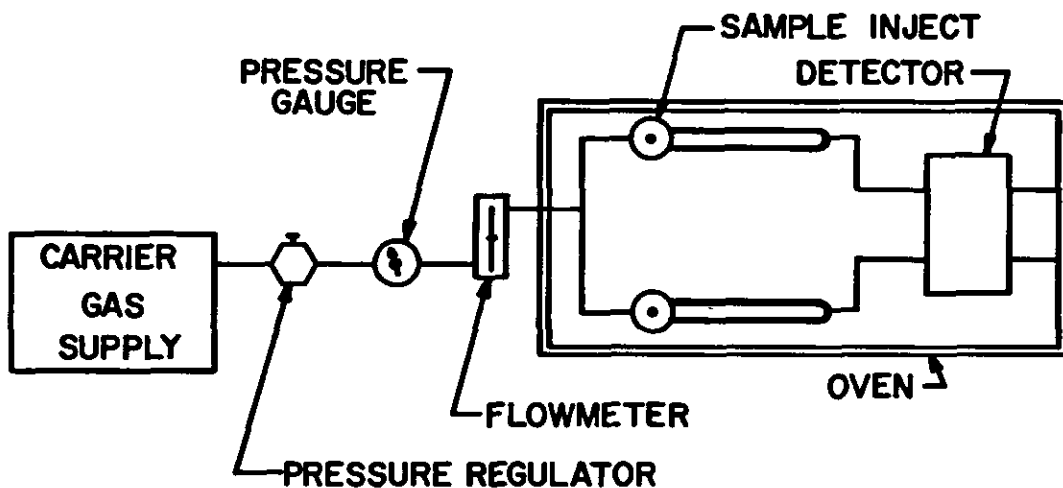
In principle, any gas which does not interfere either with the stationary phase or the components of the sample would be a suitable carrier. However, the properties of the carrier gas affect the separations in the column as well as the detection of the emerging components. The gases generally used are: helium, argon, hydrogen and nitrogen. Other gases may also be used. In selecting a carrier gas, detection is the primary factor to be considered since separation can be improved by some means other than changing the carrier gas.

Since hydrogen is so reactive and flammable, helium is the ideal carrier for use with thermal conductivity detectors. Nitrogen, though readily available, is not too useful for these detectors since its thermal conductivity does not differ too greatly from that of many sample components. The thermal detector measures the difference between the heat conductivity of the pure carrier gas and that containing the components of the sample. The greater the difference between the two heat conductivities the greater will be the observed signal. The thermal conductivity of gases is inversely proportional to the square root of their molecular weight and consequently hydrogen and helium are the most suitable carrier gases for



Instruments, Inc.: What Is Gas Chromatography. Tulsa, Oklahoma.

Figure 21-2. Single Column.



Prepared by Sandia Laboratories draftsmen.

Figure 21-3. Dual Column.

thermal conductivity detection.

The most commonly used types of carrier gases and their use with various detectors are as follows:

Air and Oxygen may be used in certain cases as carrier gas with the flame ionization and thermal detectors. However, their use is limited by the possibility of reactions with the stationary phase or the components of the sample.

Argon is the most generally used gas with radiation detectors such as Beta ionization, and with flame ionization detectors, with limited use in thermal detectors.

Carbon Dioxide is used with flame ionization and gas density balance detectors, with limited use with the thermal detector.

Carbon Monoxide is used with the flame ionization detector.

Helium is used with the thermal conductivity, thermionic emission, flame ionization and cross section detectors.

Hydrogen is used with the gas density and thermal conductivity detectors. It is used as a fuel with the flame ionization detector. To avoid the possibilities of impure hydrogen, the use of hydrogen produced from the electrolysis of water is often more suitable for the operation of flame ionization detectors.

Neon is used with radiation detectors.

Nitrogen is used with radiation, flame ionization and gas density detectors. It has limited use with the thermal conductivity detector.

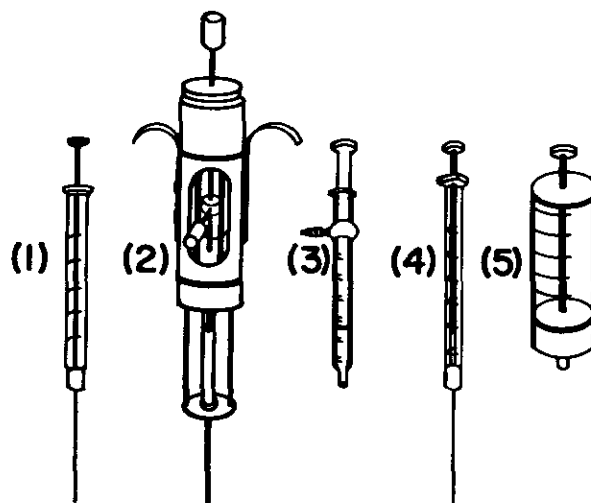
SF₆ is used when detecting permanent gases using a density balance detector.

A constant flowrate is important to eliminate the effect of changes in column resistance. Heating of the gas before it enters the sample injector is necessary in the case of some detectors and advisable in other detection methods and is accomplished by means of a pre-heater.

Sample Injection System

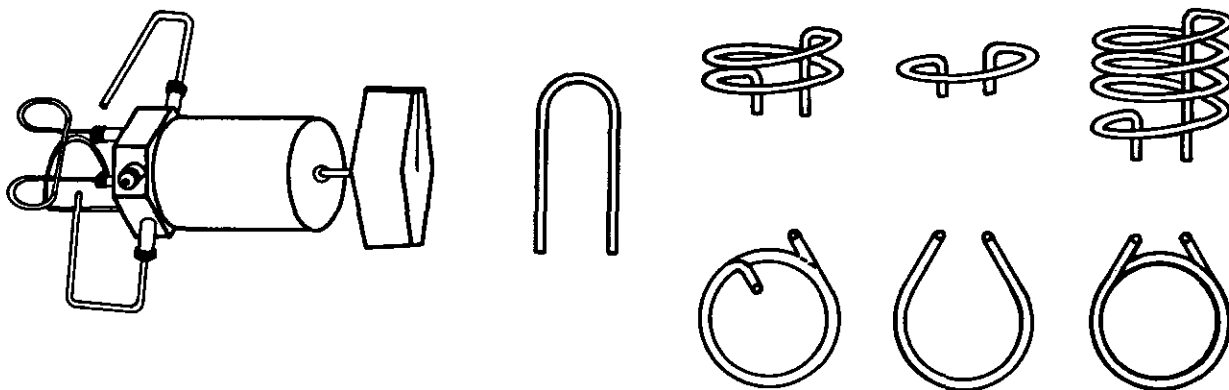
The sample injector, located ahead of the

column, is designed to allow the introduction of a sample rapidly and in a reproducible manner into the column. It is essential that representative samples of the material to be analyzed be introduced. Since such samples must be small in quantity, a careful manipulative technique must be employed with the method of injection. It is highly desirable that the sample injection be almost instantaneous to convert the sample into a composite plug of gas which is pushed through the column by the carrier gas. This is accomplished by the enclosure of the injection port in a metal



Syringes #1, 3, 4 and 5: Hamilton Syringe Catalog. Syringe #2: Beckman Syringe Instruction Sheet.

Figure 21-4. Syringes Used in Gas Chromatography (1) Hamilton 10 ul. liquid syringe, (2) Beckman variable volume liquid micro-syringe, (3) purge type gas syringe, (4) standard Hamilton gas syringe and (5) large volume transfer and dilution syringe.



Beckman Instruments, Inc.: Bulletin #756A. Fullerton, California.

Figure 21-5. Gas Sampling Valve (Beckman).

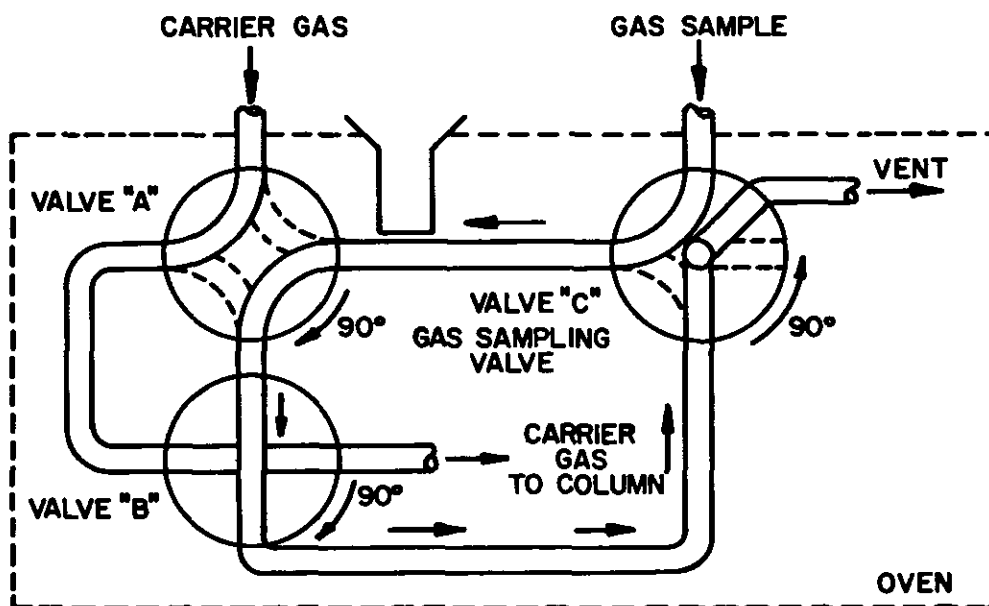
block which is heated independently to a temperature approximately 50 to 100 degrees above the column temperature. The solvent and sample are, therefore, flash evaporated when injected, without changing the gas flow or the thermal conditions of the column. The quantity of liquid sample ranges from 1 to 10 microliters and gas samples vary from 0.05 to 50 milliliters.

Most samples are introduced by means of a small, calibrated syringe or a microsyringe, such as the Hamilton syringe. These syringes are made for delivering either liquids or gases. Liquid syringes are available in sizes of 1 microliter to 500 microliters. Gas tight syringes are available in sizes of 50 microliters to 2500 microliters. For calibration with larger volumes of gases, plastic syringes are available in sizes from 0.5 to 1.5

liters. Figure 21-4 shows several types of syringes used in gas chromatography.

Samples may also be introduced to the column using a gas sampling valve, illustrated in Figure 21-5. The gas sample may be introduced to the gas sampling loop under pressure or by drawing the sample into the loop using a small vacuum pump or a two-way squeeze bulb. The gas sample can also be delivered to the loop from a pressure container, such as a plastic or rubber bag or a large syringe. The only requirement is that sufficient sample be available to thoroughly purge the sample loop, as shown in Figure 21-6.

A third method of injection is by the use of a sealed ampoule which is broken inside a chamber, which replaces the gas sampling valve, so that the sample is swept into the column.



Instruments, Inc.: What Is Gas Chromatography. Tulsa, Oklahoma.

Figure 21-6. Gas Sampling.

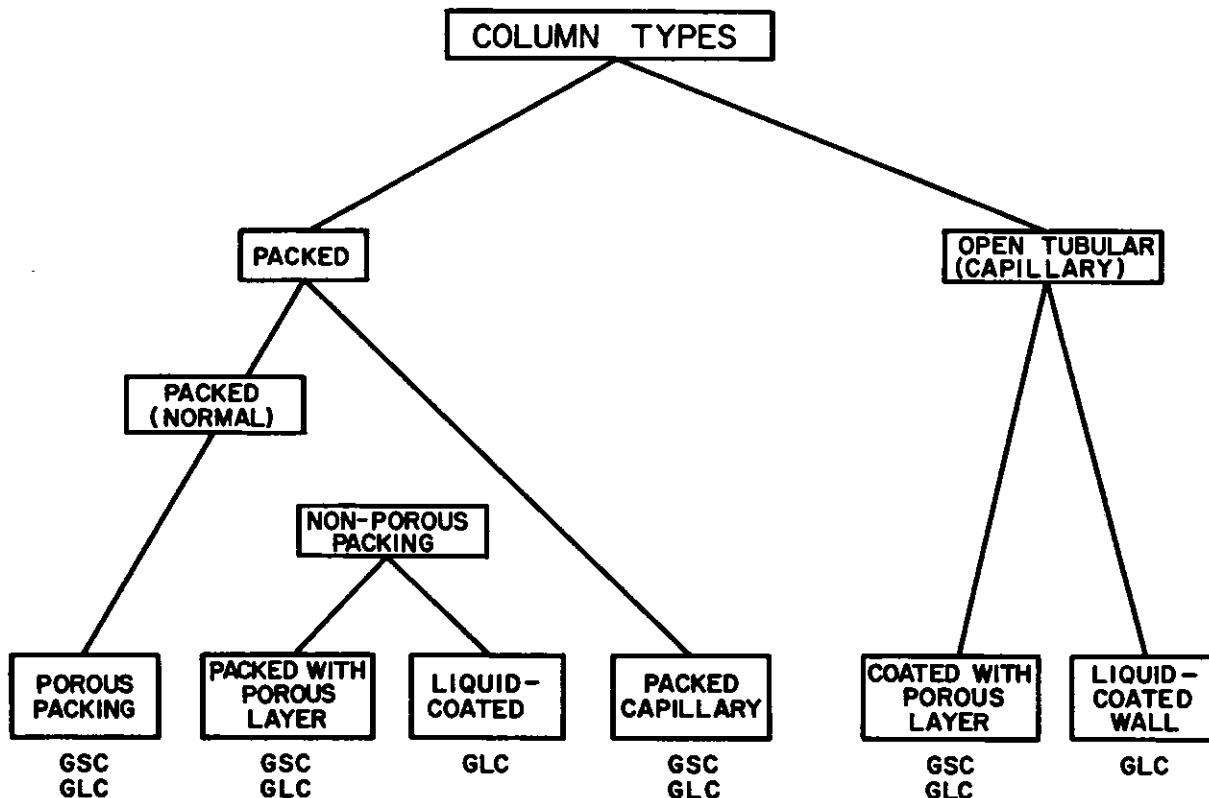
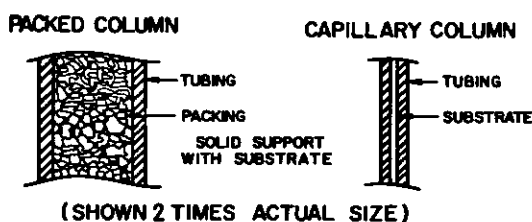
Other types of samplers include pyrolysis systems and solid samplers.

The Column

The column is the "heart" of the chromatograph. Provided that the equipment is good and operating conditions are suitably chosen, the analysis will be as good as the performance of the column selected because it is here that separation of the sample components is effected. Because of the wide variation in packing materials and liquids used as stationary phases, the long life, and the ease of changing columns in the instrument, it is possible for the analyst to select the best packing and column length for each particular sample type. Several columns with different types of packings can be built into the same apparatus and can be operated in series or parallel with each other.

Columns are rigid containers made of stainless steel, copper, aluminum or glass. There are two basic types of columns — the packed column and the capillary or open tubular column (Golay). The *packed column* consists of a length of tubing 1-6 millimeters I.D. and usually 0.5 to 6 meters in length, which is normally coiled or looped to be accommodated in the space provided in the instrument. This tubing is packed with a finely divided inert solid support, which is coated with a thin layer of a nonvolatile liquid, referred to as the liquid phase. The *capillary column* is an empty tube, the inner walls of which serve as the support or adsorbent. This type of column has an I.D. of 0.1-1.0 millimeter and usually is 30-100 meters in length.

The basic difference between gas-liquid and gas-solid chromatography is in the column pack-



Instruments, Inc.: What Is Gas Chromatography. Tulsa, Oklahoma.

Figure 21-7 & 8. Types of Columns and their Operation. Various Size Sample Tubes (usually 1 to 10 ml volume).

ing. In gas-liquid chromatography the column is packed with a solid material made up of particles on which is deposited a known volume of non-volatile liquid constituting the liquid phase. In gas-solid chromatography the packing is generally an active solid (adsorbent) which separates the sample components by differences in their adsorption characteristics. Figures 21-7 and 21-8 illustrate the two types of columns and their types of applications. The following factors influence the efficiency of a column:

Column Length — the efficiency is directly proportional to the length; however, analysis time is also increased with length due to flow resistance. Therefore, the column length is selected by references to the degree of separation and the analysis time required.

Column Diameter — the performance of the column increases with decreasing column diameter. Columns with 2-4 millimeter I.D. give optimal separation.

Nature of Solid Support — the material should be inert and porous, provide a large surface area, and be heat stable.

Granule Size of Support — the column efficiency is dependent on the particle size. The solid support phase is graded on the basis of the mesh size through which it will pass. The column diameter generally determines the proper mesh size as follows:

6-millimeter diameter column — 60/80 mesh
3-millimeter diameter column — 80/100 mesh

Quantity of Liquid Phase — the concentration is adjusted in accordance with the mesh size. The optimum range is 10-15% by weight.

Type of Liquid Phase — the principal characteristics to be considered are polarity, volatility, low viscosity and thermostability.

Temperature Control — it is essential for the temperature to be maintained thermostatically at a point suitable for separating the components of the sample. The control can either be isothermal or programmed such that the temperature is accurately reproduced for samples and standards.

Solid Supports

The purpose of the solid support is to provide a large surface area for holding a thin film of liquid phase. The main requirements for adequate support material are: chemical inertness and stability, large surface area, relatively low pressure drop and mechanical strength. Such material may be organic or inorganic but must be of a known and standard size. The most commonly used materials consist of diatomaceous earth processed or modified in various ways. Since diatomaceous earth supports are not completely inert, they are often treated chemically to inactivate them. An example of diatomaceous earth supports are the Chromosorbs (Johns-Manville Corp.)

Chromosorb P — calcinated diatomaceous earth processed from firebrick (C-22).

Chromosorb W — flux-calcinated diatomite prepared from Celite Filter Aids.

Chromosorb G — developed especially for gas chromatographic analysis.

The various Chromosorbs are available in different

qualities, such as non-acid washed, acid washed, silanized with hexamethyldisilane, and acid washed and silanized with dimethyldichlorosilane.

Besides the various diatomaceous earth supports, porous polymer beads, Teflon and glass beads are used. The Poropak^R resins are examples of porous polymer beads which have partition properties of a highly extended liquid surface without the problems of support polarity or liquid phase volatility which hamper gas-liquid chromatography. The general properties and applications of some types of Poropak[®] resins are as follows:

Poropak N — an intermediate polarity packing useful in separating formaldehyde from aqueous solution. Stable to 250 degrees C.

Poropak P — has the lowest polarity of all types and has the ability to separate systems of intermediate polarity. Usable up to 300 degrees C.

Poropak P-S — is similar to type P; however, the labile sites have been deactivated by silanization to improve peak shape and the efficiency of separation with aldehydes and glycols.

Poropak Q — separates hydrocarbons by vapor pressure and is usable up to 300 degrees C.

Poropak Q-S — is similar to type Q; however, labile sites are deactivated by silanization, and as a result highly polar materials such as organic acids may be analyzed in aqueous solution and show no tailing.

Poropak R — is suitable for the separation of water from highly reactive inorganics such as chlorine and hydrochloric acid.

Poropak S — is suitable for the separation of normal from branched alcohols and is stable up to 250 degrees C.

Poropak T — has the highest polarity of all the Poropak^R resins and is stable up to 250 degrees C.

Poropak^R resins may be used for the separation of most gases and compounds in the moderate boiling range (up to 200°C.). High boiling aromatic and cyclic materials are strongly retained by Poropak^R and are very difficult to elute. When strongly polar materials, such as acids or aldehydes, are to be analyzed silane treated supports should be used. All Poropak^R resin columns require a pre-treatment before use. The column should be purged with gas while heating to rid the resin of residual preparation chemicals.

Liquid Phase

The liquid phase of the column packing is that chemical which actually is responsible for the separation of the various compounds in the mixture in gas-liquid chromatography and must be capable of dissolving the components and releasing them, preferentially by the difference in their volatility, from the solution. The liquid used will be chosen to effect separation of the compounds to be analyzed. In general, the choice of liquid phase is based on the polarities of the substance to be separated and of the liquid phase. The higher the polarity of the liquid the more it will retain polar components compared to non-polar

substances with the same boiling point. The liquid phase should be non-volatile, thermostable, and have low viscosity. Its boiling point should be approximately 250 to 300 degrees C. which will be higher than the optimal temperature at which the analysis is performed. The column coatings which are non-polar liquids are: squalane, silicone

oil, esters of high molecular weight alcohols, dibasic acids and Apiezon L. The polar compounds are: polyethylene glycol, polyesters, ethers, carbohydrate esters, and derivatives of ethylenediamines. Table 21-1 lists some of the common liquid phases with their properties and applications.*

Table 21-1
Some Common Liquid Phases

Solvents: Acetone = A; Benzene = B; Chloroform = C; Methanol = M; Toluene = T; Water = W.

Polarity: non-polar = -; fairly polar = +; strongly polar = ++.

Liquid phase	Solvent	Maximum temperature, °C	Polarity	Applications
Tri-isobutylene	A	30	+	Saturated and unsaturated C ₁ -C ₈ hydrocarbons
Dimethylsulpholane	M	50	++	Saturated and unsaturated C ₁ -C ₈ hydrocarbons
n-Hexadecane (n-cetane)	B	50	-	C ₁ -C ₈ hydrocarbons, halogen derivatives
β, β-Oxy-dipropionitrile	M	70	++	C ₁ -C ₇ paraffins, olefins, cyclo-paraffins, aromatics, alcohols, ketones, esters
Paraffin oil	T	100	-	Hydrocarbons, chlorine compounds, sulphides
Carbowax 400 (polyethylene glycol)	M	120	++	C ₁ -C ₈ alcohols, ethers, ketones, amines
Tricresyl phosphate (tritoyl phosphate)	C	125	++	Aromatics, halogen derivatives, oxygen compounds
Carbowax 600	M	140	++	Oxygen compounds, halogen derivatives, nitrogen compounds
Squalane	T	150	-	Hydrocarbons, halogen derivatives, sulphides
(hexamethyltetracosane)				
Dinonyl phthalate*	A	150	+	Hydrocarbons, halogen derivatives, oxygen compounds
Carbowax 1500*	M	150	++	Aromatics, oxygen compounds, halogen derivatives, nitrogen compounds, sulphur compounds
Carbowax 6000	M	200	++	Aromatics, oxygen compounds, halogen derivatives, nitrogen compounds, sulphur compounds
Carbowax 20 M*	M	200	++	As above, plus polyfunctional alcohols
Ucon LB (polypropylene glycol)	M	200	+	Aromatics, alcohols, ketones, essential oils, amines
Ucon HB (polynikylene glycol)	M	200	+	As above
Silicone oil DC 550*	A	200	-	Esters, aldehydes, hydrocarbons, boranes
Benton 34	T	200	++	Aromatics
Polyesters of succinic acid (e.g. LAC 296)	C	200-240	+	} Esters of fatty acids, ethers, essential oils, and amino-acid esters
Polyesters of adipic acid (e.g. Resoflex)	C	200-240	+	
Silicone elastomer, XE 6A XE 60 (cyano)	A	250	+	Phenols, aromatics, terpenes, steroids
Apiezon M	T	275	-	Higher alcohols, fatty acid esters, essential oils
Apiezon L*	T	300	-	Higher oxygen compounds, fatty acids, nitrogen compounds, steroids, metal organic compounds
Silicone elastomer, SE 30 (dimethyl)	T	300	-	Alkaloids, steroids, nitriles, hydrocarbons, inorganic and metal organic compounds
Silicone elastomer, SE 52 (methyl-phenyl)	T	300	+	Alkaloids, steroids, carbohydrates
Silicone grease (vacuum)	T	350	-	Fatty acid esters, halogen compounds, inorganic compounds
Poly-phenyl tar	T	400	-	Polycyclic aromatics
Inorganic salts and salt cutectics (e.g. LiCl)	W	400-500	-	Inorganic and metal organic compounds, metal halides

* According to the survey of the Data Sub-Committee of the Gas Chromatography Discussion Group the most widely used liquid phases. "Gas Chromatography," Butterworth & Co. Ltd., London, England; Muszaki Konyvkiado, Budapest.

To some degree the detector used must also be considered when selecting a column. For example, if a thermal conductivity detector is used, and the sample contains water (which the detector senses), Teflon would be a better support since it suppresses the tailing of the water peak which would otherwise obscure some peaks. On the other hand, the flame ionization detector does not respond to water and therefore the problem of tailing does not occur. When the electron capture detector is used, a liquid phase with low bleeding rate is very important. In such systems, DC-200 silicone oil with high viscosity is recommended.

Adsorbents

In gas-solid chromatography various adsorbents are used as column packings. With the growth of gas-liquid chromatography, the use of adsorbents and their applications are:

Silica Gel — used in the analysis of inorganic gases and light hydrocarbons.

Molecular Sieves — used for the separation of permanent gases such as hydrogen, oxygen, nitrogen, carbon monoxide, methane and ethane. Carbon dioxide and higher hydrocarbons are adsorbed irreversibly on molecular sieves at low temperatures.

Activated Charcoal — used for the separation of air, carbon monoxide, methane, carbon dioxide, acetylene, ethylene, ethane, propylene and propane.

Chromosorb — used for the separation of nitrogen, hydrocarbons, acid gases and basic gases.

Poropak Q — can be used to separate such widely different materials in the gas phase as air, carbon dioxide, sulfur dioxide, nitrous oxide, nitric oxide, hydrogen sulfide, hydrogen cyanide, carbon oxysulfide, hydrogen chloride, chlorine and ammonia.

Poropak N — used to separate acetylene from ethylene and ethane.

The regeneration time and temperature for adsorbents is as follows:

Alumina, silica gel and activated charcoal — 30 minutes at 100°C.

Molecular sieves — 30 minutes at 300°C.

Poropak N and T — 30 minutes at 180°C.

Poropak Q, R, S, Q-S — 30 minutes at 230°C.

Chromosorb — 30 minutes at 140°C.

Detectors

Detectors must sense continually, rapidly and with high sensitivity the components which appear in the carrier gas as it emerges from the column, by means of changes in a physical or chemical property of the effluent gas stream. The corresponding electrical response is amplified and fed to a recorder. One of the chief factors in the wide-spread application of gas chromatography is the availability of a great variety of highly efficient detectors.

The essential quality of a detector is determined by the following factors: (1) sensitivity, (2) signal-to-noise ratio, (3) drift, (4) linearity, (5) independence of extraneous variables, (6) ease of calibration, (7) speed of response, (8) chemical inertness, and (9) range of application.

There are basically eight types of detectors: *Thermal Conductivity* (katharometer) — measures change in heat capacity.

Gas Density — measures change in density.

Flame Ionization — measures difference in flame ionization due to combustion of the sample.

Beta-Ray Ionization — measures current flow between two electrodes caused by ionization of the gas by a radioactive source.

Photo-Ionization — measures current flow between two electrodes caused by ionization of the gas by ultraviolet radiation.

Glow-Discharge — measures the voltage change between two electrodes caused by the change in discharge by different gas compositions.

Flame Temperature — measures change in temperature caused by difference in gas composition in the flame.

Dielectric Constant — measures the change in the dielectric constant caused by difference in composition of gas between plates of a capacitor.

A summary of the common commercial detectors is presented in Table 21-2. A description of several detectors is as follows:

Thermal Conductivity Detector — the most widely used detector. Uses either a hot wire or thermistor as the sensing element. The resistance changes due to sample components, and the detector measures the thermal con-

Table 21-2
Summary of the Common Commercial Detectors

Name	Type	Analyzable Materials	Maximum Sens. GMS/Sec.
Thermal Conductivity (Katharometer)	Measures Changes in Heat Capacity	All	10 ⁻⁷
Ion Cross Section	Beta-Ray Ionization	All	10 ⁻⁷
Argon Diode	Beta-Ray Ionization	Most Organics	10 ⁻¹³
Electron Affinity	Beta-Ray Ionization	Electron Absorbing Materials Only	10 ⁻¹⁴
Flame Ionization	Ionization In Hydrogen Flame	All Organics	10 ⁻¹²
Thermionic Emission	Hot Filament Ionization	All	10 ⁻¹⁰

ductivity of the sample stream as opposed to the reference stream of the pure carrier gas. The response is approximately proportional to the concentration of sample component in the detector. This type of detector is a non-destructive detection system. Examples of thermal conductivity are shown in Table 21-3.

Table 21-3
Examples of Thermal Conductivity

Gas	Relative Conductivity at 100°C (Air = 1)
Hydrogen	6.94
Helium	5.54
Methane	1.72
Ethane	1.09
Oxygen	1.032
Air	1.000
Nitrogen	.998
Carbon Monoxide	.924
Methyl Alcohol	.727
Carbon Dioxide	.690
Acetone	.557
Carbon Tetrachloride	.288

Ionization Gage Detector — uses a heated filament to ionize substances having ionization potentials less than that of helium. Only a small fraction of the effluent passes through the gage. The ionization current produced in the cell is a measure of the concentration of the sample component.

Flame Ionization Detector — uses hydrogen/air or hydrogen/oxygen flame. This flame ionizes the organic sample material and the ions are collected by an electrode which is positive in relation to the flame. This electrical potential causes a current flow which is an instantaneous measurement of the component concentration. This detector has a high sensitivity, about 500-2000 times that of the thermal detector. It also has a fast response time, a very small effective cell volume and a high signal-to-noise ratio.

Beta Argon Ionization Detector — a radioactive source ionizes the effluent from the column causing an ion current to flow from the collision of metastable argon ions with the sample molecules. This current is a measure of concentration. The sensitivity is much higher than that of the thermal conductivity detector for all components except light gases with ionization potentials above 11.7 electron volts. Minimum detectability of components is in the general range of 10^{-9} grams per sec. This gage is less sensitive than the flame ionization gauge.

Electrolytic Conductivity Detector — used for the detection of halogen, sulfur and nitrogen containing organic compounds. Its principal use is for the detection of residues of chlorinated hydrocarbon type pesticides and nitro-

gen containing pesticides such as carbamates and triazines. The Coulson¹⁰ electrolytic conductivity detector is probably the simplest to operate and easiest to maintain of all the element selective detectors. Yet it has good selectivity and sensitivity. The system consists of a prolyzer, a gas-liquid contactor, a gas-liquid separator, and a simple pair of platinum electrodes in a d.c. bridge circuit. The prolyzer converts the organically bound halogen, sulfur, or nitrogen to oxidized or reduced substances that form electrolytes when dissolved in water. These electrolytes are detected by the change they produce in the conductivity of water in the detector cell. Conductivity is measured between the two platinum electrodes of the cell by means of a simple d.c. bridge and recorded continuously on a one-millivolt strip-chart recorder.

Semiconductor Thin Film Detector — a detector for gaseous components, based on the fact that the adsorption and desorption of gases causes changes in electrical conductivity of semiconductors. At high temperatures (near 400°C) the adsorption and successive desorption processes on the surface of semiconductors take place very rapidly and may indicate a marked change in electrical conductivity by the use of thin film semiconductors. This property of thin film is applicable to the detection of gaseous components. An example of this type detector is the P-N junction.

P-N Junction Detector — this semiconductor thin film detector has the advantage over the original type of thin film detector in that the sensitive element is readily available and does not have to be specially prepared. The element is a reversed biased semiconductor diode. These diodes are affected by ambient gases.

Glow-Discharge Detector — the composition of the gas chromatographic effluent is measured by the change in voltage across a gaseous discharge.

Radio-Frequency Discharge Detector — the collisions between sample components and r-f excited rare gas atoms causes changes in light emission. Low vapor concentrations are measured by changes in this light emission when the solute molecules are ionized.

Micro Cross-Section Detector — a concentration of ion pairs is produced when the effluent stream is subjected to ionization radiation. The number of ion pairs is proportional to the cross-section area available for ionization in each sample. As solute concentration increases, more ion pairs are formed; thus greater current is passed.

Helium Beta Ionization Detector — a simple and ultra sensitive gas chromatographic detection device which was developed for the analysis of permanent gases. The detector consists of two electrodes closely spaced (approximately 1 mm) either in a concentric or parallel geometry. The internal detector volume is 150 microliters. A tritium impregnated

foil serves as one electrode. A constant potential is applied to one electrode while the other electrode lead is connected to an electrometer capable of measuring small (10^{-11} amps) changes in current. Helium passing from a chromatographic column is excited to the metastable state (energy level = 19.8 eV). All permanent gases except neon are ionized in turn and produce a positive increase in the detector current. Neon shows a negative peak. Sensitivity as low as 10 ppb is demonstrated with chromatograms for hydrogen, oxygen, argon, nitrogen, carbon monoxide and carbon dioxide. Linear response is shown over a range of 10,000.

Electron Capture Ionization Detector — this detector utilizes an ion chamber containing a gas with free electrons at an applied potential just great enough to collect completely the free electrons generated by a radioactive source. Molecules from the sample (which have an affinity for the free electrons) will capture the free electrons and become negative ions. The detector current decreases in the presence of the electron capturing molecules. Other types of detectors include the Gas Density Balance, Alkali Flame Ionization, and Alpha Ionization as well as mass spectrometers and automatic titrators.

Temperature Control

For precise and reproducible gas chromatographic analysis there must be temperature control of (1) the injection system, (2) the column, (3) detector and (4) fraction collector, if used. The injection system must be heated to a point that will volatilize the sample instantaneously and keep it in the vapor state until it reaches the column, which is also heated to assure that the sample components remain in the gaseous state for the passage through the separation column. The detector likewise must be heated to keep the sample components in the vapor phase. The temperature of each component part of the gas chromatograph must be precisely controlled and reproducible so that constant sample retention times may be attained.

If a fraction collector is used, its temperature must also be high enough to keep the components gaseous until collected in a cold trap.

Each instrumental component can have a separate control system or the temperature of the assembly may be controlled by a single system. In the single control system the injector, column, detector and fraction collector are all located in a constant temperature oven. When the component parts have separate controls, each can be set at an optimal value. Generally, the single temperature control is for isothermal operating conditions.

If the sample components have a very wide boiling range, programmed temperature control is most valuable. In the programmed mode, the injector, detector and collector are set at a constant temperature and the column temperature is varied at a known and constant rate. This shortens the analysis time considerably when dealing with the widely separated boiling point components. The programmed temperature control must be very reproducible or the results can be confusing. As the control must be regulated very closely, these systems are costly. A comparison of chromatograms prepared using constant and programmed column temperatures is shown in Figure 21-9.

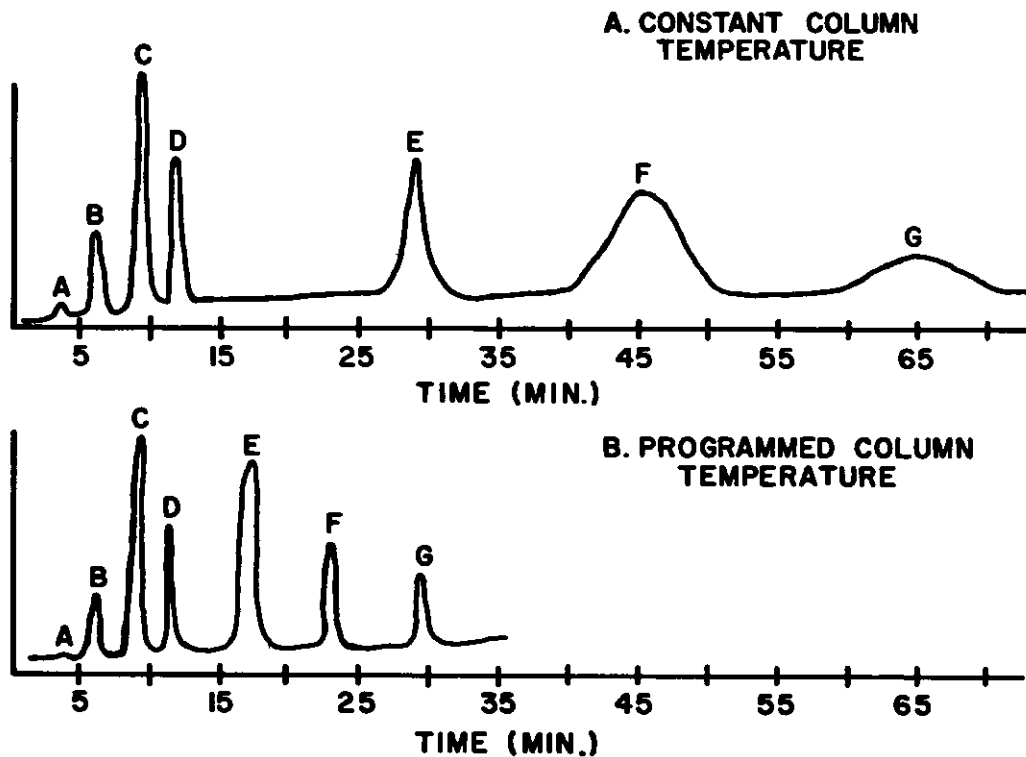
Recording Devices

The response of the detector is plotted as a chromatogram by the millivolt recorder. The chromatogram is a plot of detector response versus time. With only carrier gas flowing through the detector, the recorder is adjusted to read zero. This zero reading is referred to as the base line. Each separated component evokes a response by the detector which registers a peak on the chromatogram. The chromatogram will give two different kinds of information: (1) identification by retention time, the time it takes for the peak to appear after injection of the sample, and (2) quantitative estimation of a component of the sample, which can be obtained by comparing the area of the peak with that produced by a standard sample of the same component substance at a known concentration.

There are two types of strip chart recorders in use — the galvanometric and potentiometric. Galvanometric recorders are inexpensive but require an amplifier. Potentiometric recorders are more expensive but do not always require an amplifier.

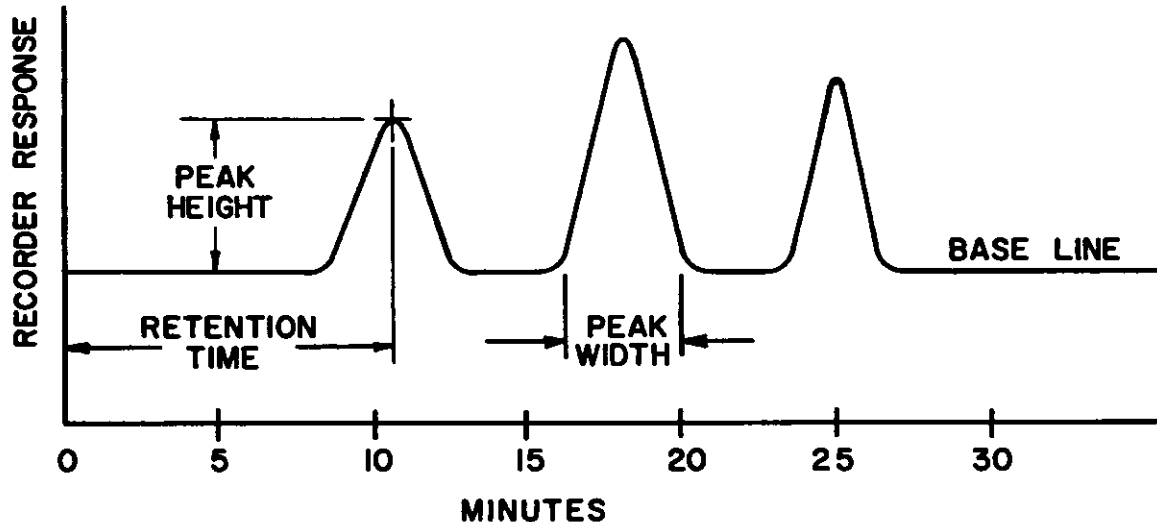
Figure 21-10 is a diagrammatic example of a typical chromatogram indicating the several measurements of interest.

Digital readout may be employed by using one of several types of printing integrators, which merely print out numbers corresponding to the area under the chromatographic curve. There are several types of integrators: mechanical, electromechanical and electronic. The most generally used is the mechanical or disc integrator, which measures mechanically the height of the curve. The electromechanical integrator converts the voltage change from the detector signal to a digital signal directly. The electronic integrator is similar to the electromechanical unit but uses a voltage totaling circuit instead of a direct signal.



Prepared by Sandia Laboratories draftsmen.

Figure 21-9. A Comparison of Chromatograms Prepared Using Constant and Programmed Column Temperatures.



Prepared by Sandia Laboratories draftsmen.

Figure 21-10. Diagrammatic Example of a Typical Chromatogram.

Other readout systems may be used as ancillary equipment, such as mass spectrometers, attached directly through concentrators to the chromatograph, or flow type infrared or ultraviolet spectrophotometers.

Collection Systems

The system for collecting chromatographed sample components can be very simple or quite elaborate. The simplest system is that of collecting the vapor on a cold plate at the detector outlet. This technique can be used with salt plates for infrared spectral analysis. The vapor may also be collected in miniature condensers cooled with ice, dry ice-acetone or other cryogenic systems. The vapor may be kept in this stage, passed through heated tubes to gas analysis systems such as infrared gas analysis cells, or introduced into mass spectrometer sampling systems through a helium separator.

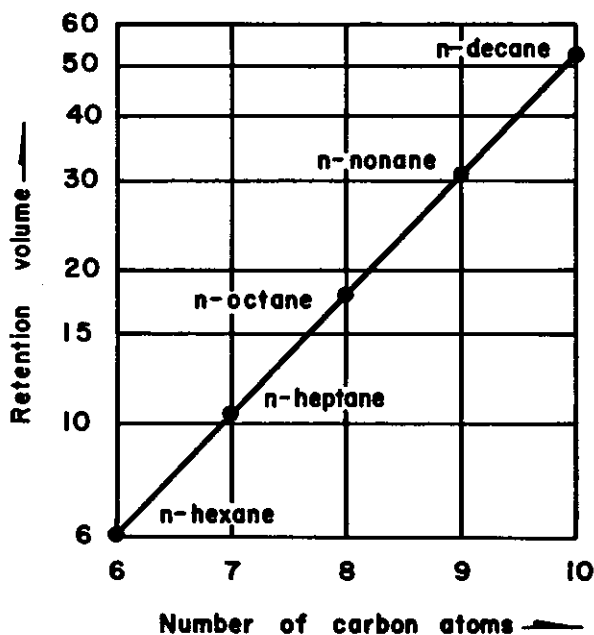
The collection system may be as original as the chromatographer can develop to satisfy the requirements of his analytical problems and instruments.

QUALITATIVE ANALYSIS

From the foregoing information it is obvious that practically any vaporous mixture can be separated by gas chromatographic techniques. One of the main problems, however, is the qualitative determination of the mixture components.

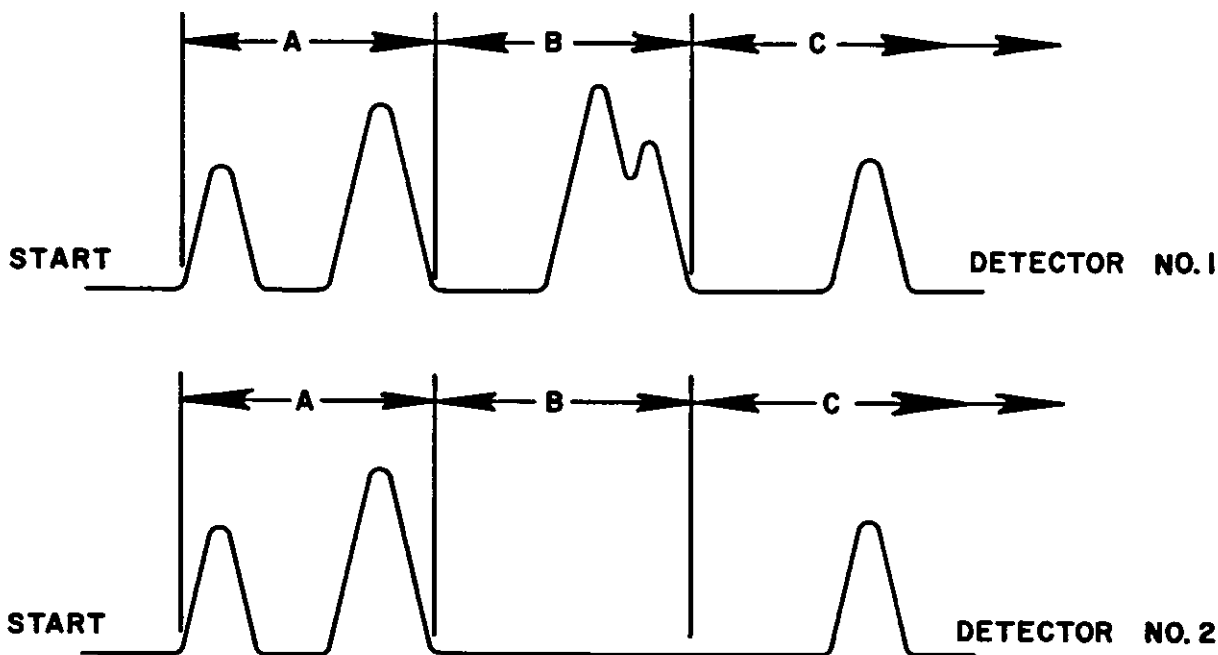
There are four basic methods which have been used for the identification of separated components: (1) comparison of known compound chromatograms with the unknown, (2) plotting of homologous series, (3) use of dual columns, and (4) identification by auxiliary instrumentation. When members of homologous series are chromat-

ographed under reproducible conditions, the results can be plotted as the number of carbon atoms versus log of retention volume. The plot can then be used for a determination of the carbon content of the component of interest. An example is shown in Figure 21-11.



Prepared by Sandia Laboratories draftsmen.

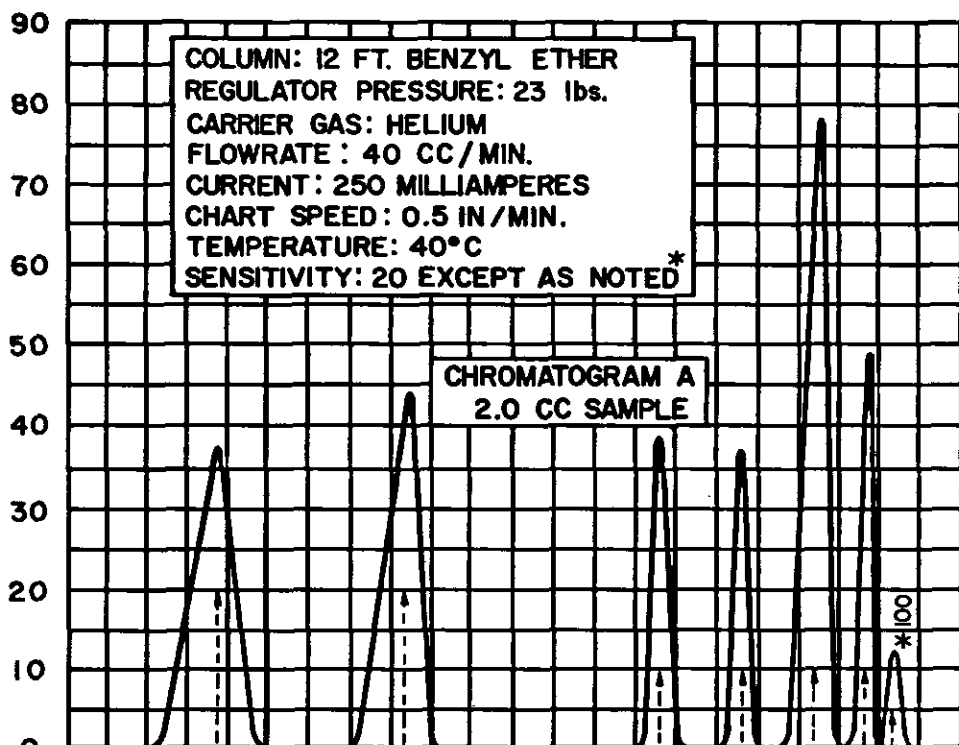
Figure 21-11. Example of Plot to Determine Carbon Content of Component.



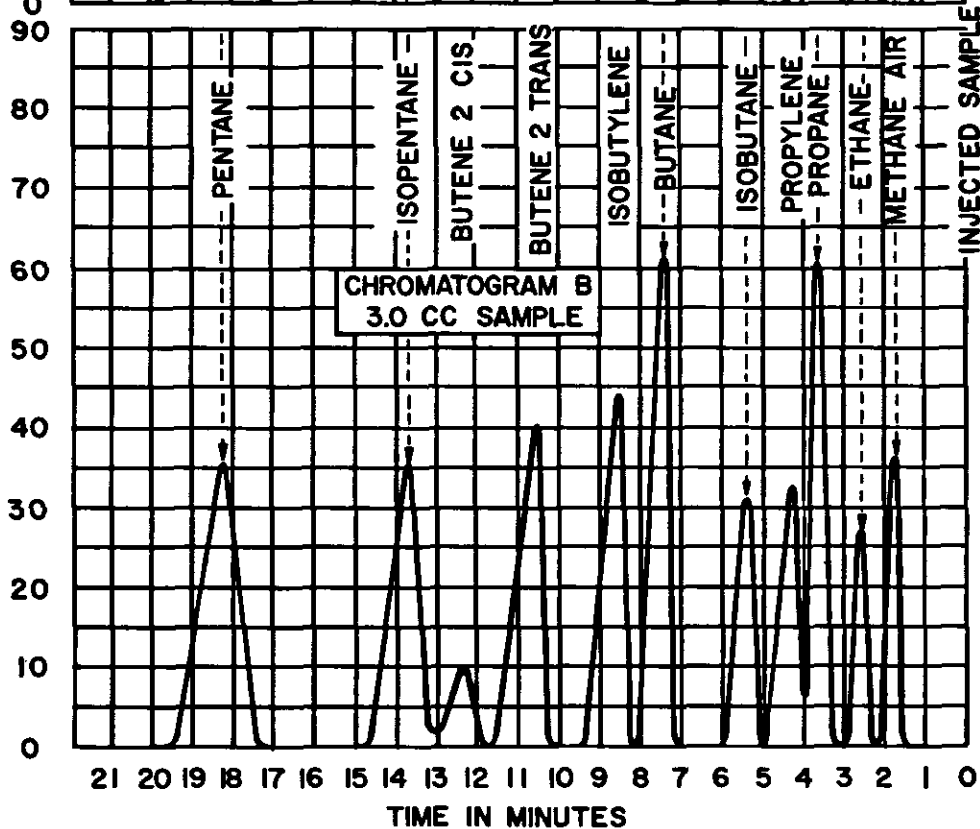
Prepared by Sandia Laboratories draftsmen.

Figure 21-12. Dual Detector Response.

UNKNOWN



KNOWN



Beckman Instruments, Inc.: Bulletin #756A. Fullerton, California.

Figure 21-13. Illustration of Use of a Known Sample to identify the Components of the Unknown Sample.

When dual columns are used different retention times of the individual components are obtained. The use of dual detectors results in a different response to the sample components due to the specificity of the detector. Figure 21-12 illustrates the dual detector response.

A more specific method for qualitative analysis is the use of auxiliary instrumentation such as infrared, ultraviolet or mass spectrometry. The sample components are trapped at the outlet from the gas chromatograph, transferred to the appropriate instrument and subjected to a qualitative analysis by the independent technique.

The separation achieved depends upon the column, the temperature, the detector and flowrate of the carrier gas. Therefore, it is imperative that all these parameters be kept the same for both the sample and the standard used for the determination of component peak location. It is important to know that the unknown component is eluted in the same time as a known compound. It is also important to know that no other compound can appear at this location with the parameters used. Figure 21-13 illustrates the use of a known sample to identify the components of the unknown sample.

QUANTITATIVE ANALYSIS

The prime application of gas chromatography is, of course, quantitative analysis. It is well known that the area under a chromatographic peak is proportional to the amount of the responsible sample component in the carrier gas stream. This means that the use of gas chromatography for quantitative analysis requires a knowledge, first, of the area of the peak and second, the proportionality factor to convert this measurement to a concentration unit.

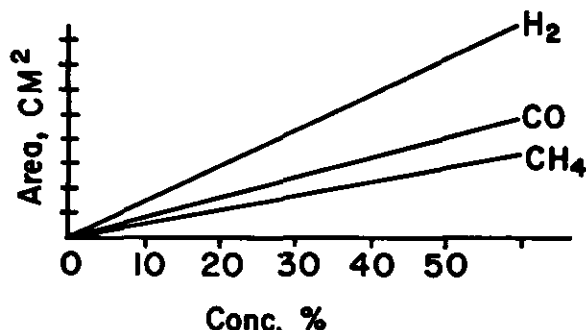
Areas can be determined by any of the following methods:

1. Automatic integrator
2. Polar planimetry
3. Cutting out the peak and weighing the chart paper on an analytical balance
4. Multiplying the peak height by the peak width at half the peak height
5. Calculating the area of the triangle formed by the two tangents drawn through the inflection point of the peak, using the base line as the base of the triangle.

The most commonly used of these methods are 1, 2 and 4. The areas are expressed in any convenient unit, the most common unit being cm^2 . In the ideal case, where detector response is the same for all components in a mixture, a simple relationship is used to calculate percentage. As an example, assume that we have an ideal four-component mixture of methane, ethane, propane and butane. The areas are 2.50, 1.25, 5.00 and 0.625 cm^2 , respectively. The total area = 9.375 cm^2 . The percentages are then: methane = 26.67%, ethane = 13.33%, propane = 53.33% and butane = 6.67%, making the total 100%. The ideal case, however, does not always apply. The response factors are different for individual compounds, and this must be taken into consideration before calculation of percentage values.

The sample components may also be collected at the detector outlet and analyzed by means of infrared or ultraviolet spectrophotometry, mass spectrometry or computer coupling.

The most popular method of quantitation in the laboratory is by means of standard curves prepared by plotting the detector response versus concentration as shown in Figure 21-14.



Prepared by Sandia Laboratories draftsmen.

Figure 21-14. Plot of Detector Response Versus Concentration.

OPERATION OF THE GAS CHROMATOGRAPH

Selection of Parameters for Operation

Carrier Gas — the choice depends on cost, availability, nature of sample, safety and the type of detector.

Type of Column — selection is dependent on the polarity and volatility of the packing as compared with the substances to be separated, (see section on "Columns").

Detector — selection is based on sensitivity for type of sample component to be analyzed, (see section on "Detectors").

Temperature Controls — the setting for the temperature of the injection block is determined by the boiling point of the least volatile compound in the sample. In general, it is maintained at a temperature of 50-100 degrees C above the column temperature, which may be maintained at the limit specified for the packing it contains. The detector must also be maintained at a specified temperature which is dependent on the type of detector used and the analysis performed. All temperature controls are set and allowed to stabilize before injection of the sample.

Column Preparation

Many liquid phases require conditioning before use. This is accomplished by heating the column at a slightly higher temperature than the intended operating temperature for six to twelve hours to "bleed off" any excessive coating in the column.

Sample Collection Methods

Samples of contaminated air may be collected in many ways, some of which are:

- (1) Glass or metal double-valved sampling flasks through which the sample is drawn by means of a small carbon vane pump or double-ended squeeze bulb.

- (2) An evacuated glass or metal single-valved flask or bulb, into which the sample is drawn.
- (3) Plastic or rubber bags which may be used for nonreactive gases are filled using either a double-ended squeeze bulb, for small volumes up to 1 liter, or by carbon vane pumps, for volumes up to 20 liters.
- (4) Adsorption on active solids while drawing the contaminated air through the solid contained in a sampling tube.
- (5) Absorption in a suitable solvent using standard air sampling equipment (i.e., impinger or bubbler).
- (6) Collection in large volume gas tight syringes which are then capped to prevent leakage.

There are two methods for the collection of air samples which are to be transported over long distances for analysis. The method of choice is to collect the air contaminant directly onto an active solid contained in a sampling tube. An alternate method is to first collect the air sample in a glass, metal, rubber or plastic container and then the air is passed through a tube containing an active solid adsorption of the contaminant. In either case the tube is sealed and sent to the laboratory for future analysis. Air volumes must always be recorded so that concentrations can be calculated.

Sample Preparation

Some substances, such as gases, can be injected directly into the chromatograph, but ordinarily, there may be some preliminary purification needed

which may be simple or complicated, depending on the compound to be analyzed. Because some substances in a mixture are similar, they cannot be separated from each other unless they are first converted into derivatives such as acetates or esters, thus producing larger molecules which may be separated more easily. Finally, after purification and derivative formation, the sample must be added to a suitable solvent which will volatilize at the temperature of the injection chamber. The solvents most frequently used for this purpose are acetone, alcohol, chloroform and hexane. In most cases, nanogram amounts of a sample are injected by means of a micro-syringe calibrated in microliters.

It is apparent that the preparation of the sample for analysis can be a tedious, time-consuming task and this phase is one of the few disadvantages of gas chromatography.

Presentation of Chromatographic Data

The precise reproduction of one's analyses or those of other investigators requires all of the pertinent information to be made available. The following data must be included in chromatographic reports: type of sample, instrument used, identification of the column and the conditions of operation, date of analysis, results and name of operator. Figure 21-15 illustrates a convenient tabulation report form.

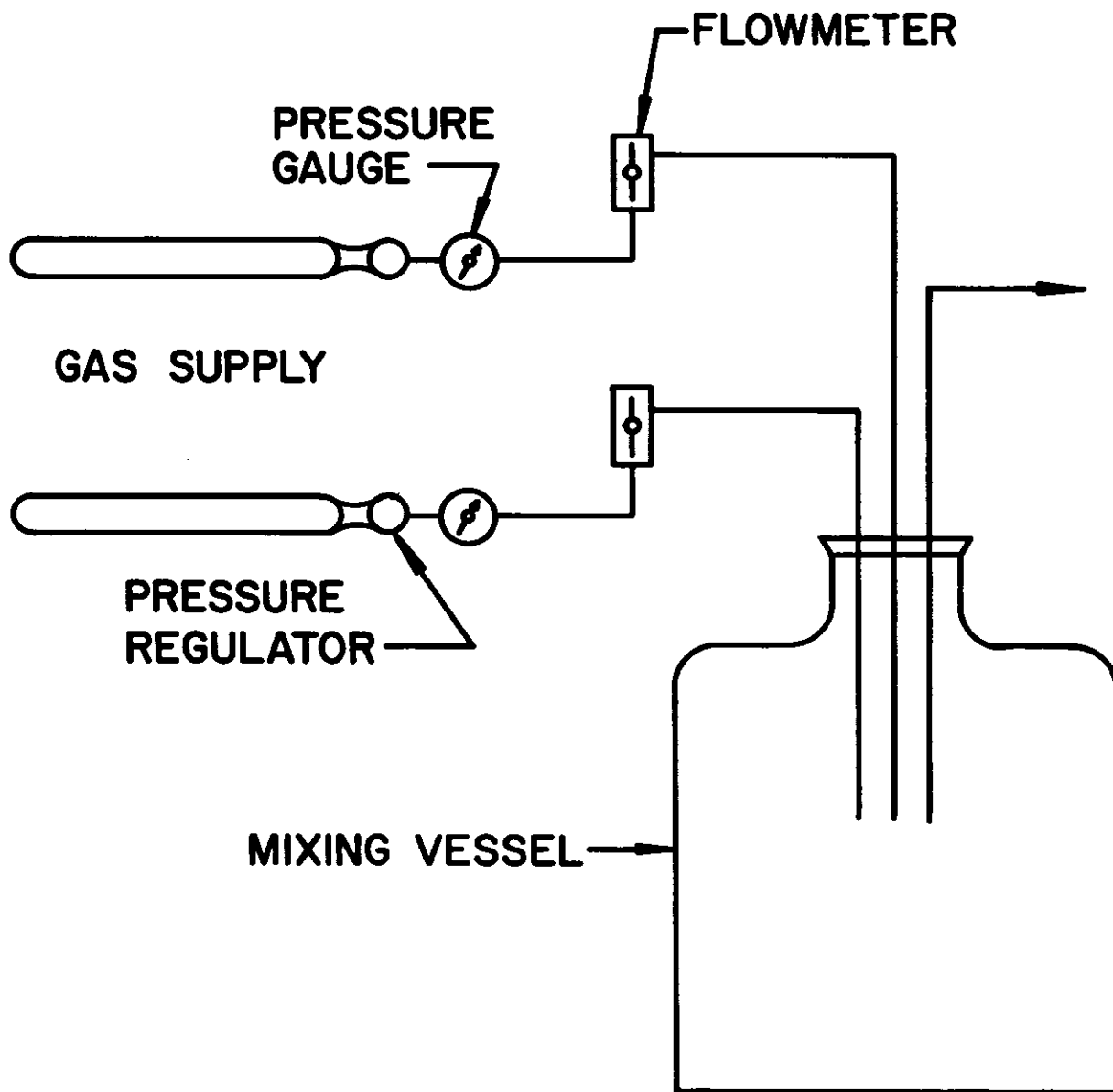
CALIBRATION

For accurate quantitative analysis the gas chromatographic system must be calibrated using

Operator _____	Date _____
Column	Detector _____
Length _____	Voltage _____
Dia. _____	Sensit. _____
Liquid Phase _____	Flow Rates, ml/min
Wt. % _____	Hydrogen _____ Air _____
Support _____	Scavenge _____
Mesh _____	Spht _____
Carrier Gas _____	Temperature, °C
Rotometers _____	Det _____ Inj _____
Inlet Press _____ psig	Column Initial _____
Rate _____ ml/min	Final _____
CHART SPEED _____	Ratio _____
SAMPLE _____	Solvent _____
Size _____	Conc. _____

known concentrations of the components of interest. Several methods are available for preparing known concentrations of gases and vapors for this purpose.

A simple system for the preparation of known concentrations of gases by a dynamic method is shown in Figure 21-16 where known amounts of the gas (A) are mixed with a diluting gas (B) to



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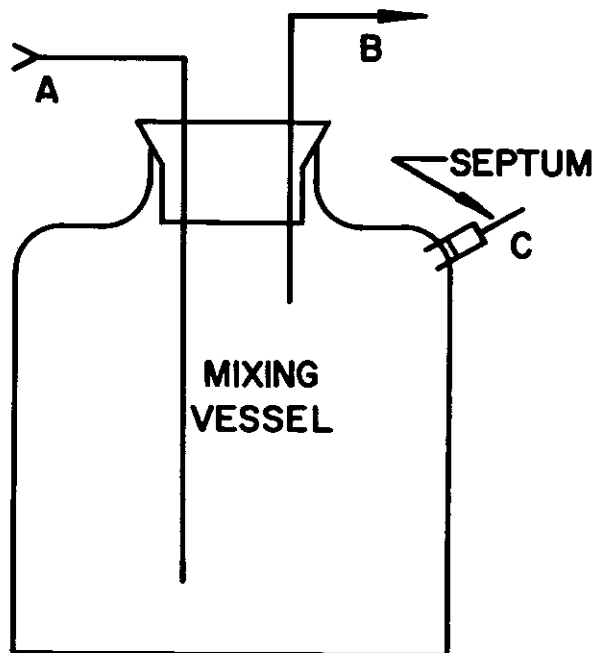
Figure 21-16. Dynamic Method.

yield the required concentration (C).

A second method which may be used for the preparation of known concentrations of either gases or vapor in air is the static method where a known volume of gas or volatile liquid is introduced (with an accurate volume measuring device) through a septum into a previously evacuated rigid container of known volume. The gas or vapor is then mixed with the diluting gas and stirred by either mechanical or thermal methods and samples are withdrawn from the vessel for use in calibra-

tion. This static system is shown in Figure 21-17, which illustrates the known gas (A), the diluting gas (B) and the known gas concentration (C).

Samples from either type of calibration system can be introduced directly to the gas sampling valve of the chromatograph or they may be contained in a plastic or rubber bag from which the samples may be removed using gas tight syringes to transfer them to the chromatograph. These standard samples are chromatographed and the detector response is plotted versus concentration.



Prepared by Sandia Laboratories draftsmen.

Figure 21-17. Static System.

For an accurate calibration, the concentration of the known mixture must be determined by standard chemical methods. Infrared spectrophotometry is a convenient procedure for determining the concentration of many components.

There are several companies which market pressure containers of gases in labeled concentrations in nitrogen or other diluents; these may be used in the calibration of gas chromatographic systems. These mixtures are very convenient, but the concentrations must be verified by independent analyses before using for calibration purposes.

SPECIAL TECHNIQUES

Displacement Chromatography

Samples collected on active solids may be analyzed chromatographically by a technique called displacement, where the sample collection tube is inserted just ahead of the chromatographic column. A solvent vapor, for which the active adsorbent has a greater affinity than for the sample components, is passed through the collection tube displacing the sample onto the chromatographic column. This technique, when properly applied, presents essentially a plug of the sample to the column, by concentrating the sample as the displacement vapor replaced the components on the active solid.

Long Line Sampling

It is possible to sample gaseous contaminants in air over relatively great distances by using 0.5-inch I.D. tubing and moving the sample through the line at 1 liter per minute using a large capacity vacuum pump. Line losses are negligible if the sample lines have been pressure checked before

samples are taken. Sampling distances up to 6500 feet have been used.¹¹

Portable Chromatographs

There are available many very good portable chromatographs which may be taken to the work areas for sample analyses. The difficulty, however, arises in obtaining a large enough sample for analysis of trace contaminants. A sample concentrating chromatograph has been developed (personal communications) which samples the air through a small tube of activated silica gel. After the sample has been collected valves are changed and the air contaminants are released from the adsorbent by heat and presented directly to the gas chromatographic column for analysis. The versatility and applications of the portable chromatograph are progressing at an encouraging pace fortunately, as this type of unit is needed greatly throughout the whole environmental health field.

Process Chromatography

The process unit is capable of performing repeat analyses of stream effluents, liquid or gaseous, for many components. This type of analysis can be programmed and the data fed to a computer for analysis; the results may be fed to a control system where necessary adjustments are made in processes if the analysis indicates the need. Process control by gas chromatography has wide-spread use in the chemical industry.

Pyrolysis

Pyrolysis, the thermal decomposition of samples, is an important new branch of the identification methods. This technique may be used in the identification of polymers, high molecular weight organic and inorganic compounds, and also low boiling compounds, by producing the characteristic breakdown products. It has also been used in the characterization of microorganisms.¹² Essentially, the technique employed is similar to that used in displacement chromatography but the displacement column is replaced by a combustion oven located just ahead of the partitioning column of the instrument. The output display has been called a pyrogram, which has an extremely complex nature. Since pyrolysis reactions are unpredictable the pyrolysis conditions must be very closely regulated for reproducible analyses.

Miscellaneous

Some recent applications have been published based on the work of investigators in the fields of air pollution, clinical medicine, toxicology and allied areas.

Air Pollution — Using a two section column, Bethea¹³ was able to determine nitrogen dioxide with a lower detection limit of 200 ppm. Gas chromatography of gases emanating from the soil has been successful in separating the component mixture using a three column system equipped with a thermal detector.¹⁴ A short silica column has been used to determine nitrogen dioxide at 50-60 degrees with hydrogen as a carrier gas.¹⁵ Nitrogen dioxide has been collected and concentrated on Molecular Sieve 5A and determined by chromatography on a Poropak Q column¹⁶. Lawson¹⁷ has determined nitrogen oxides in air by gas chromatography.

Medicine and Toxicology — Many articles are being published on the determination of alcohol in breath samples, using various chromatographic methods. Lowe¹⁸ reviewed the determination of volatile organic anesthetics in gases, blood, and tissue by gas chromatography. The direct determination of organic solvents in blood was described by Schlunegger.¹⁹

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CHAPTER 22
**QUALITY CONTROL FOR SAMPLING
AND
LABORATORY ANALYSIS**

Adrian L. Linch

INTRODUCTION

The measurement of physical entities such as length, volume, weight, electromagnetic radiation and time involves uncertainties which cannot be eliminated entirely, but when recognized can be reduced to tolerable limits by meticulous attention to detail and close control of the significant variables. In addition, errors often unrecognized, are introduced by undesirable physical or chemical effects and by interferences in chemical reaction systems. In many cases, absolute values are not directly attainable; and, therefore, standards from which the desired result can be derived by comparison must be established. Errors are inherent in the measurement system. Although the uncertainties cannot be reduced to zero, methods are available by which reliable estimates of the probable true value and the range of measurement error can be made.

In this chapter the fundamental procedures for the administration of an effective quality control program are presented with sufficient explanation to enable the investigator to both understand the principles and to apply the techniques. First, the detection and control of determinate and indeterminate error will be considered. Based on this foundation, the types of errors and meanings of the common terms used to define an accurate method are discussed as a basis for application of quality control to sampling and analysis. The theory, construction, applications and limitations of control charts are developed in sufficient depth to provide practical solutions to actual quality control problems. Additional statistical approaches are included to support those systems which may require further refinement of precision and accuracy to evaluate and control sampling and analysis reliability.

Finally, a discussion of collaborative testing projects and intralaboratory quality control programs designed to improve and test the integrity of the laboratory's performance completes the survey of quality control principles and practices.

QUALITY CONTROL PRINCIPLES

Total Quality Control

A quality control program concerned with sampling and laboratory analysis is a systematic attempt to assure the precision and accuracy of future analyses by detecting determinate errors in analysis and preventing their recurrence. Confidence in the accuracy of analytical results and

improvements in analysis precision are established by identification of the determinate sources of error. The precision will be governed by the indeterminate error inherent in the procedure, and can be estimated by statistical techniques. For a result to be accurate, the procedure must not only be precise, but must also be without bias. Techniques have been developed for the elimination of bias. The quality control program should cover instrumental control as well as total analysis control. The use of replicates submitted in support of the quality control program provides assurance that the procedure will remain in statistical control.

Quality must be defined in terms of the characteristic being measured. Control must be related to the source of variation which may be either systematic or random. Usually the basic variable is continuous (any value within some limit is possible). A numerical value of an analysis for which the range of uncertainty inherent in the method has not been established cannot be reliably considered a reasonable estimate of the true or actual value. The basic quality control program incorporates the concepts of:

1. Calibration to attain accuracy
2. Replication to establish precision limits
3. Correlation of quantitatively related tests to confirm accuracy, where appropriate.

Evaluation of the overall effectiveness of the quality control program encompasses a number of parameters:

1. Equipment and instruments
2. The current state of the art
3. Expected ranges of analytical results
4. Precision of the analytical method itself
5. Control charts to determine trends as well as gross errors
6. Data sheets and procedures adopted for control of sample integrity in the laboratory
7. Quality control results on a short term basis (daily if appropriate) as well as on an accumulated basis.

The manipulative operations which are directly influenced by quality control include:

1. Sampling techniques
2. Preservation of sample integrity (identification, shipping and storage conditions, contamination, desired component losses, etc.)
3. Aliquoting procedures
4. Dilution procedures

5. Chemical or physical concentration, separation and purification

6. Instrument operation.

Statistical Quality Control

Statistical quality control involves application of the laws of probability to systems where chance causes operate. The technique is employed to detect and separate assignable (determinate) from random (indeterminate) causes of variation. "Statistics" is the science of uncertainty; therefore, any conclusions based on statistical inference contain varying degrees of uncertainty, which is expressed in terms of probability statements. Uncertainty can be quantified in terms of well defined statistical probability distributions, which can be applied directly to quality control. The application of statistical quality control can most efficiently indicate when a given procedure is in statistical control, and a continuing program that covers sampling, instrumentation and overall analysis quality will assure the validity of the analytical program. Further development of statistical techniques and applications will be found in the following sections in this chapter.

Quality Control Charts¹

The Shewhart Control Chart² is one of the most generally applicable and easily adapted statistical quality control techniques which can be applied to almost any phase of production, research or analysis. Control charts originally were developed for control of production lines where large numbers of manufactured articles were inspected on a continuous basis. Since analyses frequently are produced on an intermittent basis, or on a greatly reduced scale, less data are available to work with. Therefore, certain concessions must be made in order to respond quickly to objectionable changes in the analytical procedure.

This control chart may serve several functions:

1. To determine empirically and to define acceptable levels of quality
2. To achieve the acceptable level established
3. To maintain performance at the established quality level.

Certain assumptions reside in this technique. The first and major assumption is that there will be variation. No process or procedure has been so well perfected, or so unaffected by its environment that exactly the same result will always be produced. Either the device used for measurement is not sufficiently sensitive or the operator performing the measurement is not sufficiently skilled. The sources of variation present in analytical work include:

1. Differences among analysts
2. Instrumental differences
3. Variations in reagents and related supplies
4. Effect of time on the differences found in items 1, 2 and 3
5. Variations in the interrelationship of items 1, 2 and 3 with each other and with time.

A "system of chance causes" is inherent in the nature of processes and procedures and will produce a pattern of variation. When this pattern is stable, the process or procedure is considered to be "in statistical control" or just "in control."

Any result which falls outside of this pattern will have an assignable cause which can be determined and corrected.

The control chart technique provides a means for separating the assignable cause variant from the stable pattern. The chart is a graphical presentation of the process or procedure test data which compares the variability of all results with the average or expected variability from small arbitrarily defined groups of the data. The control chart also compares "within group" variability to "between group" variability. The technique in effect is a graphical analysis of variance.

The data from such a system can be plotted with vertical scale in test result units and the horizontal scale in units of time or sequence of results. The average value or mean, and the limits of the dispersion (spread, or range of results) can be calculated. Details for the construction and interpretation of quality control charts can be found in later sections of this chapter.

ERRORS

Introduction

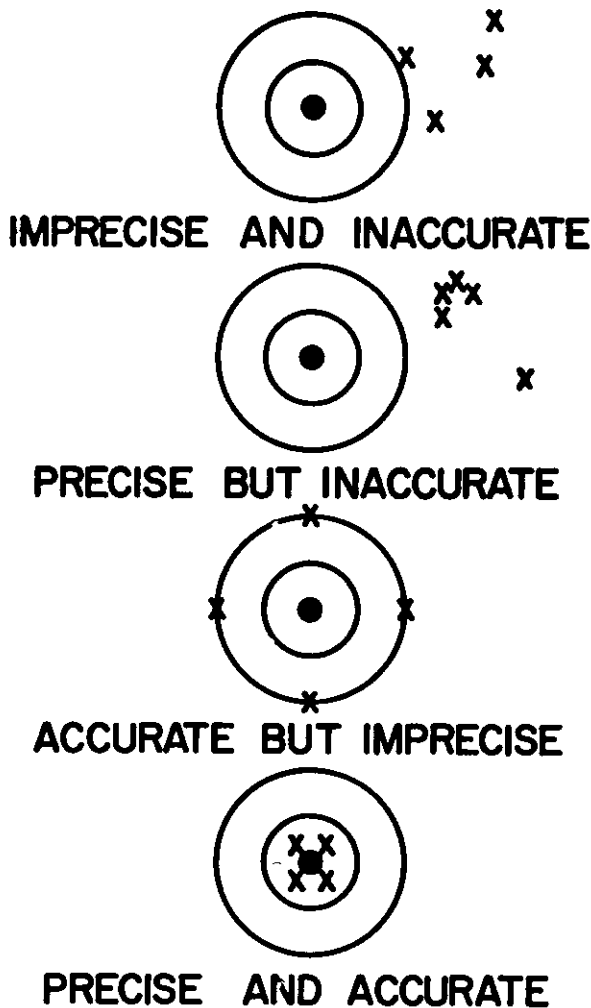
Numbers are employed to either enumerate objects or to delineate quantities. If sixteen air samples are taken simultaneously at different locations in a warehouse where gasoline-powered fork lift trucks are in motion, the number, i.e., the count, would be the same regardless of who counted them, when the count was made or how the count was made. However, if each individual sample is analyzed for carbon monoxide, sixteen different numbers, i.e., the concentration, undoubtedly would be obtained: Furthermore, when replicate determinations are made on each sample, a range of carbon monoxide concentrations would be found.³

Experimental errors are classified as determinate or indeterminate. A fifteen count of the warehouse samples would be a determinate error quickly disclosed by recount. An indeterminate error would be encountered due to the inherent variability in repetitive determinations of carbon monoxide by gas chromatography, infrared or a colorimetric technique.

If the estimation of carbon monoxide concentration is made with a length of stain detector tube and a 6.5-mm stain length equivalent to 57 ppm is recorded by the observer, whereas the true stain length is 6.0 mm and equivalent to 50 ppm, the observational error would be $(57-50) \times 100 \div 50 = 14\%$.

All analytical methods are subject to errors. The determinate ones contribute constant error or bias while the indeterminate ones produce random fluctuations in the data. The concepts of accuracy and precision as applied to the detection and control of error have been clearly defined and should be used exactly.

A concept of the difference between accuracy and precision can be visualized by the pattern formed by shots aimed at a target as shown in Figure 22-1. From the scatter of four shots, one can see that a high degree of precision can be attained without accuracy and that accuracy without precision is possible. The ultimate goal is,



Powell CH, Hosey AD (eds): The Industrial Environment — Its Evaluation and Control, 2nd Edition. Public Health Services Publication No. 614, 1965.

Figure 22-1. Precision and Accuracy

of course, accuracy with precision target number 4. (See also ASTM Designation D-1129-68 for definitions.)⁵

Accuracy. Accuracy relates the amount of an element or compound recovered by the analytical procedure to the amount actually present. For results to be accurate, the analysis must yield values close to the true value.

Precision. Precision is a measure of the method's variability when repeatedly applied to a homogeneous sample under controlled conditions, without regard to the magnitude of displacement from the true value as the result of systematic or constant determinate errors which are present during the entire series of measurements. Stated conversely, precision is the degree of agreement among results obtained by repeated measurements or "checks" on a single sample under a given set of conditions.⁴

Detection and Elimination of Determinate Error

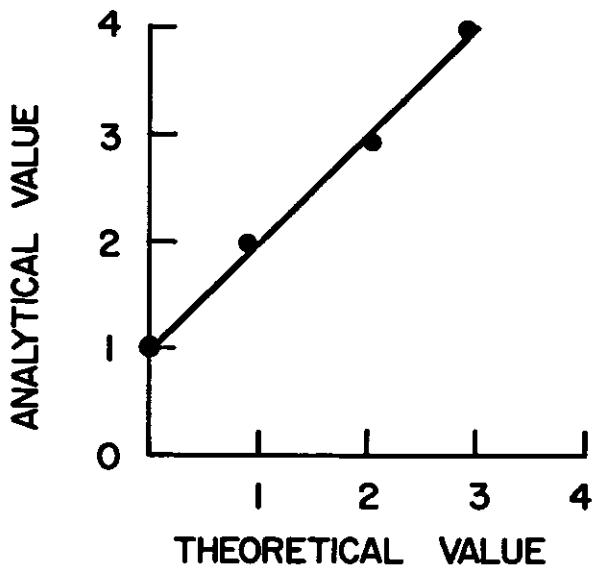
The terms "determinate" error, "assignable"

error, and "systematic" error are synonymous. A determinate error contributes constant error or bias to results which may agree precisely among themselves.

Sources of Determinate Error. A method may be capable of reproducing results to a high degree of precision, but only a fraction of the component sought is recovered. A precise analysis may be in error due to inadequate standardization of solutions, inaccurate volumetric measurements, inaccurate balance weights, improperly calibrated instruments or personal bias (color estimation). Method errors that are inherent in the procedure are the most serious and most difficult to detect and correct. The contribution from interferences is discussed later.

Personal errors other than inherent physical visual acuity deficiencies (color judgment) include consistent carelessness, lack of knowledge and personal bias which are exemplified by calculation errors, use of contaminated, or improper reagents, nonrepresentative sampling or poorly calibrated standards and instruments.

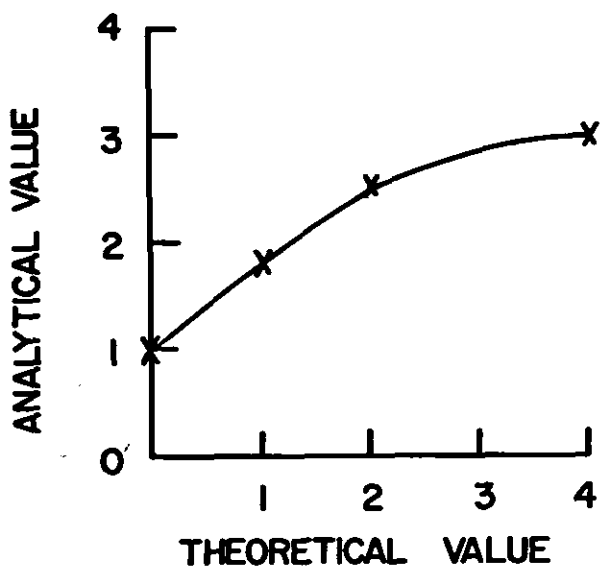
Types of Determinate Error. Additive: An additive error occurs when the mean error has a constant value regardless of the amount of the constituent sought in the sample. A plot of the analytical value versus the theoretical value (Figure 22-2) will disclose an intercept somewhere other than zero.



Powell CH, Hosey AD (eds): The Industrial Environment — Its Evaluation and Control, 2nd Edition. Public Health Service Publication No. 614, 1965.

Figure 22-2. Additive Error

Proportional: A proportional error is a determinate error in which magnitude is changed according to the amount of constituent present in the sample. A plot of the analytical value versus the theoretical value (Figure 22-3) not only fails to pass through zero, but discloses a curvilinear rather than a linear function.



Powell CH, Hosey AD (eds): *The Industrial Environment — Its Evaluation and Control*, 2nd Edition. Public Health Service Publication No. 614, 1965.

Figure 22-3. Proportional Error

Recovery of "Spiked" Sample Procedures. A recovery procedure in which spiked samples are used provides a technique for the detection of determinate errors. Although it does not provide a correction factor to adjust the results of an analysis, the technique does provide a basis for evaluating the applicability of a particular method to any given sample. It allows derivation of analytical quality control from the results, thus providing the basis for an excellent quality control program.

The recovery technique applies the analytical method to a reagent blank; to the sample itself, in at least duplicate; and to "spiked" samples, prepared by adding known quantities of the substance sought, to separate aliquots of the sample which are equal in size to the unspiked sample taken for analysis. The substance sought should be added in sufficient quantity to exceed in magnitude the limits of analytical error, but the total should not exceed the range of the standards selected.

The results are first corrected for reagent influence by subtracting the reagent blank from each standard, sample, and "spiked" sample result. The average unspiked sample result is then subtracted from each of the "spiked" determinations, the remainder divided by the known amount originally added, and expressed as percentage recovery. Table 22-1 illustrates an application of this technique to the analysis of blood for lead content.

Specifications for acceptance of analytical results usually are determined by the state of the art and the final disposition of the results. Recoveries of substances within the range of the method may be very high or very low and approach 100 percent as the errors diminish and as the upper limit of the calibration range is approached. Trace analysis procedures which inherently have relatively

large errors when operated near the limits of sensitivity deliver poor recoveries based on classical analytical criteria and yet, from a practical viewpoint of usefulness may be quite acceptable (Table 22-1 — 2 μg spike). Poor recovery may reflect interferences present in the sample, excessive manipulative losses, or the method's technical inadequacy in the range of application. The limit of sensitivity may be considered the point beyond which indeterminate error is a greater quantity than the desired result.

Control Charts. Trends and shifts in control chart responses also may indicate determinate error. The standard deviation is calculated from spiked samples and control limits (usually ± 3 standard deviations) for the analysis are established. Calculation of the standard deviation is discussed in Chapter 3 and an in-depth discussion of control limits is treated in reference⁵. In some cases, such as BOD and pesticide samples, spiking to resemble actual conditions is not possible. However, techniques for detecting bias under these conditions have been developed.⁶

Control charts may be prepared even for samples which cannot be spiked or for which the recovery technique is impractical. A reference value is obtained from the average of a series of

TABLE 22-1
LEAD IN BLOOD ANALYSIS

Basis: 10.0 g blood from blood bank pool, ashed and lead determined by double extraction, mixed color, dithizone procedure.

μg Pb added	Analyst: DJM			
	Optical Density	μg Pb found	Total Recovered	Recovery, %
None-blank	0.0969	—	—	—
5-Calibration Point	0.2596	—	—	—
None	0.1427	1.6	—	—
None	0.1337	1.3	—	—
None	0.1397	1.4	—	—
None	0.1397	1.4	—	—
Average	0.1389	1.4	—	—
2.0	0.1805	2.9	1.5	75
4.0	0.2636	5.4	4.0	100
6.0	0.3372	7.8	6.4	107
8.0	0.3925	9.4	8.0	100
10.0	0.4437	11.4	10.0	100
30.0 Total	—	36.9	29.9	96

Calculation of mean error^a

$$\text{Mean error} = 36.9 - (30.0 + 5 \times 1.4) = 0.1 \mu\text{g for entire set}$$

$$= 2.9 - (2.0 + 1.4) = 0.5 \mu\text{g for 2 } \mu\text{g spike}$$

Calculation of relative error

$$\text{Relative Error} = (0.1 \times 100) / 37.0 = 0.27\% \text{ for entire set}$$

$$= (0.5 \times 100) / 3.4 = 14.7\% \text{ for 2 } \mu\text{g spike}$$

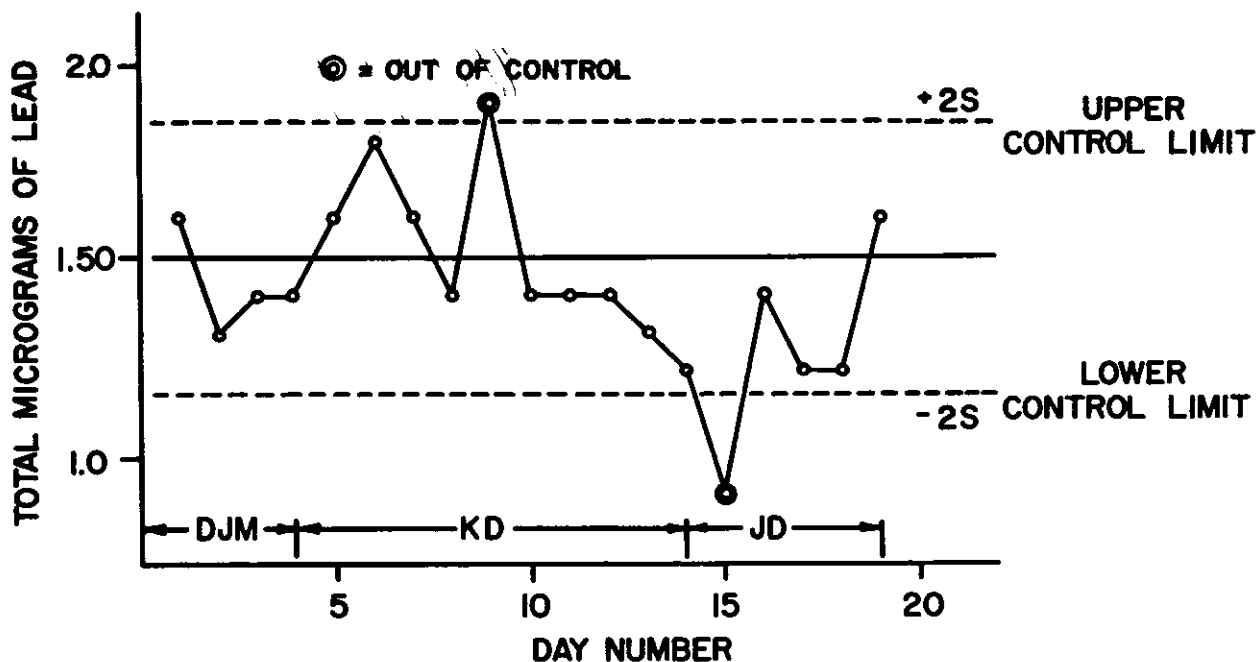


Figure 22-4. Lead in Blood Control Chart

replicate determinations performed on a composite or pooled sample which has been stabilized to maintain a constant concentration during the control period (nitric acid in urine). An example has been prepared from a blood lead study (Figure 22-4). Although these data were drawn from the same blood pool used to illustrate the application of the spiking technique for quality control, the consecutive aliquot analyses plotted as a control chart furnish additional information. The control limits were reduced to ± 2 standard deviations to further sharpen the trends. There may be preliminary evidence of personal bias as shown by KD's versus JD's performance.

Change in Methodology. Analysis of a sample for a particular constituent by two or more methods that are entirely unrelated in principle may aid in the resolution of determinate error.

In Table 22-2, an interlaboratory evaluation of three different methods for the determination of lead concentration in ashed urine specimens (mixed color dithizone, atomic absorption and polarography) is summarized. If the highly specific polarographic method was selected as the primary standard, then the dithizone procedure is subject to a $+7.4 \mu\text{g}/1$ bias as compared with a $+3.6 \mu\text{g}/1$ bias in the atomic absorption method for lead.

Effect of Sample Size. If the determinate error is additive, the magnitude may be estimated by plotting the analytical results versus a range of sample volumes or weights. If the error has a constant value regardless of the amount of the component sought, then a straight line fitted to the plotted points will not pass through the origin. The effect of urine volume on the analysis for lead is shown in Figure 22-5.

Elimination. a) Physical. In many cases error can be reduced to tolerable levels by quantitating

the magnitude over the operating range and developing either a corrective manipulation directly in the procedure or a mathematical correction in the final calculation. Temperature coefficients (parameter change per degree) are widely applied to both physical and chemical measurements. For example, the stain length produced by carbon monoxide in the detector tubes previously cited for illustration is dependent on the temperature as well as the air sampling rate and CO concentration. Therefore, when these tubes are used outside the median temperature range, a correction must be applied to the observed stain length (Table 22-3).⁷

As a general rule, most instruments exhibit maximum reliability over the center 70% of their range (midpoint $\pm 35\%$). As the extreme to either side is approached the response and reading errors become increasingly greater. Optical density measurements, for example, should be confined to the range 0.045 to 0.80 by concentration adjustment or cell path choice. Extrapolation to limits outside the range of response established for the analytical method or instrumental measurement may introduce large errors as many chemical and physical responses are linear only over a relatively narrow band in their total response capability. In absorption spectrophotometric measurements, Beer's law relating optical density to concentration may not be linear outside of rather narrow limits in some instances (colorimetric determination of formaldehyde at high dilution by the chromatropic acid method).

b) Internal Standard. The internal standard technique is used primarily for emission spectrograph, polarographic, and chromatographic (liquid or vapor phase) procedures. This technique enables the analyst to compensate for electronic and mechanical fluctuations within the instrument.

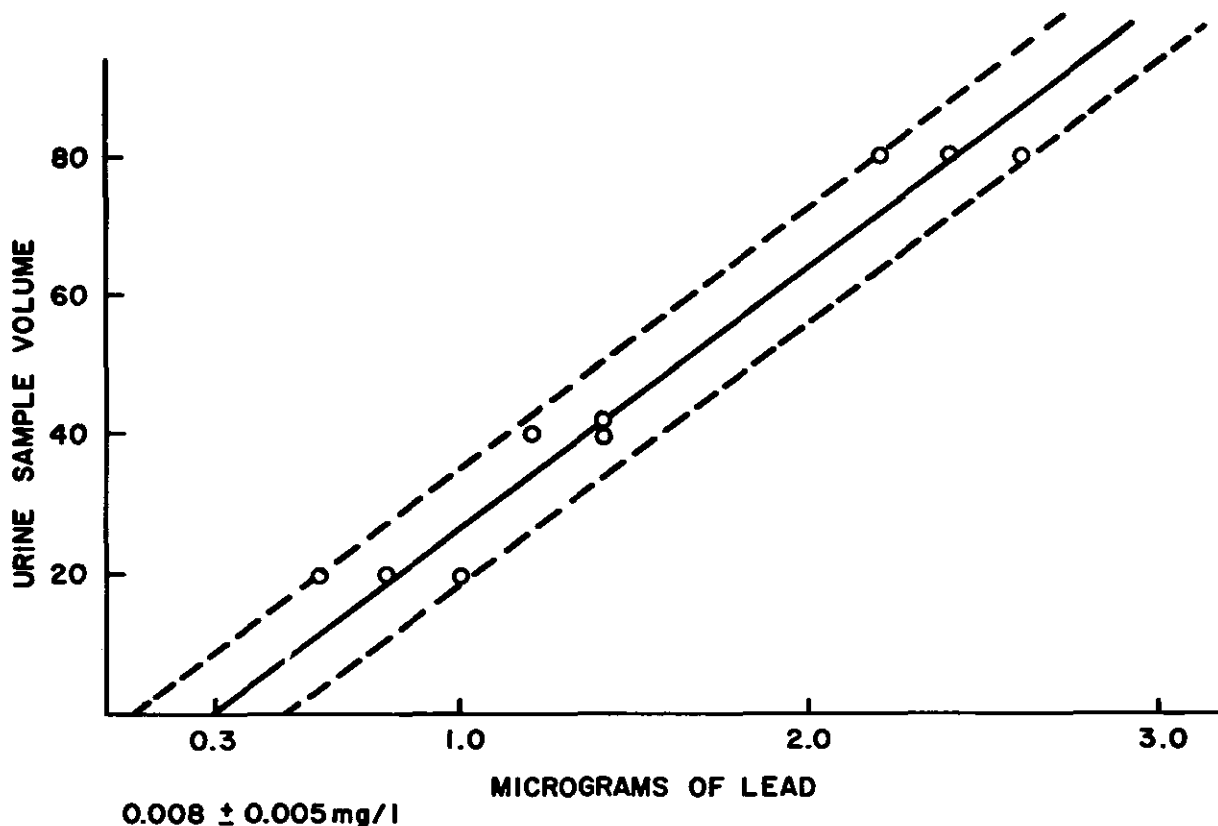


Figure 22-5. Effect of Sample Size on Determination of Lead in Urine

TABLE 22-2
AN INTERLABORATORY STUDY OF THE
DETERMINATE ERROR IN THE
DITHIZONE PROCEDURE FOR THE
DETERMINATION OF LEAD
IN NINE URINE SPECIMENS

Polarographic Method	Mixed Color Found	Dithizone Difference	Atomic Found	Absorption Difference
10	25	15	10	0
14	28	14	22	8
12	12	0	16	4
15	20	5	16	1
21	20	-1	22	1
22	30	8	24	2
27	40	13	36	9
19	22	3	22	3
12	22	10	16	4
Mean	—	+7.4	—	+3.6

In brief, the internal standard method involves the addition to the sample of known amounts of a

TABLE 22-3
KITAGAWA CARBON MONOXIDE
DETECTOR TUBE NO. 100*
Temperature Correction Table

Chart Readings (ppm)	Correction Concentration (ppm)				
	0°C (32°F)	10°C (50°F)	20°C (68°F)	30°C (86°F)	40°C (104°F)
1,000	800	900	1,000	1,060	1,140
900	720	810	900	950	1,030
800	640	720	800	840	910
700	570	640	700	740	790
600	490	550	600	630	680
500	410	470	500	520	560
400	340	380	400	420	440
300	260	290	300	310	320
200	180	200	200	200	210
100	100	100	100	100	100

*Kitagawa, T., "Carbon Monoxide Detector Tube. No. 100," National Environmental Instruments, Inc., 1971, Fall River, Mass.

substance to which the instrument will respond in a manner similar to the contaminant in the system. The ratio of the internal standard response to the contaminant response determines the concentration of contaminant in the sample. Condi-

tions during analyses will affect the internal standard and the contaminant identically, and thereby compensate for any changes. The internal standard should be of similar chemical composition to the contaminant, of approximately the same concentration anticipated for the contaminant, and of the purest attainable quality. A detailed discussion of the sources of physical error, magnitude of their effects, and suggestions for minimizing their contribution to determine bias and error will be found in the literature⁸.

c) **Chemical Interference.** The term "interference" relates to the effects of dissolved or suspended materials on analytical procedures. A reliable analytical procedure must anticipate and minimize interferences.

The investigator must be aware of possible interferences and be prepared to use an alternate or modified procedure to avoid errors. Analyzing a smaller initial aliquot may suppress or eliminate the effect of the interfering element through dilution. The concentration of the substance sought is likewise reduced; therefore, the aliquot must contain more than the minimum detectable amount. When the results display a consistently increasing or decreasing pattern by dilution, then interference is indicated.

An interfering substance may produce one of three effects:

1. React with the reagents in the same manner as the component being sought (positive interference).
2. React with the component being sought to prevent complete isolation (negative interference).
3. Combine with the reagents to prevent further reaction with the component being sought (negative interference).

The sampling and analytical technique employed for the surveillance of airborne toluene diisocyanate (TDI) in the manufacturing environment furnishes a good example in which all three factors can be encountered. The TDI vapor is absorbed and quantitatively hydrolyzed in an aqueous acetic acid-hydrogen chloride mixture to toluene diamine (MTD) which then is diazotized by the addition of sodium nitrite. The excess nitrous acid is destroyed with sulfamic acid and the diazotized MTD coupled with N-1-Naphthylethylenediamine to produce a bluish-red azo dye.⁹ In the phosgenation section of the operations, the starting material (MTD) may coexist with TDI in the atmosphere sampled. If so, then a positive interference will occur as the method cannot distinguish between free MTD and MTD from the hydrolyzed TDI.

This problem can be resolved by collecting simultaneously a second sample in ethanol. The TDI reacts with ethanol to produce urethane derivatives which do not produce color in the coupling stage of the analytical procedure. The MTD is determined by the same diazotization and coupling procedure after boiling off the ethanol from the acidified scrubber solution. Then the difference represents the TDI fraction in the air sampled.

On the other hand, if the relative humidity is high or alcohol vapors are present, negative interference will reduce the TDI recovered by formation of the carbanilide (dimer) or the urethane derivative which will not produce color in the final coupling stage. Alternative methods have not been developed for these conditions. If high concentrations of phenol are absorbed, then a negative interference will arise from side reactions with the nitrous acid required to diazotize the MTD. This loss can be avoided by testing for excess nitrous acid in the diazotization stage and adding additional sodium nitrite reagent if a deficiency is indicated.

An estimate of the magnitude of an interference may be obtained by the recovery procedure.

If recoveries of known quantities exceed 100%, a positive interference is present (Condition 1). If the results are below 100%, a negative interference is indicated (Condition 2, or 3: see reference (8) for details).

Indeterminate Error and Its Control

Nature. Even though all determinate errors are removed from a sampling or analytical procedure, replicate analyses will not produce identical results. This erratic variation arises from random error. Examples of this type of variation would be variation in reagent addition, instrument response, line voltage transients and physical measurement of volume and mass. In environmental analysis the sample itself is subject to a great variety of variability. Although indeterminate errors appear to be random in nature, they do conform to the laws of chance; therefore statistical measures of precision can be employed to quantitate their effects.

A measure of the degree of agreement (precision) among results can be ascertained by analyzing a given sample repeatedly under conditions controlled as closely as conditions permit. The range of these replicate results (difference between highest and lowest value) provides a measure of the indeterminate variations.

Quantification. 1) **Distribution of Results.** Indeterminate error can be estimated by calculation of the standard deviation (σ) after determinate errors have been removed. The calculation of this value is discussed in Chapter 3. When indeterminate or experimental errors occur in a random fashion, the observed results (x) will be distributed at random around the average or arithmetic mean (\bar{x}).

Given an infinite number of observations, a graph of the relative frequency of occurrence plotted against magnitude will describe a bell-shaped curve known as the Gaussian or normal curve (Figure 22-6). However, if the results are not occurring in a random fashion, the curve may be flattened (no peak), skewed (unsymmetrical), narrowed, or exhibit more than one peak (multi-modal). In these cases the arithmetic mean will be misleading, and unreliable conclusions with respect to deviation ranges (σ) will be drawn from the data. A typical graph illustrating skew, multi-modes, and a narrow peak is shown in Figure 22-7.

In any event the investigator should confirm the

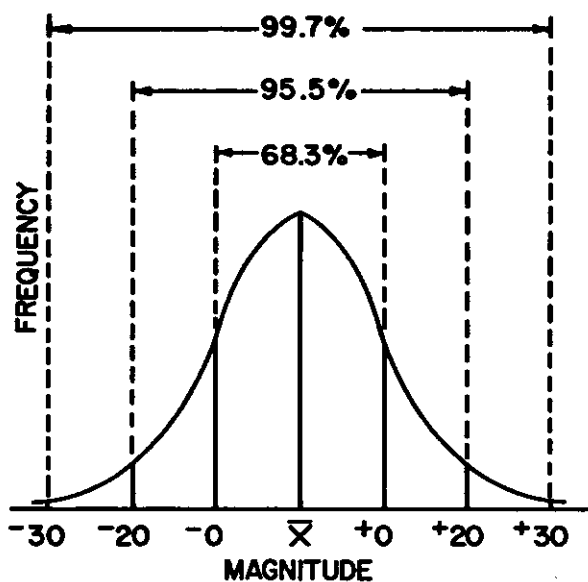


Figure 22-6. Gaussian or Normal Curve of Frequencies

normalcy of the data at hand. Various procedures are available to test this assumption.

One method is to construct a histogram, if the sample is large enough, and then to plot a normal curve having the same mean and standard deviation with the histogram to see how well the normal curve fits. This is an imprecise method at best and, unless there is an extremely good fit of a normal curve laid over the resulting histogram or polygon, the cumulated distribution should be plotted on normal probability paper before proceeding.

As an example the following table gives the frequency distribution of the results of a series of 145 similar tests:

Grams	Frequency	Grams	Frequency
0.8485	2	0.8275	21
0.8455	1	0.8245	14
0.8425	2	0.8215	5
0.8395	6	0.8185	4
0.8365	7	0.8155	3
0.8335	23	0.8125	2
0.8305	55		

These data are plotted in Figure 22-8. Now having looked at the fit, we decide how good it is. The graph does not really tell whether the depar-

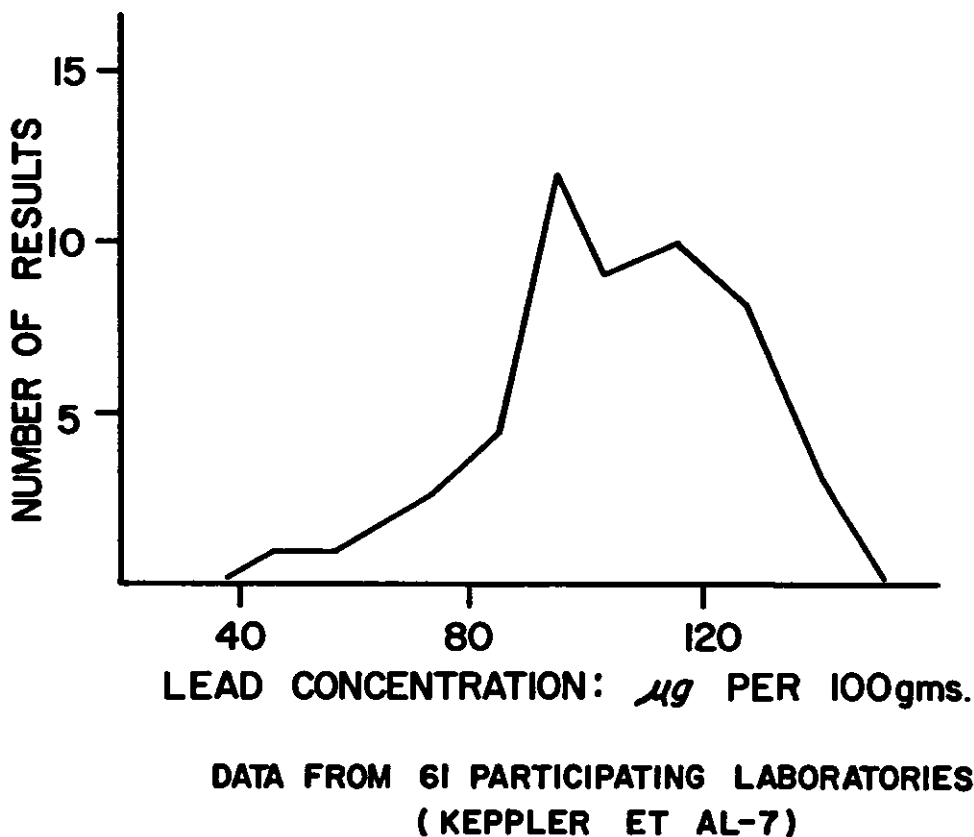


Figure 22-7. Frequency Distribution of Lead in Blood: Analytical Results

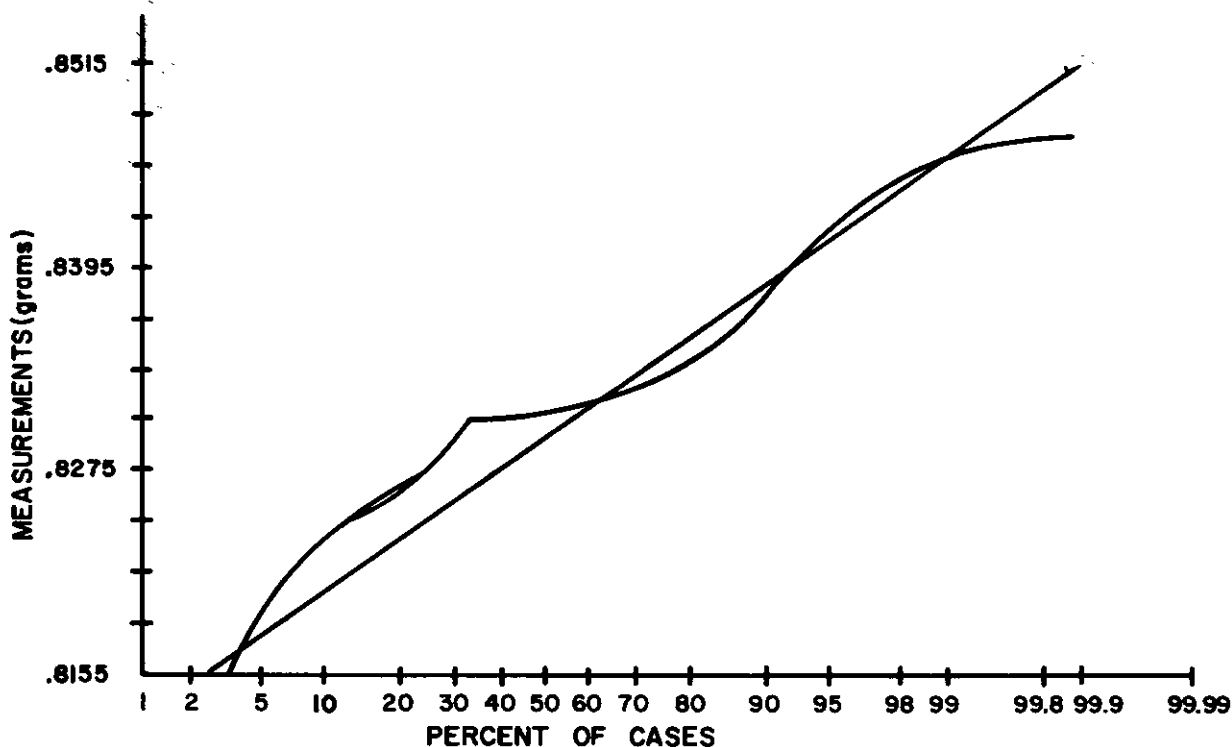


Figure 22-8. Plot of a Frequency Distribution

ture from fit is significant. The most accurate way of testing for normality is to use the X^2 test for normality of data. However, the calculations are tedious and time consuming for desk calculator computation. Standard X^2 computer programs are commonly available, but judgment must be used to weigh the cost of getting an accurate determination against the value of the information.

The distribution of results within any given range about the mean is a function of σ . The proportion of the total observations which reside within $\bar{x} \pm 1\sigma$, $\bar{x} \pm 2\sigma$ and $\bar{x} \pm 3\sigma$ have been thoroughly established and are delineated in Figure 22-6. Although these limits do not define exactly any finite sample collected from a normal group, the agreement with the normal limits improves as n increases. As an example, suppose an analyst were to analyze a composite urine specimen 1000 times for lead content. He could reasonably expect 50 results would exceed $\bar{x} \pm 2\sigma$ and only 3 results would exceed $\bar{x} \pm 3\sigma$. However, the corollary condition presents a more useful application. In the preceding example, the analyst has found \bar{x} to be 0.045 mg. per liter with $\sigma = \pm 0.005$ mg/1. Any result which fell outside the range 0.035-0.055 mg/1 ($0.045 \pm 2\sigma$) would be questionable as the normal distribution curve indicates this should occur only 5 times in 100 determinations. This concept provides the basis for tests of significance, a concept which is discussed in detail in any good statistical reference such as those cited in this chapter or Chapter 3.

2) Range of Results. The difference between the maximum and minimum of n results (range) also is related closely to σ . The range (R) for n results will exceed σ multiplied by a factor d_n only

5% of the time when a normal distribution of errors prevails.

Values for d_n :

n	d_n
2	2.77
3	3.32
4	3.63
5	3.86
6	4.03

Since the practice of analyzing replicate (usually duplicate) samples is a general practice, application of these estimated limits can provide detection of faulty technique, large sampling errors, inaccurate standardization and calibration, personal judgment and other determinate errors. However, resolution of the question whether the error occurred in sampling or in analysis can be answered more confidently when single determinations on each of three samples rather than duplicate determinations on each of two samples are made. This approach also reduces the amount of analytical work required.⁹ Additional information relative to the evaluation of the precision of analytical methods will be found in ASTM Standards.¹⁰

3) Collaborative Studies or "Round Robins." After an analytical method has been evaluated fully for precision and accuracy, collaborative testing should be initiated. The values for precision and accuracy as determined by the results from a number of laboratories can be expected to be in-

ferior when compared with the performance of the originating laboratory. Because technicians in different laboratories apply to their procedure their own characteristic determinate and indeterminate errors which may differ significantly from the original technique, the values for precision and accuracy will disclose the true reliability (*ruggedness, or immunity to minor changes*) of the method. Participation in collaborative programs will aid the investigator in evaluating his laboratory's performance in relation to other similar facilities and in locating sources of error.

Duplicate analyses are employed for the determination and control of precision within the laboratory and between laboratories. Initially, approximately 20% of the routine samples, with a minimum of 20 samples, should be analyzed in duplicate to establish internal reproducibility. A standard or a repeatedly analyzed control, if available, should be included periodically for long-term accuracy control. The control chart technique is directly applicable, and appropriate control limits can be established by arbitrarily subgrouping the accumulated results or by using appropriate estimates of precision from an evaluation of the procedure.

CONTROL CHARTS

Description and Theory

The control chart provides a tool for distinguishing the pattern of indeterminate (stable) variation from the determinate (assignable cause) variation. This technique displays the test data from a process or method in a form which graphically compares the variability of all test results with the average or expected variability of small groups of data — in effect, a graphical analysis of variance, and a comparison of the "within groups" variability versus the "between group" variability (see Figure 22-6 for the pattern of variation of data).

The data from a series of analytical trials can be plotted with the vertical scale in units of the test result and the horizontal scale in units of time or sequence of analyses. The average or mean value can be calculated and the spread (dispersion or range) can be established (Figure 22-4).

The determination of appropriate control limits can be based on the capability of the procedure itself or can be arbitrarily established at any desirable level. Common practice sets the limits at $\pm 3\sigma$ on each side of the mean. If the distribution of the basic data exhibits a normal form, the probability of results falling outside of the control limits can be readily calculated.

The control chart is actually a graphical presentation of quality control efficiency. If the procedure is "in control," the results will fall within the established control limits. Further, the chart will disclose trends and cycles from assignable causes which can be corrected promptly. Chances of detecting small changes in the process average are improved when several values for a single control point (an \bar{x} chart) are used. As the sample statistical size increases, the chance that small changes in the average will not be detected is de-

creased. A sample size of $n = 4$ usually is selected.

The basic procedure of the control chart is to compare "within group" variability to "between group" variability. For a single analyst running a procedure, the "within group" may well represent one day's output and the "between group" represents between days or day-to-day variability. When several analysts or several instruments or laboratories are involved, the selection of the subgroup unit is critical. Assignable causes of variation should show up as "between group" and not "within group" variability. Thus, if the differences between analysts should provide assignable causes of variation, their results may not be lumped together in a "within group" subgrouping.

Application and Limitations

In order for quality control to provide a means for separating the determinate from indeterminate sources of variation, the analytical method must clearly emphasize those details which should be controlled to minimize variability. A check list would include:

1. Sampling procedures
2. Preservation of the sample
3. Aliquoting methods
4. Dilution techniques
5. Chemical or physical separations and purifications
6. Instrumental procedures
7. Calculation and reporting results.

The next step to be considered is the application of control charts for evaluations and control of these unit operations. Decisions relative to the basis for construction of a chart are required:

1. Choose method of measurement
2. Select the objective
 - a. Precision (Figure 22-4) or accuracy evaluation (Figure 22-9)
 - b. Observe test results, or the range of results
 - c. Measurable quality characteristics (Figure 22-4), (Figure 22-9) and (Figure 22-10)
3. Select the variable to be measured (from the check list above)
4. Basis of subgroup, if used:
 - a. Size
A minimum subgroup size of $n = 4$ is frequently recommended. The chance that small changes in the process average remain undetected decreases as the statistical sample size increases.
 - b. Frequency of subgroup sampling
Changes are detected more quickly as the sampling frequency is increased.
5. Control Limits

Control limits (CL) can be calculated, but judgment must be exercised in determining whether or not the values obtained satisfy criteria established for the method, i.e., does the deviation range fall within limits consistent with the solution or control of the problem. After the mean (\bar{X}) of the individual results (X), and the mean of the range (\bar{R}) of the replicate re-

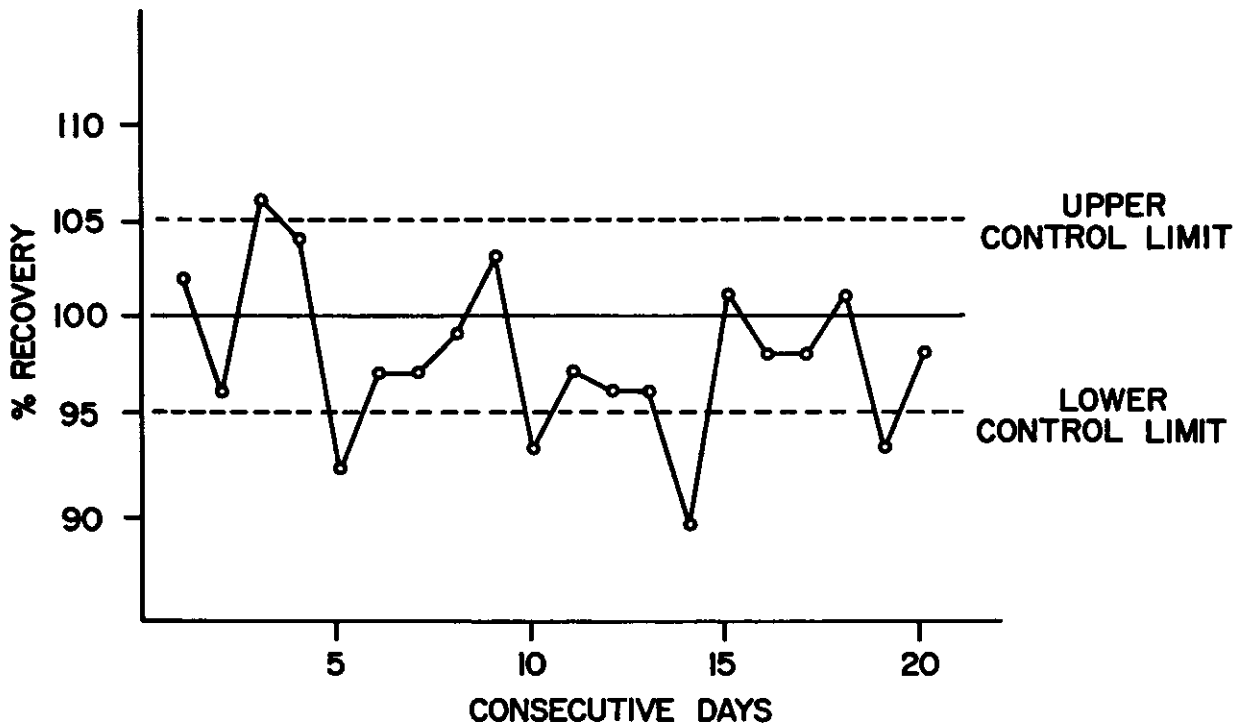


Figure 22-9. Recovery of Lead from Blood

sult differences (R) have been calculated, then CL can be calculated from data established for this purpose (Table 22-4).⁵

Grand Mean (\bar{X}) = $\frac{\sum \bar{X}}{k}$

CL's on Mean = $\bar{X} \pm A_2$

Range (\bar{R}) = $\frac{\sum R}{k}$, or $d_2 \sigma$

Upper Control Limit (UCL) on

Range = $D_4 \bar{R}$

Lower Control Limit (LCL) on

Range = $D_3 \bar{R}$

Where: k = number of subgroups A_2 , D_4 and D_3 are obtained from Table 22-4, R

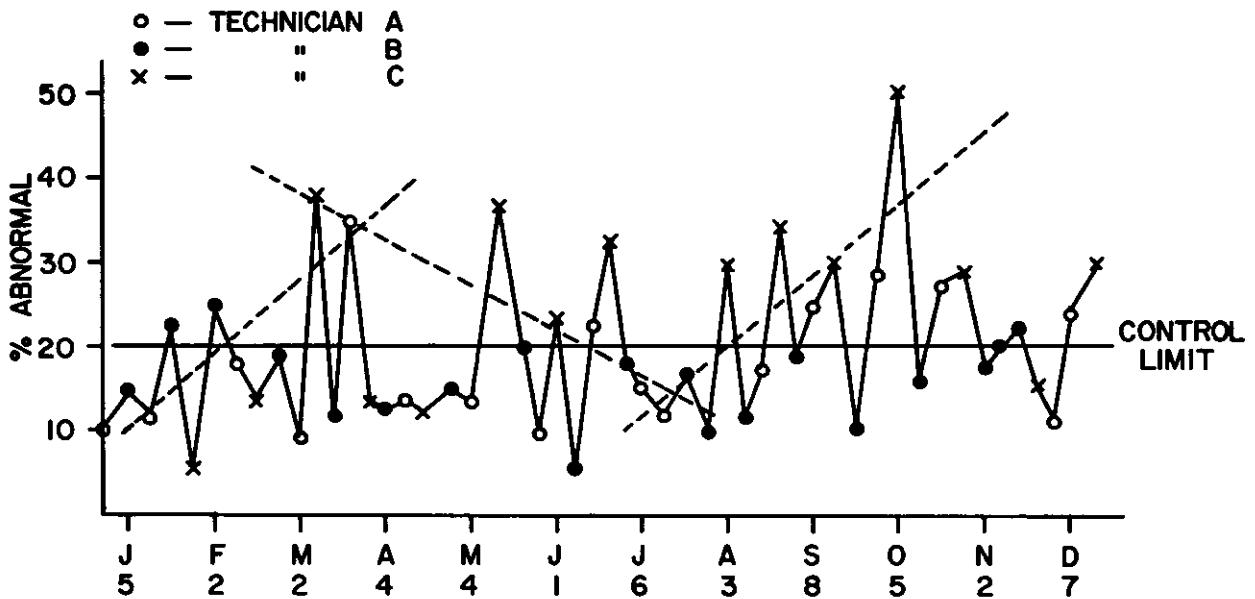


Figure 22-10. Lead in Urine Analysis — % Exceeding Threshold Limit (0.1 mg/Liter) on Weekly Basis

may be calculated directly from the data, or from the standard deviation (σ) using factor d_2 . The lower control limit for R is zero when $n \leq 6$.

The calculated CL's include approximately the entire data under "in control" conditions, and therefore, are equivalent to $\pm 3 \sigma$ limits which are commonly used in place of the more laborious calculation. Warning limits (WL) set at $\pm 2 \sigma$ limits (95%) of the normal distribution serve a very useful function in quality control (see Figure 22-4 and 22-9). The upper warning limit (UWL) can be calculated by:

$$UWL = \bar{R} + 2 \sigma_R$$

$$UWL = \bar{R} \pm 2/3 (D_4 \bar{R})$$

Where the subgrouping is $n=2$, UWL reduces to

$$UWL = 2.51 \bar{R}$$

CONSTRUCTION OF CONTROL CHARTS

Precision Control Charts

The use of range (R) in place of standard deviation (σ) is justified for limited sets of data $n \leq 10$ since R is approximately as efficient and is easier to calculate. The average range (\bar{R}) can be calculated from accumulated results, or from a known or selected σ ($d_2 \sigma$). $LCL_R = 0$ when $n \leq 6$. (LCL = lower control limit).

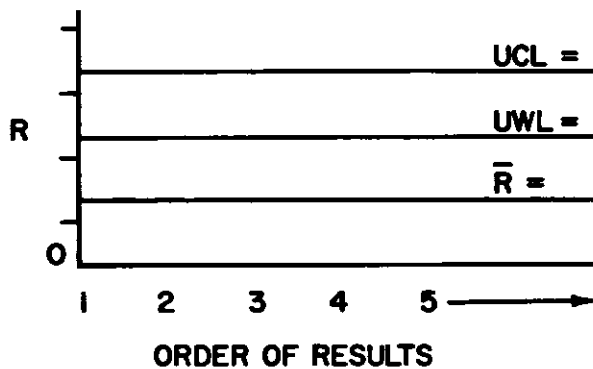
The steps employed in the construction of a precision control chart for an automatic analyzer illustrate the technique (Table 22-5):

1. Calculate R for each set of side-by-side duplicate analyses of identical aliquots.
2. Calculate \bar{R} from the sum of R values divided by the number (n) of sets of duplicates.
3. Calculate the upper control limit (UCL_R) for the range:

$$UCL_R = D_4 \bar{R}$$

Since the analyses are in duplicates, $D_4 = 3.27$ (from Table 22-4).

4. Calculate the upper warning limit (UWL):
 $UWL_R = \bar{R} + 2 \sigma_R = \bar{R} \pm 2/3 (D_4 \bar{R}) = 2.51 \bar{R}$



Permission granted, William D. Kelley, Acting Assistant Director, Division of Laboratories and Criteria Development, National Institute for Occupational Safety and Health.

Figure 22-11. Precision Control Chart

TABLE 22-4
FACTORS FOR COMPUTING CONTROL CHART LINES*

Observations in Subgroup (n)	Factor A_2	Factor d_2	Factor D_4	Factor D_3
2	1.88	1.13	3.27	0
3	1.02	1.69	2.58	0
4	0.73	2.06	2.28	0
5	0.58	2.33	2.12	0
6	0.48	2.53	2.00	0
7	0.42	2.70	1.92	0.08
8	0.37	2.85	1.86	0.14

*ASTM Manual on Quality of Materials, American Society of Testing and Materials, Philadelphia, 1951.

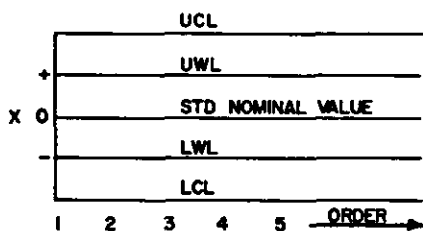
TABLE 22-5
PRECISION (DUPLICATES) DATA

Date	Data	Range (R)
9/69	# 8 25.1 24.9	0.2
	#16 25.0 24.5	0.5
	#24 10.9 10.6	0.3
10/69	# 7 12.6 12.4	0.2
	#16 26.9 26.2	0.7
	#24 4.7 5.1	0.4
2/70	# 6 9.2 8.9	0.3
	#12 13.2 13.1	0.1
	#16 16.2 16.3	0.1
	#22 8.8 8.8	0.0
4/70	# 6 14.9 14.9	0.0
	#12 17.2 18.1	0.9
	#18 21.9 22.2	0.3
5/70	# 6 34.8 32.6	2.2
	#12 37.8 37.4	0.4
6/70	# 6 40.8 39.8	1.0
	#10 46.0 43.5	2.5
	#17 40.8 41.2	0.4
	#24 38.1 36.1	2.0
7/70	# 6 12.2 12.5	0.3
	#12 25.4 26.9	1.5
	#18 20.4 19.8	0.6
		$\bar{R} = 14.9/22 = 0.68$
		$UCL = 3.27 \times 0.68 = 2.2$
		$UWL = 2.51 \times 0.68 = 1.7$

(D_4 from Table 22-4) which corresponds to the 95% confidence limits.

5. Chart \bar{R} , UWL_R and UCL_R on an appropriate scale which will permit addition of new results as obtained as shown in Figure 22-11 and Table 22-5.

- Plot results (\bar{R}) and take action on out-of-control points.



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Figure 22-12. Accuracy Control Chart

ACCURACY CONTROL CHARTS — MEAN OR NOMINAL VALUE BASIS

\bar{X} charts simplify and render more exact the calculation of CL since the distribution of data which conforms to the normal curve can be completely specified by \bar{X} and σ . Stepwise construction of an accuracy control chart for the automatic analyzer based on duplicate sets of results obtained from consecutive analysis of knowns serves as an example (Table 22-6):

- Calculate \bar{X} for each duplicate set
- Group the \bar{X} values into a consistent reference scale (in groups by orders of magnitude for the full range of known concentrations).

- Calculate the UCL and lower control limit (LCL) by the equation:

$$CL = \pm A_2 \bar{R} \quad (A_2 \text{ from Table 22-4}).$$

- Calculate the Warning Limit (WL) by the equation:

$$WL = \pm 2/3 A_2 \bar{R}$$

- Chart CL's and WL's on each side of the standard which is set at zero as shown in Figure 22-12 ("order" related to consecutive, or chronological order of the analyses) and Table 22-6.
- Plot the difference between the nominal value and \bar{X} and take action on points which fall outside of the control limits.

CONTROL CHARTS FOR INDIVIDUAL RESULTS

In many instances a rational basis for subgrouping may not be available, or the analysis may be so infrequent as to require action on the basis of individual results. In such cases X charts are employed. However, the CLs must come from some subgrouping to obtain a measure of "within group" variability. This alternative has the advantage of displaying each result with respect to tolerance, or specification limits (Figures 22-4, 5, 9 and 13). The disadvantages must be recognized when considering this approach.

- The chart does not respond to changes in the average.
- Changes in dispersion are not detected unless an R chart is included.

TABLE 22-6
ACCURACY DATA

Date	Calibration Range	Nominal (N)	Values	\bar{X}	$N-\bar{X}$
9/69	10-400 ppm	100 ppm	22.9, 21.5/	22.2	-0.7
	1.7-69.7 scale	22.9	22.7, 22.3	22.5	-0.4
10/69	10-400	100	21.6, 21.3/	21.5	0.0
	1.5-67.6	21.5			
2/70	10-400	100	23.6, 24.1/	23.9	-0.6
	1.4-62.5	24.5			
4/70	10-400	100	25.8, 26.5/	26.2	+0.2
	1.6-59.4	26.0	26.0, 26.7	26.4	+0.4
5/70	10-150	100	72.2, 70.2/	71.2	+1.2
	6.3-83.0	70.0			
6/70	10-150	100	71.0, 70.8/	71.1	+0.1
	6.6-85.0	71.0	71.0, 71.3	71.2	+0.2
7/70	10-150	60	14.9, 14.7/	14.8	-0.2
	1.8-33.5	15.0	15.1, 14.4	14.8	-0.2

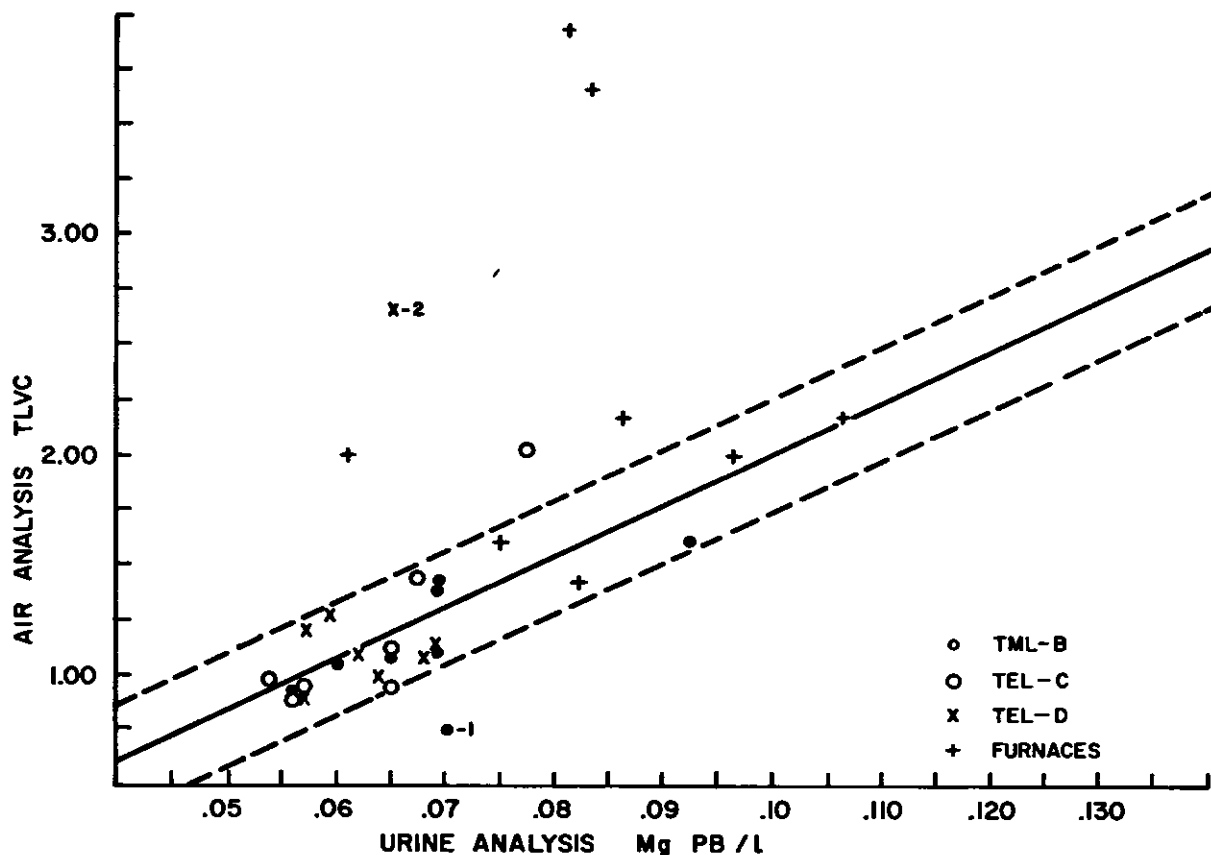


Figure 22-13. Relationship of Previous Monthly TLV Coefficient to Urinary Lead Excretion

- The distribution of results must approximate normal if the control limits remain valid.

Additional refinements, variations and control charts for other variables will be found in standard texts.^{1, 11, 12}

MOVING AVERAGES AND RANGES

The \bar{X} control chart is more efficient for disclosing moderate changes in the average as the subgrouping size increases. A logical compromise between the \bar{X} and \bar{X} approach would be application of the moving average. For a given series of analyses, the moving average is plotted. Such a set of data is shown in Table 22-7. The moving range serves well as a measure of acceptable variation when no rational basis for subgrouping is available or when results are infrequent or expensive to gather.

OTHER CONTROL CHARTS FOR VARIABLES

Although the standard \bar{X} and R control chart for variables is the most common, it does not always do the best job. Several examples follow where other charts are more applicable.

Variable Subgroup Size

The standard \bar{X} and R chart is applicable for a constant size subgroup of $n=2,3,4,5$. In some cases such a situation does not exist. Control limit

values must be calculated for each sample size. Plotting is done in the usual manner with the control size limits drawn in for each subgroup depending on its size.

R or σ Charts

In some situations the dispersion is equal over a range of assay values. In this case, a control chart for either range or standard deviation is appropriate.

When the dispersion is a function of concentration, control limits can be expressed in terms of a percentage of the mean. In practice such control limits would be given as in the example below:

± 5 units/liter for 0-100 units/liter concentration

$\pm 5\%$ for >100 units/liter concentration

An alternative procedure involves transformation of the data.¹³ For example, logarithms would be the appropriate transformation.

\bar{X} and σ Charts

If the subgroup size exceeds 10, the Range Chart becomes inefficient. The use of a σ chart would then be appropriate. Where the cost of obtaining the test data is high, the increase in efficiency using σ rather than R may be worthwhile.

OTHER STATISTICAL TOOLS

Rejection of Questionable Results

The question whether or not to reject results which deviate greatly from \bar{x} in a series of other-

TABLE 22-7
MOVING AVERAGE AND RANGE TABLE
(N=2)

Sample No.	Assay Value	Sample Nos. Included	Moving Average	Moving Range
1	17.09	—	—	—
2	17.35	1-2	17.22	+0.26
3	17.40	2-3	17.38	+0.05
4	17.23	3-4	17.32	-0.17
5	17.00	4-5	17.12	-0.23
6	16.94	5-6	16.97	-0.16
7	16.68	6-7	16.81	-0.26
8	17.11	7-8	16.90	+0.43
9	18.47	8-9	17.79	+1.36
10	17.08	9-10	17.78	-1.39
11	17.08	10-11	17.08	0.00
12	16.92	11-12	17.00	-0.16
13	18.03	12-13	17.48	+1.11
14	16.81	13-14	17.42	-1.22
15	17.15	14-15	16.98	+0.34
16	17.34	15-16	17.25	+0.19
17	16.71	16-17	17.03	-0.63
18	17.28	17-18	17.00	+0.57
19	16.54	18-19	16.91	-0.74
20	17.30	19-20	16.92	+0.76

wise normal (closely agreeing) results frequently arises. On a theoretical basis, no result should be rejected, as the one or more errors which render the entire series doubtful may be determinate errors that can be resolved. Tests which are known to involve mistakes, however, should not be reported exactly as analyzed. Mathematical basis for rejection of "outliers" from experimental data may be found in statistics text books.¹⁴

Correlated Variables — Regression Analysis

A major objective in scientific investigations is the determination of the effect that one variable exerts on another. For example a quantity of sample (x) is reacted with a reagent to produce a result (y). The quantity x represents the independent variable over which the investigator can exert control.

The dependent variable (y) is the direct response to changes made in x, and varies in a random fashion about the true value. If the relationship is linear, the equation for a straight line will describe the effect of changes in x on the response y: $y = a + b x$, in which a is the intercept with the y axis and b is the slope of the line (the change in y per unit change in x). In chemical analysis a is a measure of constant error arising from a colorimetric determination, trace impurity, blank, or other determinate source. The slope b may be controlled by reaction rate, equilibrium shift or the resolution of the method. The term "regression analysis" is applied to this statistical tool.

A typical application is exhibited in Figure 22-14 which relates the concentration of lead in blood to the standard deviation of the method.¹¹ For this relationship, $y = 0.0022 + 0.054x$. Addi-

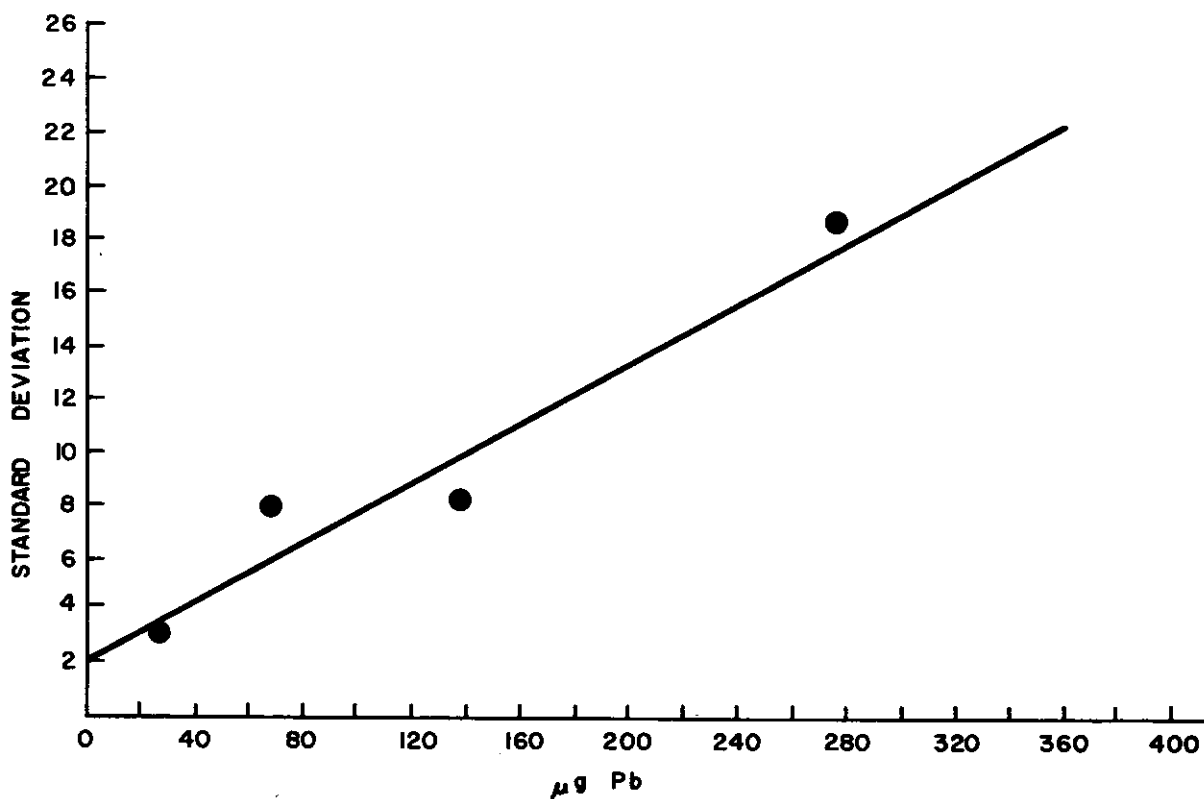


Figure 22-14. Standard Deviation of Data from 10 Laboratories (Keenan et al)

tional useful information can be obtained by certain transformations and shortcuts.^{6, 14, 15, 16}

GRAPHIC ANALYSIS FOR CORRELATIONS

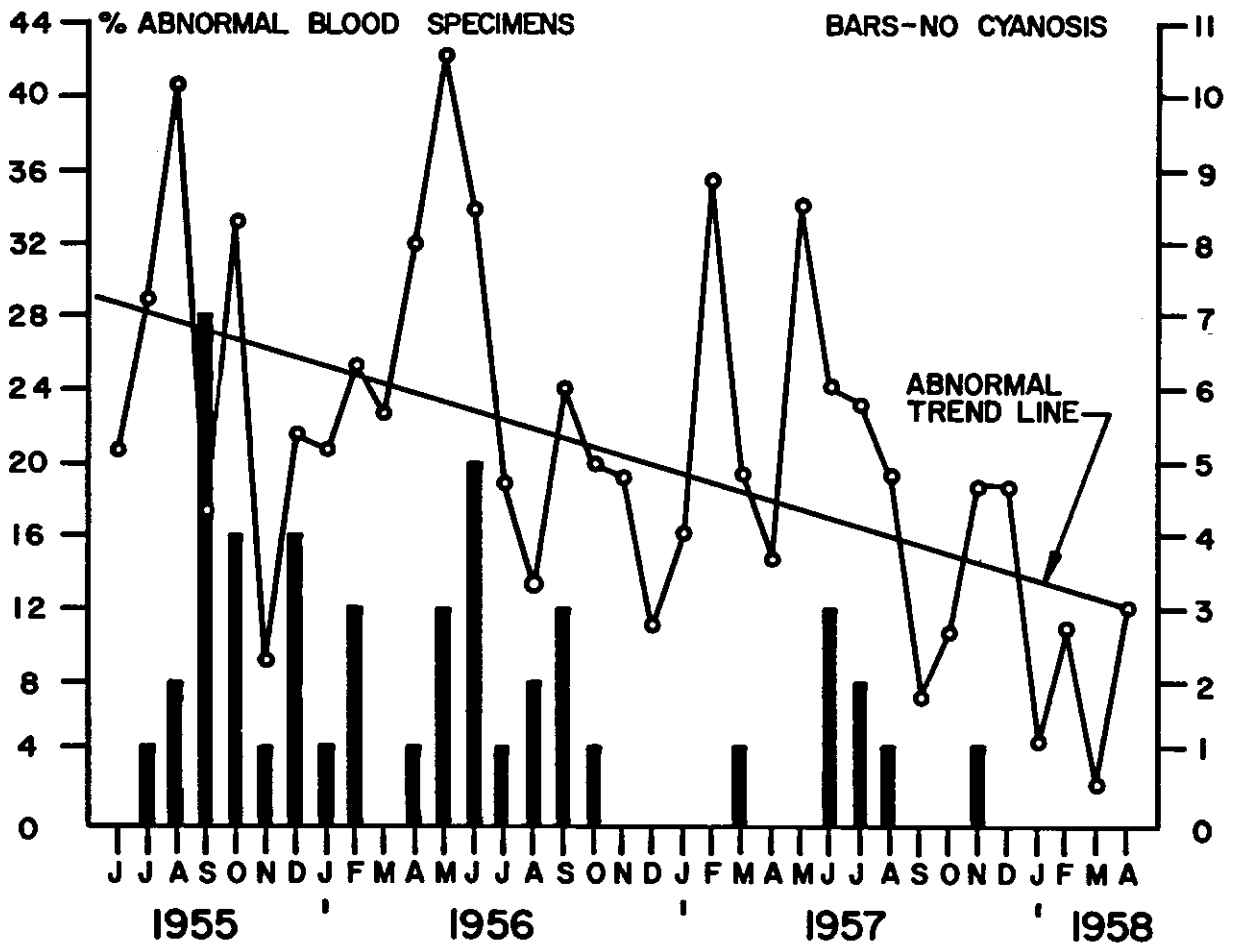
Useful shortcuts may be elected to determine whether a significant relationship exists between x and y factors in the equation for a straight line ($y = a + bX$). The data are plotted on linear cross section paper and a straight line drawn by inspection through the points with an equal number on each side or fitted by the least squares method. If the intercept a must be zero (a blank correction may produce such a situation), the fitting is greatly simplified. Then on each side equidistant from this line draw parallel lines corresponding to the established deviation (σ) of the analytical procedure, tally up the points falling inside of the band formed by the $\pm \sigma$ lines and calculate percent correlation (conformance = No. within band $\times 100$ /total points plotted). This technique is illustrated in Figure 22-13 which was used to relate urinary lead excretion to the airborne lead concentration obtained by personnel monitor sur-

veys.¹⁷ In this case more than one TLV was involved, so the TLV coefficient (TLVC) transformation was used for estimation of total lead exposure (TLVC =

$$\frac{\text{alkyl Pb found}}{\text{TLV}} + \frac{\text{Inorganic Pb found}}{\text{TLV}}).$$

A plot of the monthly coefficients versus corresponding average urinary excretion disclosed only a 69% conformance, whereas a plot of the previous month's TLVC's versus current month's average urinary excretion gave a 78% conformance. Furthermore, inspection of the chart indicated most of the "outliers" were contributed by the furnace crew. Deletion of this group raised conformance to 86% for the balance of the operation.¹⁷ Correlations above 80% are considered quite good [see also reference (16)].

Curvilinear functions can be accommodated, especially if a log normal¹⁴ function is involved and a plot of the data on semi-log paper yields a straight line.¹⁸ Log-Log paper also is available for plotting complex functions.



(J. M. Wetherhold, A. L. Linch and R. C. Charsha. Amer. Ind. Hyg. Assoc. J. 20: 396, 1959)

Figure 22-15. Relation of Abnormal Blood Specimens to Cyanosis Incidents

A combination of curvilinear and bar charts in some cases will reveal correlations not readily detected by mathematical processes. The data derived from an industrial cyanosis control program¹⁹ illustrate an application which revealed a rather significant relationship between abnormal blood specimens and the frequency of cyanosis cases on a long-term basis (Figure 22-15). In fact one trend line could be fitted to both variables, and the predicted ultimate improvement was attained in 1966 when abnormal blood specimens dropped below 2% and the cyanosis cases below 4%.²⁰

Grouping data on a graph and approximating relationships by the quadrant sum test (rapid corner test for association) can provide useful results with a minimum expenditure of time.^{16, 21}

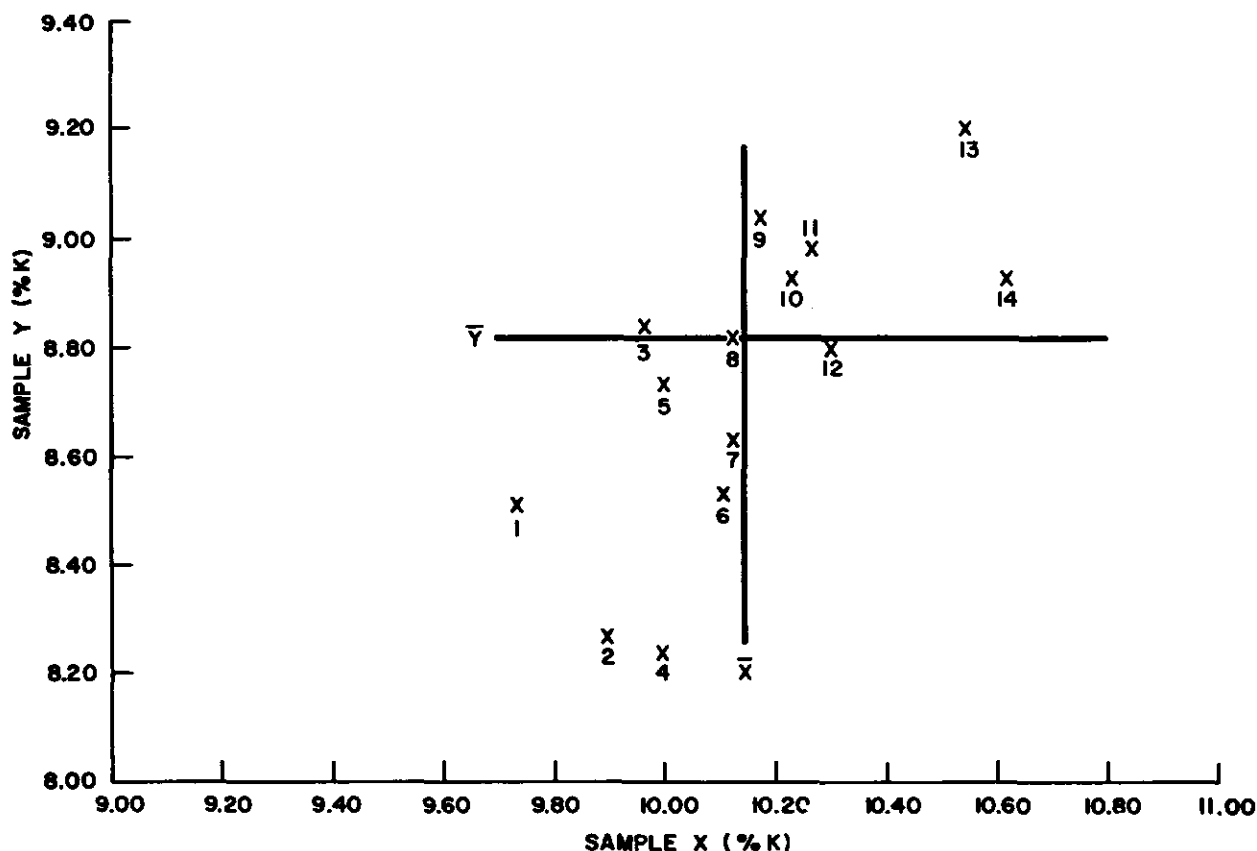
In those cases where application of mathematical tools are tedious or completely impractical, a system of ranking is sometimes applicable to the restoration of order out of chaos. Again with reference to the cyanosis control program, a relationship between causative agent structure and biochemical potential for producing cyanosis and anemia was needed. Ten factors (categories) common to some degree for each of the 13 compounds under study had been recognized. The 13

compounds were ranked in each category in reverse order of activity (No. 1 most, No. 13 least active) and the sum of the rankings obtained for each compound. These sums then were divided by the number of categories used in the total ranking to obtain the "score." The scores were then arranged in increasing numerical order in columnar form. The most potent cyanogenic and anemigenic compounds then appeared at the top of the table and the least at the bottom.²⁰

CHI SQUARE TEST

Control charts are a convenient tool for daily checking with reference standards, but the answers are not always as nearly quantitative as needed. Periodic checking of the accumulated daily reference results to determine more rigorously whether all of the data belong to the same normal distribution may become necessary. One approach to this question and to assign a probability to the answer is provided by the Chi Square (X^2) test.

The Chi Square distribution describes the probability distribution of the sums of the squares of independent variables that are normally or approximately normally distributed. The general form of the expression provides a comparison of observed versus expected frequencies.²² The Chi



Powell CH, Hoxey AD (eds): The Industrial Environment — Its Evaluation and Control, 2nd Edition. Public Health Service Publication No. 614, 1965.

Figure 22-16. Youden's Graphical Technique

Square test is applied to variables which fall within the Poisson distribution.²³

THE ANALYSIS OF VARIANCE (ANOVA)

The analysis of variance is one of the most useful statistical tools. Variation in a set of results may be analyzed in such a way as to disclose and evaluate the important sources of the variation. For a detailed description of this technique consult standard statistics textbooks.

YOUDEN'S GRAPHICAL TECHNIQUE^{1, 6, 24}

Dr. W. J. Youden has devised an approach to test for determinate errors with a minimum of effort on the part of the analyst.

Two different test samples (X and Y) are prepared and distributed for analysis to as many individuals or laboratories as possible. Each participant is asked to perform only one determination on each sample (NOTE: It is important that the samples are relatively similar in concentration of the constituent being measured.)

Each pair of laboratory results can then be plotted as a point on a graph (Figure 22-16).

A vertical line is drawn through the average of all the results obtained on sample X; a horizontal line is drawn through the average of all the results obtained on sample Y. If the ratio of the bias to standard deviation is close to zero for the determinations submitted by the participants, then one would expect the distribution of the paired values (or points) to be close to equal among the four quadrants. The fact that the majority of the points fall in the (+, +) and (-, -) quadrants indicates that the results have been influenced by some source of bias.

Furthermore, one can even learn something about a participant's precision. If all participants had perfect precision (no indeterminate error), then all the paired points would fall on a 45° line passing through the origin. Consequently the distance from such a 45° line to each participant's point provides an indication of that participant's precision.

INTRA-LABORATORY QUALITY CONTROL PROGRAM

Responsibilities

The attainment and maintenance of a quality control program in the laboratory is the direct responsibility of the laboratory manager or supervisor. The fundamental quality control techniques are based on:

1. Calibration to ensure accuracy
2. Duplication to ensure precision
3. Correlation of quantitatively related tests to confirm accuracy and continual scrutiny to maintain the integrity of the results reported.

The individual technician can contribute significant assistance in this effort by his desire to deliver the best possible answers within the inherent limits of the equipment and procedure. Part of supervision's responsibility is adequate instruction to provide the "man on the bench" with sufficient "know how" to apply the principles on a routine basis.

The guidelines established by the American Industrial Hygiene Association for Accreditation of Industrial Hygiene Analytical Laboratories¹² delineate the minimum requirements which must be satisfied in order to qualify for proficiency recognition.

Precision Quality Control

In addition to the use of internal standards, recovery procedures and statistical evaluation of routine results, the laboratory should subscribe to a reference sample service to confirm precision and accuracy within acceptable limits. Apparatus should be calibrated directly or by comparison with National Bureau of Standards (NBS) certified equipment or its equivalent, reagents should meet or exceed ACS standards, calibration standards should be prepared from AR (analytical reagent) grade chemicals,²⁵ and standardized with NBS standards if available. To illustrate, in a laboratory engaged in an exposure control program based on biological monitoring by trace analysis of blood and urine for lead content, at least two calibration points, blanks and a recovery should be included in each batch analyzed by the dithizone procedure. In addition, the wavelength integrity and optical density response of the spectrophotometer should be checked and adjusted — if necessary by calibration with NBS cobalt acetate standard solution. Until the standard deviation for the analytical procedure has been established within acceptable limits, replicate determinations should be made on at least two samples in each batch (either aliquot each sample or take duplicate samples), and thereafter with a frequency sufficient to ensure continued operation within these limits.

Control charts are probably the most widely recognized application of statistics. They provide "instant" quality control status when plotted daily, or at other intervals sufficiently short to disclose trends without undue oscillations from over-refinement of the data. Examples selected from a lead surveillance program illustrate the value of control charts. Figure 22-9 for analytical control is based on recoveries of known quantities of lead added to blood. From this chart and an analysis of the data itself, several conclusions may be drawn:

1. Background ("natural" lead) concentrations lay very close to the ultimate sensitivity of the method ($35 \pm 5 \mu\text{g}$).
2. The variability of the back-ground lead concentration exerts a relatively strong controlling effect on the recovery.
3. Although only a short period is covered, a downward trend is noticeable.
4. A control limit set at $98\% \pm 5\%$ probably is more realistic.

The same technique was applied to the evaluation of the quality of an exposure control program. A one year section from the control chart is presented in Figure 22-10. The graph provided several significant conclusions upon which action was initiated:

1. An alleged bias in the technician's performance was ruled out as each had about the same number of peaks and valleys dur-

ing the period (each technician in turn analyzed all of the urine specimens for the entire week plotted).

2. Trend lines which were drawn in by inspection disclosed a much closer correlation with production rate than with an alleged seasonal (temperature) cycle.
3. The peaks in the short term oscillations were connected with particular rotating shift crews who engaged in "dirty" work habits that were corrected from time to time.
4. No correlation could be established with fixed station air analysis data.

These examples are but two applications of a very extensive specialty within the field of statistics; therefore, the reader is referred to standard texts for additional information on refinements and procedures for extracting significant information from control charts.¹⁴⁻²⁶ On the basis of its raw simplicity, amount of information available for a minimum expenditure of time and effort, graphic presentation and the ease of comprehension, the control chart cannot be over-recommended.

Accuracy Quality Control

A standard or well defined control sample should be analyzed periodically to confirm accuracy of a procedure. The control chart technique is directly applicable to long-term evaluation of the reliability of the analyst as well as the accuracy of the procedure. To attain and maintain the high level of analytical integrity presented earlier in this chapter the three major sources of "assignable cause" errors must be reduced to a minimum level which is consistent with cost penalties and the objective of the study for which the analytical service is rendered:

1. Equipment errors can be reduced to tolerable limits by calibration with primary physical standards such as those supplied by the National Bureau of Standards.
2. Method errors can be controlled by precise standardization of reagents, use of calibrated volumetric glassware and weights, refined manipulative techniques (personal errors), recognition and correction of personal bias (color estimation), elimination of chemical interferences, and corrections for physical influences such as the effect of temperature and actinic light.
3. Personal errors other than inherent physical visual acuity (color judgment) include consistent carelessness, lack of knowledge, calculation errors, use of contaminated or improper reagents, poor sampling technique and use of poorly calibrated standards and instruments.

Interlaboratory Reference Systems

Participation in interlaboratory studies whether by subscription from a certified laboratory supplying such a service or from a voluntary program initiated by a group of laboratories in an attempt to improve analytical integrity¹¹ is highly recommended. Evaluation of the analytical method as well as evaluation of the individual

laboratory's performance can be derived by specialized statistical methods applied to the data collected from such a study. However, inasmuch as most investigators will not be called upon to conduct or evaluate interlaboratory surveys, the reader is referred to the literature in the event such specialized information is needed.^{11, 26, 27, 28} In the absence of such programs, the investigator, or laboratory supervisor, should make every effort to locate colleagues engaged in similar sampling and analytical activity and arrange exchange of standards, techniques, and samples to establish integrity and advance the art.

SUMMARY

Identification of the determinate sources of error of a procedure provides the information required to reduce assignable error to a minimum level. The remaining (residual) indeterminate errors then determine the precision of analyses produced by the procedure. Statistical techniques have been developed to estimate efficiently the precision. For a procedure to be accurate, the results must be not only precise, but bias must be absent. Several approaches are available to eliminate bias both within the laboratory and between laboratories by collaborative testing. Quality control programs based on appropriate control charts must be employed on a routine basis to assure adherence to established performance standards. The total analysis control program must include instrumental control, procedural control and elimination of personal errors. The use of replicate determinations, "spiked" sample techniques, reference samples, standard samples and quality control charts will provide assurance that the procedure remains in control.

The guidelines established by the American Industrial Hygiene Association for Accreditation of Industrial Hygiene Analytical Laboratories¹² further summarizes in a succinct fashion the requirements for proficiency.

Quality Control and Equipment

Routine quality control procedures shall be an integral part of the laboratory procedures and functions. These shall include:

1. Routinely introduced samples of known content along with other samples for analyses.
2. Routine checking, calibrating, and maintaining in good working order of equipment and instruments.
3. Routine checking of procedures and reagents.
4. Good housekeeping, cleanliness of work areas, and general orderliness.
5. Proficiency Testing — The following criteria shall be used in the proficiency testing of industrial hygiene analytical laboratories accredited by the American Industrial Association.

a) Reference Laboratories

Five or more laboratories shall be designated as reference laboratories by the American Industrial Hygiene Association based on the appraisal of

competence of the laboratories by the Association. The reference laboratories may be judged competent:

- (1) in all industrial hygiene analyses or
- (2) specific industrial hygiene analyses.

Proficiency samples shall be sent to designated reference laboratories for analyses. These data will be used for grading analytical data received from laboratories seeking or maintaining accreditation by the Association.

b) Method of Grading

Laboratories shall be graded on the basis of their ability to perform analyses within specified limits determined by the reference laboratories. Satisfactory performance shall be the reporting of results within two standard deviations of the mean value obtained by the reference laboratories. Exception shall be made in cases where too few laboratories are in existence, a new procedure has not been adequately tested, or the range in variation from reference laboratories is too great to apply this method of grading.

c) Number and Suitability of Samples

Samples shall be either environmental materials, biological fluids, or tissues or synthetic mixtures approximating these. They shall be packaged, as nearly possible, in an identical manner and the containers will be chosen so as to avoid exchange of the test material between the samples and container. Samples shall be analyzed by each participating laboratory in sufficient number and at proper intervals for the results to form an adequate basis for accreditation in the opinion of AIHA.

d) Frequency of Samples

Samples shall be submitted to each laboratory quarterly.

e) Satisfactory Performance

Satisfactory performance is a considered scientific judgment and is not to be judged exclusively by any inflexible set of criteria. The judgment shall be made, however, on the basis of the results submitted by the laboratories and a statistical estimation of whether the results obtained are probably representative of analytical competence considering inherent variables in the method.

6. Records

The industrial hygiene analytical laboratory shall maintain records and files proper and adequate for the services given. These shall include:

- a) The proper identification and numbering of incoming samples.
- b) An adequate and systematic numbering system relating laboratory samples to incoming samples.

c) An adequate record system on internal logistics of each sample including date of incoming sample, analysis and procedures, and reporting of data.

d) A records checking system of the calibration and standardization of equipment and of internal control samples.

The program includes:

1. Nature, extent of use and results of routine interlaboratory quality control procedures.
2. Procedures for routine calibration and maintenance of reagents, equipment and instruments.
3. Nature, extent and results of routine checking and evaluation of analytical procedures. Intra- and inter-laboratory evaluations of precision and accuracy.

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Preferred Reading

In addition to references 6, 8, 9, 10, 14, 15, the following periodicals are recommended:

- American Industrial Hygiene Association Journal
- Journal of the Air Pollution Control Association
- Analytical Chemistry (American Chemical Society)
- Environmental Science & Technology (American Chemical Society)
- Pollution Engineering (Technical Publishing Co.)
- Air Pollution Manual — 2nd edition — American Industrial Hygiene Association, 1971.
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CHAPTER 23
PHYSICS OF SOUND

Paul L. Michael, Ph.D.

INTRODUCTION

The sensation of sound is produced when pressure variations having a certain range of characteristics reach a responsive ear. These pressure variations may be produced by any object that vibrates in a conducting medium with the proper cycle rate, or frequency, and amplitude. Sound may consist of a single frequency and amplitude; however, common noise spectra have many different frequency components with many different amplitudes.

This chapter is concerned primarily with those practical aspects of sound that are related to its characteristics in a given space and to its propagation through specified media. Basic terminology, noise measurement, and practical calculation procedures such as combining sound levels are emphasized.

BASIC TERMINOLOGY

Amplitude:

The amplitude of sound may be described in terms of either the quantity of sound produced at a given location away from the source or the overall ability of the source to emit sound. The amount of sound at a location away from the source is generally described by the sound pressure or sound intensity, while the ability of the source to emit sound is described by the sound power of the source.

Free Field:

A free field exists in a homogeneous, isotropic medium free from boundaries. In a free field, sound radiated from a source can be measured accurately without influence from the test space. True free-field conditions are rarely found except in expensive anechoic (echo-free) test chambers; however, approximate free-field conditions may be found in any homogeneous space where reflecting surfaces are at great distances from the measuring location as compared to the wavelengths of the sound being measured.

Frequency (f):

The frequency of sound describes the rate at which complete cycles of high and low pressure regions are produced by the sound source. The unit of frequency is the cycle per second (cps) which is also called the hertz (Hz). The frequency range of the human ear is highly dependent upon the individual and the sound level, but a normal-hearing young ear will have a range of approximately 20 to 20,000 cps at moderate sound levels. The frequency of a propagated sound wave heard by a listener will be the same as the frequency of the vibrating source if the distance between the

source and the listener remains constant; however, the frequency detected by a listener will increase or decrease as the distance from the source is decreasing or increasing (Doppler effect).¹

Loudness:

The loudness of a sound is an observer's impression of its amplitude, an impression also dependent on the characteristics of the ear.

Noise and Sound:

The terms noise and sound are often used interchangeably, but generally, sound is descriptive of useful communication or pleasant sounds, such as music, while noise is used to describe discord or unwanted sound.

Period (T):

The period is the time required for one cycle of pressure change to take place; hence, it is the reciprocal of the frequency. The period is measured in seconds.

Pitch:

Pitch is used as a measure of auditory sensation that depends primarily upon frequency but also upon the pressure and waveform of the sound stimulus.

Pure Tone:

A pure tone refers to a sound wave with a single simple sinusoidal change of level with time.

Random Noise:

Random noise is made up of many frequency components whose instantaneous amplitudes occur randomly as a function of time.

Resonance:

Resonance of a system exists when any change in the frequency of forced oscillation causes a decrease in the response of the system.

Reverberation:

Reverberation occurs when sound persists after direct reception of the sound has stopped. The reverberation characteristic of a space is specified by the "reverberation time" which is the time required after the source has stopped radiating sound for the rms sound pressure to decrease 60 dB from its steady-state level.

Root-Mean-Square (rms) Sound Pressure:

The root-mean-square (rms) value of a changing quantity, such as sound pressure, is the square root of the mean of the squares of the instantaneous values of the quantity.

Sound Intensity (I):

The sound intensity at a specific location is the average rate at which sound energy is transmitted through a unit area normal to the direction of sound propagation. The units used for sound intensity are joules per square meter per second.

Sound intensity is also expressed in terms of a level (sound intensity level L_I) in decibels referenced to 10^{-12} watts per square meter.

Sound Power (P):

The sound power of a source is the total sound energy radiated by the source per unit time. Sound power is normally expressed in terms of watts. Sound power is also expressed in terms of a level (sound power level L_P) in decibels referenced to 10^{-12} watts.

Sound Pressure (p):

Sound pressure normally refers to the rms value of the pressure changes above and below atmospheric pressure when used to measure steady-state noise. Short term or impulse-type noises are described by peak pressure values. The units used to describe sound pressures are newtons per square meter (N/m^2), dynes per square centimeter (d/cm^2), or microbars. Sound pressure is also described in terms of a level (sound pressure level L_p) in decibels referenced to 2×10^{-5} newtons per square meter.

Velocity (c):

The speed at which the regions of sound-producing pressure changes move away from the sound source is called the velocity of propagation. Sound velocity varies directly with the square root of the density and inversely with the compressibility of the transmitting medium as well as with other factors; however, for practical purposes, the velocity of sound is constant in a given medium over the normal range of conditions. For example, the velocity of sound is approximately 1130 ft/sec in air, 4700 ft/sec in water, 13,000 ft/sec in wood, and 16,500 ft/sec in steel.

Wavelength (λ):

The distance required for one complete pressure cycle to be completed is called one wavelength. The wavelength (λ), a very useful tool in noise control work, may be calculated from known values of frequency (f) and velocity (c):

$$\lambda = c/f \quad (1)$$

White Noise:

White noise has an essentially random spectrum with an equal-energy-per-unit frequency bandwidth over a specified frequency band.

NOISE MEASUREMENT

Steady-state sounds, ones that have relatively constant levels over time, are usually measured with instruments having root-mean-square (rms) characteristics. The time interval over which simple periodic sound pressure patterns must be measured is equal to an integral number of periods of that sound pattern, or the interval must be long compared to a period. If the sound pressures do not follow a simple periodic pattern, the interval must be long enough to make the measured value essentially independent of small changes in the interval length. In all cases, there must be more than 10 peaks per second for the noise to be considered to be steady-state for measurement purposes.

Single prominent peak pressures which may occur over a very short period of time, and peak pressures that are repeated no more than 2 per

second, cannot be measured by conventional rms-type instruments because the peaks are not repeated often enough for long-time integrations to be meaningful. These single pressure peaks are normally measured in terms of the maximum instantaneous level that occurs during a specified time interval.

Just as rms measuring instruments cannot be used to measure single or widely spaced peak pressures, peak measuring instruments cannot be used to measure sustained noises unless the waveform is known to be sinusoidal or is otherwise predictable. In most cases, the relationship of the peak reading to the rms reading of common noises with complex waveforms cannot be established in a practical way. Peak pressure value of a sinusoidal waveform is about 3 dB greater than the rms value of that signal; however, as the waveform becomes more complex the differences may exceed 25 dB for common noises.

Noises with peak pressures occurring at rates between 2 and 10 peaks per second are difficult to measure in that they cannot be clearly defined as peak- or sustained-type noises. If the waveforms of the pressure peaks are complex and repeat between 2 and 10 times per second, an oscilloscope should be used to determine the pressure or energy contribution of the noise.

The Decibel (dB)

The range of sound pressures commonly encountered is very wide. For example, sound pressures well above the pain threshold (about 20 newtons per square meter, N/m^2) are found in many work areas, while pressures down to the threshold of hearing (about $0.00002 N/m^2$) are also of wide interest. This range of more than $10^6 N/m^2$ cannot be scaled linearly with a practical instrument because such a scale might be many miles in length in order to obtain the desired accuracy at various pressure levels. In order to cover this very wide range of sound pressures with a reasonable number of scale divisions and to provide a means to obtain the required measurement accuracy at extreme pressure levels, the logarithmic decibel (dB) scale was selected. By definition, the dB is a dimensionless unit related to the logarithm of the ratio of a measured quantity to a reference quantity. The dB is commonly used to describe levels of acoustic intensity, acoustic power, hearing thresholds, electric voltage, electric current, electric power, etc., as well as sound-pressure levels; thus, it has no meaning unless a specific reference quantity is specified.

Sound Pressure and Sound-Pressure Level

Most sound-measuring instruments are calibrated to provide a reading of root-mean-square (rms) sound pressures on a logarithmic scale in decibels. The reading taken from an instrument is called a sound-pressure level (L_p). The term "level" is used because the pressure measured is at a level above a given pressure reference. For sound measurements in air, $0.00002 N/m^2$ commonly serves as the reference sound pressure. This reference is an arbitrary pressure chosen many years ago because it was thought to approximate the normal threshold of young human hearing at

1000 Hz. The mathematical form of the L_p is written as:

$$L_p = 20 \log \frac{p}{p_0} \text{ dB} \quad (2)$$

where p is the measured rms sound pressure, p_0

is the reference sound pressure, and the logarithm (log) is to the base 10. Thus, L_p should be written in terms of decibels referenced to a specified pressure level. For example, in air, the notation for L_p is commonly abbreviated as "dB re 0.00002 N/m²."

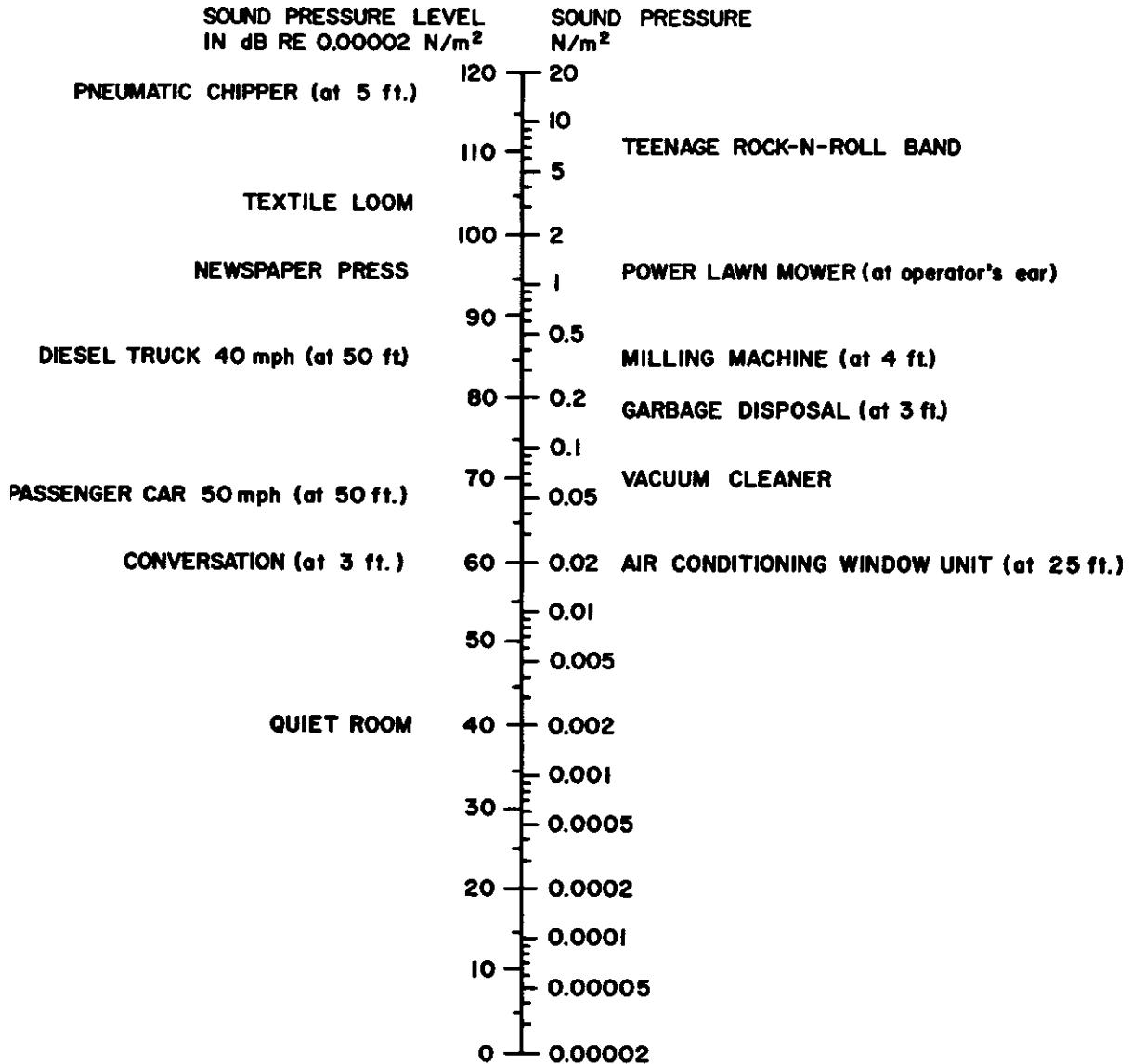


Figure 23-1. Relationship between A-Weighted Sound-Pressure Level in Decibels (dB) and Sound Pressure in N/m²

Figure 23-1 shows the relationship between sound pressure in N/m² and L_p in dB, and illustrates the advantage of using the dB scale rather than the wide range of direct pressure measurements. It is of interest to note that any pressure range over which the pressure is doubled is equivalent to six decibels whether at high or low levels. For example, a range of 0.00002 to 0.00004 N/m², which might be found in hearing measure-

ments, and a range of 10 to 20 N/m², which might be found in hearing conservation programs, are both ranges of six decibels.

*An equivalent reference 0.0002 dynes per square centimeter is often used in older literature. The microbar is also used in older literature interchangeably with the dyne per square centimeter.

The L_p referenced to 0.00002 N/m² may be written in the form:

$$\begin{aligned}
L_p &= 20 \log (p/0.00002) \\
&= 20 \log p - \log 0.00002 \\
&= 20 \log p - (\log 2 - \log 10^5) \\
&= 20 \log p - (0.3 - 5) \\
&= 20 (\log p + 4.7) \\
&= 20 \log p + 94 \text{ re } 0.00002 \text{ N/m}^2 \quad (3)
\end{aligned}$$

Sound Intensity and Sound-Intensity Level

Sound intensity (I) at any specified location may be defined as the average acoustic energy per unit time passing through a unit area that is normal to the direction of propagation. For a spherical or free-progressive sound wave, the intensity may be expressed by

$$I = \frac{p^2}{\rho c}, \quad (4)$$

where p is the rms sound pressure, ρ is the density of the medium, and c is the speed of sound in the medium. It is obvious from this definition that sound intensity describes, in part, characteristics of the sound in the medium, but does not directly describe the sound source itself.

Sound-intensity units, like sound-pressure units, cover a wide range, and it is often desirable to use dB levels to compress the measuring scale. To be consistent with Equations (2) and (4), intensity level (L_I) is defined as

$$L_I = 10 \log \frac{I}{I_0} \text{ dB}, \quad (5)$$

where I is the measured intensity at some given distance from the source and I_0 is a reference intensity. The reference intensity commonly used is 10^{-12} watts/m². In air, this reference closely corresponds to the reference pressure 0.00002 N/m² used for sound-pressure levels.

Sound Power and Sound-Power Level

Sound power (P) is used to describe the sound source in terms of the amount of acoustic energy that is produced per unit time. Sound power may be related to the average sound intensity produced in free-field conditions at a distance r from a point source by

$$P = I_{\text{avg}} 4\pi r^2, \quad (6)$$

where I_{avg} is the average intensity at a distance r from a sound source whose acoustic power is P . The quantity $4\pi r^2$ is the area of a sphere surrounding the source over which the intensity is averaged. It is obvious from Equation (6) that the intensity will decrease with the square of the distance from the source; hence, the well-known inverse-square law.

Power units are often described in terms of decibel levels because of the wide range of powers covered in practical applications. Power level L_P is defined by

$$L_P = 10 \log \frac{P}{P_0}, \quad (7)$$

where P is the power of the source, and P_0 is the reference power. The arbitrarily chosen reference power commonly used is 10^{-12} watt. Figure 23-2 shows the relationship between sound power in watts and sound-power level in dB re 10^{-12} watt.

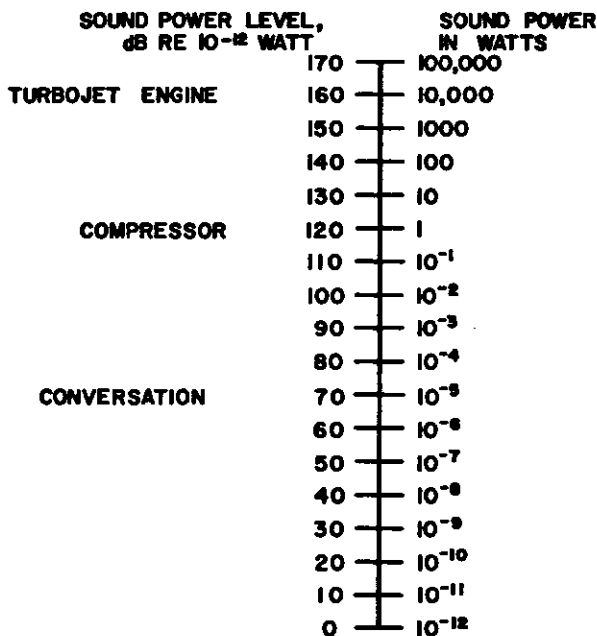


Figure 23-2. Relationship between Sound Power Level in Decibels (dB) and Sound Power in Watts

Relationship of Sound Power, Sound Intensity, and Sound Pressure

Many noise-control problems require a practical knowledge of the relationship between pressure, intensity, and power. An example would be the prediction of sound-pressure levels that would be produced around a proposed machine location from the sound-power level provided for the machine.

Example: Predict the sound-pressure level that would be produced at a distance of 100 feet from a pneumatic chipping hammer. The manufacturer of the chipping hammer states that the hammer has an acoustic power output of 1.0 watt.

From Equations (4) and (6) in free field for an omnidirectional source:

$$P = I_{\text{avg}} 4\pi r^2 = \frac{p^2 \text{ avg } 4\pi r^2}{\rho c}, \quad (8)$$

where

$$p_{\text{avg}} = \sqrt{\frac{P \rho c}{4\pi r^2}}. \quad (9)$$

If P is given in watts, r in feet, and p in N/m², then, with standard conditions, Equation (9) may be rewritten as

$$p_{\text{avg}} = \sqrt{\frac{3.5 P \times 10^2}{r^2}}$$

and, for this example,

$$p_{\text{avg}} = \sqrt{\frac{3.5 \times 1.0 \times 10^2}{(100)^2}} = 0.187 \text{ N/m}^2$$

The sound-pressure level may be determined from Equation (2) to be:

$$L_p = 20 \log \frac{0.187}{0.00002} = 79.4 \text{ dB re } 0.00002 \text{ N/m}^2.$$

Noise levels in locations that are reverberant can be expected to be somewhat higher than predicted because of the sound reflected back to the point of measurement.

COMBINING SOUND LEVELS

It may be necessary to combine sound-pressure levels (decibels) during hearing conservation or noise-control procedures. For example, it may be necessary to predict the overall levels in an area that will result from existing levels being combined with those of a new machine that is to be installed. The combination of levels in various frequency bands to obtain overall or weighted overall sound-pressure levels is another example.

Sound-pressure levels cannot be added arithmetically because addition of these logarithmic quantities constitutes multiplication of pressure ratios. To add sound-pressure levels, the corresponding sound pressures must be determined and added with respect to existing phase relationships.

For the most part, industrial noise is broadband with nearly random phase relationships. Sound-pressure levels of random noises can be added by converting the levels to pressure, then

Octave Band Center Frequency	31.5	63	125	250	500	1000	2000	4000	8000
(Hz)									
Sound-Pressure Level (dB)	85	88	94	94	95	100	97	90	88

A good procedure for adding a series of dB values is to begin with the highest levels so that calculations may be stopped when lower values are reached which do not add significantly to the total. In this example, the levels of 100 and 97 have a difference of 3 that corresponds with $L_n(3)=1.8$ in Table 23-1. Thus, $100 \text{ dB} + 97 \text{ dB} = 100 + 1.8 = 101.8 \text{ dB}$. Combining 101.8 and 95, the next higher level, gives $101.8 + 0.8 = 102.6 \text{ dB}$ which is the total of the first three bands. This procedure is continued with one band at a time until the overall sound-pressure level is found to be about 104 dB.

Octave Band Center Frequency	31.5	63	125	250	500	1000	2000	4000	8000
(Hz)									
Sound Pressure Level	45.8	61.9	77.8	85.4	91.7	100	98.2	91.0	86.9
(A-Weighted) (dB)									

These octave band levels with A-frequency weighting can be added by the procedure described above to obtain the resultant A-weighted level which is about 103 dBA.

A large majority of industrial noises have random frequency characteristics and may be combined as described in the above paragraphs. However, there are a few cases of noises with pitched or major pure-tone components where these calculations will not hold, and phase relationships must

to intensity units which may be added arithmetically, and reconvert the resultant intensity to pressure and finally to sound-pressure levels in dB. Equations (2) and (4) can be used in free-field conditions for this purpose.

A more convenient way to add the sound-pressure levels of two separate random noise sources is to use Table 23-1. To add one random noise level $L_p(1)$, measured at a point to another, $L_p(2)$, measured by itself at the same point, the numerical difference between the levels, $L_p(2) - L_p(1)$, is used in Table I to find the corresponding value of $L_p(3)$ which, in turn, is added arithmetically to the larger of $L_p(1)$ or $L_p(2)$ to obtain the resultant of $L_p(1) + L_p(2)$. If more than two are to be added, the resultant of the first two must be added to the third, the resultant of the three sources to the fourth, etc., until all levels have been added, or until the addition of smaller values do not add significantly to the total.

Example: The overall sound-pressure level produced by a random-noise source can be calculated by adding the sound-pressure levels measured in octave bands shown in the following table:

The overall sound-pressure level calculated in the above example corresponds to the value that would be found by reading a sound level meter at this location with the frequency weighting set so that each frequency in the spectrum is weighted equally. Common names given to this frequency weighting are flat, linear, 20 kc, and overall.

The corresponding A-weighted sound-pressure level (dBA)* found in many noise regulations may also be calculated from octave band values such as those in the above example if the adjustments given in Table 23-2 are first applied. For example the octave band levels with A-weighting corresponding to the above example would be:

be considered. In areas where pitched noises are present, standing waves will often be recognized by rapidly varying sound-pressure levels over short distances. It is not practical to try to predict levels in areas where standing waves are present.

*The A-weighted frequency weighting approximates the ear's response characteristics for low level sound, below about 55 dB re 0.00002 N/m².

TABLE 23-1

Table for Combining Decibel Levels of Noises with Random Frequency Characteristics

Sum (L_R) of dB Levels L_1 and L_2

Numerical Difference Between Levels L_1 and L_2	L_3 : Amount to be Added to the Higher of L_1 or L_2
0.0 to 0.1	3.0
0.2 to 0.3	2.9
0.4 to 0.5	2.8
0.6 to 0.7	2.7
0.8 to 0.9	2.6
1.0 to 1.2	2.5
1.3 to 1.4	2.4
1.5 to 1.6	2.3
1.7 to 1.9	2.2
2.0 to 2.1	2.1
2.2 to 2.4	2.0
2.5 to 2.7	1.9
2.8 to 3.0	1.8
3.1 to 3.3	1.7
3.4 to 3.6	1.6
3.7 to 4.0	1.5
4.1 to 4.3	1.4
4.4 to 4.7	1.3
4.8 to 5.1	1.2
5.2 to 5.6	1.1
5.7 to 6.1	1.0
6.2 to 6.6	0.9
6.7 to 7.2	0.8
7.3 to 7.9	0.7
8.0 to 8.6	0.6
8.7 to 9.6	0.5
9.7 to 10.7	0.4
10.8 to 12.2	0.3
12.3 to 14.5	0.2
14.6 to 19.3	0.1
19.4 to ∞	0.0

Step 1: Determine the difference between the two levels to be added (L_1 and L_2).

Step 2: Find the number (L_3) corresponding to this difference in the Table.

Step 3: Add the number (L_3) to the highest of L_1 and L_2 to obtain the resultant level $L_R = (L_1 \text{ or } L_2) + L_3$

When the sound-pressure levels of two pitched sources are added, it might be assumed that the resultant sound-pressure level $L_p(R)$ will be less, as often as it is greater, than the level of a single source; however, in almost all cases the resultant $L_p(R)$ is greater than either single source. The reason for this may be seen if two pure-tone sources are added at several specified phase differences (see Figure 23-3). At zero phase difference, the resultant of two like pure-tone sources is 6 dB greater than either single level. At a phase difference of 90°, the resultant is 3 dB greater than either level. Between 90° and 0°, the resultant is somewhere between 3 and 6 dB greater than either level. At a phase difference of 120°, the resultant is equal to the individual levels; and

TABLE 23-2

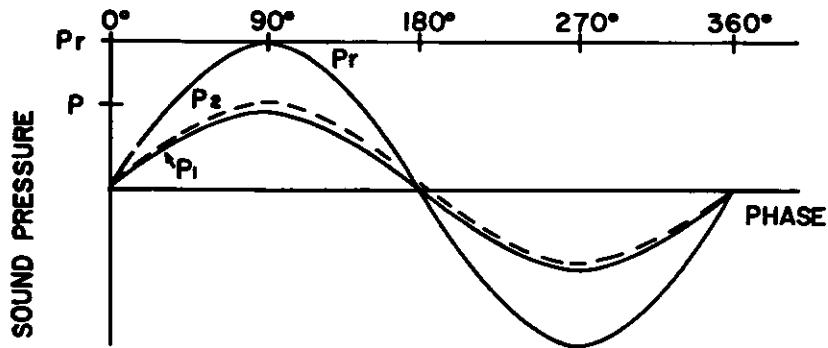
A-Frequency Weighting Adjustments

f(Hz)	Correction
25	-44.7
32	-39.4
40	-34.6
50	-30.2
63	-26.2
80	-22.5
100	-19.1
125	-16.1
160	-13.4
200	-10.9
250	-8.6
315	-6.6
400	-4.8
500	-3.2
630	-1.9
800	-0.8
1000	0.0
1250	+0.6
1600	+1.0
2000	+1.2
2500	+1.3
3150	+1.2
4000	+1.0
5000	+0.5
6300	-0.1
8000	-1.1
10000	-2.5
12500	-4.3
16000	-6.6
20000	-9.3

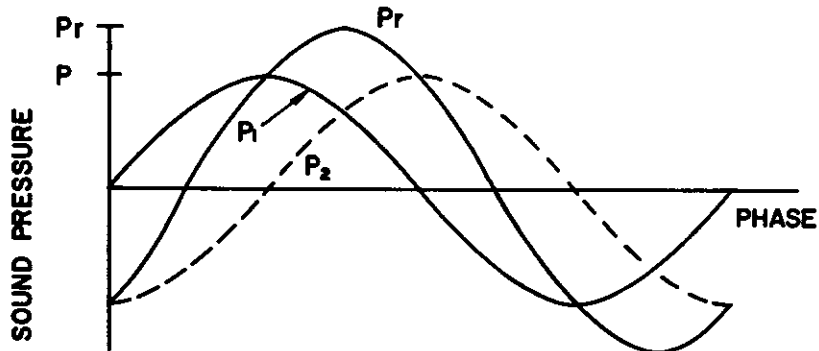
between 120° and 90°, the resultant is between 0 and 3 dB greater than either level. At 180°, there is complete cancellation of sound. Obviously, the resultant $L_p(R)$ is greater than the individual levels for all phase differences from 0° to 120°, but less than individual levels for phase differences from 120° and 180° — a factor of 2:1. Also, most pitched tones are not single tones but combinations thereof: thus, almost all points in the noise fields will have pressure levels exceeding the individual levels.

FREQUENCY ANALYSES

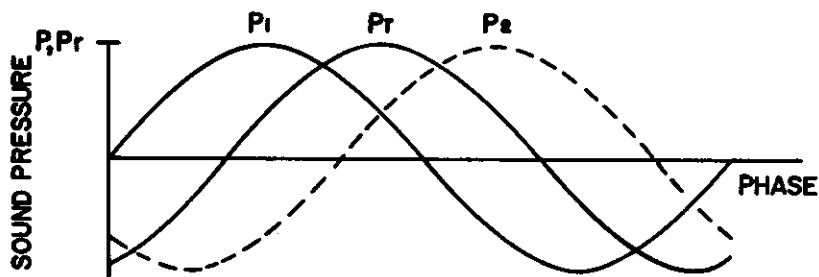
General purpose sound-measuring instruments are normally equipped with three frequency-weighting networks, A, B, and C,² that can be used to adjust the frequency response of the instrument. These three frequency weightings shown in Figure 23-4 were chosen because: 1) they approximate the ear's response characteristics at different sound levels, and 2) they can be easily produced with a few common electronic components. Also



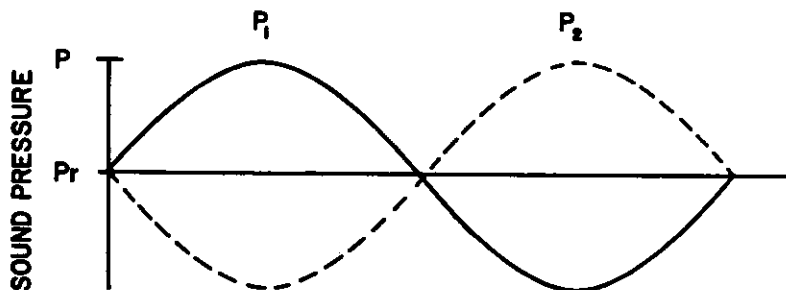
(a) 0° PHASE DIFFERENCE, $P_r = 2P$
 $(P_r = P + 6\text{dB})$



(b) 90° PHASE DIFFERENCE, $P_r = 1.4P$
 $(P_r = P + 3\text{dB})$



(c) 120° PHASE DIFFERENCE, $P_r = P$
 $(P_r = P + 0\text{dB})$



(d) 180° PHASE DIFFERENCE, $P_r = 0$

Figure 23-3. Combinations of Two Pure Tone Noises (p_1 and p_2) Phase Differences

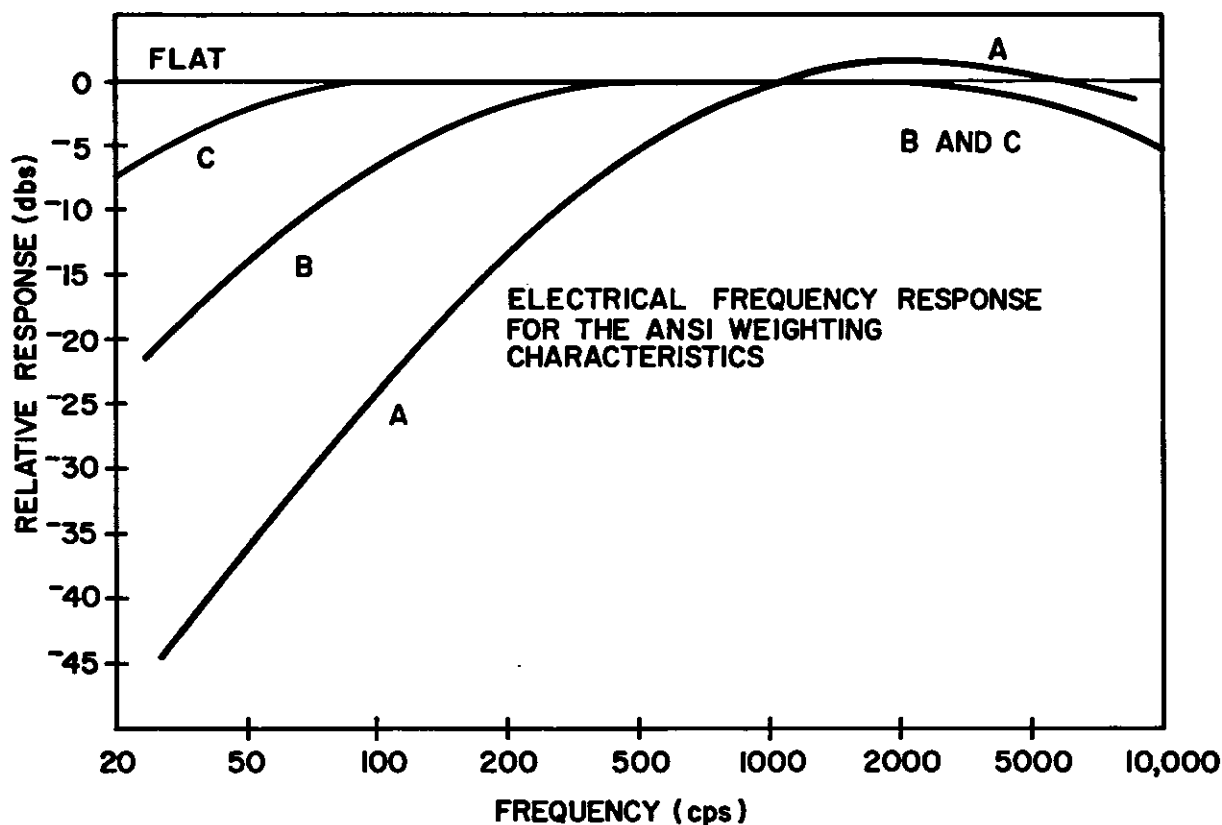


Figure 23-4. Frequency-Response Characteristics for Sound Level Meters (4)

shown in Figure 23-4 is a linear, overall, or flat response that weights all frequencies equally.

The A-frequency weighting approximates the ear's response for low-level sound, below about 55 dB re 0.00002 N/m². The B-frequency weighting is intended to approximate the ear's response for levels between 55 and 85 dB, and the C-frequency weighting corresponds to the ear's response for levels above 85 dB.

In use, the frequency distribution of noise energy can be approximated by comparing the levels measured with each of the frequency weightings. For example, if the A- and C-weighted noise levels are approximately equal, it can be reasoned that most of the noise energy is above 1000 Hz because this is the only position of the spectrum where the weightings are similar. On the other hand, if there is a large difference between these readings, most of the energy will be found below 1000 Hz.

In many cases, such as in noise control procedures, the information supplied by the A, B, and C frequency weightings do not provide enough resolution of frequency distribution of noise energy. Hence, more detailed analyses are needed from analyzers having bandwidths ranging from octaves to only a few cycles in width.

Frequency Bandwidths

The most common frequency bandwidth used

for industrial noise measurements is the octave band. A frequency band is said to be an octave in width when its upper band-edge frequency f_2 is twice the lower band-edge frequency f_1 :

$$f_2 = 2f_1 \quad (10)$$

Octave bands are commonly used for measurements directly related to the effects of noise on the ear and for some noise-control work because they provide the maximum amount of information in a reasonable number of measurements.

When more specific characteristics of a noise source are required, such as might be the case for pinpointing a particular noise source in a background of other sources, it is necessary to use narrower frequency bandwidths than octave bands. Half-octave, third-octave, and narrower bands are used for these purposes. A half-octave bandwidth is defined as a band whose upper band-edge frequency f_2 is the square root of 2 times the lower band-edge frequency f_1 :

$$f_2 = \sqrt{2} f_1 \quad (11)$$

A third-octave bandwidth is defined as a band whose upper band-edge frequency f_2 is the cube root of 2 times the lower band-edge frequency f_1 :

$$f_2 = \sqrt[3]{2} f_1 \quad (12)$$

The center frequency f_m of any of these bands is the square root of the product of the high and low band-edge frequencies (geometric mean):

$$f_m = \sqrt{f_2 f_1} \quad (13)$$

It should be noted that the upper and lower band-edge frequencies describing a frequency band do not imply abrupt cut-offs at these frequencies. These band-edge frequencies are conventionally used as the 3-dB-down points of gradually sloping curves that meet the American Standard Specification for Octave, Half-Octave, and Third-Octave Band Filter Sets, S1.11-1966.³

Comparing Levels Having Different Bandwidths

Noise-measurement data (rms) taken with analyzers of a given bandwidth may be converted to another given bandwidth if the frequency range covered has a continuous spectrum with no prominent changes in level. The conversion may be made in terms of sound-pressure levels by

$$L_p(A) = L_p(B) - 10 \log \frac{\Delta f(B)}{\Delta f(A)}, \quad (14)$$

where $L_p(A)$ = the sound-pressure level, in dB, of the band having a width $\Delta f(A)$ Hz.

where $L_p(B)$ = the sound-pressure level, in dB, of the band having a width $\Delta f(B)$ Hz.

Sound-pressure levels for different bandwidths of flat continuous spectrum noises may also be converted to spectrum levels. The spectrum level describes a continuous-spectrum wide-band noise in terms of its energy equivalent in a band one-hertz wide, assuming that no prominent peaks are present. The spectrum level $L_p(S)$ may be determined by

$$L_p(S) = L_p(\Delta f) - 10 \log \Delta f, \quad (15)$$

where $L_p(\Delta f)$ = the sound-pressure level of the band having a width of Δf Hz,

Δf = the bandwidth in Hz.

It should be emphasized that accurate conversion of sound-pressure levels from one bandwidth to another by the method described above can be accomplished only when the frequency bands have flat continuous spectra.

NOISE PROPAGATION CHARACTERISTICS

The sound-power level supplied by the manufacturer of noise-making equipment can be used to predict sound-pressure levels that will be produced by the equipment in surrounding work areas if the acoustical characteristics of the work area are known. These calculations are complex if all factors are considered, but simple approximate solutions to general cases are often helpful to estimate levels.

Noise Source in Free Field

A free field has been defined as one in which the sound pressure decreases inversely with the distance from the source. These ideal acoustical conditions are rarely found in work environments because of the reflecting surfaces of equipment, walls, ceilings, floors, etc.; however, free-field conditions may sometimes be approached outdoors or in very large rooms. For standard free-field conditions, the sound-pressure level L_p at a given distance r from a small omni-directional noise source can be written in terms of the sound-power level L_p of the source as

$$L_p = L_p - 20 \log r - 0.5, \quad (16)$$

where r is in feet, L_p is in dB referenced to 0.00002 N/m^2 , and L_p is in dB referenced to 10^{-12} watts.

Many noise sources have pronounced directional characteristics; that is, they will radiate more noise in one direction than another. Therefore, it will be necessary for the equipment manufacturer to provide the directional characteristics of the source, as well as the power levels, to predict the sound-pressure levels. The directional characteristics of the source are generally given in terms of the directivity factor Q . Q is defined as the ratio of the sound power of a small, omnidirectional, imaginary source to the sound power of the actual source where both sound powers produce the same sound-pressure level at the measurement position. The directivity factor may be added to Equation (16) in the form

$$L_p = L_p - 20 \log r - 0.5 + 10 \log Q, \quad (17)$$

where $10 \log Q$ is called the directivity index.

Example: Predict the sound-pressure level that will be produced in a free field at a distance of 100 feet directly in front of a particular machine. A directivity factor of 5 is provided by the machine manufacturer for this location. The noise source has a continuous spectrum and a sound power of 0.1 watt.

From Equation (17):

$$\begin{aligned} L_p &= 10 \log \left[\frac{0.1}{10^{-12}} \right] - 20 \log 100 - 0.5 + 10 \log 5 \\ &= 10 (\log 0.1 - \log 10^{-12}) - 20(2) \\ &\quad - 0.5 + 10(0.7) \\ &= 10(-1 + 12) - 40 - 0.5 + 7 \\ &= 76.5 \text{ dB re } 0.00002 \text{ N/m}^2. \end{aligned}$$

Noise Source in Reverberant Field

In reverberant fields where a high percentage of reflected sound energy is present, the sound-pressure levels may be essentially independent of direction and distance to the noise source. Levels in these reverberant areas depend upon room dimensions, object size, and placement in the room, and upon the acoustical absorption characteristics of surfaces in the room. Additional complications may be present in the form of regions of enforcement and cancellation of sound pressure, standing waves, caused by strong pure-tone components being reflected. Thus, it is extremely difficult to predict sound-pressure levels at a particular point in a reverberant area.

Sound Absorption

The acoustical characteristics of a room are strongly dependent upon the absorption coefficients of its surface areas. A surface that absorbs all energy incident on its surface is said to have an absorption coefficient of one, while a surface that reflects all incident energy has an absorption coefficient of zero. The absorption coefficient depends upon the nature of the material, the frequency characteristics of the incident sound, and the angle of incidence of the sound. The absorption coefficient is expressed in terms of the frac-

tion of the energy absorbed by the material under the conditions described.

A rule of thumb that may be used to determine the amount of noise reduction possible from the application of acoustically absorbent material on room surfaces is as follows:

$$\text{dB reduction} = 10 \log \frac{\text{absorption units after}}{\text{absorption units before}}$$

where the absorption units are the sum of the products of surface areas and their respective noise absorption coefficients.^{4, 5, 6} Absorption units are commonly expressed in terms of the sabin, which is the equivalent of 1 square foot of a perfectly absorptive surface.

Transmission Loss (TL) of Barriers

Sound transmission loss (TL) through a barrier may be defined as ten times the logarithm (to the base 10) of the ratio of the acoustic energy transmitted through the barrier to the incident acoustic energy. TL of a barrier may also be defined in terms of the sound pressure level reduction afforded by the barrier. Unless otherwise specified, the sound fields are diffuse on either side of the barrier. The TL of a barrier is a physical property of the material used for a given wall construction. The TL for continuous, random noise commonly found in industry increases about 5 dB for each doubling of wall weight per unit of surface area, and for each doubling of frequency.

Multiple wall construction with enclosed air spaces provides considerably more attenuation than the single-wall mass law would predict.^{7, 8, 9} However, considerable care must be taken to avoid rigid connections between multiple walls when they are constructed or any advantages in attenuation will be nullified.^{10, 11}

Noise leaks which result from cracks or holes, or from windows or doors, in a noise barrier can severely limit noise reduction characteristics of the

barrier. In particular, care must be exercised throughout construction to prevent leaks that may be caused by electrical outlets, plumbing connections, telephone lines, etc., in otherwise effective barriers.

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PHYSIOLOGY OF HEARING*Joseph R. Anticaglia, M.D.***INTRODUCTION**

The basic function of the hearing mechanism is to gather, conduct and perceive sounds from the environment. Sound waves, propagated through an elastic medium, liberate energy in a characteristic pattern which varies in frequency and intensity.

The human voice and other ordinary sounds are composed of fundamental tones modified by harmonic overtones (refer to Chapter 23). Our hearing sensitivity is greatest in childhood, but as we get older, our perception of high tones worsens, a condition labelled "presbycusis." The frequency range of the human ear extends from as low as 16 Hz to as high as 30,000 Hz. From a practical standpoint, however, few adults can perceive sounds above 11,000 Hz.

The ear responds to alterations in the pressure level of sound. The amplitude of these sound pressure alterations determines the intensity of the sound. So great is the range of intensities to which the ear responds that a logarithmic unit, the decibel (dB), is commonly used to express the pressure level of sound. The subjective correlates of frequency and intensity are pitch and loudness.

The translation of acoustical energy into perceptions involves the conversion of sound pressure waves into electrochemical activity in the inner ear. This activity is transmitted by the auditory nerves to the brain for interpretation. Although there are many gaps in our understanding of the precise mechanism of hearing, the following presentation will emphasize the peripheral processes involved in hearing.

PERIPHERAL MECHANISM OF HEARING

Sound reaches the ear by three routes: air conduction through the ossicular chain to the oval window; bone conduction directly to the inner ear; and conduction through the round window. Under ordinary conditions, bone conduction and the transmission of sound through the round window are less significant than air conduction in the hearing process. An example of bone conduction occurs when you tap your jaw. The sound you perceive is not coming through your ears but through your skull. Sound perception via air conduction is the most efficient route and it encompasses the external and middle ear conducting system which will be discussed in more detail.

Conduction of Sound

External Ear. Anatomically, the ear can be divided into an external portion (outer ear), an "air-filled" middle ear, and a "fluid-filled" inner ear (Fig. 24-1). The outer ear consists of the auricle and the external auditory meatus, or canal. The

auricle is an ornamental structure in man. Neither does it concentrate sound pressure waves significantly, nor does it function in keeping foreign bodies out of the ear canal. The two ears give us "auditory localization" or "stereophonic hearing," namely, the ability to judge the direction of sound. One explanation is that sound waves arriving at the two auricles have a slight time lag, differing in intensity and timbre since in the far ear the sound must travel a greater distance.

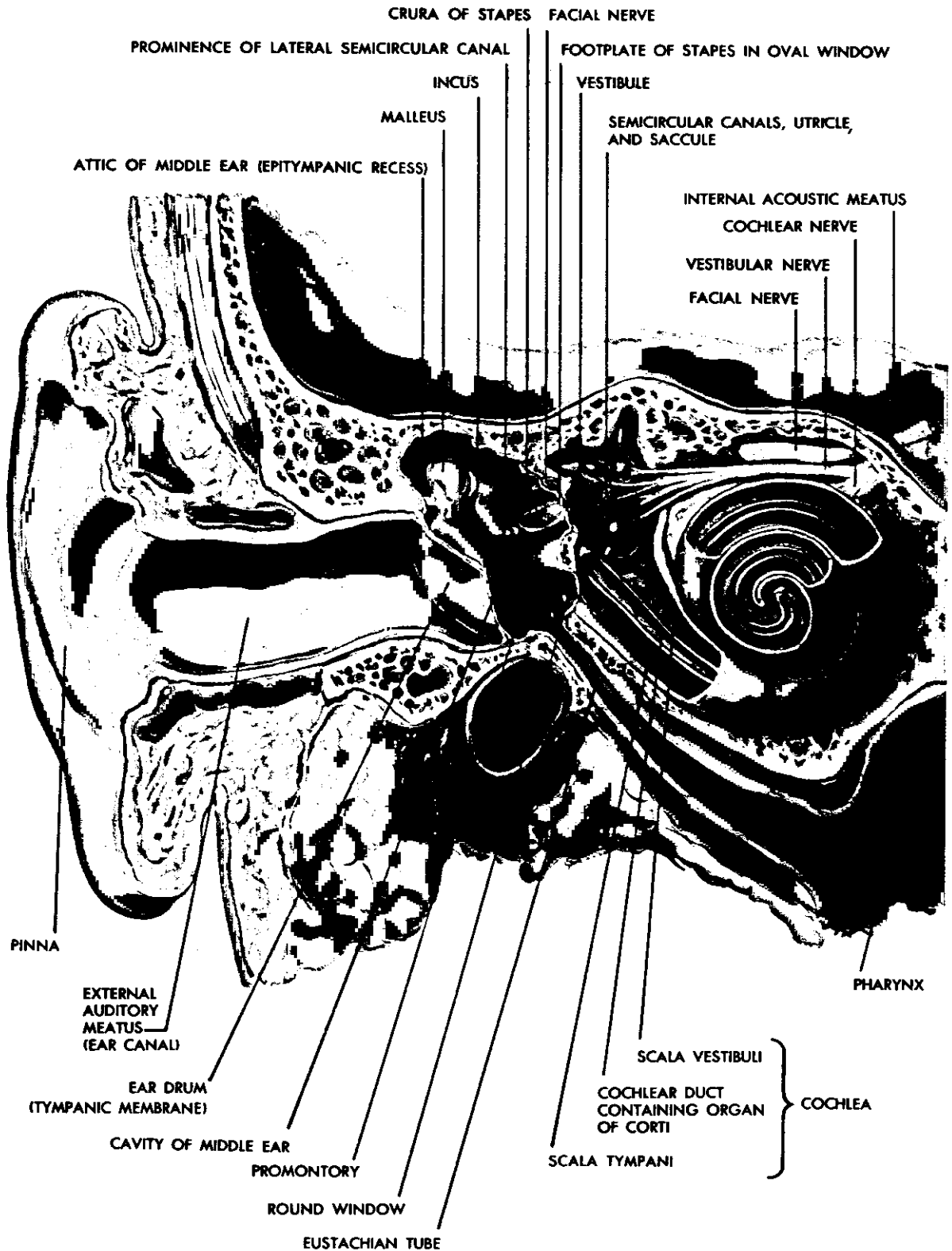
The external auditory canal is a little more than an inch in length and extends from the concha to the tympanic membrane. The skin of the cartilaginous portion of the ear canal secretes wax, which helps maintain relatively stable conditions of humidity and temperature in the ear canal. The ear canal protects the tympanic membrane and acts as a tubal resonator so that the intensity of sound pressure waves are amplified when they strike the tympanic membrane.

The tympanic membrane (TM, eardrum) separates the external ear from the middle ear. This almost cone-shaped, pearl-gray membrane is about a half-inch in diameter. The distance the eardrum moves in response to the sound pressure waves is incredibly small, as little as one billionth of a centimeter.¹ Besides vibrating in response to sound waves, the eardrum protects the contents of the middle ear and provides an acoustical dead space so that vibrations in the middle ear will not exert pressure against the round window.

Middle Ear. Medial to the eardrum is the special air-filled space called the middle ear. It houses three of the tiniest bones in the body: the malleus (hammer); the incus (anvil); and the stapes (stirrup). The handle of the malleus attaches to the eardrum and articulates with the incus which is connected to the stapes. The malleus and the incus vibrate as a unit, transmitting the sound waves preferentially to the stapedial footplate, which moves in and out of the oval window. Below and posterior to the oval window is the round window whose mobility is essential to normal hearing.

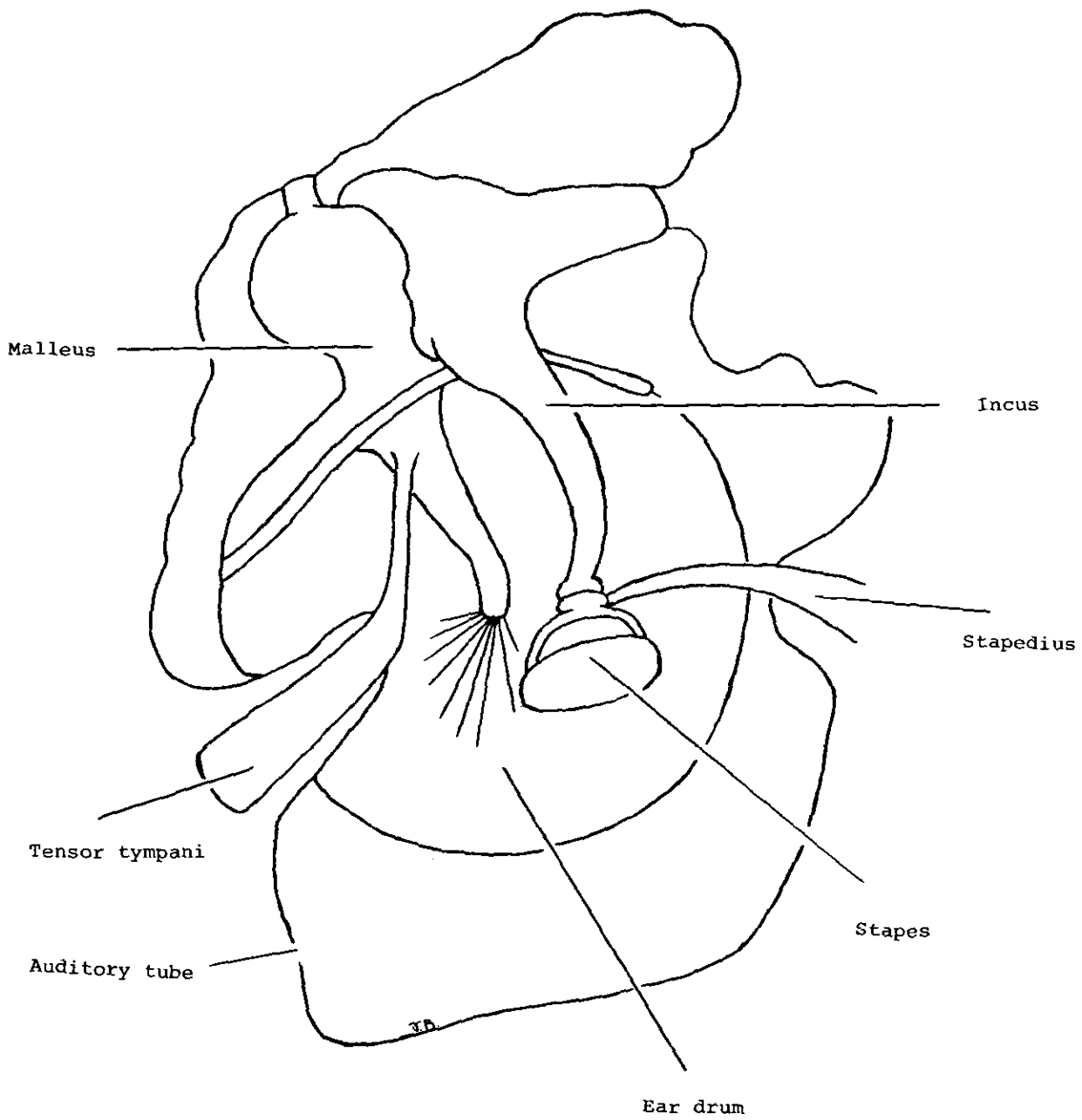
Fig. 24-2 shows the two intratympanic muscles, the tensor tympani and the stapedius. The tensor tympani extends from the canal above the eustachian tube to the handle of the malleus. It moves the malleus inward and anteriorly, and helps maintain tension on the eardrum. The stapedius muscle inserts on the posterior aspect of the neck of the stapes. It pulls the stapes outward and posteriorly.

The two muscles are antagonistic in their action, but contract only when stimulated by rela-



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Figure 24-1. Pathway of Sound Conduction Showing Anatomic Relationships.



Lockart R., Hamilton G., Fyfe F.: Anatomy of the Human Body. London, Faber & Faber, 1959, p. 463.
 Figure 24-2. Intratympanic Muscles Viewed from the Medial Wall. Faber & Faber, London.

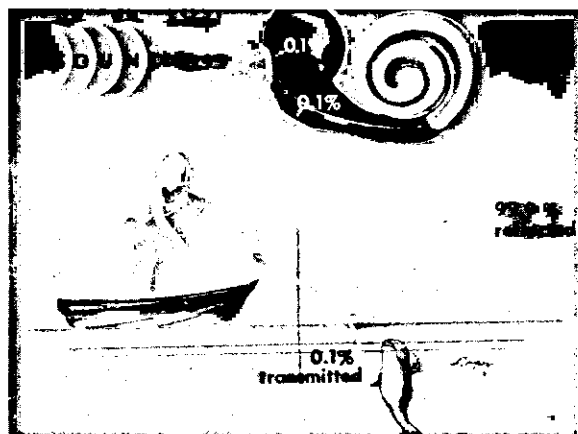
tively loud sounds. Contraction of the muscles causes rigidity of the ossicular chain with a resultant decrease in the conduction of sound energy to the oval window. A limited protective function has been ascribed to this reflex contraction of the muscles although the aural reflex does not react fast enough to provide complete protection against sudden and explosive sounds. Also, exposure to steady state noise for long periods of time would cause the muscles to adapt or fatigue to the auditory stimulus.²

The "eustachian or auditory" tube connects the anterior wall of the middle ear with the nasopharynx. It is about an inch and a half in length and consists of an outer bony portion (one third of the tube which opens into the middle ear) and an inner cartilaginous part (two thirds of the tube which opens into the throat). The lumen of the bony part is permanently opened while that of the cartilaginous portion is closed except during certain periods such as swallowing, yawning, or blowing the nose. To hear optimally, the atmospheric pressure on both sides of the eardrum should be equal. The act of swallowing, for example, forces air up the middle ear and thus equalizes the atmospheric pressure on either side of the tympanic membrane.

Yet, the fundamental problem that the middle ear must resolve is that of "impedance matching." In other words, the ear must devise a mechanism of converting the sound pressure waves from an air to a fluid medium, without a significant loss of energy. This is a noteworthy accomplishment since only 0.1% of airborne sound enters a liquid medium whereas the other 99.9% is reflected away from its surface. Stated differently, the intensity of vibration in the fluid of the inner ear is 30 decibels less than the intensity present

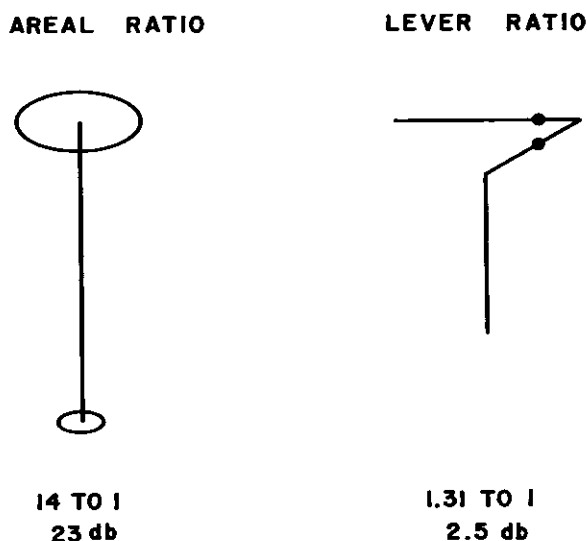
at the eardrum (Fig. 24-3). The middle ear has two arrangements to narrow this potential energy loss.

First is the "size differential" between the comparatively large eardrum and the relatively small footplate of the stapes. The eardrum has an effective areal ratio which is 14 times greater than that of the stapedial footplate. This hydraulic effect increases the force of pressure from the eardrum onto the footplate of the stapes so that there is approximately a 23 dB increase of sound intensity on the fluid of the inner ear. The "lever action" of the ossicles amplifies the intensity of sound as it traverses the middle ear by about 2.5 dB. Thus, the impedance matching mechanism of the middle ear is not perfect, but accounts for a 25.5 dB increase in the intensity of sound pressure at the air-liquid interface (Fig. 24-4).



Lawrence M., cited by De Wéese D., Saunders W.: Textbook of Otolaryngology. St. Louis, C. V. Mosby Company, 1968, p. 270, ed. 3; Courtesy of Dr. Merle Lawrence, Ann Arbor, Michigan.

Figure 24-3. Loss of Sound Energy at the Air-Water Interface.



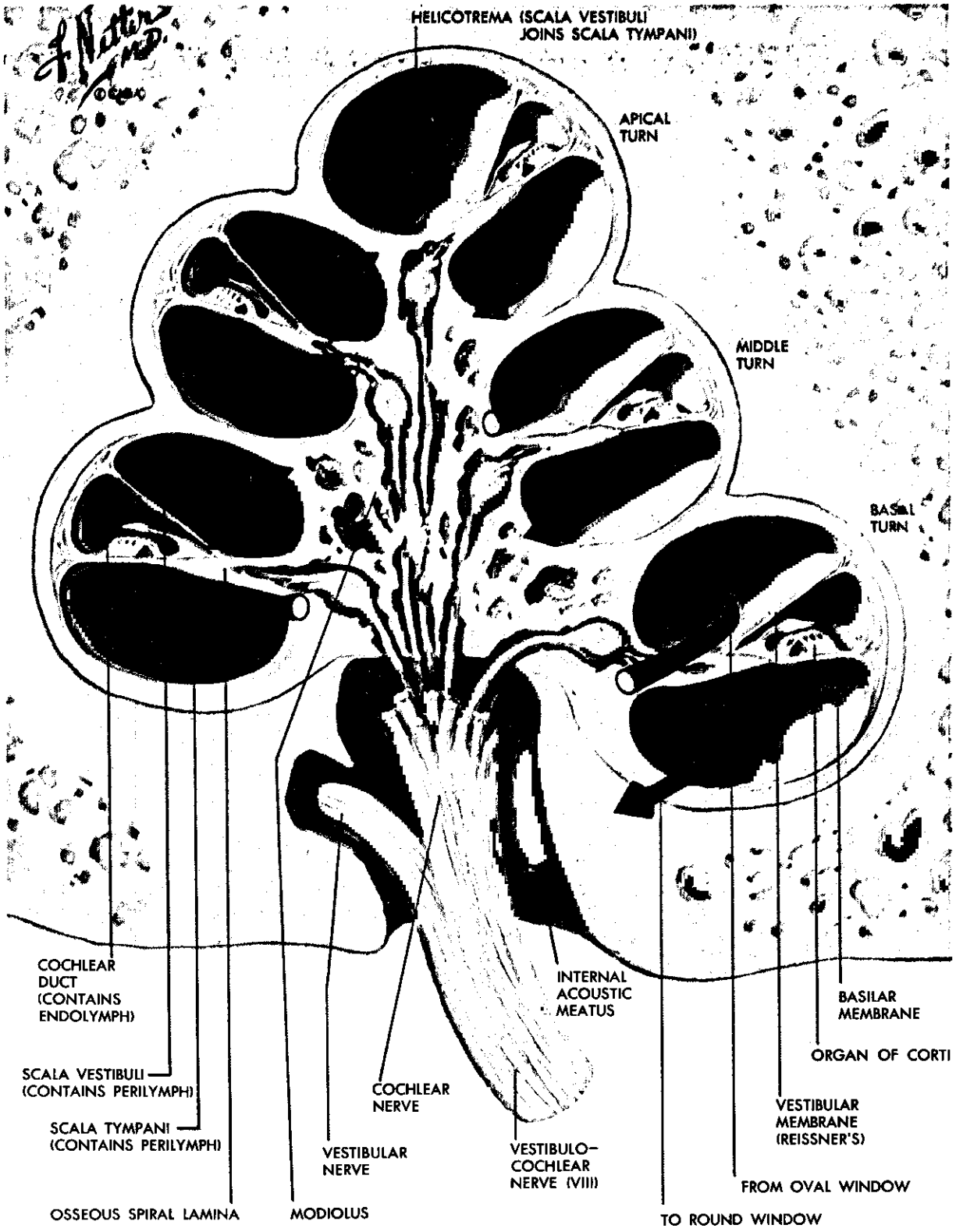
Lawrence M.: How we hear. JAMA 196:83, Copyright 1966, American Medical Association, Chicago, Ill.

Figure 24-4. Impedance Matching Mechanism of the Middle Ear which Minimizes Energy Loss as Sound Is Transferred from Air to Fluid Medium. Journal of the American Medical Association.

Perception of Sound

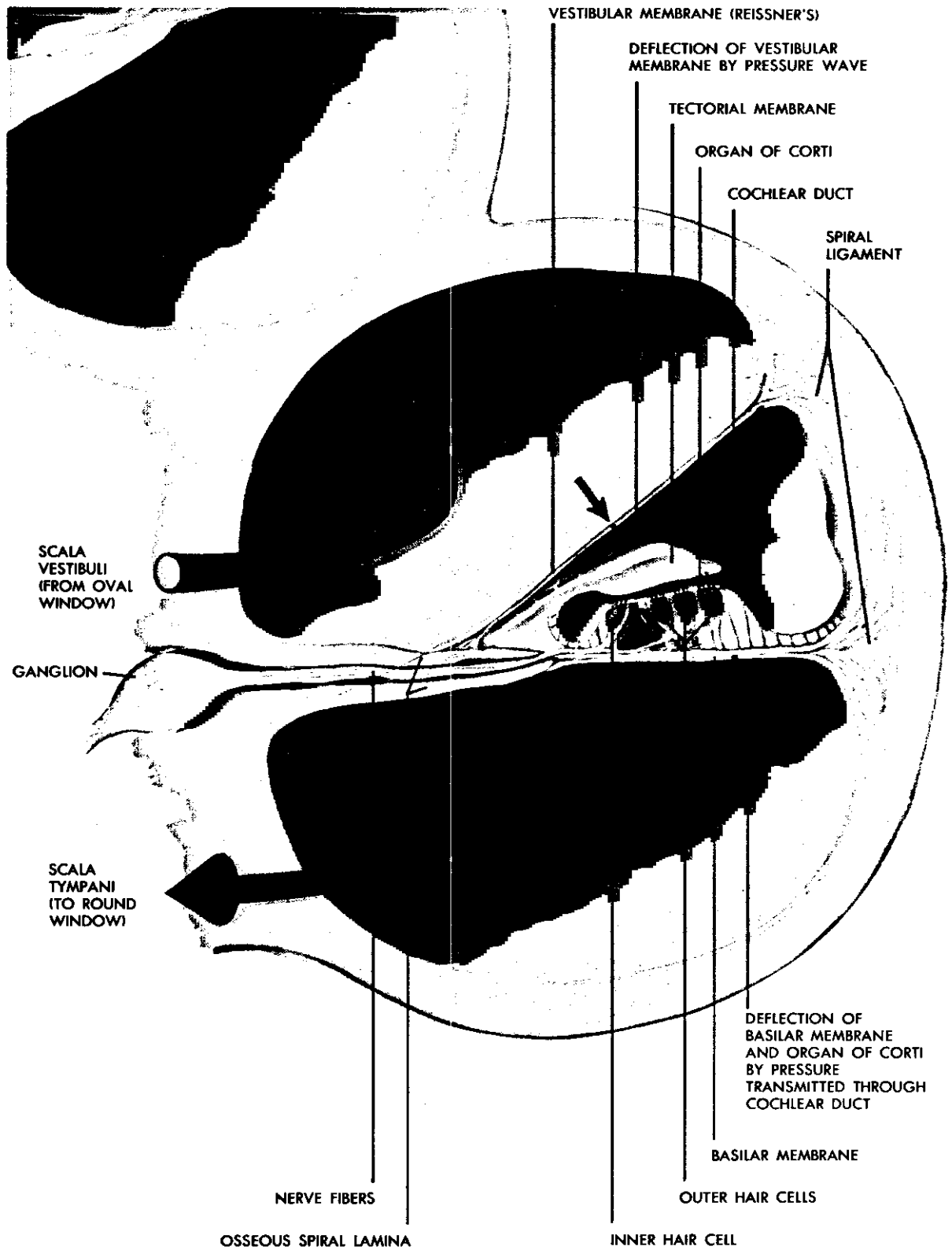
Inner Ear. The labyrinth or inner ear is a complex system of ducts and sacs which houses the end organs for hearing and balance. It consists of an outer bony and an inner membranous labyrinth. The center of the labyrinth, the vestibule, connects the three semicircular canals and the cochlea. A watery fluid, perilymph, separates the bony from the membranous labyrinth while inside the membranous labyrinth are fluids called endolymph and cortilymph.

The cochlea resembles a snail shell which spirals for about two and three-quarter turns around the bony column called the "modiolus" (Fig. 24-5). There are three stairways or canals within the membranous cochlea: the "scala vestibuli;" the "scala tympani;" and the "scala media



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Figure 24-5. Cross Section of Cochlea.



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Figure 24-6. Transmission of Sound across the Cochlear Duct Stimulating the Hair Cells.

or cochlea duct." A bony shelf, the "spiral lamina," together with the basilar membrane and the spiral ligament, separate the upper scala vestibuli from the lower scala tympani. The third canal, the scala media, is cut off from the scala vestibuli by Reissner's vestibular membrane.

The scala media is a triangular-shaped duct within which is found the organ of hearing, namely, the "organ of Corti." The basilar membrane, narrowest and stiffest near the oval window, widest at the apex of the cochlea, helps form the floor of the cochlear duct. On the surface of the basilar membrane are found phalangeal cells which support the critical "hair cells" of the organs of Corti. The hair cells are arranged in a definite pattern with an inner row of about 3,500 hair cells and three to five rows of outer hair cells numbering about 12,000. The cilia of the hair cells extend along the entire length of the cochlear duct and are imbedded in the undersurface of the gelatinous overhanging tectorial membrane (Fig. 24-6).

Inner Ear Fluids. The vestibular and tympanic canals contain perilymph and communicate with each other through a tiny opening at the uppermost part of the cochlea, the "helicotrema." The perilymph has a high sodium concentration and a low potassium content whereas the opposite is true of endolymph. Since the transmission of neural impulses should be impossible in the high concentration of potassium found in endolymph, it has been shown that the fluid which bathes the organ of Corti — Cortilymph — has a different ionic content than that of endolymph, and furnishes a suitable medium for the normal functioning of the hair cells and neural endings of the organ of Corti.^{3, 4}

The tectorial membrane appears to maintain a zero potential compared to the scala tympani while the endolymph has a positive potential and the organ of Corti, a negative potential. The positive resting potential of the endolymph has been labelled the "endocochlear or DC potential." A change in the resting potential of the endolymph results from acoustical stimulation so that the scala media is negative relative to the scala tympani, "summating potential."

In short, the fluids of the cochlear duct supply nourishment to Corti's organ, a system of removing waste products, an appropriate medium for the transmission of neural impulses, and a means of eliminating noise that its own blood supply would produce.

Transmission of Sound Waves in the Inner Ear. The two openings afforded by the oval and round windows are essential for sound pressure waves to pass through the cochlear fluids. The movement of the stapedial footplate in and out of the oval window moves the perilymph of the scala vestibuli (Fig. 24-7). This vibratory activity travels up the scala vestibuli, but causes a downward shift of the cochlear duct with distortion of Reissner's membrane and displacement of endolymph and Corti's organ. The activity is then transmitted through the basilar membrane to the scala tympani. When the oval window is pushed inward,

the round window acts as a relief point and bulges outward.

Transduction. The conversion of mechanical energy of sound into electrochemical activity is called transduction. The vibration of the basilar membrane causes a pull, or shearing force of the hair cells against the tectorial membrane. This "to and fro" bending of the hair cells activates the neural endings so that sound is transformed into an electrochemical response. It remains to be clarified whether an electrical and/or chemical process stimulates the neural endings.

Travelling Waves. In general, the hair cells at the base of the cochlea transmit high frequency sounds while those at the apex especially respond to low frequency tones. This results in the travelling wave phenomena in which there is a specific point of maximum displacement of the basilar membrane beyond which the wavelength and the amplitude become progressively smaller in character. High pitched sounds travel a short distance along the basilar membrane before they die out; the opposite occurs with low pitched sounds.

Nerve Conduction. Each nerve fiber connects with several hair cells, and each hair cell with several nerve fibers. The hair cells stimulate auditory neural endings and nerve fibers which stream out through small openings in the spiral lamina into the hollow modiolus (Fig. 24-5). The cell bodies of the nerve fibers form the spiral ganglia whose axons make up the cochlear (auditory) division of the eighth cranial nerve. The movement of the hair cells sets up action potentials, and coded information from both ears are sent to the cochlear nuclei and thereafter to the temporal lobe of the brain where cognition and association takes place. Fig. 24-7 summarizes the peripheral mechanism of hearing.

CLASSIFICATION OF HEARING LOSS

Loss of hearing can be classified into the following categories: 1. Conductive impairment; 2. Sensorineural impairment; 3. Mixed (both conductive and sensorineural); 4. Central impairment; 5. Psychogenic impairment.

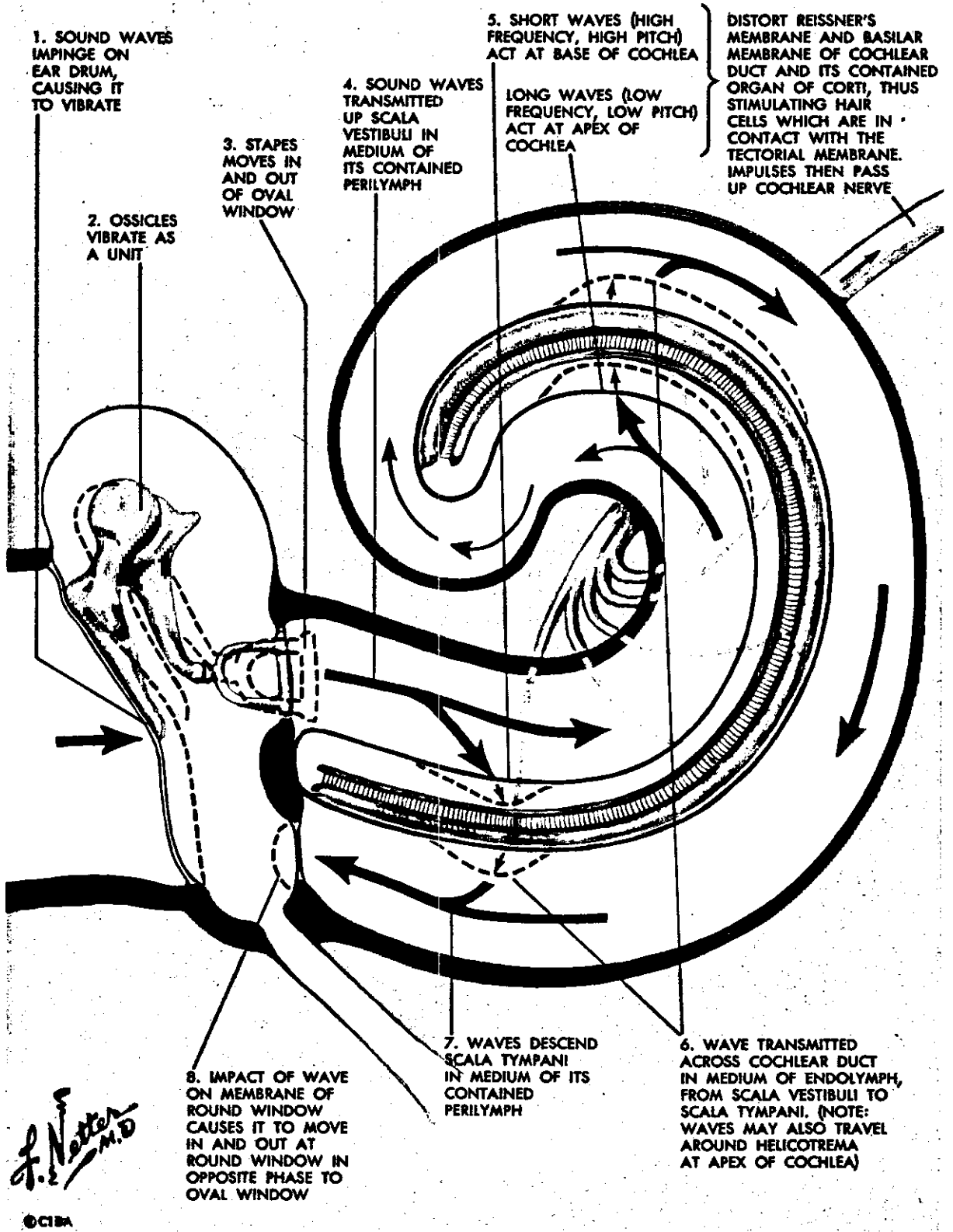
Conductive Hearing Loss

Any condition which interferes with the transmission of sound to the cochlea is classified as a conductive hearing loss. Pure conductive losses do not damage the organ of Corti nor the neural pathways.

A conductive loss can be due to wax in the external auditory canal, a large perforation in the eardrum, blockage of the eustachian tube, interruption of the ossicular chain due to trauma or disease, fluid in the middle ear secondary to infection, or otosclerosis, that is, fixation of the stapedial footplate. A significant number of conductive hearing losses are amenable to medical or surgical treatment.

Sensorineural Hearing Loss

A sensorineural hearing loss is almost always irreversible. The sensory component of the loss involves the organ of Corti and the neural component implies degeneration of the neural elements of the auditory nerve.



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Figure 24-7. Transmission of Vibrations from Drums through Cochlea.

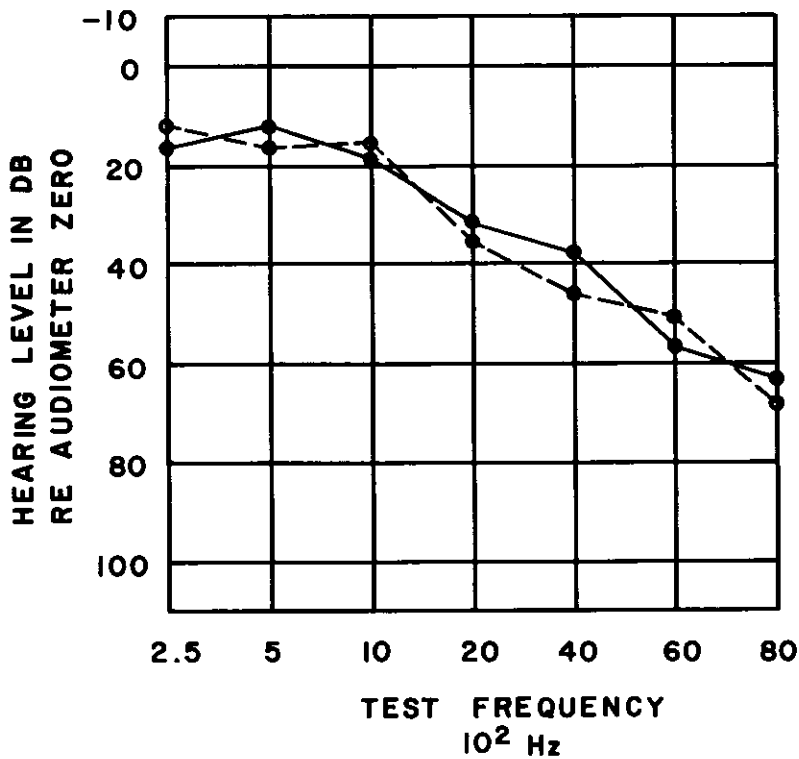
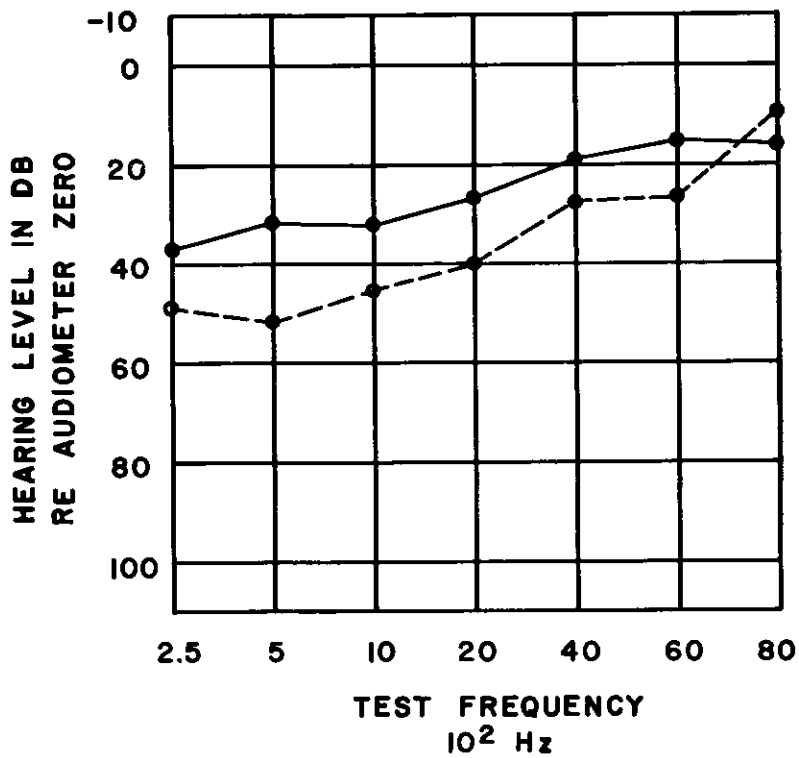


Figure 24-8. Audiograms Showing A) Conductive and B) Sensorineural Types of Hearing Loss.

Exposure to excessive noise causes an irreversible sensorineural hearing loss. Damage to the hair cells is of critical importance in the pathophysiology of noise-induced hearing loss. Invariably, degeneration of the spiral ganglion cells and the peripheral nerve fibers accompany severe injury to the hair cells.

Sensorineural hearing loss may be attributed to various causes, including presbycusis, viruses (e.g., mumps), some congenital defects, and drug toxicity (e.g., streptomycin).

Mixed Hearing Loss

Mixed hearing loss occurs when there are components and characteristics of both conductive and sensorineural hearing loss in the same ear.

Central Hearing Loss

A central hearing loss implies difficulty in a person's ability to interpret what he hears. The abnormality is localized in the brain between the auditory nuclei and the cortex.

Psychogenic Hearing Loss

A psychogenic hearing loss indicates a "non-organic" basis for an individual's threshold elevation. Two conditions in which such a loss may occur are malingering and hysteria.

AUDIOMETRY

The pure tone audiometer is the fundamental tool used in industry to evaluate a person's hearing sensitivity. It produces tones which vary in frequency usually from 250 Hz to 8,000 Hz at octave or half-octave intervals. The intensity output from the audiometer can vary from zero dB to 110 dB, and is often marked "hearing loss" or "hearing level" on the audiometer.

Zero dB or zero reference level on the audiometer is the average normal hearing for different pure tones and varies according to the "standard" to which the audiometer is calibrated. Zero reference levels have been obtained by testing the hearing sensitivity of young healthy adults and averaging that sound intensity at specific frequencies at which they were just perceptible. It is to be differentiated from the 0.0002 microbar references for the sound pressure level measurements. If a person has a 40 dB hearing loss at 4,000 Hz, it means that for the individual to perceive a tone the intensity of that tone must be raised to 40 dB above the "standard."

The audiogram serves to record the results of the hearing tests. A graphic description of the faintest sound audible is obtained by plotting the intensity against the frequency. Examples of audiograms which indicate conductive and sensorineural losses are shown in Fig. 24-8. In conductive hearing losses, the low frequencies show most of the threshold elevation, whereas the high frequencies are most often involved with the sensorineural losses.

The recording of an audiogram is deceptively simple, yet for valid test results, one must have a properly calibrated audiometer, an acceptable test environment to eliminate interfering sounds, and a qualified audiometrician. When a marked hearing loss is encountered, bone conduction audiometry and more sophisticated hearing tests are often helpful in diagnosing the site and cause of

the hearing loss.⁵ For more details concerning appropriate American National Standard Institute (ANSI) standards and the objectives of a good audiometry program, refer to the preferred reading list.

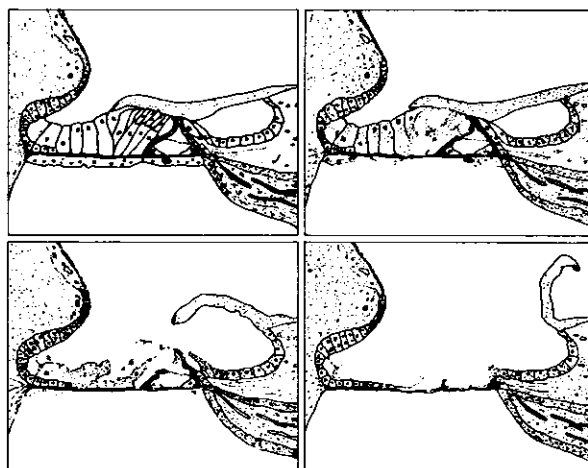
EFFECTS OF EXCESSIVE NOISE EXPOSURE

Since the ear does not have an overload switch or a circuit breaker, it has no option but to receive all the sound that strikes the eardrum. In industry, excessive noise constitutes a major health hazard. Such exposure can cause both auditory and extra-auditory effects.

Auditory Effects

Noise induced hearing loss (NIHL) can happen unnoticed over a period of years. At first, excessive exposure to harmful noise causes auditory fatigue or a temporary threshold shift (TTS). This shift refers to the difference in one's hearing sensitivity measured before and after exposure to sound. It is called "temporary" since there is a return of the individual's pre-exposure hearing level after a period of hours away from the intense sound.

However, repeated insults of excessive noise can transform this TTS into a permanent threshold shift (PTS). In fact, studies substantiate that the hearing sensitivity of factory workers in heavy industry is poorer than that of the general population. Fig. 24-9 depicts the stages of destruction



Lawrence M.: Auditory problems in occupational medicine. Arch. Environ. Health 3:2888, Copyright 1961, American Medical Association, Chicago, Ill.

Figure 24-9. Stages of Destruction of the Organ of Corti. (A) The normal organ of Corti. (B) A stage of hair cell degeneration following the first subtle changes within the cytoplasm of the cells. The internal hair cell remains intact. (C) Both inner and outer hair cells are gone, and the supporting structures are degenerating. (D) In the final stages, the entire organ of Corti is dislodged, leaving a denuded basilar membrane, which may become covered with a simple layer of epithelial cells. (Arch. Environ. Health)

of the organ of Corti in a laboratory test animal that was overstimulated by loud continuous noise.

Many factors influence the course of NIHL. The overall "decibel level" of the noise exposure is obviously important. If a noise exposure does not cause auditory fatigue, then such exposure is not considered harmful to one's hearing sensitivity.

Another consideration is the "frequency spectrum" of the noise. Noise exposure which has most of its sound energy in the high frequency bands is more harmful to a worker's hearing sensitivity than low-frequency noises.

Another factor is the daily "time distribution" of the noise exposure. In general, noise which is intermittent in character is less harmful to hearing than steady state noise exposure. As the "total work duration" (years of employment) of a worker to hazardous noise is increased, so too does the incidence and magnitude of his NIHL. However, no report of "total" hearing loss has been attributed to excessive noise exposure alone.⁶

Finally, the "susceptibility" of the worker to hazardous noise must be considered, since not every individual will suffer identical hearing impairment if exposed to the same noise intensity over the same time period. A small percentage of workers will be highly susceptible or, on the other hand, refractory to the degrading effects of noise.

The hearing loss from "acoustic trauma" should be differentiated from the insidious, irreversible sensorineural NIHL that results after months or years of exposure to excessive noise conditions. Acoustic trauma refers to the loss of hearing secondary to head or ear trauma, or after exposure to a sudden, intense noise such as that of firearms or explosions. A conductive type of hearing loss results when the trauma causes a perforated eardrum or disruption of the middle ear ossicles. The trauma can cause a sensorineural loss, but not infrequently, the hearing loss is temporary in nature. Besides causing hearing loss, hazardous noise levels can mask speech, be a source of annoyance, and occasionally degrade a worker's job performance.⁷

Extra-Auditory Effects

The extra-auditory effects of noise result in physiologic changes other than hearing. We are familiar with the reflex-like startle response of an individual to a loud, unexpected sound. Less commonly noted are the cardiovascular, neurologic, endocrine and biochemical changes secondary to intense noise exposure. Subjective complaints of nausea, malaise, and headache have been reported in workers exposed to ultrasonic noise levels. Vasoconstriction, hyperreflexia, fluctuations in hormonal secretions, disturbances in equilibrium and visual functions have been demonstrated in laboratory and field studies. These changes have been for the most part transient in character, and it remains to be clarified whether such noise exposure has long lasting ill effects on the organism.⁸

SUMMARY

The important function of the hearing mechanism is to convert the mechanical energy of sound pressure waves into an electrochemical response. Excessive noise exposure can tax the physiologic limits of the hearing mechanism and cause an irreversible, sensorineural hearing loss. Noise is just one of many causes of hearing loss, so that a relevant medical history and a detailed history of a worker's previous employment will eliminate many false conclusions concerning the cause of a worker's loss of hearing.

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NOISE MEASUREMENT AND ACCEPTABILITY CRITERIA

James H. Botsford

INSTRUMENTS FOR SOUND MEASUREMENT

There is probably a greater variety of instruments for measuring noise than for any other environmental factor of concern to industrial hygienists. Almost every measurement need can be satisfied with instrumentation available commercially today. Only those instruments more useful to the industrial hygienist will be discussed here.

Sound Level Meters

The standard sound level meter is the basic measuring instrument for the industrial hygienist.



General Radio Co., Concord, Massachusetts.

Figure 25-1. A Standard Sound Level Meter.

It consists of a microphone, an amplifier with calibrated volume control and an indicating meter. It measures the root-mean-square (rms) sound pressure level in decibels which is proportional to intensity or sound energy flow.

Sound level meters of the same type differ mainly in external shape, arrangement of controls, and other convenience features that frequently influence the selection made by a prospective user. A typical sound level meter is pictured in Figure 25-1.

Standards for sound level meters^{1, 2, 3} specify performance characteristics in order that all conforming instruments will yield consistent readings under identical circumstances. The more important characteristics specified are frequency response, signal averaging and tolerances.

TABLE 25-1

Relative Response of Sound Level Meter Weighting Networks

Frequency Hertz	Weighted Response, dB		
	A	B	C
31.5	-39	-17	-3
63	-26	-9	-1
125	-16	-4	0
250	-9	-1	0
500	-3	0	0
1000	0	0	0
2000	1	0	0
4000	1	-1	-1
8000	-1	-3	-3

Reproduced with permission of General Radio Company, West Concord, Mass., from "Handbook of Noise Measurement," 1967.

Three weighting networks are provided on standard sound level meters in an attempt to duplicate the response of the human ear to various sounds. These weighting networks cause the sensitivity of the meter to vary with frequency and intensity of sound like the sensitivity of the human ear.

The relative responses of the three networks are shown in Table 25-1 where the A, B and C weightings mimic ear response to low, medium and high intensity sounds respectively. Entries in the

table show relative readings of the meter for constant sound pressure level of variable frequency. These A, B and C meter response curves correspond to the 40, 70 and 100 phon equal loudness contours. The D-weighting network is provided on some sound level meters for approximating the "perceived noise level" used in appraising the offensiveness of aircraft noises.

The A-weighting network is the most useful one on the sound level meter. It indicates the A-weighted sound level, often abbreviated dBA, from which most human responses can be predicted quite adequately.⁴

Action of the indicating meter may be selected as "fast" or "slow." Relatively steady sounds are easily measured using the "fast" response. Unsteady sounds can be averaged with the more sluggish "slow" response to reduce meter needle swings.

The speed of meter response affects the readings obtained for transient sounds. For example,

the level of a whistle toot lasting 1/5 second would be indicated no more than 2dB low on the "fast" scale. On the "slow" scale, the level of a toot lasting 1/2 second would read 3 to 5 dB low.

American standard sound level meters are furnished in three types offering varying degrees of precision.¹ Designated Types 1, 2 and 3 in order of increasing tolerances, the Type 2 generally measures within 2 or 3 dB of true levels which is satisfactory for most purposes. Errors are about half as large with the Type 1 or "precision" sound level meter and about twice as large with the Type 3 "survey" instrument. These errors can be reduced somewhat by careful calibration.

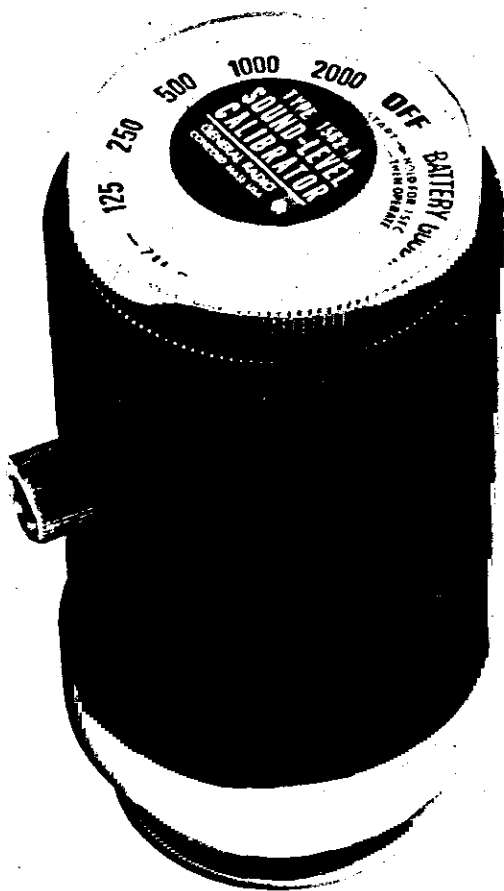
Calibrators

The overall accuracy of sound measuring equipment may be checked by using an acoustical calibrator such as is shown in Figure 25-2. It consists of a small, stable sound source that fits over the microphone and generates a predetermined sound level within a fraction of a decibel. If the meter reading is found to vary from the known calibration level, the meter may be adjusted to eliminate this error. The acoustical calibration procedure supplements the electrical calibration incorporated in some meters to check the gain of all electronic components following the microphone. Sound level calibrators should be used only with the microphones for which they are intended in order to avoid errors and microphone damage.

Impulse Meters

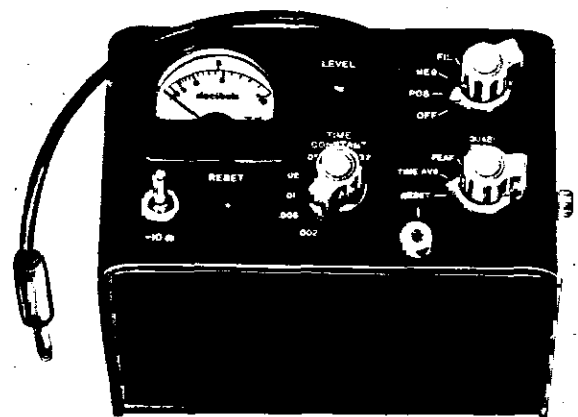
The sound level meter is too sluggish to indicate peak levels of transient noises lasting a fraction of a second such as those produced by hammer blows or punch press strokes. Such noises must be measured with a special meter that indicates the peak level.

Accessory impulse meters are available for connection to sound level meters and can be calibrated to indicate the peak level of the sound at the microphone. One of these is shown in Figure 25-3. In taking such readings, it is necessary to



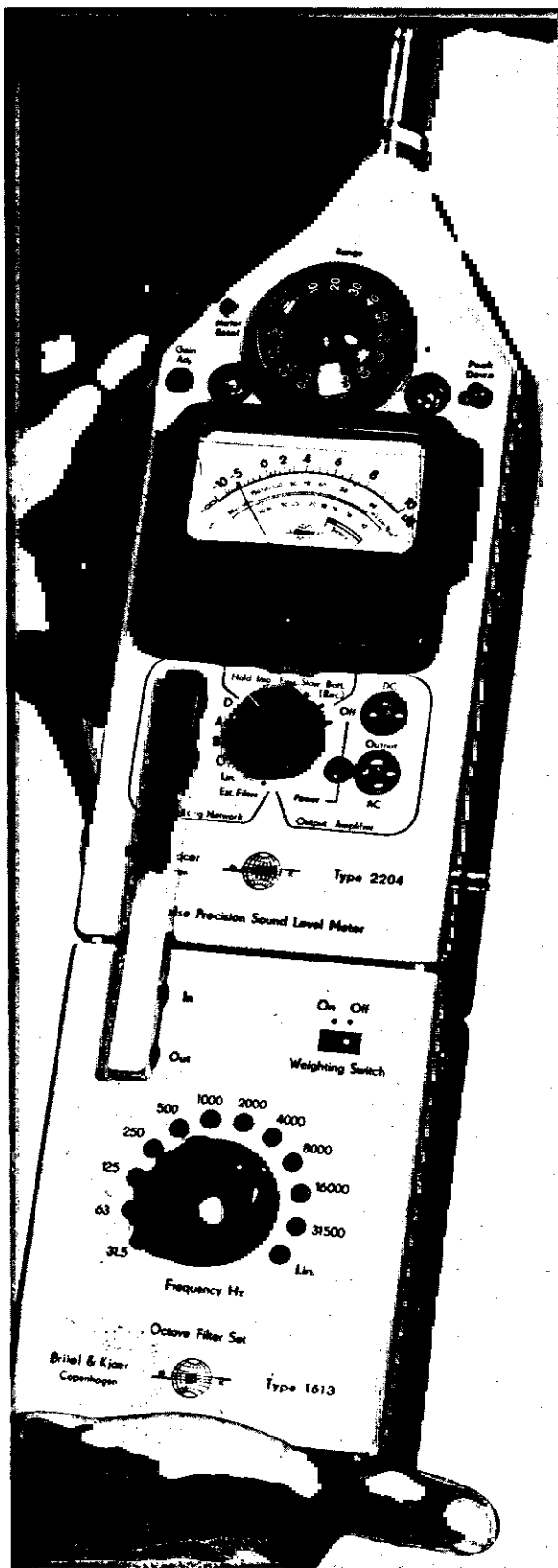
General Radio Co., Concord, Massachusetts.

Figure 25-2. A Sound Level Calibrator.



General Radio Co., Concord, Massachusetts.

Figure 25-3. A Noise Peak Meter for Connection to a Sound Level Meter.



B&K Instruments, Inc., Cleveland, Ohio.
Figure 25-4. A Precision Sound Level Meter with an Octave Band Filter Attached to the Base.

be sure that the upper sound pressure limit of the microphone is not exceeded as the indicated level will then be too low. The upper limit of the sound level meter can be extended by replacing the standard microphone with a less sensitive one that is linear to higher levels. Such microphone substitutions affect the calibration of the sound level meter and must be taken into account when interpreting readings.

The sound level meter in Figure 25-4 is equipped with a circuit for measuring impulse noise according to a German standard. It has a rather slow rise time in order that the indication of impulsive sound will correlate with the loudness perceived by the ear. For impulses that rise abruptly, the reading with this circuit is lower than would be found with a true peak meter. However, the instrument shown has been provided also with an instantaneous peak reading circuit that will indicate the true peak.

Frequency Analyzers

It is often necessary to know the frequency distribution of the sound energy. It is important in noise abatement, for example, since the reduction afforded by control devices varies with frequency. Such information is provided by one of the several types of sound spectrum analyzers available. They may be connected to the sound level meter or other sound sensing system. The electrical signal from the microphone is filtered by the analyzer circuitry so that only signals within a limited frequency range are transmitted to the indicating meter. Measurement of sound pressure level in contiguous frequency ranges provides data for a plot of sound pressure level versus frequency.

Octave band analyzers are the types most commonly encountered. An octave band filter set is shown attached to the lower end of a sound level meter in Figure 25-4. The frequency range of each band is such that the upper band limit is twice the lower band limit. Formerly, octave bands were described by these cut-off frequency limits such as 300 to 600, 600 to 1200, etc. Currently they are designated by the geometric mean of the cut-off frequencies which are called center frequencies. Thus, when the 1000 Hz band is mentioned, it is understood that it extends from 710 to 1420 Hz. The center and cut-off frequencies of octave band filters in common use are shown in Table 25-2.

Often bands narrower than octaves are required for pinpointing the frequency of a tone. In such applications, the one-third and one-tenth octave analyzers are quite valuable. Some of these can be coupled to a graphic level recorder which tunes the analyzer through the frequency range and simultaneously plots its output on a moving paper chart. This equipment is very useful in determining sources of noise in machinery since sound of a particular frequency must be generated by mechanical events such as the meshing of gear teeth, passing of fan blades, etc. which are repeated at the same rate.

Accessory Equipment

As most sound is generated by vibration of some body, it is sometimes desirable to study the

TABLE 25-2.

Center Frequencies and Limits of Octave Bands.

Traditional bands, Hz			Preferred bands, Hz		
Lower limit	Center freq.	Upper limit	Lower limit	Center freq.	Upper limit
19	27	38	22	31.5	44
38	53	75	44	63	88
75	106	150	88	125	177
150	212	300	177	250	355
300	425	600	355	500	710
600	850	1,200	710	1,000	1,420
1,200	1,700	2,400	1,420	2,000	2,840
2,400	3,400	4,800	2,840	4,000	5,680
4,800	6,800	9,600	5,680	8,000	11,360

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vibration as well as the sound. Accessory vibration pickups are available for most sound level meters to make such vibration analysis possible. They are generally accelerometers for which the electrical output is proportional to the acceleration of the surface to which they are attached. Types sensitive to the velocity or displacement of the surface are also available. Complete vibration meters are supplied too, for greater convenience.

The vibration signal may be examined for frequency content using any of the sound analyzers discussed earlier. In this way, vibration at a particular frequency may be correlated with the sound of the same frequency it produces. Calibrators are available for checking the sensitivity of the vibration pickup to reduce errors in measuring the acceleration of a surface.

The cathode ray oscilloscope is useful for observing the wave-form of a sound. It plots the sound pressure versus time on a television-type screen. From observation of the wave shape, it is sometimes possible to determine the mechanical process responsible for the noise. It is also possible to observe the peak pressures of impulsive sounds. Cameras are available for photographing the face of the cathode ray tube to obtain a permanent record of the wave form.

A graphic record of sound level may be obtained by connecting a sound level meter to a graphic level recorder which plots the sound level on a moving paper chart. The pen speed of the recorder must be capable of following the fluctuations in sound level if an accurate record is to be obtained.

The magnetic tape recorder can be used to store a sound for later analysis on replay. An instrument of broadcast quality must be used to obtain high fidelity reproduction of the sound on playback. For analysis on replay, the recorder output should be connected to the analyzer input by means of a patch cord. Too much distortion will

occur if the recording is played back through a loud-speaker and picked up with a microphone. If only the frequency content is of interest, then no precautions need be taken to keep track of level during recording and playback. However, if it is necessary to determine the true levels of the original noise on playback, careful recording of calibration tones must be undertaken. Generally, it is better to measure sound directly in the field if possible.

Sound Monitors

When sound level varies erratically over a wide range, it is difficult to describe the noise by meter readings. Therefore, statistical analyzers have been developed to assist in this process. They indicate the percentage of time that the sound level lies in certain predetermined level ranges. From these data, the mean level, standard deviation as well as other statistical indices may be calculated.

Another type of monitor evaluates noise exposures according to the rules established by the American Conference of Governmental Industrial Hygienists (ACGIH),⁵ which will be described in a section that follows. These instruments may be exposed to varying noise for a work day and will indicate whether this exposure limit has been exceeded. One of the battery-powered, wearable types is shown in Figure 25-5.

A different type of noise hazard meter recently developed integrates the effects of noise like the ear does.⁶ When exposed to non-impulsive noise of any duration, it indicates the amount of temporary shift in hearing threshold that a group of normal ears would experience in the same expo-



duPont de Nemours & Co., Wilmington, Delaware.

Figure 25-5. A Battery-Powered Noise Monitor That Can Be Worn by a Workman.

sure. Its reading is interpreted according to the theory that noise exposures producing little temporary hearing loss are not likely to produce much permanent hearing loss even after many repetitions.

ACCEPTABILITY CRITERIA

Criteria for the acceptability of noise are dictated by the effects which are to be avoided. The most important of these is hearing damage resulting from prolonged exposure to excessive noise. Another undesirable effect is speech interference or interruption of communications by noise. Annoyance is a third undesirable effect of noise more difficult to assess. There are also certain non-auditory effects of noise we are just beginning to recognize, which are discussed later in this chapter.

Hearing Damage

The damaging effect of noise on hearing depends on (1) the level and spectrum of the noise, (2) duration of exposure, (3) how many times it occurs per day, (4) over how many years daily exposure is repeated, (5) the effects on hearing regarded as damage and (6) individual susceptibility to this type of injury. All of these factors must be considered in establishing limits of acceptable exposures to dangerous noise.

Noise Evaluation. Early in the study of the effects of noise on hearing, it was learned that noise frequency as well as intensity influenced the effect produced. High frequency noise was found to be more damaging than low frequency noise of the same sound pressure level. Therefore, noise spectra were evaluated with standard octave band analyzers which were the only portable spectrum analyzers then available.

As knowledge of noise effects grew, some investigators began to feel that octave band analysis was a needlessly complicated evaluation of noise which could be replaced with the A-weighted sound level measured using a standard sound level meter. It seemed that the A-weighting network made the meter less sensitive to low frequency sounds to about the same extent that the ear is less susceptible to injury by these low frequency sounds.

In these studies, the damage to be avoided was impairment of ability to understand "everyday speech" as defined by the medical profession.⁷ This medico-legal definition allows some observable change in hearing thresholds not sufficient to affect ability to understand everyday speech significantly.

Steady Noise. All day exposure to steady noise has been investigated to determine the level at which hearing damage begins after many years of redundant exposure. Such studies are the basis for the curves in Figure 25-6 which indicate the risk of hearing impairment associated with exposure to a steady noise level at work.⁸ Each curve indicates on the vertical scale the percentage of workers that showed impaired hearing as defined by the medical profession after working continuously in the noise levels shown on the horizontal scale.

To interpret the Figure, note that the upper

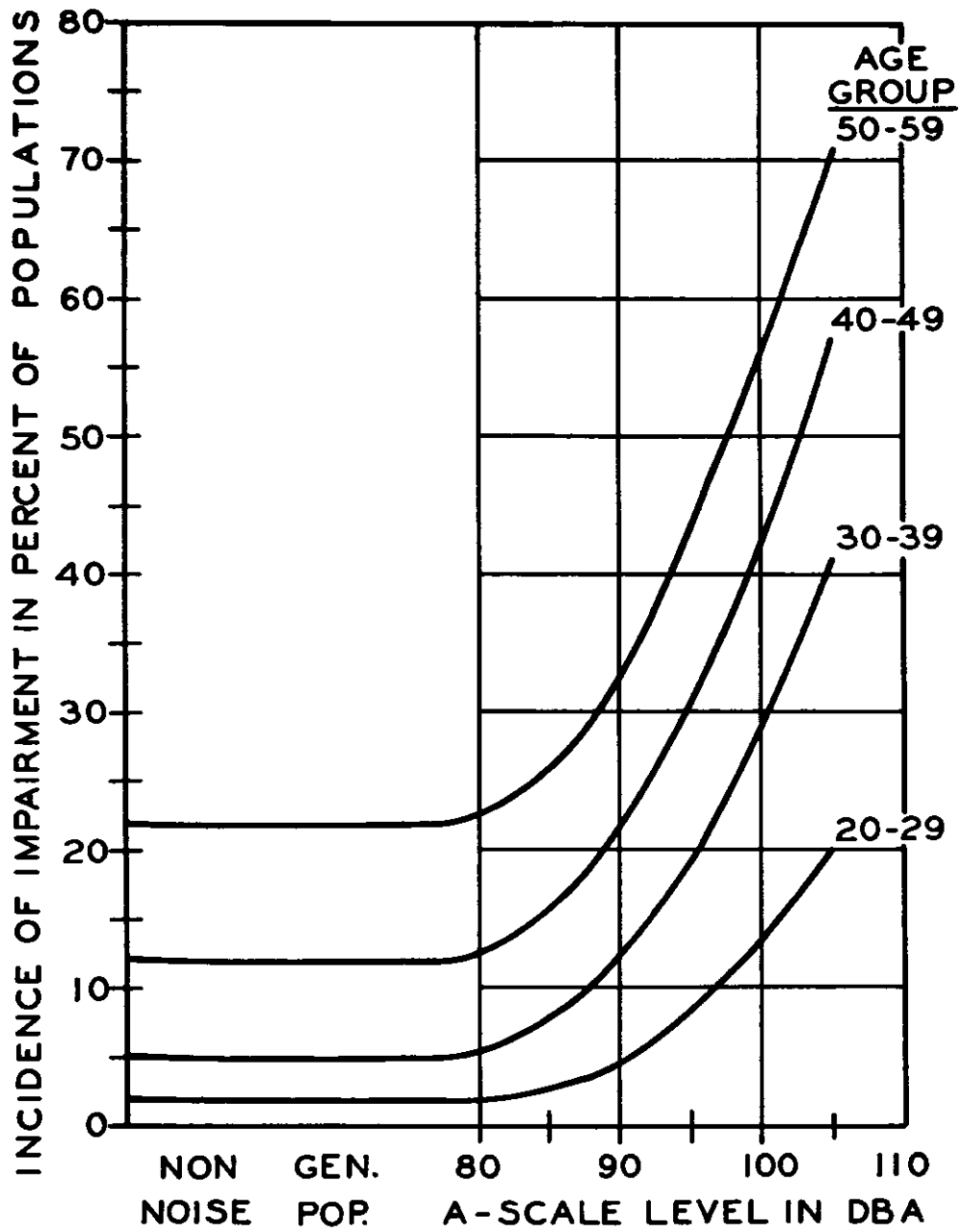
curve shows that in a group of 100 men aged 50 to 59 years, which has been exposed to 90 dBA at work for 33 years, 33 men should show evidence of impaired hearing. However, note that the lower flat portion of the same curve indicates that the general population and others not exposed to dangerous noise at work exhibit 22 cases of impaired hearing out of every hundred. Therefore, near-lifetime exposure to 90 dBA at work seems to produce about 11 more cases of impaired hearing per hundred surviving than would otherwise have occurred. As the data generating the curves of Figure 25-6 are not so consistent as the precise lines would indicate, this difference of 11 percentage points is about the smallest that can be considered significant. For lower age groups exposed for shorter periods, the increase in prevalence of impaired hearing is much less pronounced. The curves of Figure 25-6 suggest 90 dBA as one limit for steady exposure to continuous noise, a limit that has become rather widely accepted. Future standards may lower this limit.

Intermittent Noise. Most occupational noises are intermittent rather than continuous. Interrupting harmful noise allows the ear to rest and recover which reduces the likelihood of permanent damage.⁹ Such intermittent exposures have not been studied much because of the great complexities of exposure description. As a result, theories are relied upon to set limits for intermittent noise.

The theory most generally accepted postulates that the hazard of noise exposure increases in proportion to the average temporary hearing loss which the exposure would produce in a group of normal ears. This theory arises out of the observation that those noise exposures that ultimately produce permanent hearing loss also produce temporary hearing loss in normal ears. Conversely, those noise exposures that do not produce permanent hearing loss do not produce temporary hearing loss in normal ears. While the true relation between temporary and permanent hearing loss has not been established, it is logical to assume that those noise exposures that do not cause much temporary loss will not cause much permanent loss either. Any temporary threshold shift (TTS) that disappears before the next exposure to noise commences is considered acceptable.

On the basis of this assumption, results of TTS studies have been used to define safe limits for all day exposures to steady noise. These limits agree with those established by permanent threshold shift studies.

TTS studies have also indicated that intermittent noise is much less harmful than steady noise. The laws describing growth of TTS during exposure and recovery afterwards have been used to calculate exposures producing acceptably small amounts of TTS.¹⁰ Combinations of sound level, duration of exposure and degree of repetition that are considered acceptable for personnel exposures at work are shown in Table 25-3.¹¹ This method for appraising noise exposures was derived from the report describing hazardous exposure to intermittent and steady-state noise prepared by the National Academy of Science-National Research



Guidelines for noise exposure control. Sound and Vibration 4:21, 1970.

Figure 25-6. Prevalence of Impaired Hearing and Sound Levels at Work.

Council, Committee on Hearing, Bio-acoustics and Bio-mechanics, generally referred to as CHABA.¹² Maintaining exposures within the limits CHABA recommended will allow few additional cases of impaired hearing to occur.¹³

TABLE 25-3.

Maximum Permissible Sound Levels for Intermittent Noise When Occurrences Are Evenly Spaced Throughout the Day.

Total noise duration per day (8 hours)	Number of times noise occurs per day						
	1	3	7	15	35	75	160 up
8 h.	89	89	89	89	89	89	89
6	90	92	95	97	97	94	93
4	91	94	98	101	103	101	99
2	93	98	102	105	108	113	117
1	96	102	106	109	114	125	125
30 m.	100	105	109	114	125	(1½ h)	
15	104	109	115	124			
8	108	114	125	A-weighted			
4	113	125	sound levels,				
2	123	dBA					

Reproduced with permission from "Sound and Vibration" Bay Village, Ohio (4:16, 1970).

To use Table 25-3, select the column headed by the number of times the noise occurs per day, read down to the average sound level of the noise and locate directly to the left in the first column the total duration of the noise permitted for any 24 hour period. It is presumed that the noise bursts are evenly spaced throughout the work day so that an opportunity for rest and recovery between noise bursts exists. It is permissible to interpolate in the Table if necessary.

Table 25-3 shows that intermittency is as important as duration and level. For example, it shows that a continuous noise level of 91 dBA can be tolerated for 4 hours; 101 dBA can be tolerated also for 4 hours if it is presented in 15 evenly spaced bursts lasting 16 minutes each. Thus, the interruption of the higher noise reduces the effect on hearing to that which would be produced by a steady noise of equal duration 10 decibels lower. So you might say that the interruptions are equivalent to a 10 decibel noise reduction.

Impulsive Noise. Exposure limits for impulse noise are based on studies of the average TTS caused in normal ears by exposure to various impulses. Limits that will cause little TTS and, therefore, little expected permanent damage have been set.¹⁴ These limits are complicated to apply and, as a result, have not been widely used.

However, an approximate method of determining whether these limits are likely to be exceeded can be carried out with the sound level meter using

the C-weighting and "fast" meter response. To do so, set controls so that zero on the meter scale corresponds to a level of 130 dB. If the impulse does not cause the meter needle to jump above 125 dB (minus 5 on the meter scale), then it probably is not excessive.¹⁵

ACGIH TLV for Noise. The noise exposure limits expressed in Table 25-3 are inconvenient to use in practice. So, a simplification of the table was adopted in 1970 by the ACGIH as a threshold limit value (TLV) for noise.⁵ It is shown in Table 25-4. The simplification embodies the presumption that practically all noise exposures are interrupted at least a few times a day by meals or rest periods, machinery stoppages, etc. The limits of Table 25-4 correspond very closely to those of Table 25-3 for noises that occur three to seven times per day. Since these exposure limits do not take proper account of intermittency, they do not provide a true evaluation of hearing damage potential of the noise exposure. They are too liberal for absolutely continuous noise and too conservative for noise that is interrupted very frequently.

If an exposure consists of two or more noise levels, the combined effect must be considered. To do so, it is necessary to compute the ratio of the duration of each level to the duration allowed by Table 25-4. The sum of these ratios for all noise levels involved in the exposure must not exceed unity if the exposure is to be acceptable. Noise levels below 90 dBA are not considered in these calculations. The graph in Figure 25-7 is convenient for calculation of exposures involving several levels.

For impulsive sounds, ACGIH proposed a limit of 140 dB peak which is quite conservative compared to the recommendations of Coles et al.¹⁴

TABLE 25-4

Threshold Limit Values for Non-impulsive Noise Adopted by the American Conference of Governmental Industrial Hygienists

Duration per day, hours	Permissible sound level, dBA
8	90
6	92
4	95
3	97
2	100
1½	102
1	105
¾	107
½	110
¼	115 max.

Reprinted with permission of American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio from "Threshold Limit Values for Noise," 1970.

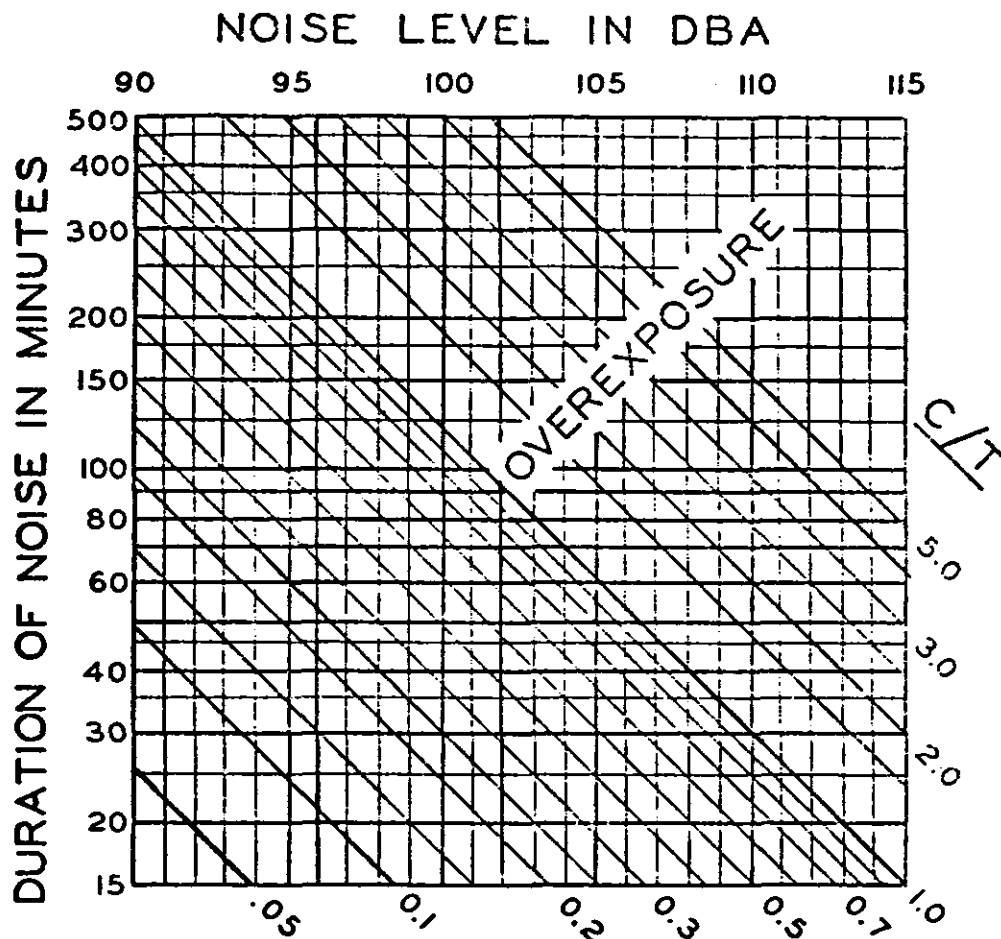


Figure 25-7. Graphical Presentation of ACGIH TLV for Noise. To use the graph, locate the point corresponding to the noise level and duration; then read off the exposure ratio C/T from the diagonal lines interpolating if necessary.

The ACGIH TLV for noise was accepted by the U.S. Department of Labor for promulgation under the provisions of the Occupational Safety and Health Act of 1970. It is being adopted also by many states for enforcement as part of their occupational health regulations.

Non-occupational Exposures. All that has been said up to now about hearing damage applies to the noise exposures at work. Medical evaluation of hearing handicap from occupational noise exposure disregards changes in hearing that do not affect ability to understand everyday speech significantly.

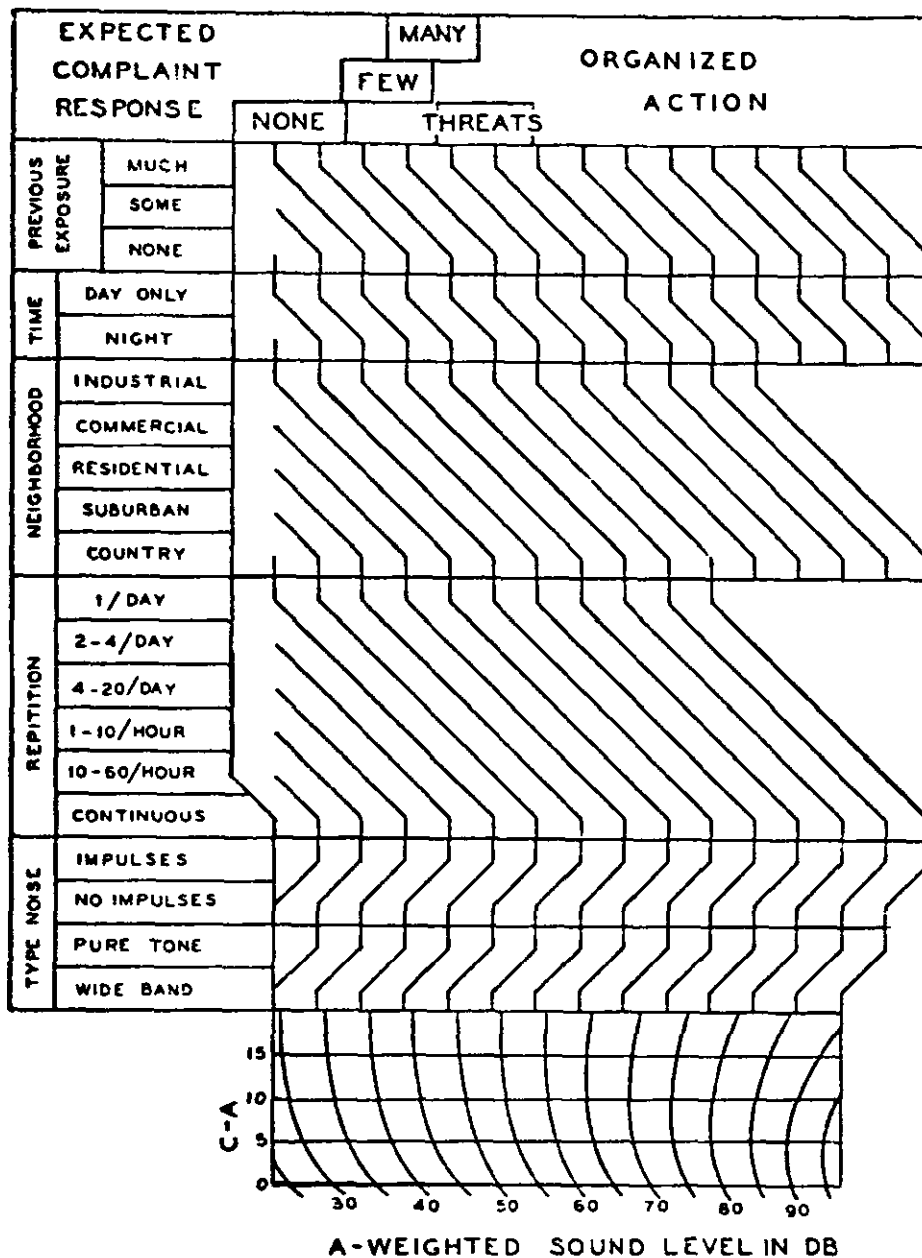
When it comes to the non-occupational exposures in transportation vehicles, public places, etc., none of these mitigating influences exist. Yet levels equalling those in industry are often encountered and there is a tendency to apply industrial standards when appraising the hazard. Stricter standards of safety should be imposed for non-occupational exposures so that no change in hear-

ing whatsoever can occur. Dr. Cohen has recommended limits 15 dB below the limits shown in Table 25-4.¹⁶

Speech Interference

Noise can mask or "blot out" speech sounds reducing the intelligibility of messages. Laboratory studies of these effects have appraised the disruptive potential of the noise by its "speech interference level" which is the average sound pressure level of 500, 1000, and 2000 Hz octave bands.¹⁷ The distances at which difficult messages can be conveyed reliably are shown in Table 25-5 as a function of speech interference level. Simple, redundant messages normally used at work can be understood at greater distances.

The speech interference level is closely related to the A-weighted sound level. It is lower by 7 decibels for most common noises. Using this conversion, the speech interference effects of various noises may be estimated from A-weighted sound levels using Table 25-5.



Botsford J. H.: Using sound levels to gauge human response to noise. *Sound and Vibration* 3:16, 1969.

Figure 25-8. Chart for Estimating Community Complaint Reaction to Noise.
 To use the chart, locate in the curved grid at the bottom the point corresponding to the sound levels of the noise under consideration (C-A is the difference between the C- and A- weighted sound levels). From this point, project directly upward into the first of the six correction sections bounded by the horizontal lines. When entering a correction section, follow the lane entered until reaching a position opposite the condition listed at the left which applies to the neighborhood noise under consideration, and then proceed vertically, disregarding lanes, until the next section is reached. In this way, work up through the lanes of the correction sections until reaching the top where the community reaction to be expected is shown.

Annoyance

Annoyance by noise is a highly subjective phenomenon which is very difficult to relate to the sound that causes it. Noises become more annoying as they get louder than the background noise on which they are superimposed. Noises that are unsteady or contain tones are most annoying as are those that convey unpleasant meaning.

Indoors, noise is likely to become annoying when the A-weighted sound level exceeds 30 dBA in auditoria or conference rooms, 40 dBA in private offices and homes, or 50 dBA in large offices or drafting rooms. Outdoors, a noise can be expected to prove annoying if it exceeds the background level by 10 dBA or more.

A procedure for rating the annoyance potential of a noise in the community is given in Figure 25-8.⁴ It provides a method for estimating community complaint reaction to a given noise condition.

TABLE 25-5
Maximum Speech Interference Levels
for Reliable Communication at Various Distances
and Vocal Efforts.

Distance, feet	Vocal Effort			
	Normal	Raised	Loud	Shout
0.5	76	82	88	94
1	70	76	82	88
2	64	70	76	82
4	58	64	70	76
8	52	58	64	70
16	46	52	58	64
32	40	46	52	68

Reproduced with permission of General Radio Company, West Concord, Mass., from "Handbook of Noise Measurement," 1967.

Non-Auditory Effects

Audible noise produces other effects which are just beginning to be examined.¹⁸ Laboratory studies have shown that noise reduces efficiency on some tasks, can upset the sense of balance, and can cause blood vessels to constrict, raising blood pressure and reducing the volume of blood flow. It causes the pupils of the eyes to dilate. Even when we are sleeping, noise can cause changes in electro-encephalograms and blood circulation without waking us. Noise can also cause fatigue, nervousness, irritability, hypertension and add to the overall stress of living. There is no convincing evidence so far that any of these effects become permanent and thus are deleterious to health.

Very intense noise below 1000 Hz can be felt as well as heard. Airborne vibrations can stimulate mechano-receptors throughout the body, including touch and pressure receptors and the vestibular organs. The respiratory system is affected by sounds in the 40 to 60 Hz range because of the resonance characteristics of the chest.

Sounds too high in frequency to be heard by the normal ear produce no significant effect when

they reach the body by air pathways. However, transmission of ultrasound into the body through fluid or solid media is more efficient and can produce cavitation of the tissue as well as deep burns.

Intense sound below the audible frequency range can cause resonant vibration of the eye balls and other organs of the body. Dizziness and nausea can result. Levels of 130 dB or more are required to cause these effects, and are not often encountered in industry.

SURVEY TECHNIQUES

One should become thoroughly familiar with operation of noise measuring instruments through study of operating instructions before attempting to make noise surveys. Set up the equipment and check its operation before embarking. At intervals during the survey, batteries should be checked as well as overall instrument calibration.

When transporting instruments, they should be protected from vibration and shock as much as practical. Instruments should also be protected from extremes of temperature. Overheating, such as might occur in the trunk of a car parked in the sunshine, can damage circuit components. Allowing the instrument to become very cold in a car parked overnight in the winter will result in condensation of water vapor in the instrument when it is used in a heated space the next morning. Water condensed from the air can cause electrical leakage resulting in low readings.

When conducting surveys, it is important to be assured that the meter indication is due to noise and not to other influences. One way of doing so is to listen to the meter output with a pair of headphones to learn whether the sound heard is the noise being measured.

Wind blowing across the microphone causes a rushing sound that is registered on the meter. Use of a wind screen can minimize this effect. Electric and magnetic fields can also cause needle deflections. This interference may occur around welding on large assemblies and becomes apparent when the meter needle does not move in step with the loudness of the noise heard. These electromagnetic effects can be reduced by reorienting the meter until minimum coupling with the electrical fields is obtained as indicated by minimum meter reading. One particularly troublesome location where electrical interference is observed is around electric furnaces. Here, the electrical interference and the noise are coincident so that it is easy to confuse these spurious signals with noise.

When taking readings, one should obtain representative data. The microphone should be moved about to determine that standing waves are not present. If they are, a spatial average should be obtained.

Exposure Surveys

When conducting exposure surveys of various kinds, the most important consideration is to measure levels that are typical of those at the auditor's location. It is not necessary, in fact it is undesirable, to measure sound right at the ear since diffraction around the head can alter the sound field. It is better to measure at some loca-

tion a few feet away where exploration with the sound level meter indicates levels are the same as at the auditor's location. When attempting to evaluate the potential for hearing damage, all factors of significance must be recorded such as sound level, duration, intermittency, etc.; necessary to make proper evaluation of an exposure, using Table 25-3.

If one is merely attempting to determine compliance with the regulatory limits shown in Table 25-4, then the ACGIH exposure evaluation procedure must be followed. When noise levels are too variable to allow this procedure to be carried out with a sound level meter and stop watch, a noise monitor may be used. Several of these are commercially available to compute automatically the fractional exposure according to the prescribed methods. One of these monitors is shown in Figure 25-5.

Source Determination

When attempting to locate sources of noise in a room or in a machine, the simplest approach is to probe the sound field with the sound level meter. The noise will increase as the source is approached and disclose its location. Extension cables can be used to remove the microphone from the meter for greater convenience in these explorations.

Another aid to locating the original sources of noise is spectral analysis of vibrating parts, the frequency of the sound will be the same as the frequency of the part vibration. Thus, narrow band analysis will often reveal frequencies that can be correlated with repetitive mechanical events or multiples thereof. These clues point to the mechanical disturbances responsible for the noise.

SUMMARY

A complete array of instruments is available for measuring steady, intermittent and impulsive noises. Sound level meters, calibrators, frequency analyzers, and accessory equipment are provided by several suppliers. Sound exposure monitors which can be worn by roving workmen record individual patterns of exposure that could be assessed in no other way.

Criteria have been established for avoiding permanent hearing loss resulting from steady, intermittent and impulsive sounds. The Threshold Limit Value for noise, adopted by the American Conference of Governmental Industrial Hygienists, has been accepted widely. Non-occupational exposures require stricter limits to provide complete protection.

Criteria for avoiding speech interference and complaints of annoyance are also available. Several non-auditory effects of noise are being studied, but no harmful effects that require safety criteria have been discovered yet. Techniques for surveying noise conditions are well developed so that any noise problem can be readily evaluated.

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CHAPTER 26 VIBRATION

Robert D. Soule

INTRODUCTION

Exposure to vibration is frequently associated with exposure to noise in industrial processes since the two often originate from the same operation. However, the adverse effects resulting from exposure to noise and to vibration are quite different in nature, the former having a more substantial basis than the latter for establishing a cause-and-effect relationship both qualitatively and quantitatively. As more information concerning industrial exposures to vibration becomes available, particularly within the United States, and appropriate exposure criteria are established and standards adopted, the now common practice of taking noise surveys in industrial situations will likely be extended by the use of a vibration sensor to assist the investigator in evaluating the exposures of workers to both noise and vibration.

The effects of exposure to noise have been thoroughly investigated and the results of these studies are reflected in current legislation. Although a significant amount of research is underway on the relationship between exposure to vibration and the health and well-being of the persons exposed, sufficient evidence for the establishment of occupational health standards has not yet been developed.

Therefore the purpose of this chapter is to acquaint the reader with the general principles involved in recognition, evaluation and control of workers' exposure to vibration. Except to the extent necessary, the chapter will not discuss considerations of vibration in noise control efforts, since this is done in detail in Chapter 37.

EFFECTS OF VIBRATION ON MAN

The human body is an extremely complex physical and biological system. When looked upon as a mechanical system, it contains a number of linear and non-linear elements, the mechanical properties of which differ from person to person. Biologically, and certainly psychologically, the system is by no means any simpler than it is mechanically. On the basis of experimental studies, as well as documented reports of industrial experience, it is apparent that exposure of workers to vibration can result in profound effects on the human body — mechanically, biologically, physiologically and psychologically.

It should be noted at this point that relatively few studies of industrial exposures to vibration have been conducted in the United States; most of the available literature on documentations of effects of vibration in industrial situations has been

published in European countries. There have been considerable numbers of military and, relatively recently, agriculturally applied research programs in the United States. The application of such studies to general industrial situations is obviously limited. However, they have been valuable in determining some of the parameters of importance in investigating the response of people exposed to vibration and, for this reason, results of some of these studies will be discussed later in this chapter.

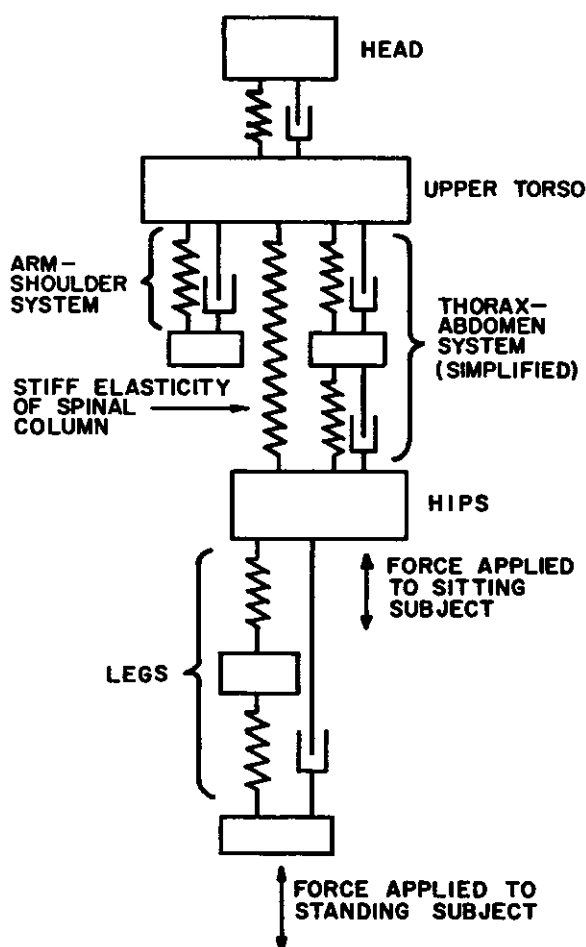


Figure 26-1. Simplified Mechanical System Representing the Human Body Standing (or Sitting) on a Vertically Vibrating Platform.¹

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When considering the effects of vibration on man, it is necessary to classify the type of vibration exposure into one of two categories on the basis of the means by which the worker contacts the vibrating medium. The first category is referred to as "whole body" vibration and results when the whole body mass is subjected to the mechanical vibration as, for example, from a supporting surface such as a tractor seat. The second category is usually referred to as "segmental" vibration and is defined as vibration in which only part of the body, for example the hand or hands operating a chain saw, is in direct contact with the vibrating medium and the bulk of the body rests on a stationary surface. This classification of vibration does not necessarily mean that parts of the body other than those in direct contact with the vibrating surface are not affected.

If the whole body is considered as a mechanical system, at low frequencies and low vibration levels it may be approximated roughly by a simplified mechanical system such as that depicted in Figure 26-1.

Results of some of the research studies conducted in the United States are presented in Figures 26-2 and 26-3.^{2, 3, 4} These studies have shown that, for whole body vibration, the tolerance of a seated man is lowest in the frequencies between approximately 3 and 14 Hertz. As with any tangible object, it is possible to apply externally generated vibrations to the human body at certain frequencies and in such a way that the body becomes more in resonance with the vibrating source than at other frequencies. These studies have indicated that such whole body resonances occur

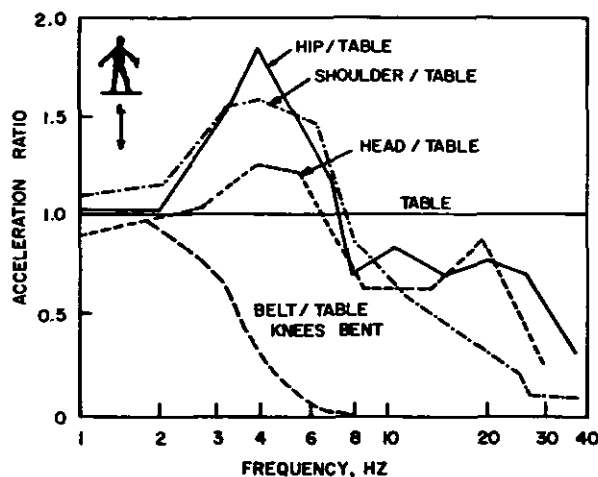


Figure 26-2. Transmissibility of Vertical Vibration from Supporting Surface to Various Parts of the Body of a Standing Human Subject as a Function of Frequency.^{2, 3, 4}

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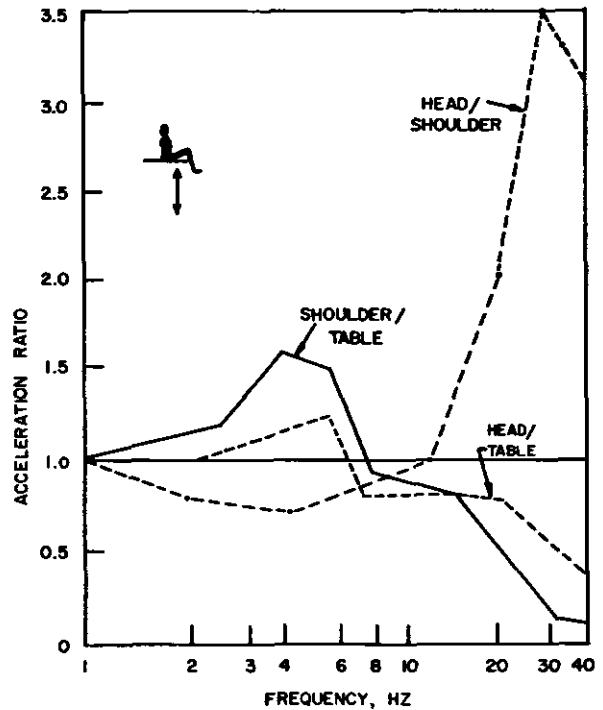


Figure 26-3. Transmissibility of Vertical Vibration from Supporting Surface to Various Parts of a Seated Human Subject as a Function of Frequency.^{2, 4}

Reprinted from "Mechanical Vibration and Shock Measurements" courtesy of Brüel & Kjaer Instruments, Cleveland, Ohio.

in the frequency range 3-6 Hertz and 10-14 Hertz. The studies have also indicated the presence of resonant effects in some of the sub-systems of the body as a result of exposure to whole body vibration. For example, resonance of the head-shoulder sub-system has been found in the 20-30 Hz range; disturbances which suggest eyeball resonance have been indicated in the 60-90 Hz range; and a resonance effect in the lower jaw and skull sub-system has been reported for the 100-200 Hz range.

The preceding discussion has dealt with mechanical responses to vibration, however, there are pronounced physiological and psychological effects resulting from exposures to whole body vibration as well. Although these effects are rather complex and usually difficult to measure, the subjective responses of man to whole body vibration have been fairly well documented in the European literature. A few causal relationships between the biomechanical effects of whole body vibration and consequent physiological changes in the body are apparent. These physiological observations have included evidence of a slight acceleration in the rate of oxygen consumption, pulmonary ventilation and cardiac output.^{5, 6, 7, 8} There is evidence of an

inhibition of tendon reflexes and an impairment in the ability to regulate the posture, possibly by actions through both the vestibular and spinal reflex pathways.^{9, 10} Alterations have been recorded in the electrical activity of the brain and there has been evidence of effects on visual acuity and performance at various levels of motor activity and task complexity during exposure to whole body vibration.^{11, 12} These and other studies conducted in Europe have indicated that whole body vibration has effects on the endocrinological, biochemical and histopathological systems of the body as well.

The most extensive investigations of industrial exposures of workers to vibration have been concerned with repeated exposure to low frequency vibration transmitted through the upper extremities of the worker; that is, during the use of hand-held power tools which incorporate rapidly rotating or reciprocating parts. Such studies therefore consider the effects of "segmental" vibration on the worker. Unfortunately, most of these studies present only general descriptions of the clinical evidence of overexposure to vibration and very few contain any controlled observations by quantitative techniques; consequently there is a large variability between the observations reported by different investigators. However, the main features of what can be called a vibration syndrome are evident.

The clinical evidence of overexposure to vibration during the use of hand tools can be conveniently grouped into four categories.¹³ These four types of disorders, in decreasing order of their appearance in the published literature, are:

1. A traumatic vaso-spastic syndrome in the form of Raynaud's phenomenon (discussed in more detail below);
2. Neuritis and degenerative alterations, particularly in the ulnar and axillar nerves, that is, a loss of the sense of touch and thermal sensations as well as muscular weakness or even paralysis, and abnormalities of the central nervous system;
3. Decalcification of the carpal and metacarpal bones; fragmentation, deformation and necrosis of carpal bones; and
4. Muscle atrophy, tenosynovitis.

As indicated earlier, the prevalence of the different symptom groups varies tremendously in the reports of different investigators. However, a fair estimate of the average overall prevalence of the vibration syndrome, at least as typified by the Raynaud phenomenon, appears to be around 50%; that is, about half of the workers exposed to segmental vibration exhibit clinical symptoms characteristic of the Raynaud phenomenon.

Raynaud's Syndrome

Raynaud's syndrome or "dead fingers" or "white fingers" occurs mainly in the fingers of the hand used to guide a vibrating tool. The circulation in the hand becomes impaired and, when exposed to cold, the fingers become white and void of sensation, as though mildly frosted. The condition usually disappears when the fingers are warmed for some time, but a few cases have been suffi-

ciently disabling that the men were forced to seek other types of work. In some instances, both hands are affected.

This condition has been observed in a number of occupations involving the use of fairly light vibrating tools such as the air hammers used for scarfing and chipping in the metal trades, stone-cutting, lumbering and in the cleaning departments of foundries where men have a good deal of overtime work. Obviously, prevention of this condition is much more desirable than treatment. Preventive measures include directing the exhaust air from the air-driven tools away from the hands so they will not become unduly chilled, use of handles of a comfortable size for the fingers, and in some instances, substituting mechanical cleaning methods for some of the hand methods which have produced many of the cases of "white fingers." In many instances, simply preventing the fingers from becoming chilled while at work has been sufficient to eliminate the condition.

The appearance of the syndrome appears to be a function of the cumulative absorption of vibration energy, its harmonic content and on personal factors such as the age of the worker. Vibration in the frequency range 40-125 Hz has been implicated most frequently in reported cases of vibration disorders.^{14, 15} In most studies it appeared that an exposure time of several months was generally needed before symptoms appeared. With continued exposure there was a progressive diversification and intensification of the symptoms; some improvement of symptoms has been reported, but rarely complete recovery, with cessation of exposure to vibration. It is the opinion of many investigators in Europe that the vibration syndrome is a widespread and alarmingly common occupational disorder.¹³ Symptoms of overexposure are reportedly grave or moderately grave in about half of those affected, and in all cases result in a varying loss of working capacity.

Results of the European studies of industrial vibration exposures are summarized in Table 26-1. These data were obtained from reports issued by investigators in several countries: Austria, Czechoslovakia, France, Finland, Germany, Great Britain, Italy, the Netherlands, Russia, Sweden and others. In general, these studies revealed abnormal changes in the vascular, gastric, neurological, skeletal, muscular and endocrine systems as well as definite effects on visual acuity and task performance. The presence of Raynaud's syndrome was common to practically all studies of exposures to segmental vibration. It is beyond the intent of this chapter to discuss any of the hundreds of articles published in the literature on these studies; bibliographies on the subject have been published and should be reviewed by the interested reader.^{13, 16}

As can be seen from Table 26-1 the vibration syndrome does indeed appear to be a widespread occupational disorder in European industry. It must be noted here again that similar studies in industries in the United States have been very limited. However, it is reasonable to assume that United States workers employed in occupations

TABLE 26-1
EUROPEAN INDUSTRIES IN WHICH
CLINICAL EVIDENCE OF OVEREXPOSURE
OF WORKERS TO VIBRATION
HAS BEEN REPORTED

Industry	Type of Vibration	Common Vibration Sources
Agriculture	Whole body	Tractor operation
Boiler Making	Segmental	Pneumatic tools
Construction	Whole body Segmental	Heavy equipment vehicles, pneumatic drills, jackhammers, etc.
Diamond cutting	Segmental	Vibrating hand tools
Forestry	Whole body Segmental	Tractor operation chain saws
Foundries	Segmental	Vibrating cleavers
Furniture manufacture	Segmental	Pneumatic chisels
Iron and steel	Segmental	Vibrating hand tools
Lumber	Segmental	Chain saws
Machine tools	Segmental	Vibrating hand tools
Mining	Whole body Segmental	Vehicle operators rock drills
Riveting	Segmental	Hand tools
Rubber	Segmental	Pneumatic stripping tools
Sheet metal	Segmental	Stamping equipment
Shipyards	Segmental	Pneumatic hand tools
Stone dressing	Segmental	Pneumatic hand tools
Textile	Segmental	Sewing machines, looms
Transportation (operators and passengers)	Whole body	Vehicle operation

similar to those listed in Table 26-1 are being potentially exposed to excessive levels of vibration during their routine work activities. The National Institute for Occupational Safety and Health (NIOSH) has initiated a comprehensive program in which the occupational exposures to vibration in American industries is being investigated.¹⁶

VIBRATION EXPOSURE CRITERIA

It is obvious from the preceding discussion that the occurrence of vibration disorders in a wide

cross section of industry is significant enough, both in terms of prevalence and magnitude, that appropriate standards for allowable exposure to vibration are desirable. However, at the present time there are no generally accepted limits for safe vibration levels and, in fact, the available literature, because of the variability of reported findings, does not permit the reliable construction of a vibration exposure standard. All this is not to say that individual standards and criteria, as well as corrective methods for dealing with excessive levels of industrial vibration, have not been attempted; in fact, they have. However, the approaches to establishment of criteria and/or im-

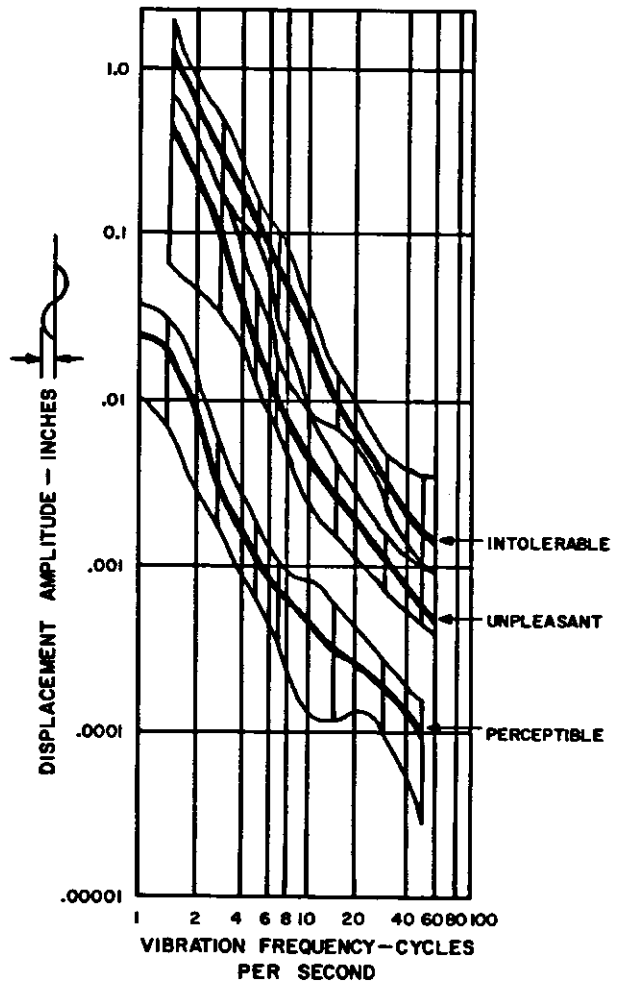


Figure 26-4. Subjective Responses to Vibratory Motion. The chart is based on the averaged values of various investigators and is valid for exposures up to a few minutes. The vertical arrows represent one standard deviation above and below the means.

McFarland RA Human engineering and industrial safety.

Reprinted from Vol. 1, F. A. Patty "Industrial Hygiene and Toxicology", 2nd edition. Courtesy Interscience Publishers, Inc., New York, N.Y., 1958.

plementation of corrective methods have been quite variable even within a given country.

Many studies have been conducted in which the subjective responses of exposed personnel to various levels of vibration have been documented. The results of experimental studies with human volunteers conducted by three different investigators are presented in Figure 26-4.¹⁷ It must be emphasized that these data and, in fact, all such data in which *experimental* exposures have been documented are useful only over a very limited time duration. Most of these studies have been conducted for military and/or aerospace programs and are concerned primarily with acute exposures; that is, relatively short duration exposure such as impact or shock type of vibrations encountered in military situations. The subjects selected for such studies, therefore, are normal young, physically fit men, such as pilots. There are obvious pitfalls, therefore, in using such information as a basis for establishment of standards for industrial exposures to vibration. In the occupational workplace the normal work force is comprised of persons constituting a wide spectrum of characteristics. The industrial worker can be female as well as male, is not necessarily as physically fit as the subjects

used in experimental studies, and certainly encompasses a greater range of age and other physical characteristics. Perhaps of more significance, however, is the fact that these experimental investigations represent acute or short-term exposures to vibration and certainly do not permit direct extrapolation to the typical industrial exposure which is comprised, for the most part, of exposure to relatively low frequency vibration of varying amplitudes for extended periods of time. In the case of the industrial worker then, one must be concerned with the cumulative effects of exposure to vibration over a working lifetime which can be comprised of exposure to vibration for, in an extreme example, 40 hours per week, 50 weeks per year for 40 years. Suffice to say, therefore, that the types of human exposure studies that have been conducted in the United States have limited application in the industrial environment.

Attempts have been made to establish vibration exposure standards and, of these, perhaps the single best vibration exposure criteria guides are those proposed by the International Standards Organization.¹⁸ These criteria, presented in Figure 26-5 as a family of curves, are valid for vibrations transmitted to the torso of a standing or sit-

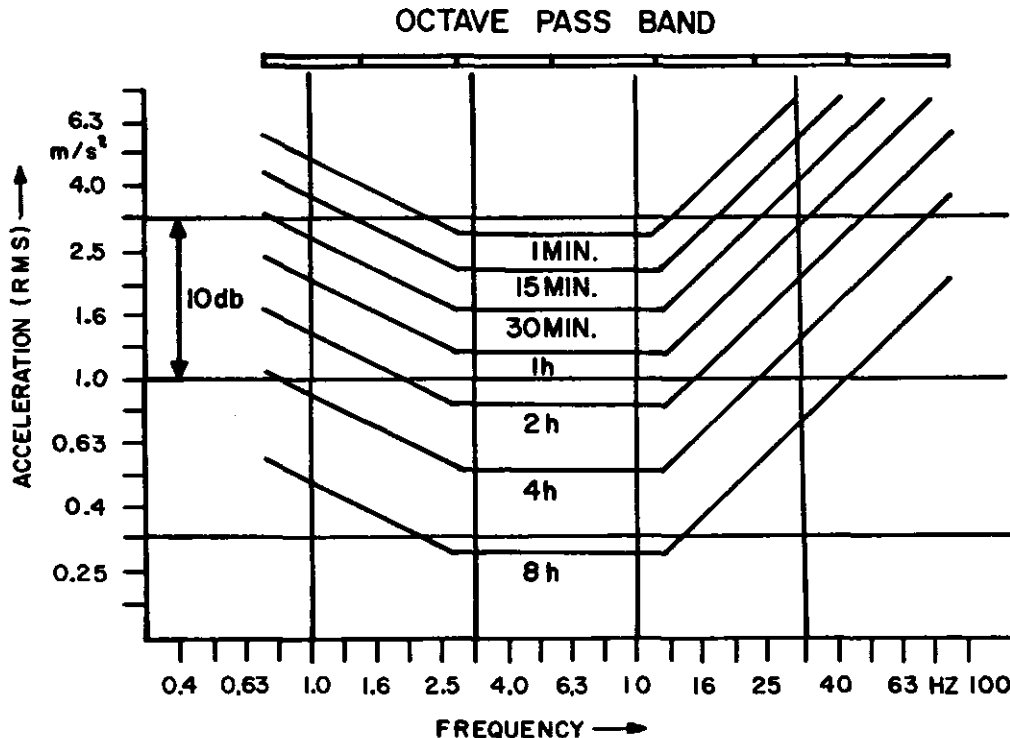


Figure 26-5. *Vibration Exposure Criteria Curves.* The vibration levels indicated by the curves in Figure 26-5 are given in terms of RMS acceleration levels which produce equal fatigue-decreased proficiency. Exceeding the exposure specified by the curves, in most situations, will cause noticeable fatigue and decreased job proficiency in most tasks. The degree of task interference depends on the subject and the complexity of the task.

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ting person and are, therefore, to be considered a guide for whole body vibration. A tentative ISO vibration guide has been proposed for segmental (hand-arm system vibrations).¹⁹ The ISO whole body vibration guide is based to a great extent on studies conducted in the aerospace medical research laboratories in formulating guides for short-term exposures, usually of a military nature and thus again may have only limited application in industrial work environments.

The vibration levels indicated in Figure 26-5 are given in terms of the root mean square acceleration levels which produce equal "fatigue-decreased proficiency" over the frequency range of 1-100 Hz. Vibrations in frequencies below 1 Hz produce annoyances which are individually unique; for instance, cinetosis or air sickness. For frequencies above 100 Hz the vibrational perceptions are mainly effective on the skin and depend greatly upon the influenced body part and on the damping layer; for example, clothing or shoes. It seems, therefore, practically impossible to state generally valid vibration exposure criteria for frequencies outside the range indicated in Figure 26-5, that is, 1-100 Hertz. Exceeding the exposures specified by the curves in most situations will cause noticeable fatigue and decreased job efficiency. The degree of task interference depends on the subject and the complexity of the task being performed. The curves indicate the general range for onset of such interferences and the time dependency observed. An upper exposure

considered hazardous to health as well as performance is considered to be twice as high (6 decibels higher) as the "fatigue-decreased efficiency" boundary shown in Figure 26-5 while the "reduced comfort" boundary is assumed to be about $\frac{1}{2}$ (10 decibels below) the illustrated levels.

Again, these criteria are presented as recommended guidelines or trend curves, rather than firm boundaries of classified quantitative biological or psychological limits. They are intended solely for situations involving healthy, normal people considered fit for normal living routines and stress of an average work day. A program for establishing vibration exposure based upon identification and characterization of exposed workers in industries in the United States and implementation of relevant studies to ascertain the extent of the industrial vibration hazard and determination of criteria for these standards to prevent adverse exposures to industrial vibration has been initiated.¹⁶

CHARACTERISTICS OF VIBRATION

In general, vibration can be described as an oscillatory motion of a system. The "motion" can be simple harmonic motion, or it can be extremely complex. The "system" might be gaseous, liquid or solid. When the system is air (gaseous) and the motion involves vibration of air particles in the frequency range of 20 to 20,000 Hertz (Hz), sound is produced. For the purposes of this chapter, only the effects on the worker caused by mo-

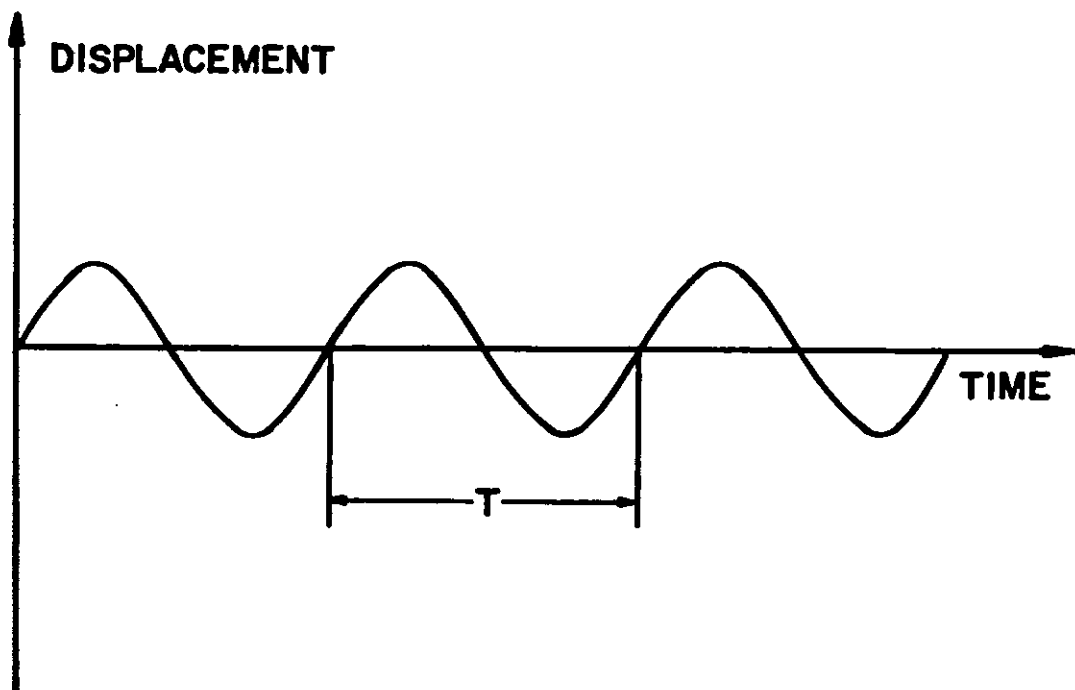


Figure 26-6. Representation of Pure Harmonic (Sinusoidal) Vibration.

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tion of *solid* systems will be considered.

The oscillation of the system may be periodic or completely random; steady-state or transient; continuous or intermittent. In any event, during vibration one or more particles of the system oscillate about some position of equilibrium.

Periodic (Sinusoidal) Vibration

Vibration is considered periodic if the oscillating motion of a particle around a position of equilibrium repeats itself *exactly* after some period of time. The simplest form of periodic vibration is called pure harmonic motion which as a function of time, can be represented by a sinusoidal curve. Such a relationship is illustrated in Figure 26-6, where T = period of vibration.

The motion of any particle can be characterized at any time by (1) displacement from the equilibrium position, (2) *velocity*, or rate of change of displacement, or (3) *acceleration*, or rate of change of velocity. For pure harmonic motion, the three characteristics of motion are related mathematically.

Displacement

The instantaneous displacement of a particle from its reference position under influence of harmonic motion can be described mathematically as:

$$s = S \sin \left(2\pi \frac{t}{T} \right) = S \sin (2\pi ft) = S \sin \omega t$$

where s = instantaneous displacement from reference position

S = maximum displacement

t = time

T = period of vibration

f = frequency of vibration

ω = angular frequency ($2\pi f$)

Of the possible vibration measurements, displacement probably is the easiest to understand and is significant in the study of deformation and bending of structures. However, only if the rate of motion, i.e. frequency of vibration, is low enough, can displacement be measured directly.

Velocity

In many practical problems, displacement is not the most important property of the vibration. For example, experience has shown that the velocity of the vibrating part is the best single criterion for use in preventive maintenance of rotating machinery.

Although peak-to-peak displacement measurements have been widely used for this purpose, it is necessary to establish a relationship between the limits for displacement and rotational speed for each machine.

Since the velocity of a moving particle is the change of displacement with respect to time, the particle's velocity can be described as:

$$v = \frac{ds}{dt} = \omega S \cos(\omega t) = V \cos(\omega t) = V \sin\left(\omega t + \frac{\pi}{2}\right)$$

where

v = instantaneous velocity

V = maximum velocity

Acceleration

In many cases of vibration, especially where mechanical failure is a consideration, actual forces

set up in the vibrating parts are critical factors. Since the acceleration of a particle is proportional to these applied forces and since equal-and-opposite reactive forces result, particles in a vibrating structure exert forces on the total structure that are a function of the masses and accelerations of the vibrating parts. Thus, acceleration measurements are another means by which the motion of vibrating particles can be characterized.

The instantaneous acceleration, i.e., the time rate of change of velocity of a particle in pure harmonic motion, can be described as:

$$a = \frac{dv}{dt} = \frac{d^2s}{dt^2} = -\omega^2 S \sin(\omega t) = A \sin(\omega t + \pi)$$

where a = instantaneous acceleration and

A = maximum acceleration.

Other terms, such as "jerk," defined as the time rate of change of acceleration, are sometimes used to define vibration. At low frequencies, jerk is related to riding comfort of automobiles and elevators and is also important for determining load tie-down in airplanes, trains and trucks. However, from the equations and definitions presented in the preceding discussion, it is apparent that, regardless of the parameter being studied, i.e., displacement, velocity, acceleration or jerk, the form and period of the vibration are the same.

As noted above, the instantaneous magnitudes of the various parameters have been defined in terms of their peak values, that is, the maximum values obtained. This approach is quite useful in the consideration of pure harmonic vibration because it can be applied directly in the above equations. However, in the consideration of more complex vibrations it is desirable to use other descriptive quantities. One reason for this is that the peak values describe the vibration in terms of a quantity dependent only upon an instantaneous vibration magnitude, regardless of the previous history of the vibration. One descriptive quantity which does take the time history into account is the "average absolute value" defined as:

$$S \text{ (average)} = \frac{1}{T} \int_0^T |s| dt$$

Although the above quantity does take the time history of the vibration into account over one period, it has very limited practical usefulness. The root mean square (rms) value is a much more useful descriptive quantity which also takes the time history of the vibration parameter into account. This quantity is defined as:

$$S_{\text{rms}} = \sqrt{\frac{1}{T} \int_0^T s^2(t) dt}$$

The importance of the rms value as a descriptive quantity lies mainly in its direct relationship to the energy content of the vibration. For example, in the case of pure harmonic motion the relationship between the various values is:

$$S_{\text{rms}} = \frac{\pi}{2\sqrt{2}} S \text{ (average)} = \frac{1}{\sqrt{2}} S$$

Or, in a more general form:

$$S_{\text{rms}} = F_f \quad S \text{ (average)} = \frac{1}{F_c} S$$

The factors, F_f and F_c , are called "form factor" and "crest factor," respectively, and give an indication of the wave shape of the vibration being studied. For pure harmonic motion

$$F_f = \frac{\pi}{2\sqrt{2}} = 1.11$$

and

$$F_c = \sqrt{2} = 1.414$$

There have been attempts to introduce the concept of "acceleration level" and "velocity level." These terms, similar in concept to the sound pressure level used in expressing noise levels, indicate the acceleration and velocity in decibels; that is, the logarithm of the ratio of the acceleration or velocity to a reference acceleration

or velocity. Although several references have been proposed, the most common velocity reference value is 10^{-8} meters per second; i.e., 10^{-6} centimeters per second. The acceleration reference value is 10^{-6} meters per second squared or 10^{-4} centimeters per second squared. Suitable "standard reference values" for acceleration, velocity and displacement are still being studied.

The discussion and certainly the equations which have been presented to this point have dealt exclusively with the periodic vibrations, and more specifically with pure harmonic periodic vibrations. It must be pointed out that most of the vibrations encountered in industry and in fact, practically anywhere, are not pure harmonic motions, even though many of them certainly can be characterized as periodic. A typical nonharmonic periodic vibration is illustrated in Figure 26-7.

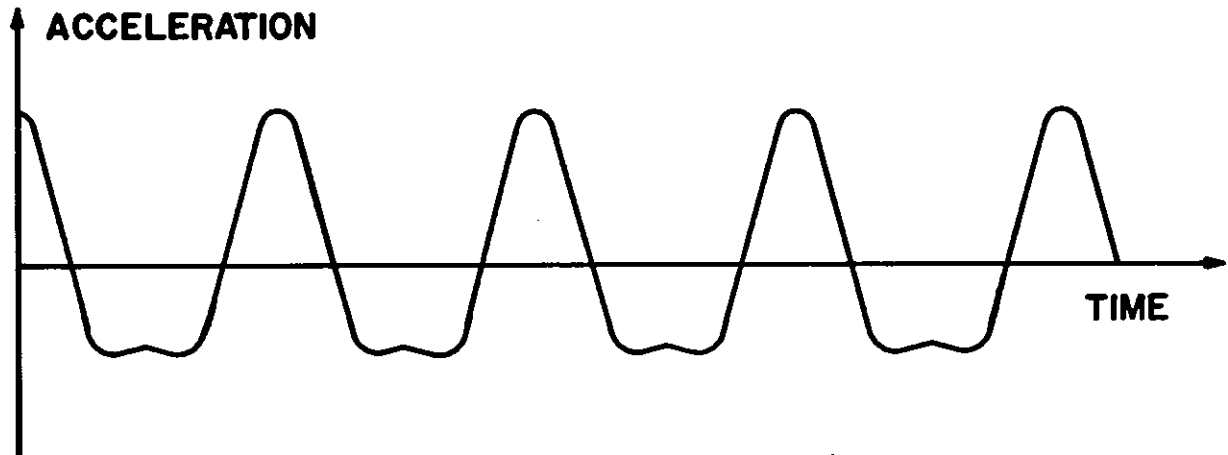


Figure 26-7. Example of a *Non-Harmonic Periodic Motion* (Piston Acceleration of a Combustion Engine).

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By examining this curve and determining the peak absolute and root mean square values of this vibration as well as the form factor and crest factor, it is obvious that the motion is not harmonic. However, on the basis of this information, it would be practically impossible to predict all of the various effects the vibration might produce in connected structural elements. Obviously, other methods of description must be used; one of the most powerful descriptive methods is that of frequency analysis, which is based on a mathematical theorem first formulated by Fourier, which states that "any periodic curve no matter how complex may be looked upon as a combination of a number of pure sinusoidal curves with harmonically related frequencies."

As the number of elements in the series increases, it becomes an increasingly better approximation to the actual curve. The various elements

constitute the vibration frequency spectrum and in Figure 26-8 the non-harmonic periodic vibration illustrated in Figure 26-7 is re-illustrated, together with two important harmonic curves which represent its frequency spectrum. A more convenient method of representing this spectrum is shown in Figure 26-9. This characteristic of periodic vibrations is evident in examining Figure 26-10. Their spectra consist of discrete lines when represented in the so-called "frequency domain"; random vibrations show continuous frequency spectra when represented in similar fashion.

Random Vibrations

Random vibrations occur quite frequently in nature and may be defined as motion in which the vibrating particles undergo irregular motion cycles that *never* repeat themselves exactly. Theoretically then, obtaining a complete description of the vi-

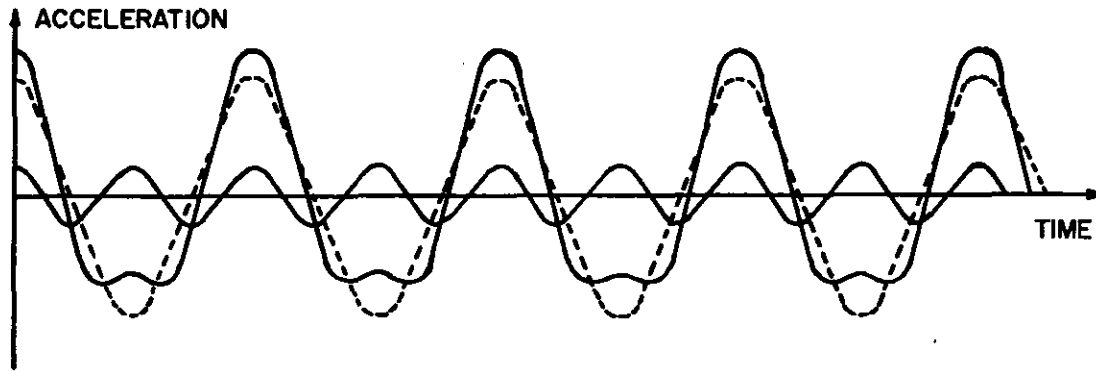


Figure 26-8. Illustration of How the Waveform Shown in Figure 26-7 Can Be "Broken Up" into a Sum of Harmonic Related Sinewaves.

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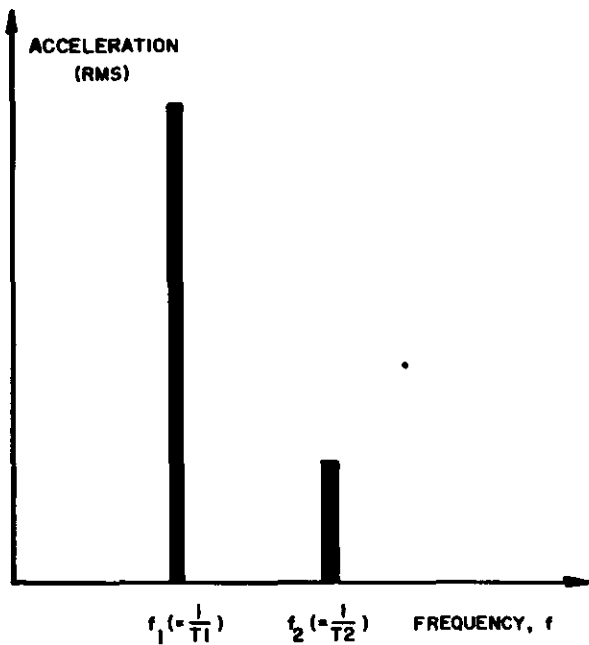


Figure 26-9. Examples of Periodic Signals and their Frequency Spectra.

- a) Description in the time domain.
- b) Description in the frequency domain.

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brations requires an infinitely long time record. This, of course, is an impossible requirement and finite time records would have to be used in practice. Even so, if the time record becomes too long, it also will become a very inconvenient means of describing the vibration, and other methods there-

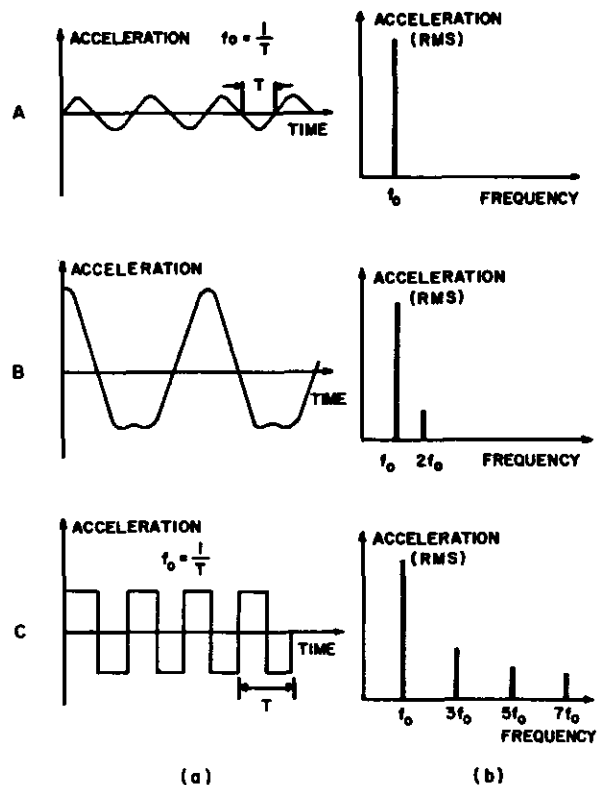


Figure 26-10. Examples of Periodic Signals and their Frequency Spectra.

- a) Description in the time domain.
- b) Description in the frequency domain.

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fore have to be devised, and are commonly used. It is beyond the purpose and intent of this chapter to discuss the theoretical and mathematical models necessary to describe complex vibrations; this information is presented in several well-written scientific and engineering texts.

VIBRATION MEASUREMENTS

Basic Elements In a Measurement System

A wide variety of component systems, consisting of mechanical or a combination of mechanical, electrical and optical elements are available to measure vibration. The most common system uses a vibration pick-up to transform the mechanical motion into an electrical signal, an amplifier to enlarge the signal, an analyzer to measure the vibration in specific frequency ranges and a metering device calibrated in vibrational units.

Vibration Pick-ups

The vibration pick-up measures the displacement, the velocity, or the acceleration of the vibration. These parameters are all inter-related by differential operations so that it does not normally matter which variable is measured. If the result is desired in terms of velocity or displacement, electronic integrators are added at the output of an accelerometer, an instrument which measures the acceleration of a mass due to the vibration signal.

Accelerometers, the most common type of vibration pick-up, are normally smaller than velocity pick-ups and their useful frequency range is wider. An accelerometer is an electromechanical transducer which produces an output voltage signal proportional to the acceleration to which it is subjected.

The most common type of accelerometer is the piezoelectric type, such as the one shown in Figure 26-11, in which two piezoelectric discs

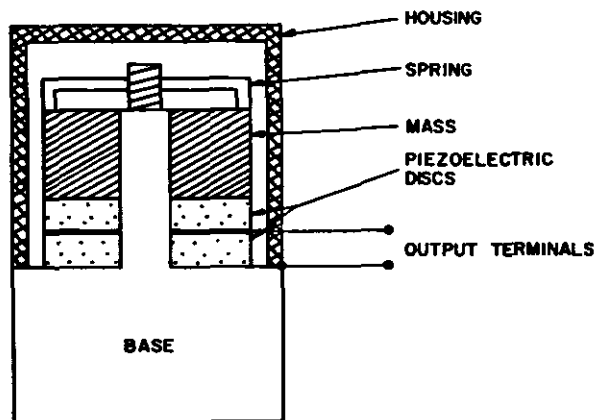


Figure 26-11. Sketch Showing the Basic Construction of the Bruel & Kjaer Compression Type Piezo-Electric Accelerometers (Single-Ended Version).

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produce a voltage on their surfaces due to the mechanical strain on the asymmetric crystals which make up the discs. The strain is in the form of vibrational inertia from a moving mass atop the discs. The output voltage is proportional to the acceleration, and thus to the vibration signal. The upper limit of the accelerometer's useful frequency range is determined by the resonant frequency of the mass and the stiffness of the whole accelerometer system. The lower limit of the frequency range varies with the cable length and the properties of the connected amplifiers. The accelerometer's sensitivity and the magnitude of the voltage developed across the output terminals depends upon both the properties of the materials used in the piezoelectric discs and the weight of the mass. The mechanical size of the accelerometer, therefore, determines the sensitivity of the system; the smaller the accelerometer, the lower the sensitivity. In contrast, a decrease in size results in an increase in frequency of the accelerometer resonance and thus, a wider useful range.²⁰

Other factors to consider in the selection of a suitable accelerometer include:

1. The transverse sensitivity, which is the sensitivity to accelerations in a plane perpendicular to the plane of the discs.
2. The environmental conditions during the accelerometer's operation, primarily temperature, humidity, and varying ambient pressure.

Often two types of sensitivities are stated by the manufacturer—the voltage sensitivity and the charge sensitivity. The voltage sensitivity is important when the accelerometer is used in conjunction with voltage measuring electronics, while the charge sensitivity, an indication of the charge accumulated on the discs for a given acceleration, is important when the accelerometer is used with charge-measuring electronics.

Preamplifier

The preamplifier is introduced in the measurement circuit for two reasons:

1. To amplify the weak output signal from the accelerometer; and
2. To transform the high output impedance of the accelerometer to a lower, acceptable value.

It is possible to design the preamplifier in two ways, one in which the preamplifier output voltage is directly related to the input voltage, and one in which the output voltage is proportional to the input charge, with the preamplifier termed a voltage amplifier or charge amplifier, respectively.

The major differences between the two types of amplifiers rest in their performance characteristics. When a voltage amplifier is used, the overall system is very sensitive to changes in the cable lengths between the accelerometer and the preamplifier, whereas changes in cable length produce negligible effects on a charge amplifier. The input resistance of a voltage amplifier will also affect the low frequency response of a system. Voltage amplifiers are generally simpler than charge amplifiers, with fewer components and are, therefore, less expensive. In selecting the appro-

appropriate preamplifier for vibration work, these above-mentioned factors should all be considered.

Analyzers

The analyzer element in a vibration measuring arrangement determines what signal properties are being measured and what kind of data can be obtained in the form of numbers or curves.

The simplest analyzer consists of a linear amplifier and a detection device measuring some characteristic vibration signal value such as the peak, root mean square, or average value of the acceleration, velocity, or displacement. The phase response of a system must be taken into account, in addition to the frequency response in choosing the correct analyzer. A signal reaching the detection device may look completely different from the signal input to the linear amplifier, due to possible distortions during linear attenuation of a complex signal's various frequency components. Serious waveshape distortion of the signal may be avoided when the fundamental vibration frequency is higher than 10 times the low frequency limit of the measuring system, and the highest significant vibration frequency component has a frequency which is lower than 0.1 times the high frequency limit of the system.²⁰ Phase response can be disregarded for measurement of only RMS values.

In most practical cases it will be necessary to determine the frequency composition of the vibration signal, which is done with a frequency analyzer. Two types of frequency analyzers are commonly available, the constant bandwidth analyzer and the constant percentage bandwidth-type analyzer. If the vibrations are periodic, the constant bandwidth-type analyzer is preferred because the frequency components are harmonically related. If the signal is not quite stable and only the first few harmonics are significant, such as characteristic of a shock signal, a constant percentage bandwidth-type analyzer is suitable. If the vibration signal is random in nature, the type of analyzer will depend on the use to be made of the measurement as well as the frequency spectrum itself.

If the vibrations are periodic, the frequency spectra are presented in terms of the RMS value of the signal, defined earlier.

In random vibrations, the RMS-value fluctuates during measurement because the averaging time is limited to a practical time limit and the time of observation is greater than the averaging time of the instrument. A decrease in averaging time will cause considerable fluctuations in the RMS values.

Vibration Recorders

Many types of metering or recording devices are available to exhibit the analyzer output. These are divided into three classes: the strip-chart recorder which prints the output on preprinted calibrated recording paper; the vibration meter which indicates some characteristic value (RMS, peak, etc.) on a precalibrated scale; and an oscilloscope, which projects the wave form on a screen for analysis and measurement.

When a strip-chart recorder is used, the aver-

aging time is determined by the writing speed of the recording pen, the input range potentiometer, and other internal properties of the recorder instead of observation time. The choice of averaging time affects the recording of a random vibration frequency spectrum.

The oscilloscope presents measurements as a function of time, and makes possible the study of instantaneous values of vibration. An oscilloscope with slow sweep rates, long-persistence screen, and a DC amplifier is recommended for most studies.

Accessories

The accessories used with vibration meters are determined by customer needs and usually can be built into any specified instrument. Integrators to interconvert displacement, velocity, and acceleration can be specified in the basic circuit design of measuring devices. Often, a series of ranges can be requested for a frequency analyzer, depending on the accuracy of the measurements required.

Additional analyzers including the third-octave-bandwidth, tenth-octave-bandwidth, one-percent-bandwidth, and a wave analyzer are available. Different recorders, dependent on desired output, can be used in conjunction with any analyzer. For peak or high speed impacts, the signal can be recorded on tape and then replayed at varied speeds to give the optimum measurement on an electric output signal.

A calibrator is an important accessory for checking the overall operation of a vibration-measuring system. The common calibrator is nothing more than an accelerometer, driven by a small, electromechanical oscillator mounted within the mass, operated at a controlled frequency and RMS acceleration. Provisions can be made for additional calibration of transducers, insert voltage, and reciprocity.

Field Measurements

The arrangement of the vibration equipment for typical field use is shown in Figure 26-12. Sources of error in field measurements must be recognized by the investigator and avoided or minimized, at least. Common sources of error are incorrect mounting, incorrect calibration, connecting cable noises, and thermal effects. In the field, consideration must be given to the location and mounting of the accelerometer in order to record the original motion and resonant frequencies of the structure. The vibration transducer should load the structural member as little as possible, since any loading effects will invalidate the measurement results. In most practical situations, the mass loading effect is negligible but can be checked by the formula:

$$AR = AS \left(\frac{MS}{MS + MA} \right)$$

where AR = Response of structure with accelerometer

AS = Response of structure without accelerometer

MS = Weight of the structure member to which the accelerometer is attached

MA = Weight of the accelerometer

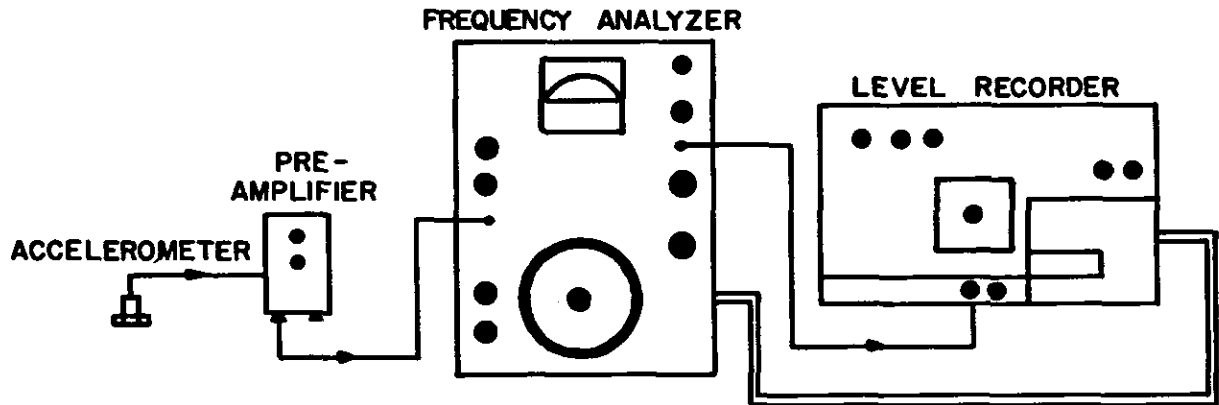


Figure 26-12. Arrangement of Equipment for Automatic Frequency Analysis.

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A number of methods can be used to mount the accelerometer, including mounting by means of a steel stud, an isolated stud and mica washer, a permanent magnet, wax or soft glue, or hand-held with a probe. Use of a steel stud gives the best frequency response, approaching the actual calibration curve supplied with the accelerometer. When electrical isolation is required between the accelerometer and vibrator, a mica washer is used because of its hardness and transmission characteristics. A permanent magnet also gives electrical isolation, but magnetic mass, and temperature effects on the accelerometer can be introduced. Handheld probes are convenient but should not be used for frequencies higher than 1000 Hz where mass loading effects begin. Wax, because of its stiffness, gives a good frequency response but should not be used at high temperatures.

Another source of error, cable noise, originates either from mechanical motion of the cable or from ground loop-induced electrical hum and noise. Mechanical noises originate from local capacity and charge changes due to dynamic compression and tension of the cable, affecting low-frequency readings. A ground loop (see Figure 26-13) induces a current and small voltage drop which adds directly to the sometimes weak accelerometer signal. Insuring that grounding of the installation is made only at one point eliminates ground looping.

In ordinary vibration measurements, temperature effects need not be considered. However, measurements of very low frequency, very low amplitude vibration will be disturbed by even small temperature changes due to the variance of the accelerometer output at a rate determined by the time constant of the accelerometer preamplifier input circuit.

Calibration of a typical vibration measuring arrangement can be made directly from curves and figures supplied by the manufacturer. Special

measuring arrangements can be calibrated using a vibration calibrator.

The following general outline points out the important considerations in a field measurement:

1. Determine placement of the vibration transducer with consideration for possible mass loading effects.
2. Estimate the types and levels of vibrations likely at the mounting point.
3. Select a suitable vibration transducer considering the mass loading effect, types of vibrations, temperature, humidity, acoustic and electric fields.
4. Determine what type of measurement would be most appropriate for the problem at hand.
5. Select suitable electronic equipment, considering frequency and phase characteristics, dynamic range and convenience.
6. Check and calibrate the overall system.
7. Make a sketch of the instrumentation system, including types and serial numbers.
8. Select the appropriate mounting method, checking vibration levels, frequency range, electrical insulation, ground loops, and temperatures.
9. Mount the accelerometer, carry out the measurements, and record the results. Record any octave band analysis of the vibrations, if necessary.
10. Note the setting of various instrument control knobs.

The apparent vibration level, similar to a background reading, should be recorded by mounting the accelerometer on a nonvibrating object in the measured system. Apparent vibrations should be less than one-third of the measured vibrations for accuracy in the actual vibration measurements.

Analysis should include measurements at different points on the machine or system to determine the areas of greatest vibration and their

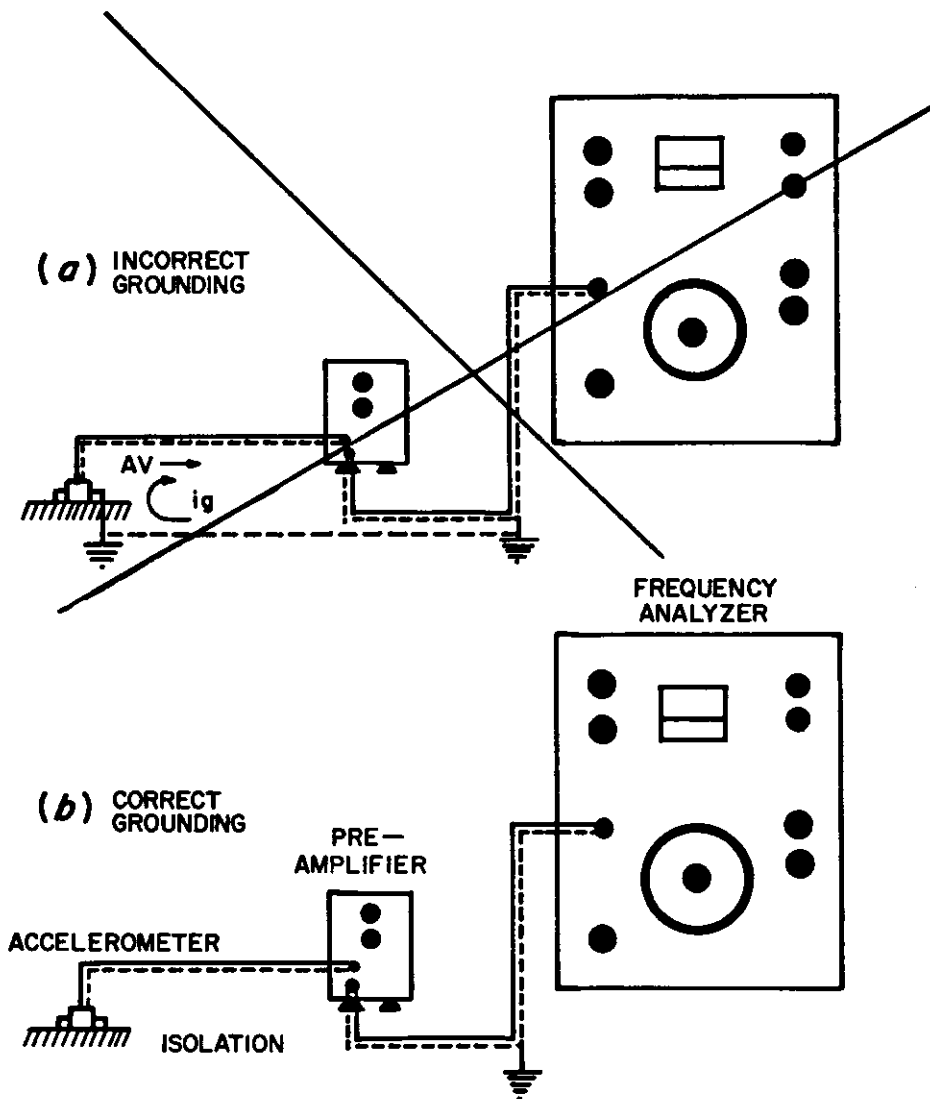


Figure 26-13. Illustration of Ground-Loop Phenomena.

- a) This method of connection forms ground loop and should be avoided.
- b) No ground-loop is formed. Recommended method of connection.

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respective frequency components. Experience is the best guide in pinpointing vibration sources in familiar machinery. Since machine vibrations produce noise, reduction of vibration often reduces noise problems as well.

CONTROL OF VIBRATION

Vibrations may be reduced by:

1. Isolating the disturbance from the radiating surface;
2. Reducing the response of the radiating surface; and
3. Reducing the mechanical disturbance causing the vibration.

Isolation

Vibration isolators effectively reduce vibration transmission when properly installed. The vibration of a machine on isolators is complex, since the machine can move along or rotate about its one vertical and two horizontal axes. The machine will have a resonant frequency for each of the six modes of vibration; thus, it is important that none of the six possible resonances occur at the frequency of the disturbance. To insure adequate isolation, the resonant frequency of the isolator should be less than half the disturbing frequency.

For the vertical mode, which is usually the most important, the resonant frequency of the iso-

lator is related to its static deflection under the weight of the machine by the following formula:

$$f = \frac{3.13}{\sqrt{d}}$$

where d is the static deflection, inches

f is the frequency, Hertz

To find the stiffness required from the isolation mount (spring) when the desired frequency has been determined, the formula:

$$K \approx 0.04 \times MS \times F_o^2 \quad \text{kg/cm}$$

can be used.

K = Spring constant

MS = Machine weight

F_o = Resonant frequency of the machine and isolation mount system.

Since the degree of isolation increases as the resonant frequency is lowered, the equation indicates that isolation is improved as the static deflection is increased.

Transmission of vibration to an adjacent structure may also be reduced by making electrical connections less rigid. For piping, electrical connections, and ductwork flexible connectors may be used. When using enclosures, the housing should be anchored to the floor rather than the machine to eliminate transmission of the vibration to the enclosures.

Another important consideration is that the vibration isolators be placed correctly with respect to the motion of the center of gravity of the machine, with the center of gravity located as low as possible. In cases of instability, i.e., "rocking", the effective center of gravity may be lowered by first mounting the machine on a heavy mass and isolating the mass from the machine.

Reduction of Surface Response (Damping)

In cases where isolation of the vibrations is not suitable, or is difficult to arrange, the principle of vibration absorbers may be used. By attaching a resonance system to the vibrating structure (which counteracts the original vibrations), the structure vibrations can be eliminated. Through mathematical differential equations it can be shown that by tuning the absorber system resonant frequency, it is theoretically possible to eliminate the vibration of the machine.

Structural elements like beams and plates exhibit an infinite number of resonances. When subjected to vibrations of variable frequency, the application of separate dynamic absorbers to structural elements becomes impractical. Since there is usually little inherent damping of resonant vibrations in the structural elements themselves, external arrangements must be made to reduce vibrations.

External damping can be applied in several ways:

1. By means of interface damping (friction)
2. By application of a layer of material with high internal losses over the surface of the vibrating element
3. By designing the critical elements as "sandwich" structures.

Interface damping is obtained by letting two

surfaces slide on each other under pressure. With no lubricating material the "dry" friction produces the damping effect, although this commonly causes fretting of the two surfaces. When an adhesive separator is used, a sandwich structure results, a concept which will be discussed later.

Mastic "deadeners" made of an asphalt base are commonly sprayed onto a structural element in layers, to provide external dampening. These deadeners are commonly made from high-polymer materials with high internal energy losses over certain frequency and temperature regions. To obtain optimum damping of the combination structural element and damping material, not only must the internal loss factor of the damping material be high, but so must its modulus of elasticity (the ratio of stress to strain).

An approximate formula (see Figure 26-14) governing the damping properties of a treated panel is given by:

$$N \approx 14 \left(\frac{N_2 E_2}{E_1} \right) \left(\frac{d_2}{d_1} \right)^2$$

N = Loss factor of the combination structure element + damping material

N_2 = Loss factor of the damping material

E_1 = Modulus of elasticity of the structural element

E_2 = Modulus of elasticity of the damping material

d_1 = Thickness of the structural element

d_2 = Thickness of the damping material layer.

The ratio $\left(\frac{d_2}{d_1} \right)^2$ is the most important factor,

usually around 3:1 for best results.

The third method of damping is the use of sandwich structures; a thick or thin layer of viscoelastic material is placed between two equally thick plates, or a thin metal sheet is placed over the viscoelastic material which is covering the panel. The damping treatment will be more effective if applied to the area where vibration is greatest, but the actual amount of treatment and the area of coverage are best determined by experiment. As a rule of thumb, the amount (density \times thickness) of material applied should equal that of the surface to which it is applied. Since this can lead to using large amounts of damping material, the method of covering the damping material with a sheet metal overlay is often used. Studies²¹ show that to a certain extent, the thickness of a layer is not the most important factor; but in cases of sandwich layers, symmetry is most significant. Sandwich layers often are preferred due to a greater dampening factor (Figure 26-14) than with single layer coatings.

Reduction of Mechanical Disturbance

Mechanical disturbances that produce vibration can be reduced by reducing impacts, sliding or rolling friction, or unbalance.

In all cases, either mechanical energy is coupled into mechanical-vibratory energy, or energy in some other form is transformed into mechanical-vibratory energy. These other forms of energy include: varying electrical fields, varying hy-

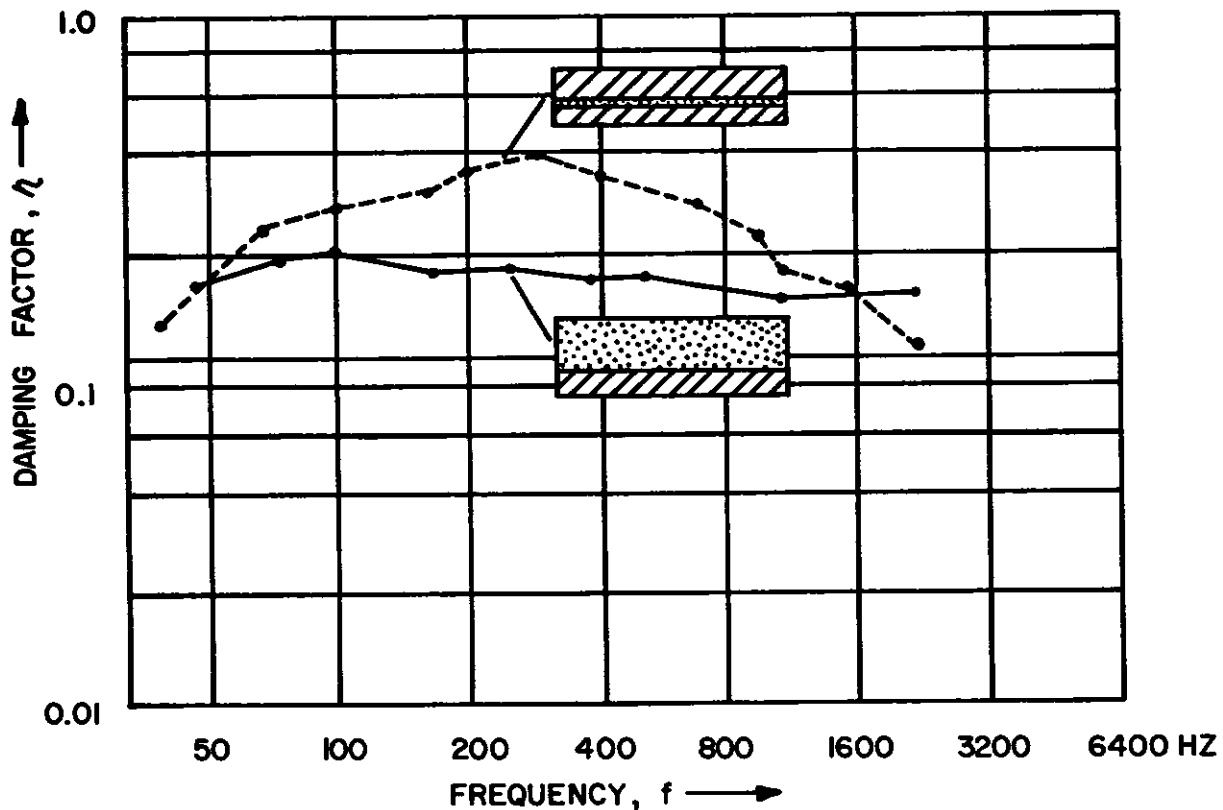


Figure 26-14. Results of Loss Factor Measurements on a Sandwich Structure with a Thin Visco-Elastic Layer, and on a Plate Supplied with One Layer Mastic Deadening ($d_2/d_1 \approx 2.5$). After Cremer and Heckl.²¹

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draulic forces, aerodynamic forces, acoustic excitation, and thermal changes.

Often mechanical vibration can be reduced by: (1) proper balancing of rotating machinery, (2) reducing response of equipment to a driving force, and (3) proper maintenance of machinery.

Limitations of Control Methods

In conjunction with the practical applications of isolators and dampers, certain limitations should be noted in the control of vibration:

1. Reduction in transmissibility can only take place by allowing the isolator to deflect by motion. Thus, certain space clearances must be provided for the isolated equipment.
2. If the resonant frequency of the isolation system is chosen incorrectly, the isolator may actually amplify the destructive characteristics. Select a spring mounting so that the natural frequency, F_0 , of the spring-mass system is considerably (at least one-half) lower than the lowest frequency component in the force system produced by the machine.
3. If the isolator produces unexpected non-

linear characteristics a great number of extra response effects may take place.

The reduction in shock severity which may be obtained by the use of isolators results from the storage of the shock energy within the isolators and its subsequent release in a "smoother" form. Unfortunately, since a shock pulse may contain frequency components ranging from nil to near infinity it is not possible to avoid excitation of the isolator-mass system.

Damping is a costly method of reducing the response of a radiating surface, and is therefore generally avoided. Mechanical disturbances, primarily dependent upon an effective maintenance program, are rarely eliminated completely.

In conclusion, all vibration problems should be approached by determining first if a quick, simple, and "common sense" solution is available. If a simple answer is not obvious, the quantitative results of measurements become essential in the analysis and solution of the problem. As various control procedures are tried, vibration measurements can be used to show the progress being made and predict the correct steps in reducing vibrations further.

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ILLUMINATION

John E. Kaufman

INTRODUCTION

Lighting of the industrial environment provides for the visibility of objects and awareness of space needed for man to perform in a productive and secure manner. Not only should the lighting be properly designed and coordinated with the thermal, spatial and sonic designs, but it should be maintained through planned servicing procedures. The only means for determining whether a particular environment has been properly designed and is correctly maintained is to perform periodic evaluations or surveys.

In evaluating the lighting in any environment it is important to know how to make an effective meaningful survey and this can only be done with a basic understanding of lighting terminology, established recommendations for quantity and quality of lighting, types of lighting equipment and design procedures, and finally survey methods and instruments to be used.

LIGHTING TERMINOLOGY

The lighting terms most often used in design and evaluation of illuminated spaces include: intensity, illumination level, luminance, reflectance, lamp and luminaire. Most often used units of measurement are: candela, lumen, footcandle and footlambert. For a more complete list of terms with their definitions see Section 1 of reference 1.

Intensity

Intensity, or more correctly luminous intensity, is an indication of how much light a source gives off in a given direction. The unit of luminous intensity is the *candela* (formerly "candle"). It is sometimes referred to as "candlepower."

Lumen

The lumen is the unit of light output from a light source. For example, a 100-watt incandescent lamp emits about 1700 lumens initially in all directions, whereas a 40-watt cool-white fluorescent lamp emits about 3200 lumens initially. By definition, a light source of one candela produces 4π lumens.

Illumination Level

Illumination level is the amount or quantity of light falling on a surface and is measured in *footcandles*. If, for example, 100 lumens from a light source falls on one square foot of a table top, the illumination level on the table would be 100 footcandles. Also, a surface one foot from a source with an intensity of 100 candelas would have an illumination level of 100 footcandles.

If the unit of surface area is in square meters rather than square feet, the illumination is measured in *lux*.

Luminance

Luminance, or photometric brightness, is a measure of the amount of light emitted or reflected from a certain area of a surface. Its unit is *foot-lamberts* when the area of surface is square feet. A surface emitting one lumen per square foot of surface has a luminance of one footlambert. A bare 40-watt fluorescent lamp has a luminance of about 2400 footlamberts, whereas the moon has a luminance of nearly 1170 footlamberts.

If the unit of surface area is in square meters rather than square feet luminance is measured in *candelas/square meter*.

Reflectance

Reflectance is a measure of how much light is reflected from a surface. Actually it is the ratio of the luminance of a surface to the illumination on the surface (i.e., $\text{reflectance} = \text{luminance} / \text{illumination}$). A completely black surface has a 0 percent reflectance. A perfectly white surface has a reflectance of nearly 1.0 or 100 percent. Most surface finishes have reflectances of between 5 to 95 percent.

Lamp

Lamp is the term used for man-made light sources. Incandescent lamps are also called "bulbs" and fluorescent lamps, "tubes." "Lamp" is also used for the name of a complete lighting device consisting of a lamp, shade, reflector, housing, etc.

Luminaire

A luminaire is a complete lighting device consisting of one or more lamps together with parts to distribute the light, to position and protect the lamps and to connect the lamps to the power supply.

PURPOSE OF LIGHTING

The purpose of lighting in industry is to provide efficient, comfortable seeing of industrial visual tasks and to help provide a safe working environment. Advantages derived from good lighting include: fewer mistakes, increased production, reduction in accidents, improved morale and improved housekeeping.

Lighting for Task Performance

Visual tasks in industry vary in degree of difficulty depending on their size, their contrast (between detail and surround), their luminance and the time available for seeing. The smaller a task size the more difficult it is to see — for equal illumination a very small letter identification on a printed circuit board is harder to see than the type on this page. Tasks of low contrast, such as a gray stain on gray cloth are more difficult to see

than higher contrast tasks such as a dark gray stain on white cloth. Also, it usually is easier to see an inspection task if more time is available for viewing.

The factors of size, contrast and in many cases time, are inherent in a visual task. On the other hand task luminance is variable and can easily affect task visibility — the higher the luminance (the greater the illumination) the more visible the task. This is due to an increase in eye sensitivity with increased luminance.

Lighting for Safety and Comfort

Lighting adequate for seeing production and inspection tasks usually will be more than needed for safety alone. If task lighting is not provided throughout the working space, adequate surrounding illumination is required to provide visibility of nearby objects which might be potential hazards or to see to operate emergency control equipment. In addition, lighting of ceiling and walls and the avoidance of glare will help provide a greater sense of well being and comfort.

ILLUMINATION REQUIREMENTS FOR INDUSTRY

Quantity of Illumination

The difficulty of seeing tasks, based on contrast, size and time for viewing as discussed above, is used as a basis for determining the levels of illumination for industrial areas. Research has shown that levels of illumination in the thousands of footcandles are required to see dark, low-contrast tasks as easily as light-colored tasks of high contrast under low levels. For light-colored, high-contrast tasks, the levels required for good visibility are very low. However, there are many factors in addition to visibility that affect the concept of easier seeing which suggest a minimum of 30 footcandles be used for all areas where seeing is done regularly, even for the simplest seeing tasks.²

The *American National Standard Practice for Industrial Lighting*³ contains a tabulation of recommended levels of illumination for specific visual tasks and areas based on task characteristics and the visual performance requirements of young adults with normal eyes. According to the *American National Standard Practice for Industrial Lighting*³ "These lighting recommendations are intended to provide guides for lighting levels desirable from an overall operational standpoint rather than from safety alone and, therefore should not be interpreted as recommendations for regulatory minimum lighting levels." Table 27-1 is a sample of the type of recommendations listed and is included here to show its form. Task areas are shown with corresponding footcandle levels recommended for the tasks in the area, these levels to be used as the minimum value on the task when the lighting system and room surface have depreciated to their lowest before maintenance procedures are effected (cleaning, relamping, painting, etc.). Also, in some cases, as denoted by a double asterisk, supplementary lighting can be used.

The levels recommended usually do not take

into account the wearing of safety goggles that materially reduce the light reaching the eyes. If they are worn, the level of illumination should be increased in accordance with the absorption of the goggles used.

Quality of Illumination

By definition, quality in lighting pertains to the distribution of luminances in a visual environment and is used in a positive sense to imply that all luminances contribute favorably to comfort, safety, esthetics as well as ease of seeing. Excessively high luminances may produce glare and veiling reflections and affect eye adaptation. Improper distribution of luminances also may affect adaptation and cause shadows. Installations of very poor quality are easily recognized but those of moderately poor quality are not, even though there may be a material loss in seeing.

TABLE 27-1.

Levels of Illumination Currently Recommended*

Area	Footcandles on Tasks*
Clothing manufacture (men's)	
Receiving, opening, storing, shipping	30
Examining (perching)	2000**
Sponging, decatizing, winding, measuring	30
Piling up and marking	100
Cutting	300**
Pattern making, preparation of trimming, piping, canvas and shoulder pads	50
Fitting, bundling, shading, stitching	30
Shops	100
Inspection	500**
Pressing	300**
Sewing	500**

*Minimum on the task at any time.

**Can be obtained with a combination of general lighting plus specialized supplementary lighting. Care should be taken to keep within the recommended luminance ratios. These seeing tasks generally involve the discrimination of fine detail for long periods of time and under conditions of poor contrast. The design and installation of the combination system must not only provide a sufficient amount of light, but also the proper direction of light, diffusion, color and eye protection. As far as possible it should eliminate direct and reflected glare as well as objectionable shadows.

Glare. There are two general forms of glare — *discomfort glare* and *disability glare* — and both may be caused by bright light sources (electric and daylight) and by bright reflections in room surfaces. Glare from light sources and luminaires is known as *direct glare*; that from surfaces, as *reflected glare*.

Discomfort glare, as its name implies, produces discomfort and may affect human performance, but does not necessarily interfere with visual performance or visibility. In some cases extremely bright sources (the sun) can even cause pain. Disability glare does not cause pain, but reduces the visibility of objects to be seen. An example is the reduced visibility of objects on a roadway at night caused by the glare of bright oncoming headlights.

An industrial environment, then, will be relatively comfortable visually, if there is no glare, and seeing will be unimpaired if there is no disability glare. The effects of glare can be avoided or minimized by mounting luminaires as far above or away from normal lines of sight as possible and by limiting their luminance and quantity of light emitted toward the eyes. In general, this can be done by shielding luminaires to at least 25 degrees down from the horizontal and preferably down to 45 degrees. In other words, the brightness of bare lamps preferably should not be seen when looking in the range from straight ahead to 45 degrees above the horizontal. For critical working areas such as offices and laboratories the quality criteria of the *American National Standard Practice for Office Lighting*⁴ should be followed. *Veiling Reflections.* When reflected glare is produced on or within the visual task itself it becomes a veiling reflection because in most cases it will veil the task (reducing its visibility) by reducing its contrast. In some cases these losses in contrast are quite apparent; in others the losses are unnoticed yet may produce a marked reduction in visibility. The effects of veiling reflections may be reduced by increased levels of illumination and or by using layouts and luminaires designed to limit the light directed toward the task that will be reflected into the eyes. See the *IES Lighting Handbook*.¹

Luminance Distribution. The eyes function more efficiently and comfortably when the luminances within the visual environment are not too different from that of the seeing task. While performing a task the eyes become adapted to the luminance of the task. If however, the eyes shift to view a window or floor of higher or lower luminance and then back to the task, the visibility of the seeing task will be reduced until the eyes readapt to the task luminance. To reduce this effect, maximum luminance ratios are recommended as shown in Table 27-2. As an aid in achieving these reduced luminance ratios, the reflectance of room surfaces and equipment should be as listed in Table 27-3. *Distribution, Diffusion and Shadows.* In industrial areas where the locations of equipment and operations are not known, it is desirable to provide uniform illumination such that the highest and lowest levels are no more than one-sixth above or below the average. This also will help maintain desirable luminance distributions as recommended above.

Depending on the type of visual task and the operation, some tasks require directional lighting and others diffuse, but in both cases shading of the task should be avoided. Most tasks can be

TABLE 27-2
Recommended Maximum Luminance Ratios³

	Environmental Classification		
	A	B	C
1. Between tasks and adjacent darker surroundings	3 to 1	3 to 1	5 to 1
2. Between tasks and adjacent lighter surroundings	1 to 3	1 to 3	1 to 5
3. Between tasks and more remote darker surfaces	10 to 1	20 to 1	*
4. Between tasks and more remote lighter surfaces	1 to 10	1 to 20	*
5. Between luminaires (or windows, skylights, etc.) and surfaces adjacent to them	20 to 1	*	*
6. Anywhere within normal field of view	40 to 1	*	*

*Luminance ratio control not practical.

A—Interior areas where reflectances of entire space can be controlled in line with recommendations for optimum seeing conditions.

B—Areas where reflectances of immediate work area can be controlled, but control of remote surround is limited.

C—Areas (indoor and outdoor) where it is completely impractical to control reflectances and difficult to alter environmental conditions.

TABLE 27-3
Recommended Reflectance Values²
Applying to Environmental Classifications
A and B

	Reflectance* (percent)
Ceiling	80 to 90
Walls	40 to 60
Desk and bench tops, machines and equipment	25 to 45
Floors	not less than 20

*Reflectance should be maintained as near as practical to recommended values.

satisfactorily illuminated by diffuse illumination, but tasks of inherently low contrast and of a three-dimensional nature often can be seen best using directional light to produce shadows and reflections to improve contrast. Examples of such tasks are glossy black thread on matte black cloth and

scratches on sheet metal. In the latter case it is especially important that the lighting be designed so that it will not produce reflected glare in the sheet metal.

Color. For equal levels of illumination variations in the color quality of currently used "white" light sources have little or no effect upon clearness or speed of seeing. However, when contrast is low and color discrimination is important, source and surrounding surface colors should be selected carefully.

INDUSTRIAL LIGHTING EQUIPMENT

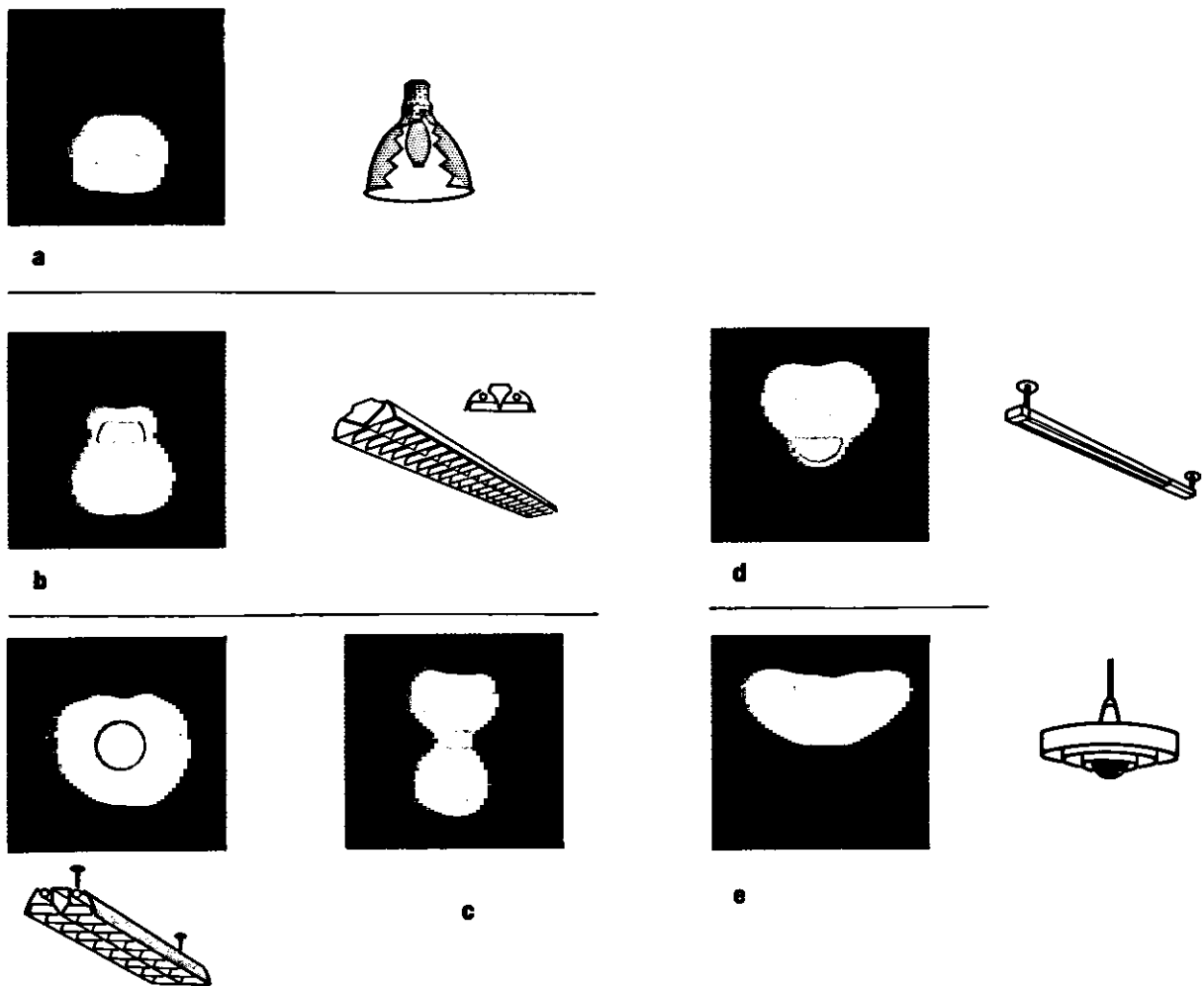
Light Sources

Daylight and electric light are the two main sources of light for industrial areas. The use of daylight depends on building design orientation and site conditions as well as the availability of daylight at the location;² however, because daylight is not always available electric lighting is provided.

Electric light sources used for industrial application fall into three categories: incandescent (including tungsten-halogen), fluorescent and high-intensity discharge (including mercury, metal halide and high pressure sodium). Although all types can be used, there are certain applications for which some are better suited than others. For detailed information on their physical and operating characteristics as well as industry averaged photometric data (lumen values) consult the *IES Lighting Handbook*.¹

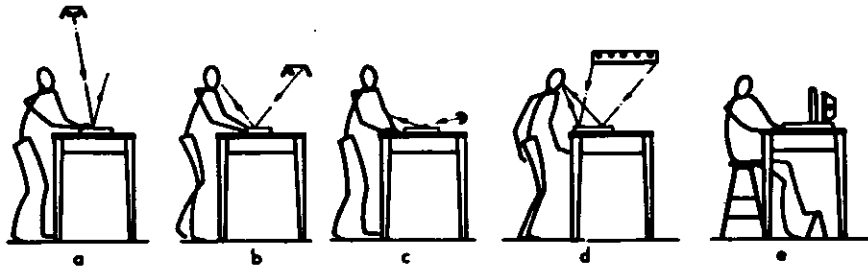
Luminaires

There are two categories of luminaires for industrial lighting — general and supplementary. *General Luminaires* are classified into five types according to their light distribution, as shown in Figure 27-1, and are used to provide general lighting throughout an area or localized general lighting, where the luminaries are located to provide higher levels at specific task locations yet provide some degree of general lighting. Each type of dis-



Illuminating Engineering Society, New York, New York.

Figure 27-1. Luminaire Classifications by Light Distribution: (a) Direct Lighting, (b) Semi-Direct Lighting, (c) General-Diffuse and Direct-Indirect Lighting, (d) Semi-Indirect Lighting and (e) Indirect Lighting.



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Figure 27-2. Examples of Placement of Supplementary Luminaires: (a) Luminaire Located to Prevent Reflected Glare — Reflected Light Does Not Coincide with Angle of View. (b) Reflected Light coincides with Angle of View. (c) Low-Angle Lighting to Emphasize Surface Irregularities. (d) Large-Area Surface Source and Pattern are Reflected toward the Eye. (e) Transillumination from Diffuse Sources.

tribution has an application in industrial lighting, for example: *direct* types are the most efficient (but may produce disturbing shadows and glare unless units are of large size, mounted close together and have some upward light), whereas at the other extreme *indirect* types are least efficient but produce more comfortable lighting. No one system can be recommended over all the others. Each should be evaluated based on the quantity and quality requirements of the space.

Supplementary luminaires are luminaires used along with a general lighting system but are located near the seeing task to provide the higher levels or quality of lighting not readily obtainable from the general lighting system. They are divided into five major types from Type S-I to S-V, based on their light distribution and luminance characteristics. Each has a specific group of applications and locations, as shown in Figure 27-2, to best illuminate the seeing task involved.

LIGHTING DESIGN

In industrial areas where the primary function of the lighting installation is to provide illumination for quick, accurate performance of visual tasks, the task itself is the starting point in the lighting design. Factors to be considered in the design process are listed below, but it should be recognized that the success of the design also depends on the accuracy of the information available to the designer.

1. Visual Task.

- a. What commonly found visual tasks are to be lighted?
- b. How should the tasks be portrayed by the lighting? Should the lighting be diffuse or directional? Are shadows important for a three dimensional effect? Will the tasks be susceptible to veiling reflections? Is color important?
- c. What level of illumination should be provided in accordance with the *American National Standard Practice for Industrial Lighting*?⁸

2. Area in Which Task Is Performed.

- a. What are the dimensions of the area and reflectances of surfaces?
- b. What should the surface luminances be to minimize eye adaptation effects without creating a bland environment?
- c. Might the surfaces produce reflected glare?
- d. Is illumination uniformity desirable (general illumination or task illumination)?

3. Luminaire Selection.

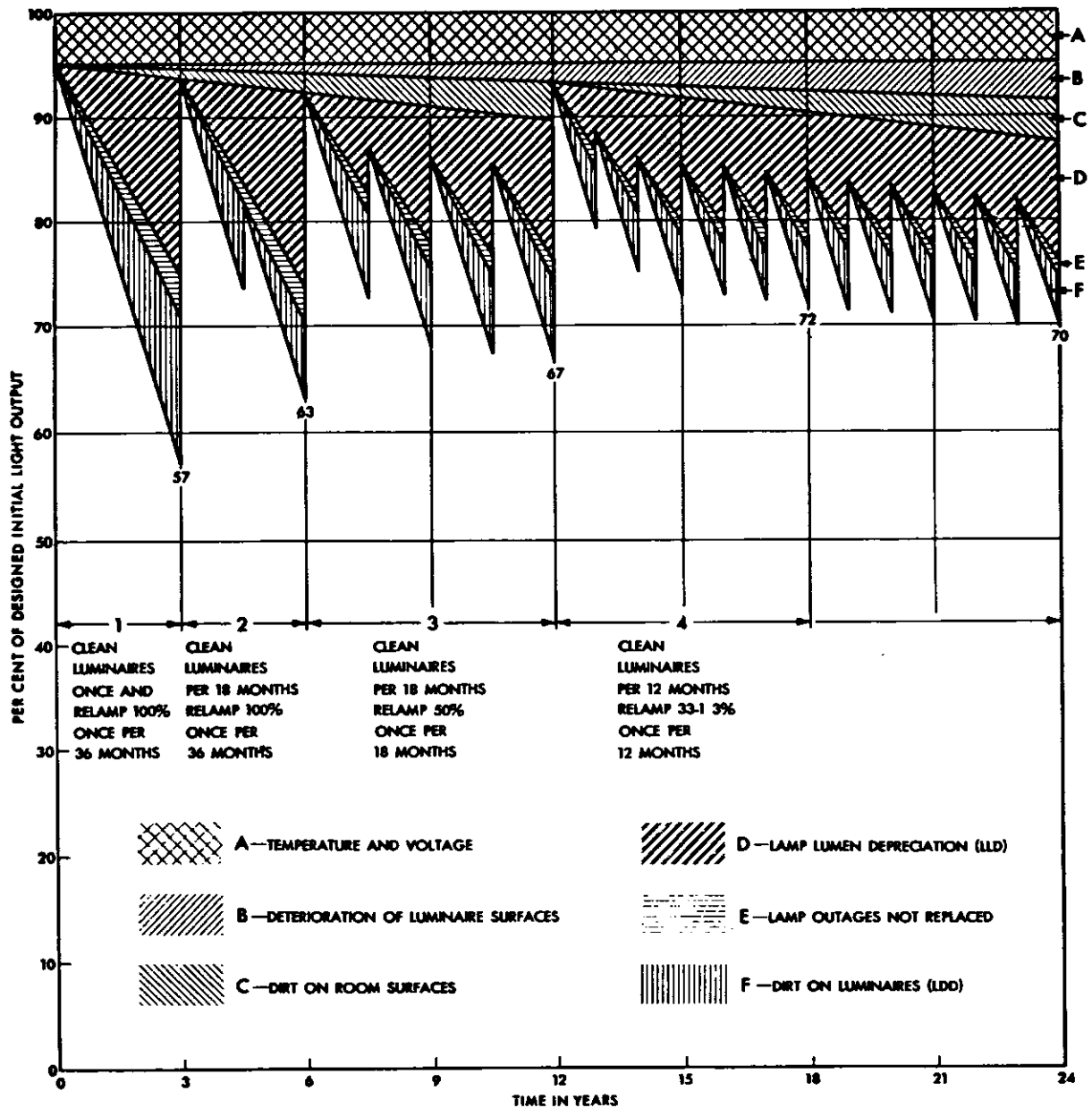
- a. What type of distribution and lamp color quality is needed to properly portray the task (for diffusion, shadows or avoiding veiling reflections) and provide a comfortable environment (visually, thermally and sonically)?
- b. What type is needed to illuminate the area surfaces (for eye adaptation, for avoiding reflected glare)?
- c. What is the area atmosphere and therefore the type of maintenance characteristics needed?
- d. What are the economics of the lighting system?

4. Calculation, Layout and Evaluation.

- a. What layout of luminaires will portray the task best (illumination level, direction of illumination, veiling reflections, disability glare)?
- b. What layout will be most comfortable (visually — direct and reflected glare, thermally)?
- c. What layout will be most pleasing esthetically?

General Illumination

When task locations are not known or a flexible arrangement of operations is desirable, lighting is usually designed to provide general illumination of the required amount throughout the area. This is also true where supplementary luminaires are used for task illumination alone. The calculation procedure for designing general illumination



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Figure 27-3. Six Causes of Light Loss. Example above uses 40-watt T-12 cool white rapid start lamps in enclosed surface mounted units, operated 10 hours per day, 5 days per week, 2600 hours per year. All four maintenance systems are shown on the same graph for convenience. For a relative comparison of the four systems, each should begin at the same time and cover the same period of time.

is the *Lumen Method*, where, with a uniform layout of luminaires, a relatively uniform level of illumination will be provided on a horizontal work-plane at a given distance above the floor. A detailed outline of this method can be found in *General Procedure for Calculating Maintained Illumination*.⁶

Task Illumination

When task locations are known, *Point Method* procedures are used for design. Methods are

available⁷ for calculating illumination levels at specific locations on horizontal, vertical and inclined surfaces, from all types of general or supplementary lighting systems. Use of these methods is the most accurate means of checking illumination levels on tasks during the design stage.

Maintenance

As mentioned above, the success of the lighting design is dependent on the accuracy of the information available to the designer, including

the lighting servicing plan for maintaining the lighting from installation to end of life. Figure 27-3 illustrates the sizeable effects of various elements of light loss (temperature, voltage, dirt on luminaires and room surfaces, lamp depreciation and burnouts and deterioration of luminaire parts) on the level of illumination from initial operation (100 hours use) through various stages of servicing procedures. It is important to know or correctly assume these losses. It is equally as important to know the type of servicing plan so that minimum maintained levels can be designed for; so that during a lighting survey the surveyor will know if initial or lowest expected values are being measured, or whether the survey is somewhere between.

Guidance for the use of light loss factors in design and information on lighting maintenance can be found in the *IES Lighting Handbook*.¹

LIGHTING SURVEYS

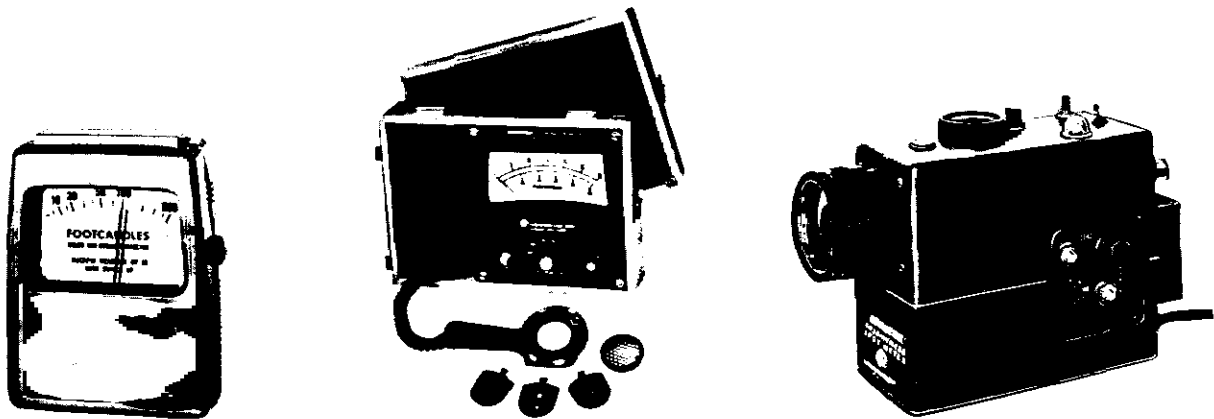
Evaluation of the lighting in an industrial environment depends on the amount and type of information obtained during survey procedures

and on the evaluator's knowledge and understanding of industrial operations and their associated lighting recommendations. The material presented so far in this chapter deals with lighting recommendations. The following deals with the survey and evaluation.

Measurable Quantities

A lighting survey can be as simple or as comprehensive as desired, but in any case three essential quantities are measured or determined: illumination (footcandles), luminance (footlamberts) and reflectance (percent). For the more comprehensive surveys, temperature and voltage are also measured.

Illumination readings are made at task locations for task lighting, at various locations on the horizontal work-plane for general lighting, and in some cases on various room surfaces to determine luminances and reflectances. *Luminance* readings are made of luminaires and room and task surfaces. *Reflectance* determinations are made of room surfaces. *Temperature* is measured in the air near luminaires. *Voltage* is measured at the luminaire input.



Illuminating Engineering Society, New York, New York.

Figure 27-4. Typical Photoelectric Meters Used in Lighting Surveys: (a) Pocket-Size Illumination Meter, (b) Paddle-Type Illumination Meter with Operational Amplifier, and (c) Luminance Meter.

Instruments

Illumination (Light) Meters. Figure 27-4a and b shows two typical illumination meters — a pocket-type and a more accurate paddle-type. The degree of accuracy required dictates the type of meter to be used, but in any case, instruments should be color corrected (to account for the response of the eye to light), cosine corrected (to compensate for light reflected from the light-detecting cell surface), calibrated for accuracy and with scale ranges so that no measurements are made below one-quarter full scale. A luminance meter (see below) can be used to measure illumination if a

target of known reflectance is measured (illumination = luminance ÷ reflectance).

Luminance (Brightness) Meters. Figure 27-4c shows a typical direct reading portable luminance meter. Again the degree of accuracy required dictates the type of meter to be used and its corrections, sensitivity and calibration. Luminance of surfaces also can be measured using an illumination meter if the reflectance of the surface is known (luminance = illumination × reflectance).

Reflectance can be measured directly using a Baumgartner reflectometer,¹ however in field surveys, reflectance is usually determined by visual

comparison of the unknown surface with color chips of known reflectance (Munsell Value Scales¹) or by calculation using measurements (reflectance = luminance ÷ illumination).

Survey Procedures

The publication *How to Make a Lighting Survey*,⁷ developed by the Illuminating Engineering Society in cooperation with the U. S. Public Health Service, provides a uniform detailed lighting survey form along with instructions for use. The survey involves recording the following information:

1. Description of the illuminated area — room dimensions; colors, reflectances and condition of room surfaces; and temperature surrounding luminaires.

2. Description of the general lighting system — quantities, condition, wattages, lamps, distribution, spacing and mounting.

3. Description of any supplementary lighting equipment used — as in 2, above.

4. Description of instruments used — manufacturer, model and date of last calibration.

5. Illumination measurements — at specific locations, depending on type of lighting system used.

6. Luminance measurements — from specific work locations in normal viewing directions.

7. Answers to a series of questions concerning the lighting servicing procedure and a subjective evaluation of the lighting.

Evaluation of Results

The measurements and other data recorded are used to determine: (a) illumination levels (for compliance with footcandle recommendations), (b) luminance values (for compliance with luminance ratio limits for visibility and safety) and (c) an indication of the degree of comfort and pleasantness in the area (from answers to related questions). In addition, these data are useful in de-

termining if adequate maintenance or lighting servicing procedures are in effect. Also, they can indicate if deficiencies exist and what changes can be made for improvement; (e.g., application of higher or lower surface reflectances, better use of color, different luminaire locations for uniformity and to avoid shadows and glare, more light on the ceiling and better control of the daylighting).

It should be realized, of course, that the conditions existing during the survey may not be the same as those assumed by the designer in his design procedure, and the surveyor and evaluators should be aware of this.

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NON-IONIZING RADIATION

George M. Wilkening

INTRODUCTION

Current Interest in the Non-Ionizing Radiations

Interest in the public health aspects of the non-ionizing radiations has increased many fold due to the expanded production of electronic products which use or emit radiation, e.g., lasers, microwave ovens, radar for pleasure boats, infrared inspection equipment and high intensity light sources. All such sources generate so-called "non-ionizing" radiation, a term which is defined in the section entitled "Nature of Electromagnetic Energy." Because of the proliferation of such electronic products as well as a renewed interest in electromagnetic radiation hazards, the Congress recently enacted Public Law 90-602, the "Radiation Control for Health and Safety Act of 1968."

PL 90-602 has as its declared purpose the establishment of a national electronic product radiation control program which includes the development and administration of performance standards to control the emission of electronic product radiation. The most outstanding feature of the Act is its omnibus coverage of all types of both ionizing and non-ionizing electromagnetic radiation emanating from electronic products, i.e., gamma, X rays, ultraviolet, visible, infrared, radiofrequencies (RF) and microwaves. Performance standards have already been issued under the Act for TV sets and microwave ovens; preparations are underway for the issuance of a laser standard. In similar fashion, the recent enactment of the federal "Occupational Safety and Health Act of 1970" gives due attention to the potential hazards of non-ionizing radiations in industrial establishments.

For the purposes of this chapter more formal treatment is given to ultraviolet radiation, lasers, and microwave radiation than to the visible and infrared (IR) radiations. However, the information on visible and IR radiation presented in the section on "Laser Radiation" is generally applicable to noncoherent sources.

Nature of Electromagnetic Energy

The electromagnetic spectrum extends over a broad range of wavelengths, from less than 10^{-12} cm to greater than 10^{10} cm. The shortest wavelengths are generated by cosmic and X-rays; the longer wavelengths are associated with microwave and electrical power generation. Ultraviolet, visible and infrared radiations occupy an intermediate position. Radio frequency waves may range from 3×10^{10} μm to 3×10^2 μm ; infrared rays, from 3×10^2 μm to about 0.7 μm ; the visible spectrum, from approximately 0.7 μm to 0.4 μm ; ultraviolet, from approximately 0.4 μm to 0.1 μm ;

and gamma and x radiation, below 0.1 μm (see Fig. 28-1). The photon energies of electromagnetic radiations are proportional to the frequency of the radiation and inversely proportional to wavelength. Hence, the higher energies, e.g., 10^8 electron volts (eV) are associated with X-ray and gamma radiations, and the lower energies (e.g., 10^{-9} eV) with RF and microwave radiations.

Whereas the thermal energy associated with molecules at room temperature is approximately 1/30 eV, the binding energy of chemical bonds is roughly equivalent to a range of <1 to 15 eV. The nuclear binding energies of protons may be equivalent to 10^8 eV and greater. Since the photon energy necessary to ionize atomic oxygen and hydrogen is of the order of 10-12 eV it seems in order to adopt a value of approximately 10 eV as a lower limit in which ionization is produced in biological material. Hence, those electromagnetic radiations that do not cause ionization in biological systems may be presumed to have photon energies less than 10-12 eV and, therefore, may be termed "nonionizing." An extremely important qualification however is that non-ionizing radiations may be absorbed by biological systems and cause changes in the vibrational and rotational energies of the tissue molecules, thus leading to possible dissociation of the molecules or, more often, dissipation of energy in the form of fluorescence or heat.

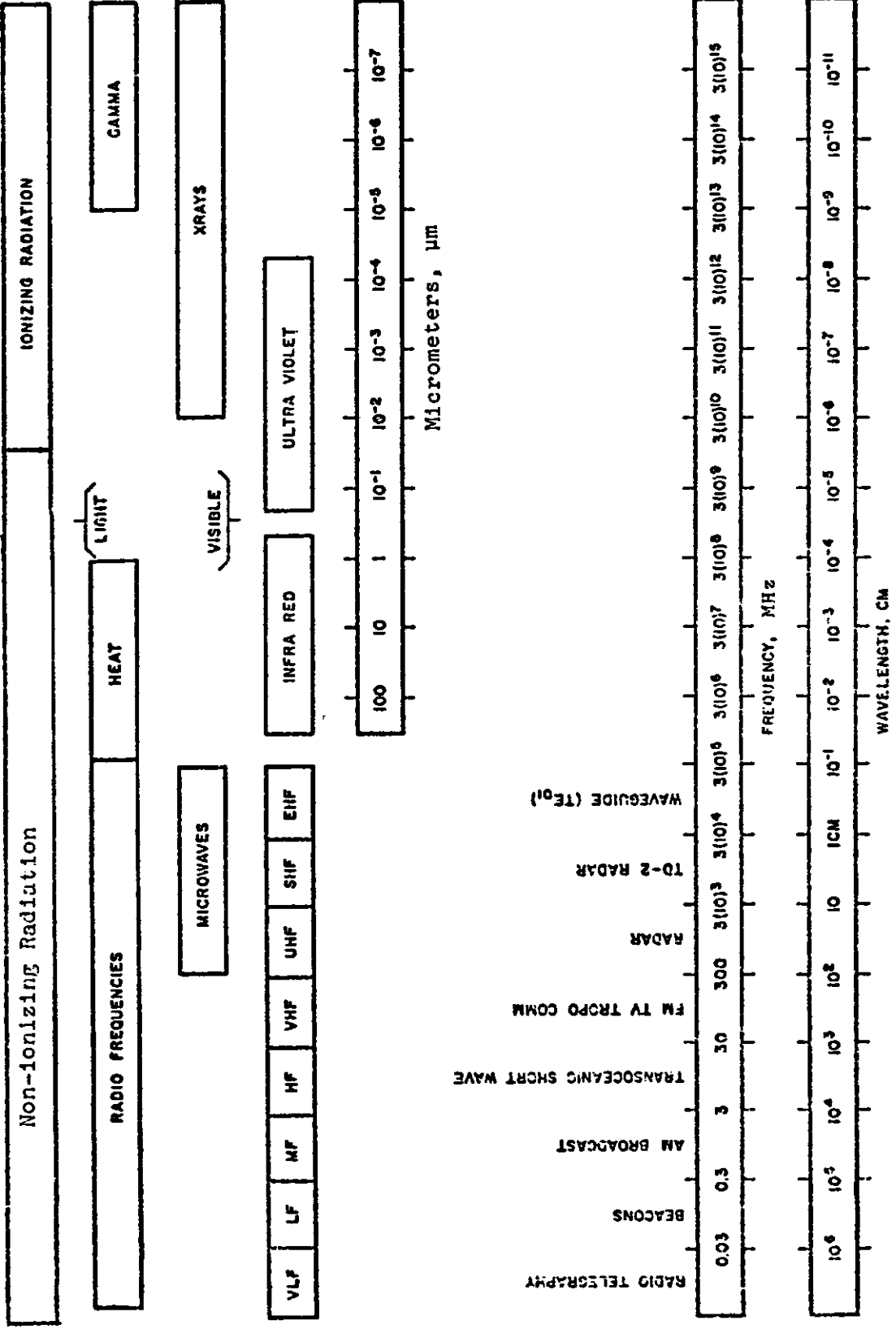
In conducting research into the bioeffects of the nonionizing radiations the investigator has had to use several units of measurement in expressing the results of his studies. For this reason Appendix A, containing definitions of many useful radiometric terms has been included. Appendix B provides a simple means for expressing radiant exposure and irradiance units in a number of equivalent terms.

Since the eye is the primary organ at risk to all of the non-ionizing radiations, Appendix C has been added to provide the reader with a general scheme of absorption and transmission of electromagnetic radiations within the human eye.

ULTRAVIOLET RADIATION

Physical Characteristics of Ultraviolet Radiation

For the purpose of assessing the biological effects of ultraviolet radiation the wavelength range of interest can be restricted to 0.1 μm to 0.4 μm . This range extends from the vacuum ultraviolet (0.1 μm) to the near UV (0.4 μm). A useful breakdown of the ultraviolet region is as follows:¹



Mumford WW: Some Technical Aspects of Microwave Radiation Hazards. Proc. IRE 49:427-47, 1961.

Figure 28-1. The Electromagnetic Spectrum.

UV Region	—Range, μm .	Photon Energy (electron volts)
Vacuum	<0.16	>7.7
Far	0.16-0.28	7.7-4.4
Middle	0.28-0.32	4.4-3.9
Near	0.32-0.4	3.9-3.1

The photon energy range for wavelengths between 0.1 μm and 0.4 μm is 12.4 to 3.1 electron volts respectively. Certain transmission, absorption and reflectance characteristics of ultraviolet radiation are given in Tables 28-1 and 28-2.

Representative Sources of Ultraviolet Radiation

The major source of ultraviolet radiation is the sun, although absorption by the ozone layer permits only wavelengths greater than 0.29 μm to reach the surface of the earth. Low and high pressure mercury discharge lamps and welding

TABLE 28-1
Transmission, Absorption Characteristics of Ultraviolet Radiation

λ range, μm	Transmission, Absorption Properties
0.3-0.4	Transmits through air — Partially transmits through ordinary glass, quartz, water.
0.2-0.32	Transmits through air, quartz. Absorbed by ordinary window glass. Ozone layer absorbs sun's radiation at λ less than 0.29 μm . Absorbed by epithelial layers of skin and cornea.
0.16-0.2	Poorly transmitted through air and quartz.
<0.16	Air and quartz completely absorb these λ . Radiations can exist only in vacuum.

and plasma torches constitute significant man-made sources. In low pressure mercury vapor discharge lamps over 85% of the radiation is usually emitted at 0.2537 μm . At the lower pressures (fractions of an atmosphere) the characteristic mercury lines predominate whereas at higher pressures (up to 100 atmospheres) the lines broaden to produce a radiation continuum. In typical quartz lamps the amount of energy at wavelengths below 0.38 μm may be 50% greater than the radiated visible energy, depending upon the mercury pressure. Other man-made sources include xenon discharge lamps, lasers and relatively new types of fluorescent tubes which emit radiation at wavelengths above 0.315 μm reportedly at an irradiance less than that measured outdoors on a sunny day.

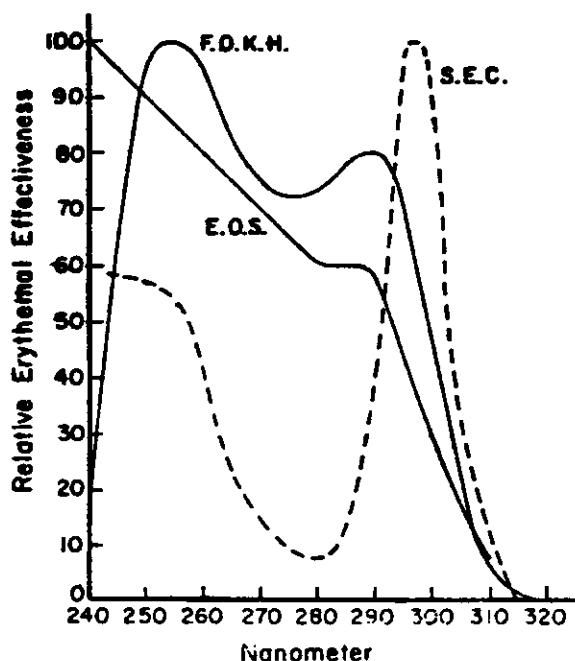
Biological Effects of Ultraviolet Radiation

The biological action spectrum for erythema (reddening) produced by ultraviolet radiation of the skin has been the subject of investigation for many years. The most recent data show that a maximum erythemal effect is produced at 0.260 μm with the secondary peak at approximately

TABLE 28-2
Reflectance of 0.2537 μm Radiation From Various Surfaces

Material	% Reflectance*
Aluminum, etched	88
Aluminum foil	73
Chromium	45
Nickel	38
Stainless Steel	20-30
Silver	22
Tin-plated steel	28
White wall plaster	40-60
White paper	25
White cotton	30
White oil paints	5-10
White porcelain enamel	5
Glass	4
Water paints	10-30

*Values obtained at normal incidence. The percentage reflectance increases rapidly at angles greater than 75%. Reprinted from American Industrial Hygiene Journal, 3:1964, Akron, Ohio.



Industrial Hygiene Highlights, vol. 1, p. 145.

Figure 28-2. Comparison of Standard Erythemal Curve (S.E.C.) with Relative Erythemal Curve (S.E.C.) with Relative Erythemal Effectiveness Curves of Everett, Olsen and Soyer (E.O.S.) and Freeman, Owens, Knox and Hudson (F.O.K.H.)

0.290 μm .^{2,3} Erythral response to wavelengths above 0.32 μm is predictably poor (see Fig. 28-2). The greatly increased air absorption of wavelengths below 0.25 μm and the difficulty in obtaining monochromatic radiations in this region probably account for the lack of definitive bioeffects data. This may change with the increase in the number of UV lasers available for research and study.

Wavelengths between 0.28 μm and 0.32 μm penetrate appreciably into the corium or dermis; those between 0.32 μm and 0.38 μm are absorbed primarily in the epidermis, while those below 0.28 μm appear to be absorbed almost completely in the stratum corneum of the epidermis.

Depending upon the total UV dose, the latent period for erythema may range from two to several hours; the severity may vary from simple erythema to blistering and desquamation with severe secondary effects. A migration of melanin granules from the basal cells to the malpighian cell layers of the epidermis may cause a thickening of the horny layers of the skin. The possible long-term effects of the repeated process of melanin migration is not completely understood. The available data seem to support the contention that some regions of the ultraviolet may produce or initiate carcinogenesis in the human skin. The experiments which have supported this contention indicate that the biological action spectrum for carcinogenesis is the same as that for erythema (see Fig. 28-3).

Cases of skin cancer have been reported in workers whose occupation requires them to be exposed to sunlight for long periods of time. The reportedly high incidence of skin cancer in outdoor workers who are simultaneously exposed to chemicals such as coal tar derivatives, benzpyrene, methyl cholanthrene and other anthracene compounds raises the question as to the role played by ultraviolet radiation in these cases. It is a matter of common knowledge that significant numbers of workers who routinely expose themselves to coal tar products while working outdoors experience a photosensitization of the skin.

Abiotic effects from exposure to ultraviolet radiation occur in the spectral range of 0.24 to 0.31 μm . In this part of the spectrum, most of the incident energy is absorbed by the corneal epithelium at the surface of the eye. Hence, although the lens is capable of absorbing 99% of the energy below 0.35 μm only a small portion of the radiation reaches the anterior lenticular surface.

Photon-energies of about 3.5 eV (0.36 μm) may excite the lens of the eye or cause the aqueous or vitreous humor to fluoresce thus producing a diffuse haziness inside the eye that can interfere with visual acuity or produce eye fatigue. The phenomenon of fluorescence in the ocular media is not of concern from a bioeffects standpoint; the condition is strictly temporary and without detrimental effect.

The development of photokeratitis usually has

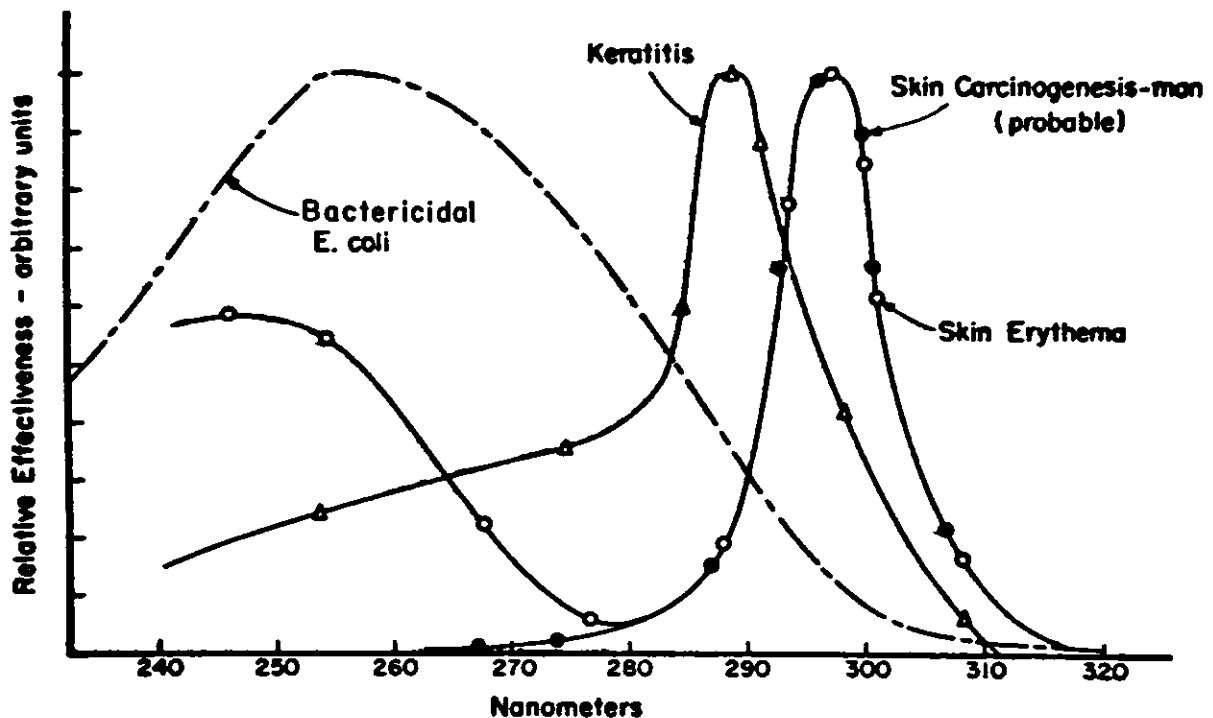


Figure 28-3. Action Spectra: Bactericidal, Hollaender; Keratitis, Cogan and Kinsey; Erythral, I.E.S. Lighting Handbook, 4th Ed.; Carcinogenesis, Rusch, Kline and Baumann.

a latency period varying from 30 minutes to as long as 24 hours depending upon the severity of the exposure. A sensation of "sand in the eyes" accompanied by varying degrees of photophobia, lacrimation and blepharospasm is the usual result. Blepharospasm is a reflex protective mechanism characterized by an involuntary tight closing of the lids, usually over a damaged cornea.

Exposure Criteria

The biological action spectrum for keratitis peaks at 0.28 μm . At this wavelength, the threshold for injury has been determined to be approximately 0.15×10^6 ergs.⁴ It has been suggested that the corneal reaction is due primarily to selective absorption of UV by specific cell constituents; for example, globulin.

Verhoeff and Bell⁵ gave the first quantitative measurement of the ultraviolet energy necessary for threshold damage as 2×10^6 ergs/cm² for the whole UV spectrum. More recent data by Pitts et al.,^{6,7} using 10 nm bands of radiation produced a threshold of approximately 0.5×10^6 ergs per square centimeter in rabbit eyes.

The exposure criteria adopted by the American Medical Association based on erythral thresholds at 0.2537 μm radiation are as follows: 0.5×10^{-6} W/cm² for exposure up to seven hours; 0.1×10^{-6} W/cm² for exposure periods up to and exceeding 24 hours.⁸ Although these criteria are generally thought to be very stringent, they are nevertheless in common use.

The American Conference of Governmental Industrial Hygienists⁹ has published a "Notice of Intent" to establish Threshold Limit Values for ultraviolet radiation. The Notice states that the total irradiance of the unprotected skin or eye by ultraviolet energy in the 0.32 to 0.4 μm wavelength range should not exceed 10^{-3} W/cm² for a period of 16 minutes. For ultraviolet in a range from 0.2 μm to 0.315 μm , the radiant exposure should not exceed values which vary from 0.1 J/cm² to 1.0 J/cm², respectively.

Measurement of Ultraviolet Radiation

Various devices have been used to measure ultraviolet radiation; e.g., photoelectric cells, photoconductive cells, photovoltaic cells and photochemical detectors. It is common practice to employ the use of selective filters in front of the detecting device in order to isolate that portion of the ultraviolet spectrum of interest to the investigator.

A commonly used detector is the barrier or photovoltaic cell. Certain semiconductors such as selenium or copper oxide deposited on a selected metal develop a potential barrier between the layer and the metal. Light falling upon the surface of the cell causes the flow of electrons from the semiconductor to the metal. A sensitive meter placed in such a circuit will record the intensity of radiation falling on the cell.

Ultraviolet photocells take advantage of the fact that certain metals have quantitative photoelectric responses to specific bands in the UV spectrum. Therefore, a photocell may be equipped with metal cathode surfaces which are sensitive to certain UV wavelengths of interest. One of the drawbacks of photocells is solarization or deterior-

ation of the envelope, especially with long usage or following measurement of high intensity ultraviolet radiation. This condition requires frequent recalibration of the cell. The readings obtained with these instruments are valid only when measuring monochromatic radiation, or when the relationship between the response of the instrument and the spectral distribution of the source is known.

A desirable design characteristic of ultraviolet detectors is to have the spectral response of the instrument closely approximate that of the biological action spectrum under consideration. However, such an instrument is unavailable at this time. Since available photocells and filter combinations do not closely approximate the UV biological action spectra, it is necessary to standardize (calibrate) each photocell and meter. Such calibrations are generally made at a great enough distance from a standard source that the measuring device is in the "far field" of the source. Special care must be taken to control the temperature of so called standard mercury lamps because the spectral distribution of the radiation from the lamp is dependent upon the pressure of the vaporized mercury.

A particularly useful device for measuring ultraviolet is the thermopile. Coatings on the receiver elements of the thermopile are generally lamp black or gold black to simulate black body radiation devices. Appropriate thermopile window material should be selected to minimize the effects of air convection, the more common windows being crystal quartz, lithium fluoride, calcium fluoride, sodium chloride and potassium bromide. Table 28-3 shows the sensitivity, impedance and response time of certain junction detectors.¹⁰ Low intensity calibration may be made by exposing the thermopile to a secondary standard (carbon filament) furnished by the National Bureau of Standards.

TABLE 28-3
Sensitivity, Impedance and Response Time
of Junction Detectors

Type (Circular)	Sensitivity $\mu\text{V}/\mu\text{W cm}^{-2}$	Impedance OHM	Response Time (1/e) sec
1-junction: Const- Mang	0.005	2	0.1
4-junction: Cu-Const	0.025	5	0.5
4-junction: Bi-Ag	0.05	5	0.5
8-junction: Bi-Ag	0.10	10	1.0
16-junction: Bi-Ag (linear)	0.20 0.05	25 10	2.0 0.5)
12-junction: Bi-Ag	0.05	10	0.5

Reprinted from Bulletin No. 3 (1964), p. 5, Eppley Laboratory, Inc., Newport, Rhode Island.

Other UV detection devices include: 1) photo-diodes, e.g., silver, gallium arsenide, silver zinc sulfide and gold zinc sulfide (peak sensitivity of these diodes is at wavelengths below $0.36 \mu\text{m}$; the peak efficiency or responsivity is of the order of 50-70%); 2) thermocouples, e.g., Chromel-Alumel; 3) Golay cells; 4) superconducting bolometers; and 5) zinc sulfide Schottky barrier detectors.¹¹

Care must be taken to use detection devices having the proper rise time characteristics (some devices respond much too slowly to obtain meaningful measurements). Also, when measurements are being made special attention should be given to the possibility of UV absorption by many materials in the environment; e.g., ozone or mercury vapor, thus adversely affecting the readings. The possibility of photochemical reactions between ultraviolet radiation and a variety of chemicals also exists in the industrial environment.

Control of Exposure

Because ultraviolet radiations are so easily absorbed by a wide variety of materials, appropriate attenuation is accomplished in a straight forward manner. The exposure criteria given in the section entitled "Exposure Criteria" should be used for the specification of shielding requirements. In the case of ultraviolet lasers no firm bioeffects criteria are available; however, the data of Pitts^{6,7} may be used because of the narrow band UV source used in his experiments to determine thresholds of injury to rabbit eyes. In using the data in the section "Exposure Criteria" it is important to remember that photosensitization may be induced in certain persons at levels below the suggested exposure criteria.

LASER RADIATION

Sources and Uses of Laser Radiation

The rate of development and manufacture of devices and systems based on stimulated emission of radiation has been truly phenomenal. Lasers are now being used for a wide variety of purposes, including micromachining, welding, cutting, sealing, holography, optical alignment, interferometry, spectroscopy, surgery, and as communications media.

Generally speaking, lasing action has been obtained in gases, crystalline materials, semiconductors and liquids. Stimulated emission in gaseous systems was first reported in a helium neon mixture in 1961.¹² Since that time lasing action has been reported at hundreds of wavelengths from the ultraviolet to the far infrared (several hundred micrometers). Helium neon (He-Ne) lasers are typical of gas systems where stable single frequency operation is important. He-Ne systems can operate in a pulsed mode or continuous wave (CW) at wavelengths of 0.6328 micrometers (μm), 1.15 μm or 3.39 μm , depending upon resonator design. Typical power for He-Ne systems is of the order of 1-500 mW. The carbon dioxide gas laser system operates at a wavelength of 10.6 μm in either the continuous wave, pulsed or Q-switched modes. A Q switch is a device for enhancing the storage and dumping of energy to produce extremely high power pulses. The power output of $\text{CO}_2\text{-N}_2$ sys-

tems may range from several watts to greater than 10 KW. The CO_2 laser is attractive for terrestrial and extraterrestrial communications because of the low absorption window in the atmosphere between 8 μm and 14 μm . Of major significance from the personal hazard standpoint is the fact that enormous power may be radiated at a wavelength which is invisible to the human eye. The argon ion gas system operates predominantly at wavelengths of 0.488 μm and 0.515 μm in either a continuous wave or pulsed mode. Power generation is greatest at 0.488 μm , typically at less than 10 watts.

Of the many ions in which laser action has been produced in solid state crystalline materials, perhaps neodymium (Nd^{3+}) in garnet or glass and chromium (Cr^{3+}) in aluminum oxide are most noteworthy (see Table 28-4). Garnet (yttrium aluminum garnet) or YAG is an attractive host for the trivalent neodymium ion because the 1.06 μm laser transition line is sharper than that in other host crystals. Frequency doubling to 0.530 μm using lithium niobate crystals may produce power approaching that available in the fundamental mode at 1.06 μm . Also through the use of electro-optic materials such as KDP, barium-sodium niobate or lithium tantalate, "tuning" or scanning of laser frequencies over wide ranges may be accomplished.¹³ The ability to scan rapidly through wide frequency ranges requires special consideration in the design of protective measures.

Perhaps the best known example of a semiconductor laser is the gallium arsenide types operating at 0.840 μm ; however, semiconductor materials have operated in a range of approximately 0.4 to 5.1 μm . Generally speaking, the semiconductor laser is a moderately low-powered (milliwatts to several watts) CW device having relatively broad beam divergence thus tending to reduce its hazard potential. On the other hand, certain semiconductor lasers may be pumped by multi kilovolt electron beams thus introducing a potential ionizing radiation hazard.¹⁴

TABLE 28-4

Certain Ions Which Have Exhibited Lasing-Action

Active ion	Wavelength μm
Nd^{3+}	0.9-1.4
Ho^{3+}	2.05
Er^{3+}	1.61
Cr^{3+}	0.69
Tm^{3+}	1.92
U^{3+}	2.5
Pr^{3+}	1.05
Dy^{3+}	2.36
Sm^{2+}	0.70
Tm^{2+}	1.12

Biological Effects of Laser Radiation

The body organ most susceptible to laser radiation appears to be the eye; the skin is also susceptible but of lesser importance. The degree of risk to the eye depends upon the type of laser beams used, notably the wavelength, output power, beam divergence and pulse repetition frequency. The ability of the eye to refract long ultraviolet, visible and near infrared wavelengths is an additional factor to be considered in assessing the potential radiation hazard.

In the case of ultraviolet wavelengths (0.2 to 0.4 μm) produced by lasers the expected response is similar to that produced by noncoherent sources; e.g., photophobia accompanied by erythema, exfoliation of surface tissues and possibly stromal haze. Absorption of UV takes place at or near the surface of tissues. The damage to epithelium results from the photochemical denaturation of proteins (see section entitled "Ultraviolet Radiation").

In the case of infrared laser radiation, damage results exclusively from surface heating of the cornea subsequent to absorption of the incident energy by tissue water in the cornea. Simple heat flow models appear to be sufficiently accurate to explain the surface absorption and damage to tissue.

In the case of the visible laser wavelengths

(0.4 to 0.75 μm) the organ at risk is the retina and more particularly the pigment epithelium of the retina. The cornea and lens of the eye focus the incident radiant energy so that the radiant exposure at the retina is at least several orders of magnitude greater than that received by the cornea. Radiant exposures which are markedly above the threshold for producing minimal lesions on the retina may cause physical disruption of retinal tissue by steam formation or by projectile-like motion of the pigment granules.^{15, 16} In the case of short transient pulses such as those produced by Q-switched systems, acoustical phenomena may also be present.¹⁵

There are two transition zones in the electromagnetic spectrum where bio-effects may change from one of a corneal hazard to one of a retinal hazard. These are located at the interface of the ultraviolet-visible region and the visible near infrared region. It is possible that both corneal and retinal damage, as well as damage to intermediate structures such as the lens and iris, could be caused by devices emitting radiation in these transitional regions.

Figures 28-4 and 28-5 show the percent transmission of various wavelengths of radiation through the ocular media and the percent absorption in the retinal pigment epithelium and choroid, respectively. These graphs illustrate why the retina

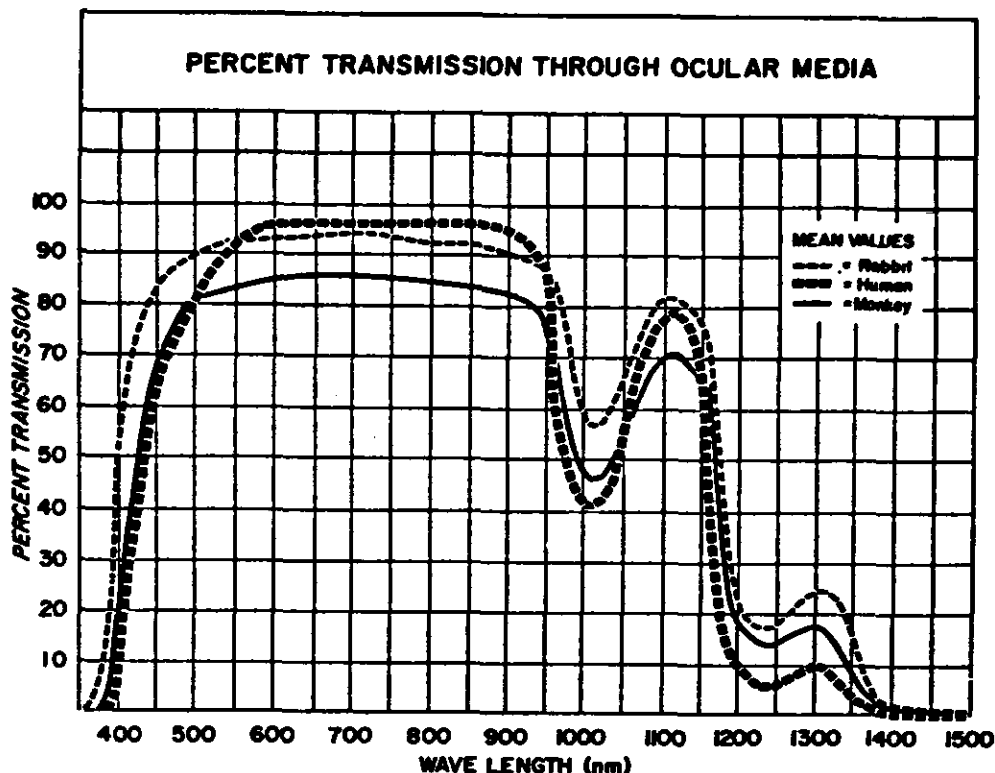


Figure 28-4. Percent Transmission through Ocular Media. Percent transmission for light of equal intensity through the ocular media of human, monkey (rhesus), and rabbit eyes. From Geeraets, W. J. and Berry, E. R., *Amer. J. Ophthalm.*, 66, 15, 1968.

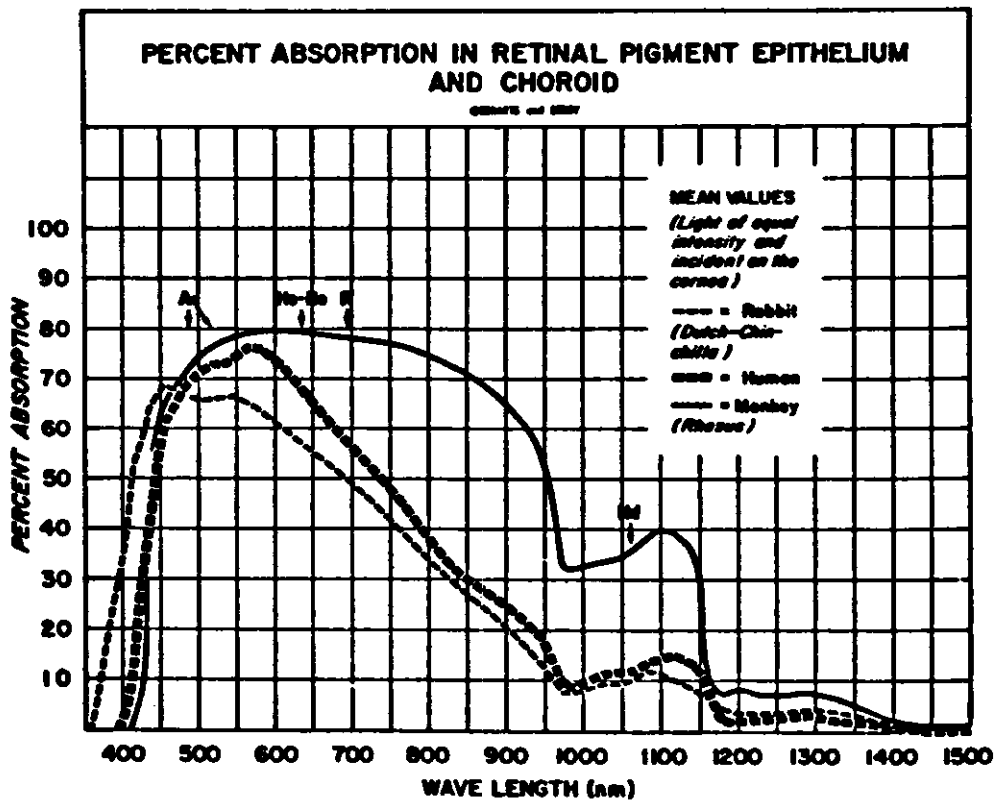


Figure 28-5. Percent Absorption in Retinal Pigment Epithelium and Choroid. Percent absorption of light of equal intensity at the cornea in the retinal pigment epithelium and choroid for rabbits, monkey, and man. Redrawn to include correction for reflection from Figure 2 of Geeraets, W. J. and Berry E. R., Amer. J. Ophthal. 66, 15, 1968.

is the organ at risk with visible wavelength-radiation whereas the cornea and skin surfaces are at risk with infrared and ultraviolet radiation. Several investigators^{17, 18} noticed irreversible changes in electroretinograms, with attendant degeneration of visual cells and pigment epithelium, when albino and pigmented rats were exposed to high illumination environments.

The biological significance of irradiating the skin with lasers is considered to be less than that caused by exposure of the eye since skin damage is usually repairable or reversible. The most common effects on the skin range from erythema to blistering and charring depending upon the wavelength, power and time of exposure to the radiation. Depigmentation of the skin and damage to underlying organs may occur from exposure to extremely high powered laser radiation, particularly Q-switched pulses. In order that the relative eye/skin hazard potential be kept in perspective, one must not overlook possible photosensitization of the skin caused by injection of drugs or use of cosmetic materials. In such cases the maximum permissible exposure (MPE) levels for skin might be considerably below the currently recommended values.

Exposure Criteria

Permissible levels of laser radiation impinging upon the eye have been derived from studies of short term exposure and an examination of damage to eye structures as observed through an ophthalmoscope. Some investigators¹⁹ have observed irreversible visual performance changes at exposure levels as low as 10% of the threshold determined by observation through an ophthalmoscope. McNeer and Jones^{19, 20} found that at 50% of the ophthalmoscopically determined threshold, the ERG B wave amplitude was irreversibly reduced. Davis and Mautner²¹ reported severe changes in the visually evoked cortical potential at 25% of the ophthalmoscopically determined threshold. Since most if not all of the so-called laser exposure criteria have been based on ophthalmoscopically-determined lesions on the retina, the findings of irreversible functional changes at lower levels cause one to ponder the exact magnitude of an appropriate safety factor which should be applied to the ophthalmoscope data in order to derive a reasonable exposure criterion.

There is unanimous agreement that any proposed maximum permissible exposure (MPE) or threshold limit value (TLV) does not sharply di-

vide what is hazardous from what is safe. Usually any proposed values take on firm meaning only after years of practical use. However, it has become general practice in evaluating a laser exposure to:

1. Measure the radiant exposure (J/cm^2) or irradiance (W/cm^2) in the plane of the cornea rather than making an attempt to calculate the values at the retina. This simplifies the measurements and calculations for the industrial hygienists and radiation protection officers.
2. Use a 7 mm diameter limiting aperture (pupil) in the calculations. This assumes that the largest amount of laser radiation may enter the eye.
3. Make a distinction between the viewing of collimated sources; (e.g., lasers) and extended sources (e.g., fluorescent tubes or incandescent lamps). The MPE for extended source viewing takes into account the solid angle subtended at the eyes in viewing the light source; therefore, the unit is $Watts/cm^2 \cdot sr$ (Watts per square centimeter and steradian).
4. Derive permissible levels on the basis of the wavelength of the laser radiation; e.g., the MPE for neodymium wavelength ($1.06 \mu m$) should be increased; i.e., made less stringent by a factor of approximately five than the MPE for visible wavelengths.
5. Urge caution in the use of laser systems

that emit multiple pulses. A conservative approach would be to limit the power or energy in any single pulse in the train to the MPE specified for direct irradiation at the cornea. Similarly the average power for a pulse train could be limited to the MPE of a single pulse of the same duration as the pulse train. More research is needed to precisely define the MPE for multiple pulses.

Typical exposure criteria for the eye proposed by several organizations are shown in Table 28-5 and Table 28-6. These data do not apply to permissible levels at ultraviolet wavelengths or to the skin. A few supplementary comments on these factors are in order. There appears to be general agreement on maximum permissible exposure levels of radiation for the skin; e.g., the MPE values are approximately as follows: for exposure times greater than 1 sec., an MPE of $0.1 W/cm^2$; exposure times 10^{-2} to 1 sec., $1.0 W/cm^2$; for 10^{-4} to 10 sec., $0.1 J/cm^2$ and for exposure times less than 10^{-4} sec., $0.01 J/cm^2$. The MPE values apply to visible and infrared wavelengths. For ultraviolet radiations the more conservative approach is to use the standards established by the American Medical Association. These exposure limits (for germicidal wavelengths viz. $0.2537 \mu m$) should not exceed $0.1 \times 10^{-6} W/cm^2$ for continuous exposure. If an estimate is to be made of UV laser thresholds, then it is suggested that the more recent work of Pitts^{6,7} be consulted (see section entitled "Ultraviolet Radiation").

TABLE 28-5
Eye Exposure Guidelines for Laser Radiation
as Recommended by Various Organizations

Wavelength and Pulse Duration	Air Force*	Army/Navy**	ACGIH***
	Total Energy or Power Entering Eye	Total Energy or Power Over a 7 mm Aperture (Pupil)	Total Energy or Power Over a 7 mm Aperture (Pupil)
Visible (0.4-0.7 μm)			
Q switched	$0.5 \times 10^{-6} J$	$1 \times 10^{-6} W/cm^2$	$1 \times 10^{-7} J/cm^2$ (1 ns to 1 μs)
Long Pulse	$1 \times 10^{-6} J$	$1 \times 10^{-7} J/cm^2$	$1 \times 10^{-6} J/cm^2$ (1 μs to 0.1s)
Continuous Wave	$1 \times 10^{-3} W$ (10-500ms) $2 \times 10^{-3} W$ (2-10ms)	$1 \times 10^{-6} J/cm^2$	$1 \times 10^{-6} W/cm^2$ ($>0.1s$)
Near Infrared (1.06 μm)			
Q switched (10-100ms)	$2.5 \times 10^{-6} J$		
Long Pulse (0.2-2ms)	$2.0 \times 10^{-5} J$		
CW-YAG (2-10ms)	$1 \times 10^{-2} W$		
CW-YAG (10-500ms)	$5 \times 10^{-3} W$		
Infrared (10.6 μm)			
	$1 W/cm^2$ (50-250ms) $3 W/cm^2$ (10-50ms) $8 W/cm^2$ ($<10ms$)	$1 \times 10^{-1} W/cm^2$	$1 \times 10^{-1} W/cm^2$

*See Reference 43

***See Reference 45

**See Reference 44

TABLE 28-6
Maximum Permissible Exposure (MPE)
for Direct Ocular Intra-beam Viewing for Single
Pulses or Exposures (ANSI Z136)*

Wavelength (μm)	Exposure Time (t in seconds)	Maximum Permissible Exposure (MPE)	Notes for Calculation and Measurement
UV			
.200-.302	$10^{-2} - 3 \times 10^4$	3×10^{-3}	1 mm limiting aperture. In no case shall the total irradiance, over all the wavelengths within the UV spectral region, be greater than 1 watt per square centimeter upon the cornea.
.303	$10^{-2} - 3 \times 10^4$	4×10^{-3}	
.304	$10^{-2} - 3 \times 10^4$	6×10^{-3}	
.305	$10^{-2} - 3 \times 10^4$	1.0×10^{-2}	
.306	$10^{-2} - 3 \times 10^4$	1.6×10^{-2}	
.307	$10^{-2} - 3 \times 10^4$	2.5×10^{-2}	
.308	$10^{-2} - 3 \times 10^4$	4.0×10^{-2}	
.309	$10^{-2} - 3 \times 10^4$	6.3×10^{-2}	
.310	$10^{-2} - 3 \times 10^4$	1.0×10^{-1}	
.311	$10^{-2} - 3 \times 10^4$	1.6×10^{-1}	
.312	$10^{-2} - 3 \times 10^4$	2.5×10^{-1}	
.313	$10^{-2} - 3 \times 10^4$	4.0×10^{-1}	
.314	$10^{-2} - 3 \times 10^4$	6.3×10^{-1}	
.315-.400	10^{-2} to 10^3	1	
.315-.400	$10^3 - 3 \times 10^4$	$1 \times 10^{-3} \text{W} \cdot \text{cm}^{-2}$	
Visible and near IR^a			
.4 - 1.4	$10^{-9} - 2 \times 10^{-5}$	$5 \times 10^{-7} \text{J} \cdot \text{cm}^{-2}$	7 mm limiting aperture.
	$2 \times 10^{-5} - 10$	$1.8 \times 10^{-3} t^{3/4} \text{J} \cdot \text{cm}^{-2}$	
	$10 - 10^4$	$10^{-2} \text{J} \cdot \text{cm}^{-2}$	
	$10^4 - 3 \times 10^4$	$10^{-6} \text{W} \cdot \text{cm}^{-2}$	
Far IR^b			
1.4-10 ³	$10^{-9} - 10^{-7}$	$10^{-2} \text{J} \cdot \text{cm}^{-2}$	
	$10^{-7} - 10$	$0.56 t^{1/4} \text{J} \cdot \text{cm}^{-2}$	
	>10	$0.1 \text{W} \cdot \text{cm}^{-2}$	

^aSpecial Qualifications and Correction Factors Are Given in ANSI Document.

^bSpecial Qualifications, Correction Factors and Dimensions of Limiting Apertures Are Given in ANSI Document.

*See Reference 46.

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Measurement of Laser Radiation

The complexity of radiometric measurement techniques, the relatively high cost of available detectors and the fact that calculations of radiant exposure levels based on manufacturers' specifications of laser performance have been found to be sufficiently accurate for protection purposes, have all combined to minimize the number of measurements needed in a protective program. In the author's experience, the output power of commonly used laser systems, as specified by the manufacturers, has never been at variance with precision calibration data by more than a factor of two.

All measurement systems are equipped with detection and readout devices. A general description of several devices and their application to laser measurements follows.

Because laser radiation is monochromatic, certain simplifications can be made in equipment design. For example, it may be possible to use

narrow band filters with an appropriate type of detector thereby reducing sources of error. On the other hand, special care must be taken with high powered beams to prevent detector saturation or damage. Extremely short Q-switched pulses require the use of ultrafast detectors and short time-constant instrumentation to measure power instantaneously. Photoelectric detectors and radiation thermopiles are designed to measure instantaneous power, but they can also be used to measure total energy in a pulse by integration, provided the instrumental time-constants are much shorter than the pulse lengths of the laser radiation. High current vacuum photo-diodes are useful for measuring the output of Q-switched systems and can operate with a linear response over a wide range.

Average power measurements of CW laser systems are usually made with a conventional thermopile or photo-voltaic cells. A typical thermopile will detect signals in the power range from 10 μ watts to about 100 milliwatts. Because ther-

mopiles are composed of many junctions the response of these instruments may be nonuniform. The correct measure of average power is therefore not obtained unless the entire surface of the thermopile is exposed to the laser beam. Measurements of the CW power output of gas lasers may also be made with semiconductor photocells.

The effective aperture or aperture stop of any measurement device used for determining the radiant exposure (J/cm^2) or irradiance (W/cm^2) should closely approximate if not be identical to the pupillary aperture. For purposes of safety the diameter should correspond to that of the normal dark-adapted eye; i.e., 7 mm. The response time of measurement systems should be such that the accuracy of the measurement is not affected, especially when measuring short pulse durations or instantaneous peak power.

Many calorimeters and virtually all photographic methods measure total energy, but they can also be used for measuring power if the time history of the radiation is known. Care should be taken to insure that photographic processes are used within the linear portion of the film density versus log radiant exposure (gamma) curve.

Microammeters and voltmeters may be used as read-out devices for CW systems; microvoltmeters or electrometers coupled to oscilloscopes may be used for pulsed laser systems. These devices may be connected in turn to panel displays or recorders, as required.^{22, 23}

Calibration is required for all wavelengths at which the instrument is to be used. It should be noted that tungsten ribbon filament lamps are available from the National Bureau of Standards as secondary standards of spectral radiance over the wavelength region from approximately 0.2 to $2.6\mu m$. The calibration procedures using these devices permit comparisons within about 1% in the near ultraviolet and about a half percent in the visible. All radiometric standards are based on the Stefan-Boltzmann and Planck laws of black-body radiation.

The spectral response of measurement devices should always be specified since the ultimate use of the measurements is a correlation with the spectral response of the biological tissue receiving the radiation insult.

Control of Exposure

It stands to reason that certain basic control principles apply to many laser systems: (1) the need to inform appropriate persons as to the potential hazards, the procedures and engineering control measures required to prevent injury, the electrical hazard, particularly with the discharge of capacitor banks associated with solid state Q-switched systems; and (2) the need to rely primarily on engineering controls rather than procedures; e.g., enclosures, beam stops, beam enlarging systems, shutters, interlocks and isolation of laser systems, rather than sole reliance on memory or safety goggles. The "exempt" laser system is an exception to these measures. In all cases, particular attention must be given to the safety of unsuspecting visitors or spectators in laser areas.

"High powered" systems deserve the ultimate in protective design: enclosures should be equipped with interlocks. Care should be taken to prevent accidental firing of the system and where possible, the system should be fired from a remote position. Controls on the high powered systems should go beyond the usual warning labels; e.g., an integral warning system such as a "power on" audible signal or flashing light which is visible through protective eye wear should be installed.

Infrared laser systems should be shielded with fireproof materials having an appropriate optical density (O.D.) to reduce the irradiance below MPE values. The main hazard of these systems is absorption of excessive amounts of IR energy by human tissue or by flammable or explosive chemicals.

Before protective eye wear is chosen, one must determine as a minimum the radiant exposure or irradiance levels produced by the laser at the distance where the beam or reflected beam is to be viewed; one must know the appropriate MPE value for the laser wavelength; and finally one must determine the proper optical density of protective eyewear in order to reduce levels below the MPE. Likewise, the visible light transmission characteristics should be known because sufficient transmission is necessary for the person using the device to be able to detect ordinary objects in the immediate field of vision. The minimum optical density required of protective eyewear is shown in Table 28-7. Table 28-8 lists the characteristics of most laser protective eyewear now available on the American market.²⁴

TABLE 28-7
Minimum Optical Densities Required of
Protective Eyewear

$$(OD_{min} = \log_{10} H_0/MPE \\ \text{or } \log_{10} E_0/MPE)$$

E_0/MPE or H_0/MPE	OD_{min}
1 = 10^0	0
10 = 10^1	1
100 = 10^2	2
1000 = 10^3	3
10000 = 10^4	4
100000 = 10^5	5
1000000 = 10^6	6

Where H_0 is equal to the emergent beam radiant exposure in Joules per square centimeter and E_0 is equal to the emergent beam irradiance in Watts per square centimeter.

TABLE 28-8
Laser Eye Protection Goggles
Based on Manufacturers' Information†
OPTICAL DENSITY = $\log_{10} \frac{1}{\text{Transmittance}}$

Manufacturer or Supplier	Catalogue Number	Ar 4880 Å	HeNe 6328 Å	Ruby 6943 Å	GaAs 8400 Å	Nd 10600 Å	CO ₂ 10.6 μ	UV <4000 Å >3000 Å	Coated Filter	Approx. Cost \$	No. of glass filters & thickness of each	Visible Light transmission	Useful Range • Å
American Optical Co.	SCS-437,*	0.15	0.20	0.36	1	5	High	No	No	55	1, 3.5 mm	90 %	10600
	SCS-440												10600
	580, 586*	0.2	2	3.5	4	2.7	—	>0.2	No	35, 25*	1, 3.5 mm	27.5%	—
	581, 587*	0.6	4.1	6.1	5.5	3	—	>1.6	No	35, 25*	1, 3.5 mm	9.6%	6328
	584	0	1	5	13	11	High	>0.6	No	55	2, 2 mm	46 %	10600
	585	0.3	2	8	21	17	High	>0.6	No	55	2, 2 mm	35 %	6943-10600
	598*	13	0	0	0	—	—	>14	No	25*	1, 3 mm	23.7%	4550-5150
	599	11	0	0	0	—	—	>14	No	35	1, 2.5 mm	24.7%	4550-5150
	680	0	0	0	0	0	50	No	No	35	1, 2.7 mm	92 %	10600
698	13	1	4	11	8.5	High	>14	No	55	2, 2&3mm	5 %	10600 and 5300	
Bausch & Lomb	5W3754	15	0.2	0	0	0	III 35	20	Yes	39	1, 7.9 mm	4.3%	3300-5300
	5W3755	4	0	0	0	0.1	III 35	10	Yes	39	1, 7.9 mm	57 %	4000-4600
	5W3756	0.8	12	15	5.6	4.8	III 35	3	Yes	39	1, 6.4 mm	6.2%	6000-8000
	5W3757	0.9	4.5	7.7	12	5.7	III 35	2	Yes	39	1, 7.1 mm	4.7%	7000-10000
	5W3758	1.9	1.8	2.2	4.8	7.5	III 35	2	Yes	39	1, 7.6 mm	3 %	10000-11500
Control Data Corp.	TRG-112-1	—	5	12	30	30	—	No	No	50	1, 6 mm	22 %	6943
	TRG-112-2	10	0	0	0	0	—	No	No	50	1, 6 mm	31 %	4880
	TRG-112-3	5	2	6	15	15	—	No	No	50	2, 3 mm	5 %	6943-4880
	TRG-112-4	—	—	—	—	—	High	No	No	50	1, 5 mm	92 %	106000
Fish-Schurman Corp.	FS650AL/18	0.34	3.8	10	>10	>10	—	No	No	30	1, 6 mm	30 %	6943, 8400, 106000
Glendale Optical Co.	NDGA**	1	0.5	2	16	16	High	>20	No	25	Plastic	60 %	8400, 10600
	R**	0.4	2.2	6.3	0.4	0.0	High	5	No	25	Plastic	19 %	6943
	NH**	0.4	5	2.5	0.6	0.5	High	>10	No	25	Plastic	19 %	6328
	A**	15	0	0	0	0	High	>12	No	25	Plastic	59 %	4880, 5143
	NN**	0	0	0	0	0	High	>12	No	25	Plastic	70 %	3320, 3370
Spectrolab	—	8	5	9	13	12	0	8	Yes	115	2, 3.2 mm	<5 %	Broadband

*Spectacle Type. †See reference 24.

**Available in goggles or spectacle type.

CAUTION

1. Goggles are not to be used for viewing of laser beam. The eye protective device must be designed for the specific laser in use.
2. Few reliable data are available on the energy densities required to cause physical failure of the eye protective devices.
3. The establishment of engineering controls and appropriate operating procedures should take precedence over the use of eye protective devices.
4. The hazard associated with each laser depends upon many factors, such as output power, beam divergence, wavelength, pupil diameter, specular or diffuse reflection from surfaces,

MICROWAVE RADIATION

Physical Characteristics of Microwave Radiation

Microwave wavelengths vary from about 10 meters to about one millimeter; the respective frequencies range from 30 MHz to 300 GHz. Certain reference documents,²⁵ however, define the microwave frequency range as 10 MHz to 100 GHz. The region between 10 MHz and the infrared is generally referred to as the RF, or radiofrequency, region. Reference may be made to Figure 28-1 to determine the position occupied by microwaves relative to other electromagnetic radiations. Certain bands of microwave frequencies have been assigned letter designations by industry (see Table 28-9); others, notably the ISM (Industrial, Scientific, Medical) frequencies have been assigned by the Federal Communications Commission for industrial, scientific and medical applications (see Table 28-10). For a more complete classification

of microwave frequency ranges, including a comparison of American and Soviet designations, reference should be made to Table 28-11.

Sources of Microwave Radiation

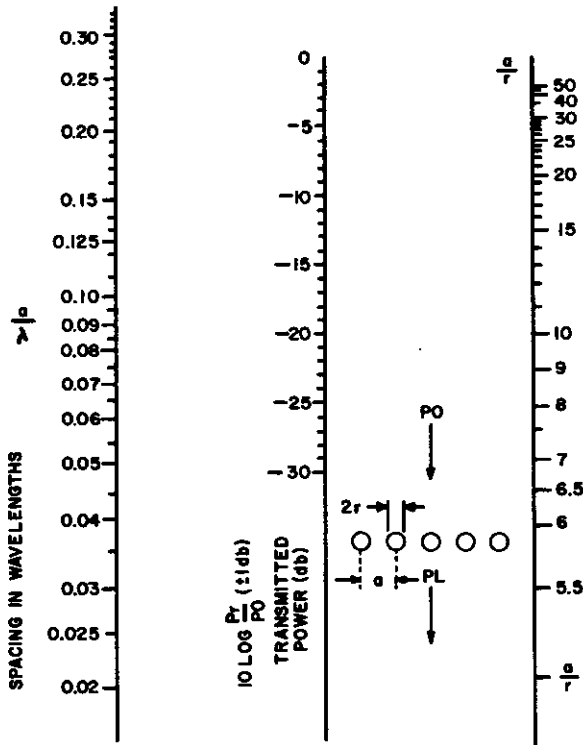
Microwave radiation is no longer of special interest only to those involved with communications and navigational technology. Because of the growing number of commercial applications of microwaves; e.g., microwave ovens, diathermy, materials drying equipment, there is widespread interest in the possible new applications as well as an increased awareness of potential hazards. Typical sources of microwave energy are klystrons, magnetrons, backward wave oscillators and semiconductor transit time devices (IMPATT diodes). Such sources may operate continuously as in the case of some communications systems or intermittently as in microwave ovens, induction heating equipment and diathermy equipment, or in the pulsed mode

TABLE 28-9
Letter Designation of Microwave Frequency Bands

Band	Frequency — MHz
L	1,100- 1,700
LS	1,700- 2,600
S	2,600- 3,950
C	3,950- 5,850
XN	5,850- 8,200
X	8,200-12,400
Ku	12,400-18,000
K	18,000-26,500
Ka	26,500-40,000

TABLE 28-10
Industrial, Scientific, and Medical (ISM) Uses.
ISM Frequencies Assigned by the FCC

- 13.56 MHz ± 6.78 kHz
- 27.12 MHz ± 160 kHz
- 40.68 MHz ± 20 kHz
- 915 MHz ± 25 MHz
- 2,450 MHz ± 50 MHz
- 5,800 MHz ± 75 MHz
- 22,125 MHz ± 125 MHz



Mumford, W.W.: Some Technical Aspects of Microwave Radiation Hazards. Proc. IRE 49:427-47, 1961.

Figure 28-6. Transmission through a Grid of Wires of Radius r and Spacing a.

TABLE 28-11
Radiofrequency and Microwave
Band Designations

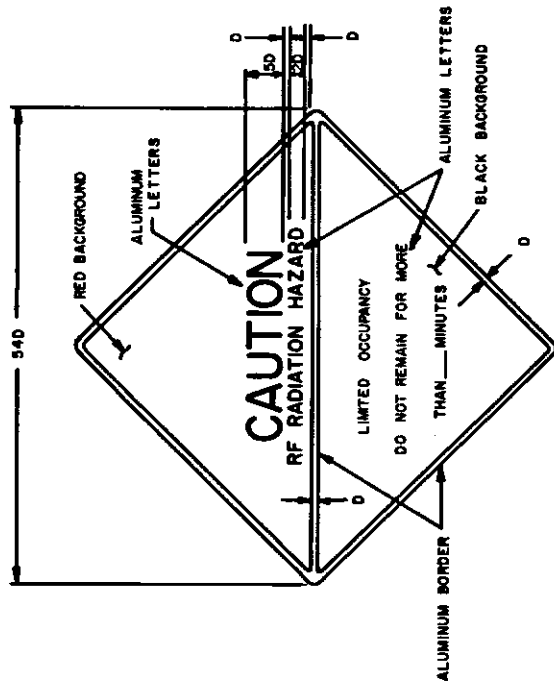
Band Designations		Wavelengths	Frequencies	Typical Uses*	
USA	USSR				
Radiofrequency Bands	Low frequency (LF) Long	VCh } (HF) } UHF }	10 ⁴ -10 ³ m	30-300 KHz	Radionavigation, radio beacon
	Medium frequency (MF) Medium		10 ³ -10 ² m	0.3-3 MHz	Marine radiotelephone, Loran, AM broadcast
	High frequency (HF) Short		10 ² -10m	3-30 MHz	Amateur radio, world-wide broadcasting, medical diathermy, radio astronomy
Microwave Bands	Very high frequency (VHF) Ultra-short (meter)	Super HF }	10-1m	30-300 MHz	FM broadcast, television, air traffic control, radionavigation
	Ultra high frequency (UHF) Decimeter		1-0.1m	0.3-3 GHz	Television, citizens band, microwave point-to-point, microwave ovens, telemetry, tropo scatter and meteorological radar
	Super high frequency (SHF) Centimeter		(SHF) 10-1 cm	3-30 GHz	Satellite communication, airborne weather radar, altimeters, shipborne navigational radar, microwave point-to-point
	Extra high frequency (EHF) Millimeter		1-0.1 cm	30 GHz-300 GHz	Radio astronomy, cloud detection radar, space research, HCN (hydrogen cyanide) emission

*Modified after Table 1 in Reference 26

GENERAL WARNING



LIMITED OCCUPANCY



DENIED OCCUPANCY



1. PLACE HANDLING AND ROUTING INSTRUCTIONS ON REVERSE SIDE.
2. D=SCALING UNIT.
3. LETTERING RATIO OF LETTER HEIGHT TO THICKNESS OF LETTER LINES.

UPPER TRIANGLE:	5 to 1 LARGE
	6 to 1 MEDIUM
LOWER TRIANGLE:	4 to 1 SMALL
	6 to 1 MEDIUM
4. SYMBOL IS SQUARE, TRIANGLE ON RIGHT-ANGLE ISOSCALES

Derived from an ANSI C95.2 Standard. American National Standards Institute, New York, New York.
Figure 28-7. Radio Frequency Signs.

in radar systems. Natural sources of RF and microwave energy also exist. For example, peak field intensities of over 100 volts per meter (V/m) are produced at ground level by the movement of cold fronts. Solar radiation intensities range from 10^{-18} to 10^{-17} watts per square meter per Hz ($\text{Wm}^{-2} \text{Hz}^{-1}$); however, the integrated intensity at the earth's surface for the frequency range of 0.2 to 10 GHz is approximately 10^{-8} mW/cm². This value is to be compared with an average value of 10^2 mW/cm² on the earth's surface attributable to the entire (UV, visible IR and microwave) solar spectrum.²⁶

Biological Effects of Microwave Radiation

The photon energy in RF and microwave radiation is considered to be too low to produce photochemical reactions in biological matter. However, microwave radiation is absorbed by biological systems and ultimately dissipated in tissue as heat. Irradiation of the human body with a power density of 10 mW/cm² will result in the absorption of approximately 58 watts²⁷ with a resultant body temperature elevation of 1°C, a value which is considered acceptable from a personal hazard standpoint. By way of comparison, the human basal metabolic rate is approximately 80 watts for a person at rest; 290 for a person engaged in moderate work.

Microwave wavelengths less than 3 centimeters are absorbed in the outer skin surface, 3 to 10 centimeter wavelengths penetrate more deeply (1 mm to 1 cm) into the skin and at wavelengths from 25 to 200 centimeters, penetration is greatest with the potential of causing damage to internal body organs. The human body is thought to be essentially transparent to wavelengths greater than about 200 centimeters. Above 300 MHz the depth of penetration changes rapidly with frequency, declining to millimeter depths at frequencies above 3000 MHz. Above 10 GHz the surface absorption of energy begins to approach that of infrared radiation.

Carpenter and Van Ummersen²⁸ investigated the effects of microwave radiation on the production of cataracts in rabbit eyes. Exposures to 2.45 GHz radiation were made at power densities ranging from 80 mW/cm² to 400 mW/cm² for different exposure times. They found that repeated doses of 67 J/cm² spaced a day, a week or two weeks apart produced lens opacities even though the single threshold exposure dose at that power density (280 mW/cm²) was 84 J/cm². When the single exposure dose was reduced to 50 J/cm², opacities were produced when the doses were administered one or four days apart, but when the interval between exposures was increased to seven days, no opacification was noted even after five such weekly exposures. At the low power density of 80 mW/cm² (dose of 29 J/cm²) no effect developed, but when administered daily for 10 or 15 days, cataracts did develop. The conclusion is that microwaves may exert a cumulative effect on the lens of the eye if the exposures are repeated sufficiently often. The interval between exposures is an important factor in that a repair mechanism

seems to act to limit lens damage if adequate time has elapsed between exposures.

Certain other biological effects of microwave radiation have been noted in literature. One of these is the so-called "pearl chain effect" where particles align themselves in chains when subjected to an electric field. There is considerable disagreement as to the significance of the pearl chain effect.

Investigators at the Johns Hopkins University²⁹ have suggested a possible relationship between mongolism (Down's Syndrome) in offspring and previous exposure of the male parent to radar. This suggested relationship was based on the finding that of two hundred sixteen cases of mongolism, 8.7 percent of the fathers having mongol offspring versus 3.3 percent of the control fathers (no mongol offspring) had contact with radar while in military service. This possible association must be regarded with extreme caution because of many unknown factors including the probability of a variety of exposures to environmental agents (including ionizing radiation) while in military service.

Soviet investigators claim that microwave radiation produces a variety of effects on the central nervous system with and without a temperature rise in the organism.³⁰⁻³³ Claims are also made for biochemical changes, specifically a decrease in cholinesterase and changes in RNA at power density levels of approximately 10 mW/cm². The reported microwave effects on the central nervous system usually describe initial excitatory action; e.g., high blood pressure followed by inhibitory action, e.g., low blood pressure over the long term.³⁰ Electroencephalographic data have been interpreted as indicating the presence of epileptiform patterns in exposed subjects. Other reported effects ranged from disturbances of the menstrual cycle to changes in isolated nerve preparations.

What is often overlooked in any description of the biological effects of microwave radiation is that such radiations have produced beneficial effects. Controlled or judicious exposure of humans to diathermy or microthermy is widely practiced. The localized exposure level in diathermy may be as high as 100 milliwatts per square centimeter.

Exposure Criteria

Schwan³⁴ in 1953 examined the threshold for thermal damage to tissue, notably cataractogenesis. The power density necessary for producing such changes was approximately 100 mW/cm² to which he applied a safety factor of 10 to obtain a maximum permissible exposure level of 10 milliwatts per square centimeter. This number has been subsequently incorporated into many official standards. The current American National Standards Institute C95 standard²⁵ requires a limiting power density of 10 milliwatts per square centimeter for exposure periods of 0.1 hour or more; also an energy density of 1 milliwatt-hour per square centimeter (1 mWh/cm²) during any 0.1 hour period is permitted. The latter criterion allows for intermittency of exposure at levels above 10 mW/cm², on the basis that such intermittency does not produce a temperature rise in human tissue greater

than 1 degree centigrade. More recently, Schwan²⁵ has suggested that the permissible exposure levels be expressed in terms of current density rather than power density, especially when dealing with measurements in the near or reactive field where the concept of power density loses its meaning. He suggests that a permissible current density of approximately 3 milliamps per square centimeter be accepted since this value is comparable to a far field value of 10 mW/cm². At frequencies below 100 KHz this value should be somewhat lower and for frequencies above 1 GHz it can be somewhat higher.

The new performance standard for microwave ovens specifies a level of 1 milliwatt per square centimeter at any point 5 centimeters or more from the external oven surfaces at the time the oven is fabricated by the manufacturer. Five milliwatts is permitted throughout the useful life of the oven.

Because Soviet investigators believe that effects on the central nervous systems (CNS) are more appropriate measures of the possibly detrimental effects of microwave radiation than are thermally induced responses, their studies have reported "thresholds" which are lower than those reported in Western countries. Soviet permissible exposure levels are several orders of magnitude below those in Western countries.

The Soviet Standards for whole body radiation are as follows: 0.01 milliwatts per square centimeter for five hours per day exposure, 0.1 milliwatts per square centimeter for two hours exposure per day and 1 milliwatt per square centimeter for a 15 to 20 minute exposure provided protective goggles are used. These standards apply to frequencies above 300 MHz.

There appears to be no serious controversy about the power density levels necessary to produce thermal effects in biological tissue. The non-thermal CNS effects reported by the Soviets are not so much controversial as they are a reflection of the fact that Western investigators have not used the conditioned reflex as an end point in their investigations.

Measurement of Microwave Radiation

Perhaps the most important factor underlying some of the controversy over biological effects is the lack of standardization of measurement techniques used to quantify results. Unfortunately, there seems to be little promise that such standardization will be realized in the near future.

The basic vector components in any electromagnetic wave are the electric field (E) and the magnetic field (H). The simplest type of microwave propagation consists of a plane wave moving in an unbounded isotropic medium where the electric and magnetic field vectors are mutually perpendicular to each other and both are perpendicular to the direction of wave propagation. Unfortunately, the simple proportionality between the E and H fields is valid only in free space or in the so-called "far field" of the radiating device. The far field is the region which is sufficiently removed from the source to eliminate any interaction between the propagated wave and the source. The

energy or power density in the far field is inversely proportional to the square of the distance from the source and in this particular case the measurement of either E or H suffices for their determination.

Plane-wave detection in the far field is well understood and easily obtained with equipment which has been calibrated for use in the frequency range of interest. Most hazard survey instruments have been calibrated in the far field to read in power density (mW/cm²) units. The simplest type of device uses a horn antenna of appropriate size coupled to a power meter.

To estimate the power density levels in the near field of large aperture circular antennas, one can use the following simplified relationship:²⁶

$$W = \frac{16P}{\pi D^2} = \frac{4P}{A} \quad (\text{near field})$$

where P is the average power output, D is the diameter of the antenna, A is the effective area of the antenna and W is power density. If this computation reveals a power density which is less than a specified limit (e.g., 10 mW/cm²), then no further calculation is necessary because the equation gives the maximum power density on the microwave beam axis. If the computed value exceeds the exposure criterion then one assumes that the calculated power density exists throughout the near field. The far field power densities are then computed from the Friis free space transmission formula:

$$W = \frac{GP}{4\pi r^2} = \frac{AP}{\lambda^2 r^2} \quad (\text{far field})$$

where λ is the wavelength, r is the distance from the antenna and G is the far field antenna gain, and W, P, and A are as in the equation above.

The distance from the antenna to the intersection of the near and far fields is given by:

$$r_1 = \frac{\pi D^2}{8\lambda} = \frac{A}{2\lambda}$$

These simplified equations do not account for reflections from ground structures or surfaces; the power density may be four times greater than the free space value under such circumstances.

Special note should be made of the fact that microwave hazard assessments are made on the basis of the average, not the peak power of the radiation. In the case of radar generators, however, the ratio of peak to average power may be as high as 10⁶.

Most microwave measuring devices are based on (1) bolometry, (2) calorimetry, (3) voltage and resistance changes in detectors and (4) radiation pressure on a reflecting surface. The latter three methods are self-explanatory. Bolometry measurements are based upon the absorption of power in a temperature sensitive resistive element, usually a thermistor, the change in resistance being proportional to absorbed power. This method is one of the most widely used in commercially available power meters. Low frequency radiation of less than 300 MHz may be measured with loop or short whip antennas. Because of the larger wavelengths in the low frequency region, the field

strength in volts per meter (V/m) is usually determined rather than power density.

One troublesome fact in the measurement of microwave radiation is that the near field (reactive field) of many sources may produce unpredictable radiative patterns. Energy density rather than power density may be a more appropriate means of expressing hazard potential in the near field.^{37, 38} In the measurement of the near field of microwave ovens, it is desirable that the instrument have certain characteristics; e.g., the antenna probe should be electrically small to minimize perturbation of the field, the impedance should be matched so that there is no backscatter from the probe to the source, the antenna probe should behave as an isotropic receiver, the probe should be sensitive to all polarizations, the response time should be adequate for handling the peak to average power of the radiation and the response of the instrument should be flat over a broad band of frequencies.

In terms of desirable broad band characteristics of instruments it is interesting to note that one manufacturer has set target specifications for the development of a microwave measurement and monitoring device as follows: frequency range 20 KHz to 12.4 GHz and a power density range of 0.02 to 200 mW/cm² ± 1 dB. Reportedly,³⁹ two models of this device will be available: one a hand-held model with complete meter readout, the other a lapel model equipped with audible warning signals if excessive power density levels develop.

Control Measures

The installation of engineering controls is usually the most satisfactory means for controlling exposures to microwave radiation. The engineering measures may range from the restriction of azimuth and elevation settings on radar antennas to complete enclosures of magnetrons in microwave ovens. The use of personnel protective devices has its place, but is of much lower priority importance to engineering controls. Various types of microwave protective suits, goggles and mesh have been used for special problems. In this connection Figure 28-6 showing the transmission loss through a wire grid may prove useful.⁴⁰ Similarly, the general order of attenuation provided by various types of material (Table 28-12) may be of use in designing shields or enclosures.⁴¹

It has been shown recently⁴² that cardiac pacemakers, particularly those of the demand type, may have their function seriously compromised by microwave radiation. Furthermore, the radiation levels which cause interference with the pacemaker may be orders of magnitude below levels which cause detrimental biological effects. The most effective method of reducing the susceptibility of these devices to microwave interference seems to be improved shielding. Manufacturers of cardiac pacemakers are engaged in a major program to minimize such interference.

The judicious use of appropriate signs and labels may prove useful in alerting people to the presence of dangerous microwave sources. Figure 28-7 illustrates the RF and microwave warning

signs adopted by the American National Standards Institute C95 committee.

TABLE 28-12
Attenuation Factors (Shielding)

Material	Frequency			
	1-3 GHz	3-5 GHz	5-7 GHz	7-10 GHz
60 × 60 mesh screening	20 dB	25 dB	22 dB	20 dB
32 × 32 mesh screening	18 dB	22 dB	22 dB	18 dB
16 × 16 window screen	18 dB	20 dB	20 dB	22 dB
¼" mesh (hardware cloth)	18 dB	15 dB	12 dB	10 dB
Window Glass	2 dB	2 dB	3 dB	3.5 dB
¾" Pine Sheathing	2 dB	2 dB	2 dB	3.5 dB
8" Concrete Block	20 dB	22 dB	26 dB	30 dB

Presented at Am. Ind. Hyg. Conf., 1967: Palmisano, W., U. S. Army Environmental Hygiene Agency, Edgewood Arsenal, Md.

Research Needs

A major need is to conduct intermediate and long term bioeffects research at low (≤ 10 mW/cm²) radiation levels. In this connection it is desirable to replicate certain of the Soviet work on CNS effects. Perhaps of greater importance is the need to standardize or at least coordinate all such research, particularly the measurement techniques used in the investigations.

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APPENDIX A
USEFUL RADIOMETRIC AND RELATED UNITS

Term	Symbol	Description	Unit and Abbreviation
Radiant Energy	O	Capacity of electromagnetic waves to perform work	Joule (J)
Radiant Power	P	Time rate at which energy is emitted	Watt (W)
Irradiance or Radiant Flux Density (Dose Rate in Photo-biology)	E	Radiant Flux Density	Watt per square meter ($W \cdot M^{-2}$)
Radiant Intensity	I	Radiant Flux or Power Emitted per solid angle (steradian)	Watt per steradian ($W \cdot sr^{-1}$)
Radiant Exposure (Dose in Photo-biology)	H	Total Energy Incident on Unit Area in A Given Time Interval	Joule per square meter ($J \cdot m^{-2}$)
Beam Divergence	ϕ	Unit of Angular Measure. One Radian $\approx 57.3^\circ$ 2π Radians = 360°	Radian

APPENDIX B
Conversion Factors
A-Radiant Energy Units

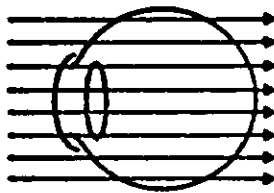
	erg	joule	W sec	μW sec	g-cal
erg =	1	10^{-7}	10^{-7}	0.1	2.39×10^{-8}
joule =	10^7	1	1	10^6	0.239
W sec =	10^7	1	1	10^6	0.239
μW sec =	10^8	10^{-6}	10^{-6}	1	2.39×10^{-7}
g-cal =	4.19×10^7	4.19	4.19	4.19×10^6	1

B-Radiant Exposure (Dose) Units

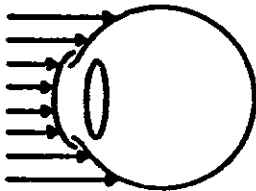
	erg/cm ²	joule/cm ²	W sec/cm ²	μW sec/cm ²	g-cal/cm ²
erg/cm ² =	1	10^{-7}	10^{-7}	0.1	2.39×10^{-8}
joule/cm ² =	10^7	1	1	10^6	0.239
W sec/cm ² =	10^7	1	1	10^6	0.239
μW sec/cm ² =	10^8	10^{-6}	10^{-6}	1	2.39×10^{-7}
g-cal/cm ² =	4.19×10^7	4.19	4.19	4.19×10^6	1

C-Irradiance (Dose Rate) Units

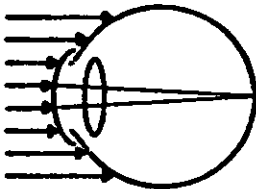
	erg/cm ² ·sec	joule/cm ² ·sec	W/cm ²	μW /cm ²	g-cal/cm ² ·sec
erg/cm ² ·sec =	1	10^{-7}	10^{-7}	0.1	2.39×10^{-8}
joule/cm ² ·sec =	10^7	1	1	10^6	0.239
W/cm ² =	10^7	1	1	10^6	0.239
μW /cm ² =	10^8	10^{-6}	10^{-6}	1	2.39×10^{-7}
g-cal/cm ² ·sec =	4.19×10^7	4.19	4.19	4.19×10^6	1



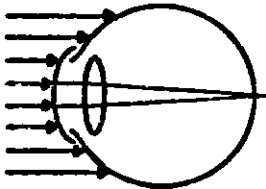
**HIGH ENERGY X-RAYS, GAMMA RAYS;
99% PASS COMPLETELY THRU THE EYE,
1% ABSORBED.**



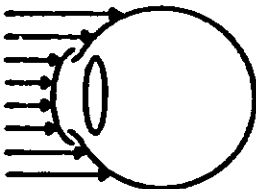
**SHORT UV; ABSORPTION PRINCIPALLY AT
CORNEA. (INTERMEDIATE UV; ABSORPTION
AT CORNEA AND LENS.)**



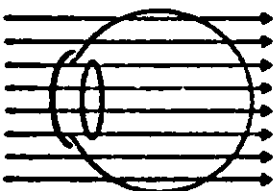
**LONG UV, VISIBLE; TRANSMITTED THRU
EYE AND FOCUSED ON RETINA.**



**NEAR IR; PARTIALLY ABSORBED BY LENS,
IRIS, AND MEDIA, PARTIALLY FOCUSED
AT RETINA.**



**FAR IR; ABSORPTION LOCALIZED AT
CORNEA FOR SHARP H₂O ABSORPTION
WAVELENGTHS, OTHER WAVELENGTHS
ABSORBED ALSO BY LENS AND IRIS.**



**MICROWAVE; GENERALLY TRANSMITTED
WITH PARTIAL ABSORPTION IN ALL
PARTS OF THE EYE.**

Figure also appears in Bell Laboratories: Policies and Practices for Personnel Using Laser Devices. Murray Hill, New Jersey.

Appendix C. General Absorption Properties of the Eye for Electromagnetic Radiation.

IONIZING RADIATION

Edgar C. Barnes

INTRODUCTION

Definition and General Description

Ionizing radiation, in general, is any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, by interaction with matter. In the specific situation being considered here, the industrial environment — and usually in considering radiation protection matters — that portion of the electromagnetic spectrum having frequencies in the ultraviolet portion and lower is excluded (see Chapter 28). Stated in more explicit terms, the International Commission on Radiation Units and Measurements (ICRU)¹ defines ionizing radiation as: “any radiation consisting of directly or indirectly ionizing particles or a mixture of both. Directly ionizing particles are charged particles (electrons, protons, alpha particles, etc.) having sufficient kinetic energy to produce ionization by collision. Indirectly ionizing particles are uncharged particles (neutrons, photons, etc.) which can liberate directly ionizing particles or can initiate nuclear transformations.” Thus, ionizing radiation encompasses consideration both of atomic particles having a variety of physical and electrical characteristics streaming at velocities from nearly zero, to values approaching the speed of light, and of electromagnetic radiations (photons) having a wide range of energies streaming at the speed of light. Photons, which have no mass, are referred to as “particles” for theoretical reasons. In this chapter “radiation” implies “ionizing radiation.”

In the industrial environment, the radiations of primary concern are: x, gamma, alpha, beta and neutron. X and gamma radiations may be called x rays and gamma rays. Also, alpha and beta radiations are called alpha and beta particles. Except for very small amounts from natural background radiation, proton and some other kinds of radiation are not of concern unless there is equipment designed to specifically produce them. Research facilities, such as large accelerators, are not discussed in this chapter.

X and gamma radiations both are penetrating electromagnetic radiations having wavelengths much shorter than that of visible light but they are of different origin. X rays originate in the extra nuclear part of the atom, whereas gamma rays are emitted from the nucleus in the process of nuclear transition or during particle annihilation. (Annihilation is the process by which a negative electron and a positive electron, called a positron, combine and disappear with emission of electromagnetic radiation.)

Ordinarily, useful x rays are produced in an evacuated tube by accelerating electrons from a heated filament to a metal target with voltages of 50 to 500 kilovolts (kV). Sometimes much higher or somewhat lower voltages are used. The electrons interact with orbital electrons of atoms in the target causing energy level changes that result in the emission of “characteristic” x rays, and also with the nucleus of the atom to produce electromagnetic radiation having a “continuous” spectrum (called bremsstrahlung).

All radionuclides undergo a spontaneous transformation, called decay, during which radiation is emitted and a new nuclide, called a daughter (or decay product) is formed. The radiations are of a specific type (or types) and energy, or energy distribution, for each species of radionuclide. Tabulated data for many radionuclides are presented in *Radiological Health Handbook*.²

Gamma rays are emitted by the nucleus of certain radionuclides during their decay. Each such radionuclide emits one or more gamma rays having a specific energy. Gamma rays also are produced by neutron interactions with nuclei.

Alpha radiation consists of a stream of alpha particles, each particle being physically identical to the helium nucleus — two neutrons and two protons. They are emitted spontaneously during the radioactive decay of certain radionuclides, primarily those of higher molecular weight — bismuth and higher. Because of the comparatively large size and double positive charge of the alpha particles, alpha radiation does not penetrate matter readily. The more energetic radiation is completely stopped by the skin. Inside the body, however, it produces dense ionization in tissues.

Beta radiation consists of a stream of beta particles, which are either electrons of negative charge or electrons of positive charge, called positrons, which have been emitted by an atomic nucleus — or by a neutron in the process of transformation. Radionuclides that spontaneously emit beta particles span the entire range of the elements. These nuclides emit particles having a maximum energy characteristic of that nuclide, along with many other particles of lower energy.

Neutron radiation consists of a stream (flow) of neutrons. Radionuclides do not emit neutrons spontaneously, although a small number of very heavy radionuclides fission spontaneously with the emission of neutrons. Neutron radiation is produced by various nuclear reactions, by nuclear fission and by interactions of alpha or gamma radiation with certain nuclei. Since neutrons are

uncharged, the radiation readily penetrates matter. Neutrons decay into a proton and an electron with a half-life of 11.7 minutes. Neutron energies, expressed in electron volts (eV) or the multiples kiloelectron volts (keV) and megaelectron volts (MeV), span a very wide range of values, and are commonly classified into three general groups — slow, intermediate and fast. The range of energies for each of these general groups is indefinite, different ranges being selected according to specific needs. One such classification is <1 eV, 1 eV to 0.1 MeV and >0.1 MeV, respectively.³ There are also more specific classes, e.g., thermal, which are those essentially in thermal equilibrium with the medium in which they exist (mean value 0.025 eV at 20°C).

Quantities and Units

In quantitating radioactive materials, a unique situation exists because one property of primary interest is continually changing. As decay takes place, the activity, or number of nuclear disintegrations occurring in a given quantity of material per unit time decreases exponentially. Therefore, a time dependent factor, half-life, becomes part of any quantitative evaluation. Each radionuclide has a definite half-life, however the range of half-lives for different radionuclides is very great, from fractions of a second to billions of years. Since the mass of material does not change significantly during this decay, the quantity of a radionuclide or of a radioactive material is usually specified in terms of its activity, with the exception that mass may be used in some situations (e.g., nuclear fuel manufacturing) where half-lives of the useful radionuclides are very long. Since activity in a given specimen (and the radiation from it) may come from one or more radionuclides, each decaying exponentially, the composition and activity must be specified as of a definite date, the accuracy (year, month, day, minute, second) depending on the relation of the half-lives to previous or subsequent periods of interest. The activity is commonly expressed in curies (or its multiples) although for some measurements, disintegrations per minute (dpm) or per second (dps) are commonly used. One curie equals 3.7×10^{10} disintegrations per second.

Another unique and complex situation exists in quantitating the effect of radiation on living organisms. The different kinds of radiation interact in a wide variety of ways both with living organisms (e.g., body tissues) and inanimate things (e.g., shielding). Furthermore, the interactions may be different for different energies of the same type of radiation; and the spatial distribution of the interaction is not uniform. They all, however, impart energy to matter through which they pass; and for living organisms the absorbed dose — energy imparted in a volume element divided by the mass of irradiated material in that volume element — provides a common base for considering the degree of effect produced by specific amounts of any of the different types of radiation. The unit of absorbed dose is the rad. One rad equals 100 ergs per gram.

The biological effect for equal absorbed doses

from different types and energies of radiation, however, is not constant. Therefore dose equivalent, which is the absorbed dose modified by pertinent factors, particularly the "quality factor," is used for radiation protection evaluations to take into account the difference in the biological effect of the different radiations. Values of the quality factor for commonly encountered radiations, suitable for general use, have been determined (see page 391). The special unit of dose equivalent is the rem, which is the product of absorbed dose in rads and the applicable quality factor. For special situations, a factor in addition to the quality factor may be used. Dose-limiting recommendations are expressed as maximum permissible dose equivalent in rems, commonly called "maximum permissible dose (MPD)." A similar concept is expressed as a Radiation Protection Guide (RPG) by the Federal Radiation Council.⁴

In some situations, it may be convenient and sufficiently accurate to express dose-limiting recommendations for x and gamma radiation (or to make related measurements) in terms of ionization in air, at the point of interest. The measure of ionization produced in air by x or gamma radiation is called "exposure," its special unit being the roentgen (R). It is customary, for radiation protection purposes, to consider that one R at the point of interest would be equivalent to a dose equivalent of one rem.

A comprehensive collection of data, graphs and tables will be found in the *Radiological Health Handbook*.² It should prove to be a useful adjunct to this chapter, since extensive tables and graphs are not included here.

Glossary

This glossary includes a limited number of terms used in radiation protection practice. These definitions are mostly from reference (3) which contains definitions of other terms. References (2) and (3) also include pertinent definitions.

activity (A). The number of nuclear disintegrations occurring in a given quantity of material per unit time.

body burden. The total quantity of a radionuclide present in the body.

body burden, maximum permissible. That body burden of a radionuclide which, if maintained at a constant level, would produce the maximum permissible dose equivalent in the critical organ.

bremsstrahlung. The electromagnetic radiation associated with the deceleration of charged particles. The term is also applied to the radiation associated with the acceleration of charged particles.

controlled area. A specified area in which exposure of personnel to radiation or radioactive material is controlled and which is under the supervision of a person who has knowledge of the appropriate radiation protection practices, including pertinent regulations, and who has responsibility for applying them.

curie (Ci). The special unit of activity. One curie equals 3.7×10^{10} disintegrations per second exactly. By popular usage, the quantity of any

radioactive material having an activity of one curie.

daughter. A nuclide, stable or radioactive, formed by radioactive decay. A synonym for decay product.

dose. A general term denoting the quantity of radiation or energy absorbed in a specified mass. For special purposes, its meaning should be appropriately stated, e.g., absorbed dose.

dose, absorbed. The energy imparted to matter in a volume element by ionizing radiation divided by the mass of irradiated material in that volume element.

dose equivalent. The product of absorbed dose, quality factor, and other modifying factors necessary to express on a common scale, for all ionizing radiations, the irradiation incurred by exposed persons.

dose equivalent, maximum permissible (MPD). The largest dose equivalent received within a specified period which is permitted by a regulatory agency or other authoritative group on the assumption that receipt of such dose equivalent creates no appreciable somatic or genetic injury. Different levels of MPD may be set for different groups within a population. (By popular usage, dose, maximum permissible, is an accepted synonym.)

exposure. A measure of the ionization produced in air by x or gamma radiation. It is the sum of the electrical charges on all of the ions of one sign produced in air when all electrons liberated by photons in a volume element of air are completely stopped in the air, divided by the mass of the air in the volume element.

genetically significant dose (GSD). The dose which, if received by every member of the population, would be expected to produce the same total genetic injury to the population as do the actual doses received by the various individuals.

half-life, radioactive. For a single radioactive decay process, the time required for the activity to decrease to half its value by that process.

half-value layer. The thickness of a specified substance which, when introduced into the path of a given beam of radiation, reduces the value of a specified radiation quantity by one-half. It is sometimes expressed in terms of mass per unit area.

isotopes. Nuclides having the same atomic number but different mass numbers. NOTE: this term is often used inaccurately as a synonym for nuclide.

nuclide. A species of atom characterized by its mass number, atomic number, and energy state of the nucleus, provided that the mean life in that state is long enough to be observable.

quality factor. A linear energy transfer dependent factor by which absorbed doses are to be multiplied to obtain the dose equivalent.

rad. The special unit of absorbed dose. One rad equals 100 ergs per gram.

radiation source. An apparatus or a material

emitting or capable of emitting ionizing radiation.

Radiation Protection Guide (RPG). The radiation dose which should not be exceeded without careful consideration of the reasons for doing so; every effort should be made to encourage the maintenance of radiation doses as far below this guide as practicable.

Radioactivity Concentration Guide (RCG). The concentration of radioactivity in the environment which is determined to result in organ doses equal to the Radiation Protection Guide.

roentgen (R). The special unit of exposure. One roentgen equals 2.58×10^{-4} coulomb per kilogram of air.

sealed source. A radioactive source sealed in a container or having a bonded cover, where the container or cover has sufficient mechanical strength to prevent contact with and dispersion of the radioactive material under the conditions of use and wear for which it was designed.

PHYSICAL ASPECTS OF IONIZING RADIATION

Electromagnetic Radiation

In the electromagnetic spectrum, gamma radiation spans an energy range from approximately 8×10^3 eV to 10^7 eV, the corresponding frequencies being 2×10^{18} to 2.5×10^{21} hertz. X rays span a somewhat wider range of values, although there is no clear break at the lower energy boundary and at higher energies special equipment, such as an accelerator, is used for their production.

A beam of x rays from x-ray equipment encompasses a range of energies. The highest photon energy in the beam corresponds to the electron accelerating voltage, with the median being considerably below this value. The beam will include both photons having energies which are "characteristic" of the target material and photons having a continuous spectrum (bremsstrahlung), the proportion of the latter being greater at higher electron accelerating voltages. The energy spectrum, or quality of the beam, may be expressed either in terms of an "effective energy" or in terms of its half-value layer. The accelerating voltage may be constant or may come from a pulsating generator, which influences the photon energy distribution, the latter being designated in terms of peak voltage (kVp). Ordinarily, x-ray tubes and their housings are arranged so that there is shielding in all directions except for a "window" where the useful beam is emitted. The solid angle and shape of the useful beam is determined by the size of the window and by collimating devices, such as diaphragms and cones, made of shielding materials. Some low energy x rays are absorbed in the target, while others are removed from the useful beam by the material in the tube window and usually also by filters that preferentially absorb the less penetrating radiation. Accelerators used to produce high energy x rays are commonly arranged for beam emission to accomplish a specific purpose.

Sealed sources, consisting of a radionuclide encased in a metal capsule, are a common source of gamma radiation used in industry. They are used in radiography, measuring devices and a number of other special applications. The radionuclides in them are selected to provide radiation of the desired photon energy. Some emit photons of one energy, such as cesium-137 (.66MeV); others a range of energies, such as radium (.047 to 2.4 MeV due to retained daughters).

There are two basic processes by which electromagnetic radiation interacts with matter: scattering, in which the direction of the photon and its energy are altered; and absorption, in which the photon disappears with transfer of its energy to other radiations.

Along the path of a primary beam of photons, there are interactions between the electric fields of these photons and the electrons in the material being penetrated which cause "scattering" of some of the primary beam photons. Further reactions ensue with a resulting 360° angular distribution of scattered photons having a range of energies down to nearly zero. The shape of this angular, and associated energy, distribution is a function of the energy of the original photons. For a mathematical treatment of scattering, see *Principles of Radiation Protection*.⁵

Absorption of photons occurs primarily by three processes—the photoelectric effect, the Compton effect and pair production. These are also treated mathematically in the above book.⁵ The photoelectric effect predominates for the lower energy photons, the Compton effect where the energy is greater than approximately 0.5 MeV, and for pair production a minimum of 1.02 MeV is required.

The photoelectric effect involves an interaction between incident photons and the electrons in the shells around the nuclei. Electrons are ejected from the atoms with an energy equal to the difference between the photon energy and the binding energy of the ejected electron. Subsequently, x rays or electrons are emitted as the shell vacancies are corrected, the x rays having a wide range of

energies which are higher for the higher atomic number materials. The portion of photons interacting by the photoelectric process increases with increasing atomic number and decreasing energy.

The Compton effect involves interactions of photons incident on orbital electrons. The photon gives up part of its energy to the electron causing it to recoil and the balance of its energy goes into a scattered photon. From conservation of energy and momentum, the angular relationships of the recoil electron, scattered photon and incident photon can be determined. The original photon energy determines the distribution of these angles; at lower energies, the angles at which electrons are scattered is greater.

Pair production occurs by the interaction of a photon with the electric field surrounding a charged particle. The original photon disappears with the formation of an electron-positron pair. The photon energy must exceed 1.02 MeV and it is divided equally between the electron and the positron. The portion of incident photons which interact with a nucleus by pair production increases with increasing atomic number.

As a beam of photons traverses matter, the scattering and absorption of photons by all processes results in attenuation of the beam exponentially. This is expressed by the equation:

$$I = I_0 e^{-\mu x} \quad (1)$$

where I is exposure rate at a depth x
 I_0 is exposure rate at zero depth
 μ is the attenuation coefficient

The value of the attenuation coefficient depends on the photon energy and the absorbing material. This coefficient may be expressed in terms of thickness, as a linear attenuation coefficient (cm^{-1}), or as a mass attenuation coefficient (cm^2/g) obtained by dividing the linear coefficient by the density ρ of the absorbing material. Table 29-1 presents some of these values. More extensive tables are available in reference (2). In matter being traversed by a beam of electromagnetic radiation, there is actually a higher intensity of photons at any point, particularly at great depth,

TABLE 29-1
Mass Attenuation Coefficients

Photon energy MeV	Mass attenuation coefficient in cm^2/g for —				
	Aluminum	Iron	Lead	Water	Concrete
0.01	26.3	173	133	5.18	26.9
0.02	3.41	25.5	85.7	0.775	3.59
0.05	0.369	1.94	7.81	0.227	0.392
0.1	0.171	0.370	5.40	0.171	0.179
0.5	0.0844	0.0840	0.161	0.0968	0.087
1.0	0.0613	0.0599	0.0708	0.0707	0.0637
5.0	0.0284	0.0314	0.0424	0.0303	0.0290
10.0	0.0231	0.0298	0.0484	0.0222	0.0231

Reprinted from "Radiological Health Handbook", U.S. DHEW, Public Health Service, 1970.

TABLE 29-2
Dose Buildup Factor (B) for a Point Isotropic Source

Material	MeV	μx^*						
		1	2	4	7	10	15	20
Water	0.255	3.09	7.14	23.0	72.9	166	456	982
	0.5	2.52	5.14	14.3	38.8	77.6	178	334
	1.0	2.13	3.71	7.68	16.2	27.1	50.4	82.2
	2.0	1.83	2.77	4.88	8.46	12.4	19.5	27.7
	3.0	1.69	2.42	3.91	6.23	8.63	12.8	17.0
	4.0	1.58	2.17	3.34	5.13	6.94	9.97	12.9
	6.0	1.46	1.91	2.76	3.99	5.18	7.09	8.85
	8.0	1.38	1.74	2.40	3.34	4.25	5.66	6.95
	10.0	1.33	1.63	2.19	2.97	3.72	4.90	5.98
Aluminum	0.5	2.37	4.24	9.47	21.5	38.9	80.8	141
	1.0	2.02	3.31	6.57	13.1	21.2	37.9	58.5
	2.0	1.75	2.61	4.62	8.05	11.9	18.7	26.3
	3.0	1.64	2.32	3.78	6.14	8.65	13.0	17.7
	4.0	1.53	2.08	3.22	5.01	6.88	10.1	13.4
	6.0	1.42	1.85	2.70	4.06	5.49	7.97	10.4
	8.0	1.34	1.68	2.37	3.45	4.58	6.56	8.52
	10.0	1.28	1.55	2.12	3.01	3.96	5.63	7.32
Iron	0.5	1.98	3.09	5.98	11.7	19.2	35.4	55.6
	1.0	1.87	2.89	5.39	10.2	16.2	28.3	42.7
	2.0	1.76	2.43	4.13	7.25	10.9	17.6	25.1
	3.0	1.55	2.15	3.51	5.85	8.51	13.5	19.1
	4.0	1.45	1.94	3.03	4.91	7.11	11.2	16.0
	6.0	1.34	1.72	2.58	4.14	6.02	9.89	14.7
	8.0	1.27	1.56	2.23	3.49	5.07	8.50	13.0
	10.0	1.20	1.42	1.95	2.99	4.35	7.54	12.4
Lead	0.5	1.24	1.42	1.69	2.00	2.27	2.65	(2.73)
	1.0	1.37	1.69	2.26	3.02	3.74	4.81	5.86
	2.0	1.39	1.76	2.51	3.66	4.84	6.87	9.00
	3.0	1.34	1.68	2.43	2.75	5.30	8.44	12.3
	4.0	1.27	1.56	2.25	3.61	5.44	9.80	16.3
	5.1097	1.21	1.46	2.08	3.44	5.55	11.7	23.6
	6.0	1.18	1.40	1.97	3.34	5.69	13.8	32.7
	8.0	1.14	1.30	1.74	2.89	5.07	14.1	44.6
	10.0	1.11	1.23	1.58	2.52	4.34	12.5	39.2

* μx = mass absorption coefficient (μ/ρ) \times shield thickness (cm) \times shield density (g/cm³).

NOTE: For concrete use an average of aluminum and iron; e.g., B(conc) = [B(iron) + B(Al)] \div 2.

Reprinted from "Radiological Health Handbook", U.S. DHEW, Public Health Service, 1970.

than would be predicted solely by attenuation (equation 1) because of the presence of x rays and secondary or scattered photons. This increase in exposure rate, called buildup (B), is not easily calculated. It can be included as a factor B in the attenuation equation $I = BI_0 e^{-\mu x}$ and tabulated values of B for one set of conditions is shown in Table 29-2. Additional values appear in reference (2). To assure proper accuracy, it is us-

ually necessary to consider this buildup factor.

Since absorption of energy is the physical quantity used in specifying absorbed dose, a mass energy absorption coefficient similar to the attenuation coefficient is useful.

Table 29-3 presents some of these values. More extensive tables will be found in *Physical Aspects of Irradiation*.⁶

TABLE 29-3
Mass Energy-absorption Coefficients

Photon energy MeV	Mass energy-absorption coefficient in cm ² /g for			
	Water	Air	Bone	Muscle
0.01	4.89	4.66	19.0	4.96
0.02	0.523	0.516	2.51	0.544
0.05	0.0394	0.0384	0.158	0.0409
0.1	0.0252	0.0231	0.0368	0.0252
0.5	0.0330	0.0297	0.0316	0.0327
1.0	0.0311	0.0280	0.0297	0.0308
5.0	0.0190	0.0173	0.0186	0.0188
10.0	0.0155	0.0144	0.0159	0.0154

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Shielding of radiation sources is commonly provided to reduce the exposure rate in occupied areas. For economy, the shield should be as close as possible to the radiation source. For discrete energies, the attenuation by a shield can be calculated from the attenuation equation, including buildup. In practice, extensive data on attenuation (or transmission), presented in graphic form, is available and used for shielding calculations. This data is presented in a variety of ways and selection of the most useful form will simplify shielding calculations. Because attenuation is exponential, the thickness of a "half-value layer" (HVL) for different shielding materials is a common and convenient form to present such data. A shield thickness of 2 HVL reduces exposure rate by a factor of 4, 3 HVL by a factor of 8, etc. Table 29-4 presents such data for the gamma radiation from several radionuclides, as well as their specific gamma ray constants (exposure rate constants). The latter are useful in determining exposure rate at varying distances, in air, from a point source using the inverse square relationship between exposure rate and distance from the source. Additional values are included in reference (2). Comprehensive shielding data for x rays appear in *Safety Standard for Non-medical X-ray and Sealed Gamma-ray Sources*,⁷ and *Medical X-ray and Gamma-ray Protection for Energies up to 10 MeV*.⁸

Particulate Radiation

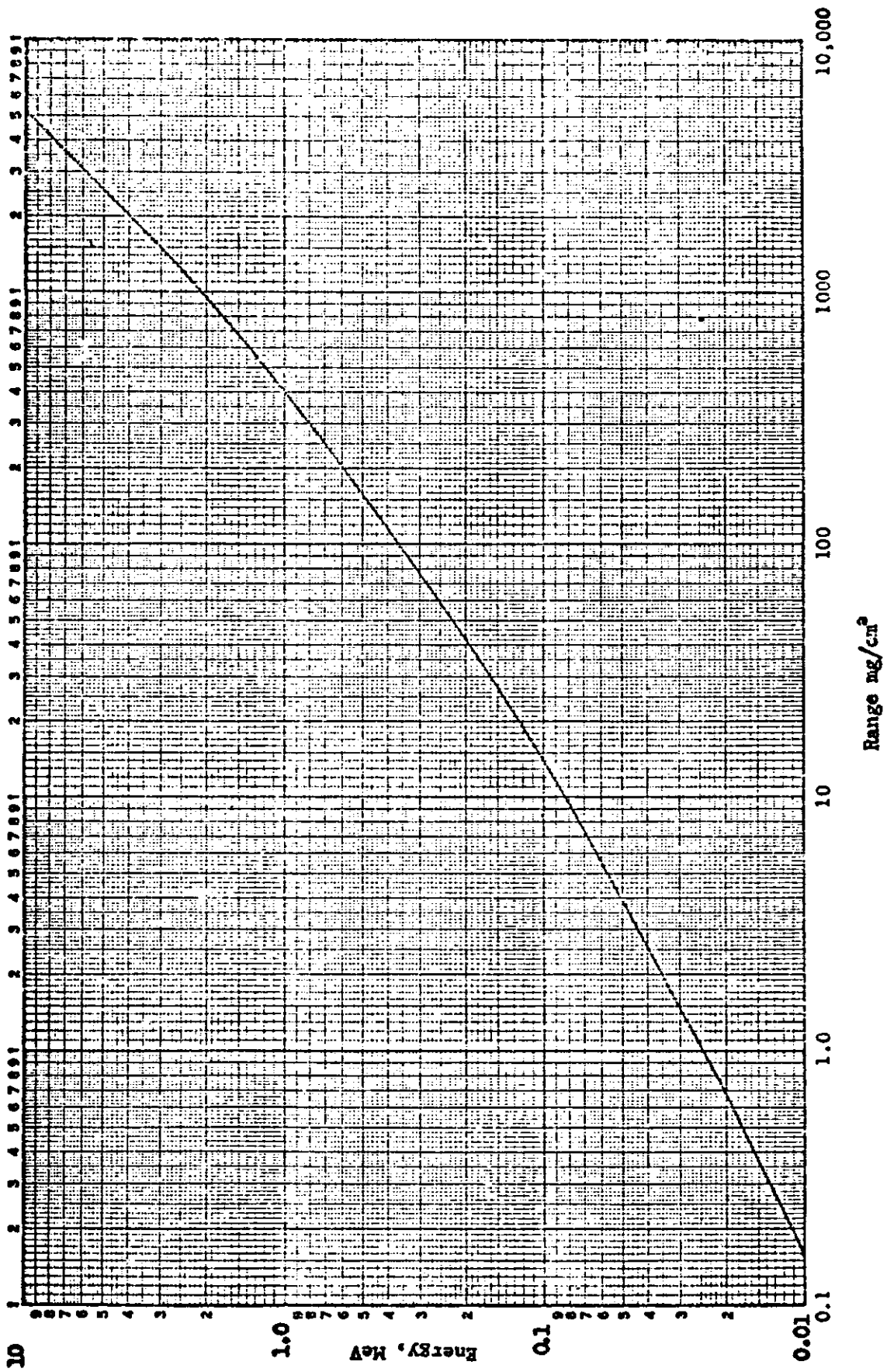
Beta radiation is emitted by a large percentage of the radionuclides, frequently accompanied by x or gamma radiation. Each nuclide, which decays by beta particle emission, emits beta particles having a maximum energy characteristic of that nuclide along with many other particles of lower energy. The average of these energies is much less than the maximum and for different nuclides the ratios of maximum to average span a wide range of values. For different nuclides, the range of maximum energies is from a few keV to slightly over 4 MeV. In contrast to electromagnetic radi-

ation which is attenuated exponentially, beta radiation has a definite range as it traverses matter, the maximum being determined by its energy and the density of the material. If this distance is divided by density, a graph showing range in mg/cm² versus energy in MeV is applicable to all materials. Values for a given energy from the graph in Figure 29-1, divided by the density of the material being traversed (mg/cm³), gives the thickness of that material (cm) which will completely stop that beta radiation. It should be noted that complete shielding for beta radiation is provided by reasonable thicknesses of commonly available materials. Correspondingly, measuring instruments must be selected which will not significantly impede the beta radiation, this being of particular importance at low energies. As beta radiation traverses matter, the electrons occasionally interact in a manner to produce electromagnetic radiation (bremsstrahlung), the amount of this radiation increasing as the beta energy and atomic number of the absorber increase.

Alpha radiation is emitted primarily by the heavier radionuclides. The alpha particles are emitted at a specific energy characteristic of each nuclide. The energy range of these alpha particles from the different nuclides is predominantly between 4 and 8 MeV. Alpha radiation, like beta, has a definite range in the materials it traverses. The distances traversed, however, are much shorter than for beta. The horny layer of the skin completely stops alpha radiation and air stops it in a few centimeters. Figure 29-2 is a graph showing the range in air for different energy alpha particles.

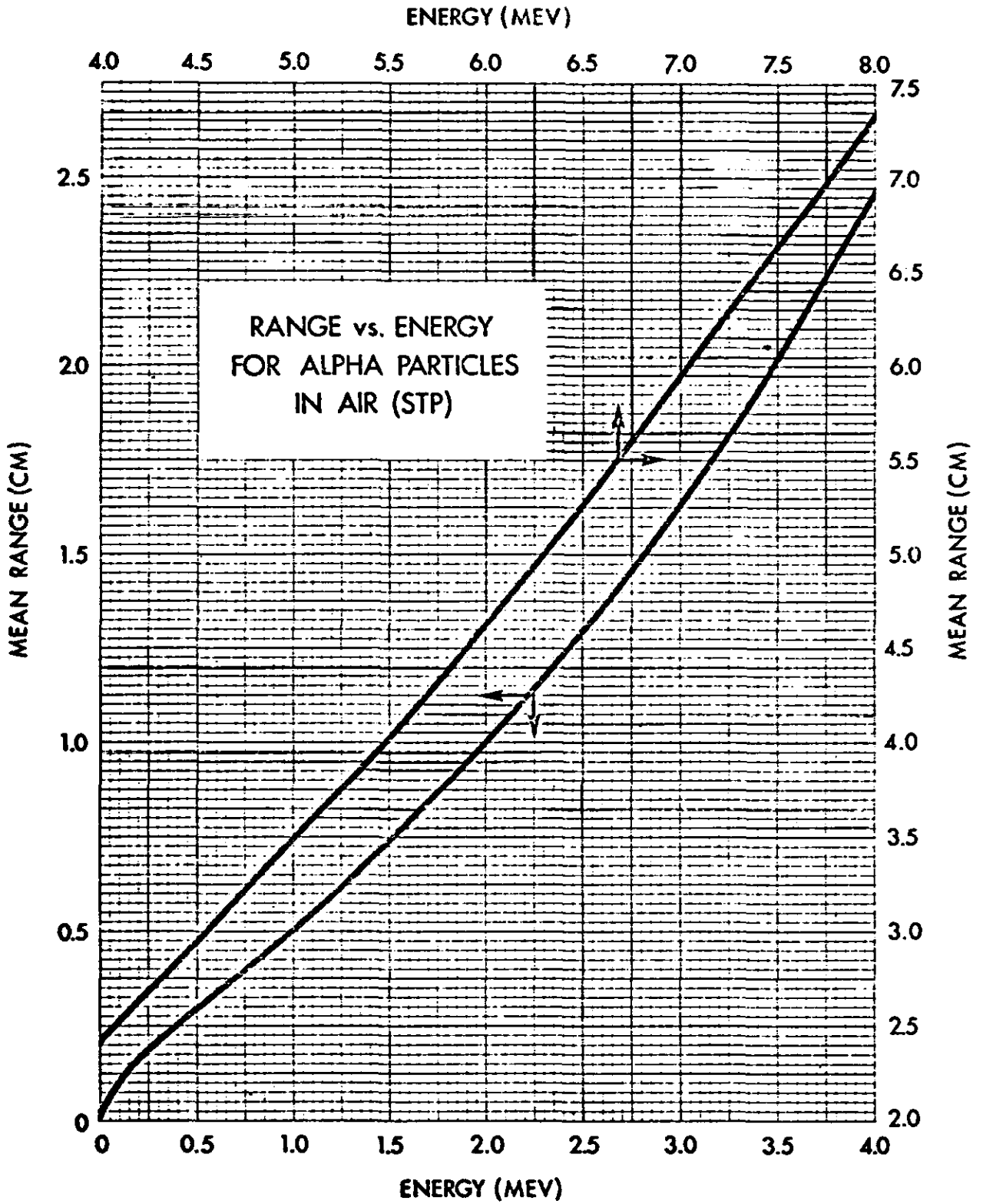
Although neutrons are not emitted by radionuclides other than by a few that fission spontaneously, there are several types of radioactive neutron sources available and in use. Of course, neutron radiation exists around the core of any nuclear reactor and it will be produced in the event of an accidental nuclear criticality incident. The radioactive neutron sources are sealed sources, normally of relatively small size. Their neutrons are produced by interactions of alpha or gamma radiation with nuclei of appropriate materials (target materials). Alpha emitting radionuclides having a high specific activity are mixed with or alloyed with the target material; and in sources using gamma interactions, the target material usually surrounds the radionuclide. These sources emit neutrons with a maximum energy characteristic of the radionuclide and target material; and many more neutrons at lower energies, with a distinctive energy spectrum. Characteristics of some radioactive neutron sources are shown in Table 29-5. When neutron radiation traverses matter it is attenuated by elastic and inelastic scattering, capture, and induced nuclear reactions. The extent of these processes depends both on the energy (or energy spectrum) of the radiation and the specific nuclides in the matter being traversed. Moderation (slowing down) of the neutrons by elastic collisions progressively changes the energy spectrum. The probability of these interactions taking place is specified in terms of cross-sections,

**BETA PARTICLE
RANGE ENERGY CURVE**



Radiological Health Handbook. U.S. Dept. of Health, Education and Welfare, Public Health Service, 1970.

Figure 29-1. Beta Particle Energy Range Curve.



Radiological Health Handbook. U.S. Dept. of Health, Education and Welfare, Public Health Service, 1970.

Figure 29-2. Alpha Particle Energy Range Curve.

with their area expressed in units of barns (1 barn = 10^{-24} cm²). These various interactions result in the production of secondary radiations, particularly gamma rays, which must always be considered when neutron radiation is present. The complexities of neutron interactions with matter do not permit adequate treatment of energy absorption and shielding here (see *Protection Against Neutron Radiation*).⁹

Dosimetry

Dosimetry involves the evaluation of radiation,

often complex as to its nature, energy, direction and quantity, in terms related to its effect on biological systems or other matter. Theoretically, it would seem that measurements could be made to completely describe the radiation field itself at any point of interest including time variations, and from this, the dose or other quantity of interest determined. In practice, however, measurements are made at the place of interest in a manner which relates the measurement directly to the quality of interest — usually absorbed dose or

TABLE 29-4
Data for Gamma-Ray Sources

Radioisotope	Atomic Number	Half Life	Gamma Energy MeV	Half-Value Layer ^a			Tenth-Value Layer ^a			Specific Gamma-Ray Constant R cm ² /m Ci-h ^b
				Conc.	Steel	Lead	Conc.	Steel	Lead	
				in	in	cm	in	in	cm	
Cesium-137	55	27 y	0.66	1.9	0.64	0.65	6.2	2.1	2.1	3.2
Cobalt-60	27	5.24 y	1.17, 1.33	2.6	0.82	1.20	8.2	2.7	4.0	13.0
Gold-198	79	2.7 d	0.41	1.6	—	0.33	5.3	—	1.1	2.32
Iridium-192	77	74 d	0.13 to 1.06	1.7	0.50	0.60	5.8	1.7	2.0	5.0 ^c
Radium-226	38	1622 y	0.047 to 2.4	2.7	0.88	1.66	9.2	2.9	5.5	8.25 ^d

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^a Approximate values obtained with large attenuation.

^b These values assume that gamma absorption in the source is negligible. Value is R/millicurie-hour at 1 cm can be converted to R/Ci-h at 1 meter by multiplying the number in this column by 0.10.

^c This value is uncertain.

^d This value assumes that the source is sealed within a 0.5 mm thick platinum capsule, with units of R/mgh at 1 cm.

TABLE 29-5
Data for Neutron Sources

Source	Half-life	Max. energy MeV	Avg. energy MeV	Yield n/sec. x 10 ⁻⁶ /curie
210 _{Po} -Be	138.4 d	10.8	4.3	2.5
Ra DEF-Be	19.4 y	10.8	4.5	2.5
226 _{Ra} -Be	1622 y	13.2	3.6	15
239 _{Pu} -Be	24,400 y	10.6	4.5	2.0

Reprinted from NBS Handbook 85-196, National Bureau of Standards, Washington, D.C.

dose equivalent. To the maximum possible extent, there is a summation of the quantities of interest. Furthermore, due to the complexity of any biological response to irradiation by various types and quantities of radiation, as well as their measurement, it is customary to utilize environmental measurements for radiation protection purposes, with precise determinations of dose and dose distribution in biological systems limited to situations of special interest — usually abnormal exposures.

Thus, dose-limiting recommendations, although specified in terms of dose equivalent in the body, are commonly evaluated by strictly environmental measurements.

There are a variety of detectors, with associated readout devices which are used for radiation monitoring or measurement. The most important are: Geiger-Müller (GM) tubes, ionization chambers, proportional counters, luminescent detectors, scintillation detectors, photographic emulsions, chemical reaction detectors, induced radiation detectors and fissionable materials. None are universally applicable and selection of the most appropriate detector or detectors for each radiation measurement (or type of measurement) becomes a matter of great importance. These detectors, with associated readout equipment, are used to perform two distinctly separate functions — to measure the radiation in the environment (monitoring or surveying); and to determine the activity or kind of radionuclide, or both, in solids or fluids, commonly samples from a larger quantity of material (analysis).

G-M tubes detect ionizing events which take place within their sensitive volume, each event causing an output voltage pulse. These pulses may be counted or summed in various ways, usu-

ally to give a count rate (counts per minute, cpm). Two types of G-M survey meters are in common use. One uses a cylindrical tube encased in a protective metal shield with an opening on one side over which various absorbers can be placed. The other has the opening at one end of the cylinder where the tube has a very thin "window." The output (cpm) is not proportional to exposure or absorbed dose rate for different types and energy of the radiation. Although scales on survey meters are frequently marked "R per hour," these values are only true for the calibrating radiation. Significant errors can occur from use where the radiation is different than the calibrating radiation. When G-M tubes are used for analysis, proper calibration is likewise essential.

Ionization (ion) chambers are commonly used to measure dose or dose rate (or exposure or exposure rate) from beta, gamma and x radiation. Ions formed by the radiation passing through a selected gas in a chamber are measured either by applying voltage continuously with measurement of the extremely low current flow or by using the chamber as a condenser which is first charged, then exposed to the radiation and the amount of discharge determined. The chamber walls, internal components and gas filling are usually either air equivalent or tissue equivalent.

Proportional counters usually consist of a gas filled cylinder (chamber) containing a central wire to which a potential is applied. The potential is selected so that the output voltage signals are proportional to the energy released by the radiation causing the ionization events in the chamber. This permits selective measurement of different radiations. These counters are commonly used to measure alpha or neutron radiation. The gas in the chamber may be either static or flowing. They may be used as survey meters or for analysis, including spectrometric analysis (measurement of radiation intensity as a function of energy). The alpha survey meters have a very thin "window" to minimize absorption of the radiation.

Luminescent detectors are solids in which energy changes produced by radiation are stored so that subsequent processing will cause them to emit a quantity of light proportional to the energy change. Commonly used materials are metaphosphate glass and calcium or lithium fluoride. The glass is processed by irradiation with ultraviolet and the fluorides by heating. The latter, called thermoluminescent dosimeters (TLD), are finding many uses because of good sensitivity with small pieces. They are used for personnel monitoring, including neutron exposure evaluation.

Scintillation detectors use the phenomenon of light production due to interaction of radiation with crystals or other phosphors (solid, liquid or gas). Light pulses from the scintillator are measured with a photomultiplier tube and its associated electronic equipment. Since the light output and in turn the electrical signal is proportional to the radiation energy absorbed in the scintillator, these devices find a wide variety of uses. They are used as survey meters and for analysis, including spectrometric analysis.

Radiation produces a latent image in photographic emulsions, resulting in darkening of the film when developed by usual techniques. Two general types of film are used, one in which the radiation (beta, gamma, x ray) produces a general blackening, and the other in which small tracks are produced by charged particles, usually protons from fast or thermal neutron interactions in the film. The blackening due to gamma and x rays is not proportional to air or tissue absorbed dose at different energies, and various absorbers are placed adjacent to the film to minimize this aberration. Blackening due to beta radiation varies a small amount with energy. A major use of film for dosimetry has been in personnel monitoring badges. Using both shielded and unshielded sections permits measurement of beta as well as gamma and x rays.

Chemical reaction detectors are systems in which radiation produces a chemical change in a material in such a manner that a chemical analysis or indicator will measure the amount of change. An example is a system using a chlorinated hydrocarbon, such as chloroform, with water and a dye indicator to measure the acid formed due to irradiation. These detectors are not used extensively because of their low sensitivity.

Induced radiation detectors are materials in which the radiation interacts to form radionuclides whose radiation can be measured. They are particularly useful for detecting or measuring neutron radiation. A typical example is the use of indium foil for detection of neutron radiation exposures. Proper selection of foil materials permits evaluation of a neutron energy spectrum. Fissionable materials also are useful for neutron radiation detection and measurement.

CATEGORIES OF RADIATION EXPOSURE

Natural Radiation

Individuals continually receive a dose from natural radiation that comes both from sources external to the body and from naturally occurring radionuclides deposited within the body. The external sources are primarily cosmic radiation and gamma radiation from materials naturally present in the ground and in building materials. From foods, drinking water and in the air, several radionuclides are deposited in the body including uranium and its decay products, thorium and its decay products, radiopotassium and radiocarbon. Natural radiation in the United States results in an estimated average annual dose equivalent to individuals of about 125 mrem (100 mrem external and 25 mrem internal). It is unlikely to be less than 100 mrem for any individual and unlikely to be more than 400 mrem for any significant number of people.¹⁰

Environmental Radiation

In addition to natural radiation, environmental radiation from man-made sources adds a small increment of dose to the population generally. This dose comes from a wide variety and type of sources including: fallout from nuclear weapons testing; effluents from nuclear and other facilities processing or using radionuclides; luminous dial

clocks or watches and signs; and electronic devices, such as television sets, using high voltages. The average annual dose equivalent to the population from these sources is estimated to be only a few percent of natural radiation, probably about five or six mrem per person per year.

Medical Irradiation

The planned exposure of patients to radiation is a category which involves a large percentage of the general population. Occupational exposures received incidentally by physicians and supporting staff are not considered part of this exposure category. Diagnostic and therapeutic procedures involve external irradiation with beta, gamma or x radiation, internal irradiation from ingested or injected radionuclides, and irradiation from implanted sealed sources. Doses to individuals vary over an extremely wide range but usually involve only partial body irradiation. Average annual dose equivalent to the population members from these sources has been estimated to be between 50 and 70 mrem per year.¹⁰ Ordinarily, medical and occupational exposures are considered separately. With the exception of a high dose due to an occupational accident, necessary medical exposures are not restricted because of occupational exposures.

Occupational Irradiation

Occupational radiation exposures arise from practically every type of radiation and radiation source. The major groups of occupationally exposed personnel are medical or para-medical workers and workers in the expanding nuclear energy programs. However, there are many exposures to radiation or radioactive materials throughout industry, in underground mining, and in many types of research. On the basis of occupational radiation exposure records of the U. S. Atomic Energy Commission and its contractors for 1967, the average annual occupational exposure is estimated at about 500 mrem per person to 100,000 adults (95% of them received less than 1 rem each).¹⁰ Assuming a similar dose to other workers, the estimated average annual dose equivalent to the population members is a fraction of a millirem per year.

BIOLOGICAL ASPECTS OF IRRADIATION

Somatic and Genetic Effects

Irradiation of humans produces two types of effect — somatic and genetic. The somatic effect is the effect on tissues, organs or whole body. Independent of any somatic effect, irradiation of the gonads may cause genetic effects since mutations, which are caused by heritable changes in the germ plasm, may occur. Of course, only the irradiation prior to conception can have this influence.

Somatic effects vary over a wide range — from rapid death due to short term whole body exposures of 10,000 Roentgens or greater to slight reddening of the skin due to minimal exposure.

Effects, including those of particular concern — neoplasms, cataracts and life shortening — may also be delayed for long periods. Within the body,

cells react with varying degrees of sensitivity. Tissues also respond differently, depending on dose equivalent rate. Dose fractionation has an ameliorating effect and there is repair of tissues and organs when time permits and the change is not irreversible. Partial body irradiation has much less effect than whole body irradiation. Age is a significant factor; for a given dose many effects are less as age increases. For equal absorbed doses, different types (and energies) of radiation do not produce the same degree of response.

In the study of biological effects, the variation due to different kinds of radiation is referred to as "relative biological effectiveness" (RBE) — the ratio of absorbed doses that produce equal effect, with cobalt-60 gamma rays or 200-250 kV x rays used as the reference. This ratio is reflected indirectly in the quality factor used in radiation protection practice. Those somatic effects (e.g., neoplasms) that are delayed for long periods of time may occur only in a small fraction of the exposed individuals — the *probability* of the effect occurring increasing with increased dose equivalent.

Genetic effects are of general concern because radiation-induced mutations are added to the "load" of defective genes present in the population. Because of the presence of defective genes in all members of the population, it is not possible to identify an abnormality in an offspring with possible mutations caused by irradiation of the parent. Thus, genetic effects relate to population groups, not individuals. Because of this, the radiation exposure to the entire population group is the matter of primary concern, and the genetically significant dose (GSD) has been established as a measure of this population exposure. Furthermore only gonadal exposures during the reproductive period of a lifetime have an influence. Thus, the age at which radiation exposures occur, as well as the dose equivalent, is of prime concern in relation to genetic effects.

Acute and Chronic Exposures

Practically all occupational irradiation involves chronic exposures, i.e., small weekly doses (e.g., <100 mrem) occurring over many months and years. Occasionally, due to an accident, an acute exposure may occur, i.e., a high dose (e.g., >25 rem) in a period of a day or less. Somatic response to acute exposure is different from and greater than that for an equal chronic exposure. In a lifetime of occupational exposure without any observable effect, an individual's total dose can be large enough so that an equal dose given in a few hours would be seriously disabling or fatal. Effects of acute exposures may be early, delayed or secondary, and late. Early effects as a result of an acute whole body exposure are shown in Table 29-6. There is less effect for partial body exposures. Delayed effects may occur some time after the early effects have been ameliorated, the extent depending on the dose. In addition to possible loss of hair, one such effect of general concern (often misunderstood) is sterility. Permanent sterility occurs only with absorbed doses to the

TABLE 29-6
Representative Dose-effect Relationships
in Man for Whole Body Irradiation

Nature of Effect	Representative absorbed dose of whole body x or gamma radiation (rads)
Minimal dose detectable by chromosome analysis or other specialized analyses, but not by hemogram	5-25
Minimal acute dose readily detectable in a specific individual (e.g., one who presents himself as a possible exposure case)	50-75
Minimal acute dose likely to produce vomiting in about 10% of people so exposed	75-125
Acute dose likely to produce transient disability and clear hematological changes in a majority of people so exposed.	150-200
Median lethal dose for single short exposure	300

The dose entries in this table should be taken as representative compromises only of a surprisingly variable range of values that would be offered by well-qualified observers asked to complete the right hand column. This comes about in part because whole body irradiation is not a uniquely definable entity. Mid-line absorbed doses are used. The data are a mixed derivative of experience from radiation therapy (often associated with "free-air" exposure dosimetry), and a few nuclear industry accident cases (often with more up to date dosimetry). Also, the interpretation of such qualitative terms as "readily detectable" is a function of the conservatism of the reporter.

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gonads of 500-600 rads of x or gamma radiation; and a single dose of 50 rads may induce brief temporary sterility in many men and some women.¹⁰ Late effects as the result of acute exposure, such as leukemia, may occur many years after exposure, their *probability* increasing as dose increases. From chronic exposures, there are no secondary or delayed effects and the possibility of late effects is minimal. If chronic occupational doses are within the NCRP dose limiting recommendations, the probability of any late effect is so small that it has not been possible to establish clearly whether any such somatic effect exists.

Internal and External Radiation Sources

External radiation sources, i.e., those sources which are located external to the body, present an entirely different set of conditions than radionuclides which have gained entrance to the body

with their attendant continuous irradiation of the cells and tissues in which they exist. Such radionuclides are called internal radiation sources — sometimes internal emitters.

Entry of internal radiation sources into the body during occupational exposures is principally from breathing air containing particulate or gaseous radionuclides, although ingestion may be a significant mode. Absorption through the skin is significant for some compounds of a few radionuclides, particularly tritium; and implantation under the skin may occur as the result of accidental skin puncture or laceration. Once inside the body, radionuclides are absorbed, metabolized and distributed throughout the tissues and organs according to the chemical properties of the elements and compounds in which they exist. Their effects on organs or tissues depends on the type and energy of the radiation and residence time. Both radioactive decay and biological elimination remove radionuclides from the body and its organs, these removal rates frequently being expressed as half-lives. The net rate is designated as the "effective half-life." While metabolically similar, the degree of effect from different radioactive isotopes of the same element will vary according to the type and energy of the radiation they emit and their radioactive half-life. Acute or early effects do not occur from internal radiation sources, with the possible exception of a very large intake of certain radionuclides.

While radiation measurements can be made in the environment of workers which characterize their dose equivalent from external radiation sources, no comparable environmental radiation measurement will reveal dose equivalent from exposures to internal radiation sources. Instead, evaluation (and control) is based on activity concentrations in air or water, a specific relation between these concentrations and the resulting dose equivalents for each radionuclide having been determined from human experience when available, or from calculations. Thus, practical dose-limiting recommendations are expressed in terms of maximum permissible concentrations (MPC) for inhaled or ingested radionuclides. A similar concept is expressed as a Radioactivity Concentration Guide (RCG) by the Federal Radiation Council.⁴ For essentially insoluble gases producing beta or gamma radiation, such as the inert gases argon and krypton, the amount of the radionuclide that becomes an internal radiation source is so small that the external irradiation from an infinite cloud surrounding the individual will produce the greater dose equivalent.

The effect from external radiation sources depends on the penetrating ability of the particular radiation. Thus, alpha radiation is of no concern externally, and beta is stopped in the outer tissues, the depth depending on energy. Very low energy x or gamma radiation is attenuated quite rapidly.

The effect of radiation on any organ or tissue is dependent on the total dose equivalent from both internal and external radiation sources. Thus, the total dose equivalent must be considered when comparisons with the MPD are made. Theoretic-

ally, it should be possible to sum these separate dose equivalents but in practice such quantitation is difficult, if not impossible. Therefore, it is customary to use the two different dose-limiting recommendations conservatively.

Critical Organs and Tissues

The various tissues and organs of the body are not affected equally by equal irradiation. Their responses vary considerably and for radiation protection purposes it is essential that dose equivalent to the most sensitive organs essential to well being be given primary consideration. For uniform whole body irradiation, the blood forming organs (red bone marrow), the lens of the eye, and the gonads are more susceptible to significant effects and these are designated as "critical organs." Of course, for individuals past reproductive age the gonads are not a critical organ. For those internal radiation sources that do not irradiate the body uniformly the distribution and metabolic pattern for each radionuclide will determine which organs and tissues receive the larger dose. Again, for radiation protection purposes, any essential organ or tissue which is likely to be affected the most by the radiation from internal radiation sources is of primary concern and these are also designated as critical organs. These critical organs (and tissues), sometimes designated as limiting organs, are: lung, GI tract, bone, muscle, fatty tissue, thyroid, kidney, spleen, pancreas and prostate.

The total activity (curies) of a radionuclide in the body is designated as the "body burden." Distribution may be inhomogeneous, with a large fraction in one or more organs or tissues. While the activity in the critical organ is the limiting factor, the body burden corresponding to the MPD for the critical organ indicates the total activity that should be present in the entire body. It is designated as the maximum permissible body burden.

RADIATION PROTECTION CONSIDERATIONS

Occupational and Public Exposures

Occupational radiation exposures involve a select age group of healthy individuals. Their exposures occur for periods not exceeding approximately eight hours per day and 250 days per year. This group is a very small portion of the general population and they are trained in radiation protection practices. In contrast, the general population necessarily includes the unborn, the very young, the sick or disabled; and their exposures can be continuous — 24 hours per day, 365 days per year. For these, and other reasons, dose-limiting recommendations for the general population are set at lower limits than for occupational exposure, commonly by a factor of 10 or greater. Dose-limiting recommendations applicable to the public are designated frequently as "dose limits," those for occupational exposure as "maximum permissible dose equivalent (MPD)." The Federal Radiation Council designates both as RPG's. Only those individuals whose duties involve ex-

posure to radiation should be classed as "occupationally exposed" and their training in radiation protection should be assured.

Dose Assessment

To accurately determine the true dose equivalent to the critical organs of all occupationally exposed individuals is a desirable objective which in practice becomes impractical, if not impossible. Activities in the workplace are varied in space and time, the energy and frequently the type of radiation varies, parts of the body being irradiated change with time, irradiation may occur from both internal and external radiation sources, and measurement devices have varying degrees of accuracy. Environmental measurements, however, can be made in a manner such that they provide a conservative evaluation of the dose equivalent to the critical organs and in turn assure that dose-limiting recommendations are not exceeded. This is accomplished by a combination of radiation surveys, area monitoring and personnel monitoring. If radiation surveys or other adequate data indicate that external irradiation will be less than one fourth of the applicable dose-limiting recommendation, personnel monitoring devices are not recommended. Above this, suitably selected personnel monitoring devices are required for evaluation of the radiation environment in which the individual works. The dose equivalents indicated by these are normally conservative with respect to any critical organ dose equivalent, and for general control purposes their readings can be compared to the applicable dose-limiting recommendation. Personnel monitoring devices are normally worn on the trunk of the body, but for some types of work they are required on extremities, particularly hands and forearms, as well. The dose-limiting recommendations permit higher doses here. Possible doses from small beams not intercepted by personnel monitoring devices must be evaluated by other means.

For exposures to airborne radioactive materials, the activity concentration in the breathing zone of the worker, averaged over a 40-hour weekly period, is compared with the tabulated values of maximum permissible concentrations (MPC) for the radionuclides of concern (see page 390). These concentrations, if breathed 40 hours per week indefinitely, will produce a dose equivalent in the critical organ equal to the dose-limiting recommendation.

If a valid determination of total dose equivalent to the whole body, the parts of the body, or the critical organ is required, such as after an abnormal exposure or to establish a monitoring procedure, a detailed evaluation based on all pertinent data should be made.

To convert absorbed dose to dose equivalent, the rounded practical values of the quality factor in Table 29-7 may be used. Methods of calculating a quality factor are described in reference (10). If neutron flux density and energy are measured or known, the dose equivalents may be found in Table 29-8.

TABLE 29-7
Practical Quality Factors
Radiation Type

	Rounded QF
X rays, gamma rays, electrons or positrons, Energy >0.03 MeV	1
Electrons or positrons, Energy <0.03 MeV	1
Neutrons, Energy <10 keV	3
Neutrons, Energy >10 keV	10
Protons	10
Alpha particles	20
Fission fragments, recoil nuclei	20

TABLE 29-8
Mean quality factors, QF^a, and values of neutron flux density which in a period of 40 hours results in a maximum dose equivalent of 100 mrem.

Neutron Energy MeV	\overline{QF}	Neutron Flux Density cm ⁻² s ⁻²
2.5 × 10 ⁻⁸ (thermal)	2	680
1 × 10 ⁻⁷	2	680
1 × 10 ⁻⁶	2	560
1 × 10 ⁻⁵	2	560
1 × 10 ⁻⁴	2	580
1 × 10 ⁻³	2	680
1 × 10 ⁻²	2.5	700
1 × 10 ⁻¹	7.5	115
5 × 10 ⁻¹	11	27
1	11	19
2.5	9	20
5	8	16
7	7	17
10	6.5	17
14	7.5	12
20	8	11
40	7	10
60	5.5	11
1 × 10 ²	4	14
2 × 10 ²	3.5	13
3 × 10 ²	3.5	11
4 × 10 ²	3.5	10

^aMaximum value of \overline{QF} in a 30-cm phantom.

Tables 29-7 and 29-8 reprinted with permission of National Council on Radiation Protection and Measurements, from "NCRP Report No. 39" — (1971) Washington, D.C.

TABLE 29-9

NCRP Dose-limiting Recommendations

Maximum Permissible Dose Equivalent for Occupational Exposure

Combined whole body occupational exposure	
Prospective annual limit	5 rems in any one year
Retrospective annual limit	10-15 rems in any one year
Long term accumulation to age N years	
	(N - 18) × 5 rems
Skin	15 rems in any one year
Hands	75 rems in any one year (25/qtr)
Forearms	30 rems in any one year (10/qtr)
Other organs, tissues and organ systems	15 rems in any one year (5/qtr)
Fertile women (with respect to fetus)	0.5 rem in gestation period

Dose Limits for the Public, or Occasionally Exposed Individuals

Individual or occasional	0.5 rem in any one year
Students	0.1 rem in any one year

Population Dose Limits

Genetic	0.17 rem average per year
Somatic	0.17 rem average per year

Emergency Dose Limits—Life Saving

Individual (older than 45 years if possible)	100 rems
Hands and forearms	200 rems, additional (300 rems total)

Emergency Dose Limits—Less Urgent

Individual	25 rems
Hands and forearms	100 rems, total

Family of Radioactive Patients

Individual (under age 45)	0.5 rem in any one year
Individual (over age 45)	5 rems in any one year

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The dose to the whole body or to the critical organs from internal radiation sources continues as long as the radionuclide is present. When intake is stopped, the dose decreases with time — frequently exponentially. Where the effective half-life is long, the total dose equivalent is rather large in comparison to that produced during and shortly after the time of exposure. This total dose equivalent, integrated over a lifetime, is designated as the "dose commitment." It is useful in a number of different types of evaluations.

Dose-Limiting Recommendations

The National Council on Radiation Protection and Measurements (NCRP) is generally recognized as an authoritative source of radiation protection information, data and criteria in the United States. NCRP Report No. 39¹⁰ discusses radiation protection criteria in detail and presents their dose-limiting recommendations, which are shown in Table 29-9. The NCRP comment on the occupational limits is: "There will be occasions when the measured or estimated actual dose equivalent exceeds the prospective limit of 5 rems in a year. No deviation from sound protection is implied if the retrospective dose equivalent does not exceed 10 to 12 rems for dose increments well distributed over time or even 15 rems for exceptionally well-distributed increments. Repetition of retrospective dose equivalents in excess of planned limits is controlled by the long-term occupational accumulated dose equivalent." The NCRP recommendations serves as the basis for various regulations and standards in which interpretations are made according to specific needs. Regulations of states, U.S. Atomic Energy Commission and other governmental agencies may not be the same as NCRP recommendations and must be consulted and used as applicable (see Chapter 9 and page 392).

Similarly, NCRP has provided tabulated values of maximum permissible body burdens and maximum permissible concentrations of radionuclides in air and water for occupational exposures. Some of these values are shown in *Radiological Health Handbook*.² The complete tabulation is in NCRP Report No. 22¹¹ and a similar tabulation, with the derivation data and methods, is in a report of the International Commission on Radiation Protection.¹² The various regulations also contain such tabulations, usually including values applicable to the general public.

IRRADIATION BY EXTERNAL RADIATION SOURCES

Exposure Control

A basic concept in radiation protection practice is the establishment of a "controlled area." Access to these areas must be controlled and within them supervision and control of occupational exposures is provided. Emergence of beams and escape of radioactive materials from these areas are also controlled. These areas are identified by use of the standard radiation symbol¹³ with associated warning notices. This symbol, a purple trefoil on a yellow background, also identifies any radiation source.

Since the useful beam of x-ray equipment may inflict a year's MPD in minutes or less, the design of industrial x-ray facilities must of necessity give proper consideration to the establishment of a suitably controlled area which will assure proper radiation protection for two groups of individuals — those who operate the equipment (occupationally exposed) and those in the environs, either normally or casually (not occupationally exposed). Where possible, the x-ray equipment should be within a room or other enclosure arranged with controls outside and having interlocks

to prevent entry when equipment is energized. Shielding can then be provided so that the exposure rate outside the enclosure will be low enough to insure that the applicable MPD or dose limit will not be exceeded. Small devices or instruments using x rays, such as laboratory equipment, usually can be totally enclosed with adequate shielding, but accessibility to the inside of the shield requires special consideration (interlocks, etc.). Where work requires truly mobile or portable equipment, exposure time and distance from the equipment become the basic method for controlling exposure rates to values which will insure that no individual exceeds the applicable MPD or dose limit. Portable shielding can be an aid. *American National Standard Z54.1-1963*⁷ classifies x-ray and sealed gamma-ray source installations into three types: exempt, enclosed and open. Shielding design and operational requirements are given. Although intended for medical installations, *Medical X-ray and Gamma-ray Protection for Energies up to 10 MeV*⁸ may provide useful data; shielding data is also presented in reference (2). For accelerators, *American National Standard Radiological Safety in the Design and Operation of Particle Accelerators*¹⁴ establishes safety requirements.

In addition to x-ray equipment, there may be other sources of x rays in industry, such as high voltage (>10kV) electron tubes, which may require shielding or other means of control to assure adequate radiation protection for workers (or the public).

Gamma radiation, usually from a sealed source, is used for a variety of purposes in industry. The larger sources produce beams comparable in exposure rate to x-ray equipment. Detailed descriptions cannot be given here, but rather a few general considerations. Gamma radiation cannot be turned off like x rays. This imposes a severe requirement on retention of the sealed source at a predetermined specific location where exposure control is assured or within appropriate shielding at all times. Procedures and surveys must guarantee this control. The integrity of the encapsulation or bonded cover of the sealed source must be assured at all times to prevent release of the radioactive material into the environment where it could be dispersed and inhaled or ingested. Periodic tests, such as smears of the sealed source or its container, should be made. Appropriate testing of radium sources is particularly important because any failure will release radon gas which, with its daughters, can contaminate the surrounding area. Exposure rates from sealed sources, in air, can be calculated from the specific gamma-ray constant (see page 382). As an approximation, the gamma exposure rate (R/hr) at 1 foot is 6CE, where C is the number of curies and E is the total energy per disintegration in MeV. As for x-ray installations, references (7) and (8) provide useful shielding information.

Beta radiation sources, which are frequently built into some piece of equipment such as a thickness gauge, must be shielded and arranged so that access to the beta radiation is prevented. Of par-

ticular concern is control of exposures during any maintenance procedures. Consideration must be given to any associated gamma radiation; and to the bremsstrahlung exposure rate, particularly for sources of high activity and energy. To permit escape of the beta radiation, the encapsulating material must be relatively thin, at least over the useful area of the source. Damage to this encapsulation will permit release of the radionuclide to the environment where it can be dispersed and inhaled or ingested.

Radioactive neutron sources are commonly small sealed sources of relatively substantial construction. Yield of neutrons is proportional to the activity in the source. See page 385 for neutron source data. Consideration must be given to gamma radiation as well as neutron radiation from them. If the radionuclide in them is radium, the gamma dose equivalent rate is higher than that from neutrons and the possibility of radon leakage must be recognized. Leakage of any of the radionuclides used in these sources presents a hazard of considerable magnitude which necessitates care in use and periodic testing. Commonly used shielding materials are concrete, polyethylene, boronated polyethylene or boron in other materials such as aluminum. Shielding and other useful data will be found in *Physical Aspects of Irradiation*⁶ and *Protection Against Neutron Radiation*⁹.

External radiation sources involve a wide variety of equipment which cannot be described here. Descriptions and useful data will be found in *Radiation Hygiene Handbook*.¹⁵

Exposure Evaluation

Applicable regulations (or NCRP recommendations) established the time period during which specific dose equivalents may be given to workers. Currently, most regulations permit a limit of 1.25 rem/quarter indefinitely to the whole body, gonads, bloodforming organs and lens of the eye; or, for individuals whose previous radiation history has been established, a limit of 3 rems/quarter* with an overriding yearly limitation of 5(N-18) rems, N being age in years. Separate quarterly and usually yearly limits, with higher values, are specified for extremities and skin. Exposure evaluations therefore must be related to these time periods, no matter whether measurements are made in rems (or R) per hour, per day, per week or per month. Administratively, daily or weekly limits are frequently used for general control.

The evaluations to establish dose equivalent from external radiation sources are accomplished by conducting radiation surveys and monitoring the environment in which the individuals work. The radiation survey establishes the parameters that must be measured and depicts whether occasional or essentially continuous surveillance with measuring instruments is required. Proper instruments must be selected for the survey so that all possible types and energies of the radiation will be measured with reasonable accuracy. A wide

*This was a former NCRP recommendation.

selection of instruments is available commercially^{6, 16, 17} but caution must be exercised to be certain their specified capability will fulfill the required needs. A comprehensive discussion of instrumentation is in *Radiation Protection Instrumentation and Its Application*.¹⁸ Proper calibration for the radiation to be measured is essential. The higher the instantaneous dose rates or potential dose rates in the work area and the greater the complexity of the operations, the greater the need for continuous or frequent surveillance measurements; and correspondingly, closer control over the exposure time of the workers. Where abnormal situations may occur, area monitoring by permanently installed instruments at key locations, with readouts under observation at a central location, will aid in detecting any significant changes of the radiation levels in the general environment. Use of alarms may be indicated in extreme cases.

Except where it can be assured that dose equivalent rates are consistently very low (<25% MPD), personnel monitoring devices must be used to measure the radiation incident on a worker's body (or extremities), integrated over pre-selected time periods. Film badges, available from commercial services,^{16, 17} have been used extensively with time periods usually being from a week to a month. Currently, there is increasing use of thermoluminescent dosimeters (TLD) for these and longer periods. Where dose equivalent rates are high and variable, the dose accumulated during minutes or hours of exposure becomes critical and pocket dosimeters (ionization chambers) provide a convenient means of such measurement. There are two types, those that require an instrument for readout and those that can be read directly. The latter are particularly useful when the worker can read them frequently and limit his work period or procedures accordingly. A film badge or TLD is normally used in addition to the pocket dosimeter to provide a back-up for an off-scale reading. There may be discrepancy between the two readings because of different response characteristics. A pocket-size instrument with an alarm sensitive to either dose or dose rate is available and can be used if operating conditions warrant. Indium foils may be added to film badges or other badges worn by workers if accidentally high neutron exposures may occur, the induced activity permitting a rapid qualitative check for a high neutron exposure.

External irradiation of the body tissues or organs may occur from radionuclides deposited on the skin or in the clothing. To detect (or measure) this requires a very careful probing over the entire body with a suitable instrument. A probe on a flexible cord is desirable; or where the contamination is limited to the hands or shoes, a "hand and foot counter" may be used.

Although periodic medical examinations are desirable for many reasons, they cannot be used as a means of exposure evaluation unless dose equivalents are many times the MPD (see Table 29-6). A relatively new cytogenetic technique involving a determination of chromosome irregu-

larities found in somatic human blood cells,¹⁹ although nonspecific, can provide a means of measuring dose equivalents slightly above the MPD, but use of this technique is severely limited due to the many man-hours required for each determination.

General administrative practices for radiation monitoring are presented in *American National Standard Guide for Administrative Practices in Radiation Monitoring*.²⁰

IRRADIATION BY INTERNAL RADIATION SOURCES

Mode of Entry

Internal radiation sources gain entry to the body by breathing gaseous or particulate airborne radioactive materials, by swallowing radioactive materials that have gotten into the mouth from contaminated lips, hands, foods, or liquids, and by absorption through or implantation under the skin. After entry, a rather complex distribution throughout the body may occur as indicated in Figure 29-3. Although there may be irradiation throughout the body, the organs or tissues where the residence time and concentration are greatest receive most of the dose equivalent from alpha and beta radiation, while gamma dose is more distributed.

When inhaled, a fraction of radioactive gases and particulates are retained and absorbed in accordance with chemical and physical properties (not radioactive properties), the balance being exhaled. The retained material is distributed along all respiratory passages — that deposited in the upper passages being subsequently swallowed after clearance by drainage or ciliary action. Retention of particulates in the several sections of the respiratory tract is a function of the particle size distribution, the larger particles (>10 μm dia.) not reaching the lung. Soluble materials, when deposited in the lung, are taken up in the blood stream, their subsequent distribution and excretion being determined by the metabolic pattern for that element. Insoluble materials are retained in the lung with a relatively slow clearance rate (e.g., ~ 120 day half-life). Without specific data, ICRP recommends an assumption that 25% is exhaled, 50% is deposited in the upper respiratory passages and 25% is deposited in the lungs, with all of that in the upper passages and half of that in the lungs being swallowed.

Ingested materials, including those cleared from the respiratory tract, pass through the gastrointestinal tract, with their absorption and excretion being determined by solubility of the particular chemical compound and metabolic pattern of the element.

Embedded materials, unless very soluble, tend to remain in the tissues near the site of entry with a slow clearance rate from that site. Those few materials which can be absorbed through the skin are promptly distributed throughout the body tissues.

The tabulated values of MPC for air and water take all of these various ramifications into account except for embedded materials, yet for exposure

control and exposure evaluation purposes some of the above factors require consideration.

Exposure Control

Work with radioactive materials that are not effectively contained necessitates the establishment of a well defined controlled area. Preferably it should be a room or other totally enclosed area which will prevent atmospheric dispersion of the radioactive materials to outside areas. Exhaust of air from the room through filters may be required. Movement of individuals or materials through the exit (entrance) should be controlled to prevent inadvertent transfer of radioactive materials outside. Any liquids containing radioactive materials should either be retained for safe disposal at an authorized location or be put into a drain which fulfills pertinent requirements for release of radioactive materials to the environment. Only workers, properly trained, or visitors properly controlled, should be permitted entry. The degree of these controls will vary over a wide range for different kinds of work depending on the activity (Ci) involved, the MPC of the radionuclides in air or liquid, the dispersion characteristics of the materials and the size or complexity of the operations.

Within the controlled area, the workers must be protected against breathing radionuclides in concentrations greater than the MPC averaged over a 40 hour week. Where exposure times are less or greater than 40 hours in a week, the tabulated MPC may be adjusted up or down proportionately. Although the MPC's are set for 40 hours per week exposures indefinitely, most regulations require that each week be considered separately. For work with very small amounts of material, e.g., less than the activity in a few maximum permissible body burdens, rather simple exposure controls are required — perhaps gloves and a lab coat. As the activity and dispersibility increase, protective measures progress through ventilated hoods, specially designed exhaust hoods, total enclosures and glove boxes. Some of these are described in reference (15). Use of personal protective equipment such as coveralls, gloves, head covers and shoe covers may be indicated (see Chapter 36). Where the concentration of airborne radioactive materials cannot be adequately controlled by exhaust and enclosures, respiratory protective equipment approved for radioactive materials is required.²¹ Where abnormal concentrations may occur, continuous air sampling devices with an alarm may be needed. Contamination of surfaces with radioactive materials throughout the controlled area may require control, such measurements being made by counting smears taken on filter papers from 100 cm^2 areas. Clothing change rooms with shower facilities, located at the exit (entrance) of the controlled area, may be required to prevent spread of radioactive materials from the area and to assure removal of contamination from workers' bodies. Possible remaining contamination is checked with an instrument probe.

For a laboratory, many or all of these factors require consideration. *American National Stand-*

ard Design Guide for a Radio-Isotope Laboratory (Type B)²² is a general guide to these requirements.

Exposure Evaluation

Except for an accident, internal radiation sources resulting from occupational exposures usually accumulate gradually in the body of workers. Breathing airborne radioactive materials either intermittently or continuously is a prime source. Thus, a knowledge of the radionuclides and their average activity concentration in the air breathed by workers becomes important in any assessment of dose equivalent to critical organs or the corresponding bodily intake in relation to the MPC. Usually it is sufficient to assure that the weekly average airborne radioactivity concentration in the breathing zone of workers is less than the MPC, although other possible modes of entry should be considered. Hence, where dispersible radioactive materials are used, an air sampling program becomes a necessity. This program may vary from an occasional spot check where concentrations are readily maintained at a small fraction of the MPC, to continuous sampling either at or near the breathing zone of workers where exposure may average near the MPC or equipment failures may produce abnormal conditions.

Air sampling techniques and instruments discussed in Chapters 13, 14 and 15 may be used for radioactive materials provided the sample is suitable for radioactivity analysis. Samplers using filter paper or membranes have found general application because the activity measurement can be made readily. For some situations, samplers which provide a size separation are used. The samplers may be portable instruments with a sampling head that can be positioned or held near the breathing zone of workers, or be permanently mounted equipment. *American National Standard Guide to Sampling Airborne Radioactive Materials in Nuclear Facilities*²³ provides a complete guide to sampling airborne radioactive materials.

Radionuclides are removed from the body by excretion in the urine and feces, the rate and partitioning between the two depending on many factors including mode of entry into the body, elemental composition, solubility and rate of intake. For many radionuclides, sufficient knowledge of excretion patterns and rates are available so that measurements of excretion rates can be quantitatively related to intake rates, or activity in the body, or both. Data obtained from analysis of urine or feces — frequently called bioassays — can serve as an assessment of previous and current intake rates to verify air sampling data. By discontinuing current intake for a period, an estimate of the body burden or critical organ burden can be made from such excretion measurements — usually a series of measurements over a period of a week or longer. When used to assess current intake rates it is common practice to establish, for each radionuclide, an “investigation level” or “check point.” These are discussed in *Recommendations of the International Commission on Radiological Protection, Report of Committee IV on Evaluation of Radiation Doses to Body Tissues*

from Internal Contamination Due to Occupational Exposure,²⁴ with very conservative values listed. For excretion rates or activity concentrations in the excreta which are below an appropriate investigation level, it is assumed that exposure controls and evaluations have been adequate; but if above these levels, an examination of the adequacy of current practices is made.

A further means of assessing the current status of a worker with respect to intake and retention of radionuclides is an in vivo determination of body burden or critical organ burden by measuring the gamma radiation being emitted from his body (or critical organ). The simplest of these is measurement of radioiodine in the thyroid by placing an instrument adjacent to the thyroid. For most radionuclides, a “whole body counter” is required. It consists of one or more measuring instruments which scan the whole body, usually in a well shielded enclosure to minimize the effect of background radiation.²⁵ Such measurements require skilled personnel and very sensitive measuring devices, properly calibrated. Such measurements can be made for radionuclides emitting x rays, such as uranium-235, plutonium-239 and americium-241, as well as for radionuclides emitting higher energy gamma radiation.

As with external irradiation, medical examinations cannot be used to evaluate dose equivalent from internal radiation sources when exposures are at or below MPC, and the cytogenetic technique (page 392) may be useful in a qualitative way at slightly higher exposures.

PARTICULAR CONDITIONS

Nuclear Criticality Safety

A few of the heavier radionuclides which are capable of sustaining a nuclear chain reaction require handling and processing techniques which will avoid the possibility of inadvertently forming a critical mass, with the attendant emission of intense radiation. The mass of these fissile materials at any one location or their geometric arrangement must be controlled with a high degree of confidence. Information about the basic limiting parameters used to assure nuclear criticality safety are in *American National Standard N16.1*²⁶ Additionally, all fissile materials are used under Atomic Energy Commission regulations and license — in which they are designated as “Special Nuclear Materials.” The regulations designate the masses of fissile materials below which nuclear criticality safety controls are not required and licenses specify the limiting conditions of use for greater amounts. A standard symbol is used to identify fissile materials and areas in which they are used.²⁷ It is similar to the radiation symbol with circular bars around it.

Nuclear Reactor Industry

The nuclear reactor industry presents an array of radiation protection problems much too complex to discuss in this Chapter. During mining of uranium ore there are exposures to radon gas and its daughters, as well as to uranium dust;²⁸ and similar problems occur during the processing to extract the uranium from the ore.²⁹ The uran-

ium enrichment (in uranium-235) process involves various chemical forms of uranium including uranium hexafluoride, a gas. After enrichment, nuclear criticality safety controls become mandatory for all subsequent handling and processing. Fuel manufacturing³⁰ involves a chemical conversion process and various treatments of the resulting solids prior to loading into the fuel rods. The fuel rods are sealed and subsequent handling involves no further exposure to airborne radioactive materials. Fuel manufacturing and much of the previous processing involves only relatively minor external irradiation problems. In a nuclear reactor facility, control of exposure to external radiation sources as well as control of fission and corrosion products which may become airborne becomes necessary. Fuel reprocessing plants take spent fuel, which is highly radioactive, and pass it through complex chemical processes to separate the fuel materials (including plutonium) from the fission products, so that both external irradiation and complex airborne radioactive materials, including gases, require control and evaluation. Fuel manufacturing may include fuel elements that contain plutonium — requiring sophisticated controls to prevent release of plutonium. Throughout the industry, control and evaluation of releases of radioactive materials to the environment is essential.

Transportation

Radioactive materials are shipped by all normal transportation methods including the U. S. Postal Service, railroads, airplanes, trucks and ships. There are some limitations on the types and quantities that will be accepted by some of these, particularly the Postal Service. Regulations of the U. S. Department of Transportation (DOT) are applicable to all interstate transport except for the Postal Service. There are separate regulations for the Coast Guard and Federal Aviation Agency, although these conform to the DOT Regulations. Most states have regulations applicable to intrastate transport and a few cities have some regulations. Turnpikes, bridges and tunnels operated by authorities may have separate regulations, limitations and requirements. Packaging of fissile materials and large quantities of radioactive materials are subject to Atomic Energy Commission Regulations, 10 CFR 71 (see Chapter 9). International transport is subject to regulations of the International Atomic Energy Agency.

In all cases the shipper is required to provide packaging which fulfills the requirements of the pertinent regulations except for small quantities that are exempted. For detailed packaging and labelling requirements, the regulations applicable to the mode of shipment should be consulted.^{31, 32}

Records

Since some diseases and attendant disability that may be caused by exposure to radiation or radioactive materials can occur after many years of exposure or many years after exposure, retention of suitable records relating to exposures and working conditions for long periods of time is desirable and usually required by regulations. Workmen's Compensation Laws usually permit

filing claims for radiation injury many years after exposure occurred, and for these adequate records will be required. A comprehensive presentation of information about records and their retention is in *American National Standard N2.2*.³³

Regulations

The use of radiation and radioactive materials is subject to official regulation by various governmental agencies. Such regulations are discussed in Chapter 9. It is essential that any user of radiation or radioactive materials become intimately familiar with the details of all current rules and regulations applicable to his operations. Licenses, permits or notifications are commonly required. Before preparing a license application the person who will subsequently issue the license should be consulted. Because of the length, detailed provisions and variability of these rules and regulations, only a few general provisions have been mentioned in this chapter.

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PHYSIOLOGY OF HEAT STRESS

David Minard, M.D., Ph.D.

INTRODUCTION

Industrial heat exposure often exceeds that encountered in the hottest natural climate. Because hot industrial jobs usually require heavy work, the added burden of metabolic heat production may exceed the worker's physiologic capacity to regulate his body temperature, leading to impaired performance or clinical signs of heat illness. The physiologist's aim is to determine the duration and intensity of work (internal heat load) in combination with heat exposure (external heat load), which can be tolerated without excessive heat strain on thermoregulatory systems. By reason of physical fitness, work capacity, age, health status, living habits, and level of acclimatization, men vary in ability to tolerate heat stress. The purpose of this chapter will be to discuss a) homeostatic control of body temperature by balancing heat loss and heat gain, b) physiological indices of heat strain, c) acclimatization and other factors affecting heat tolerance, and d) clinical

illnesses resulting when adaptations fail.

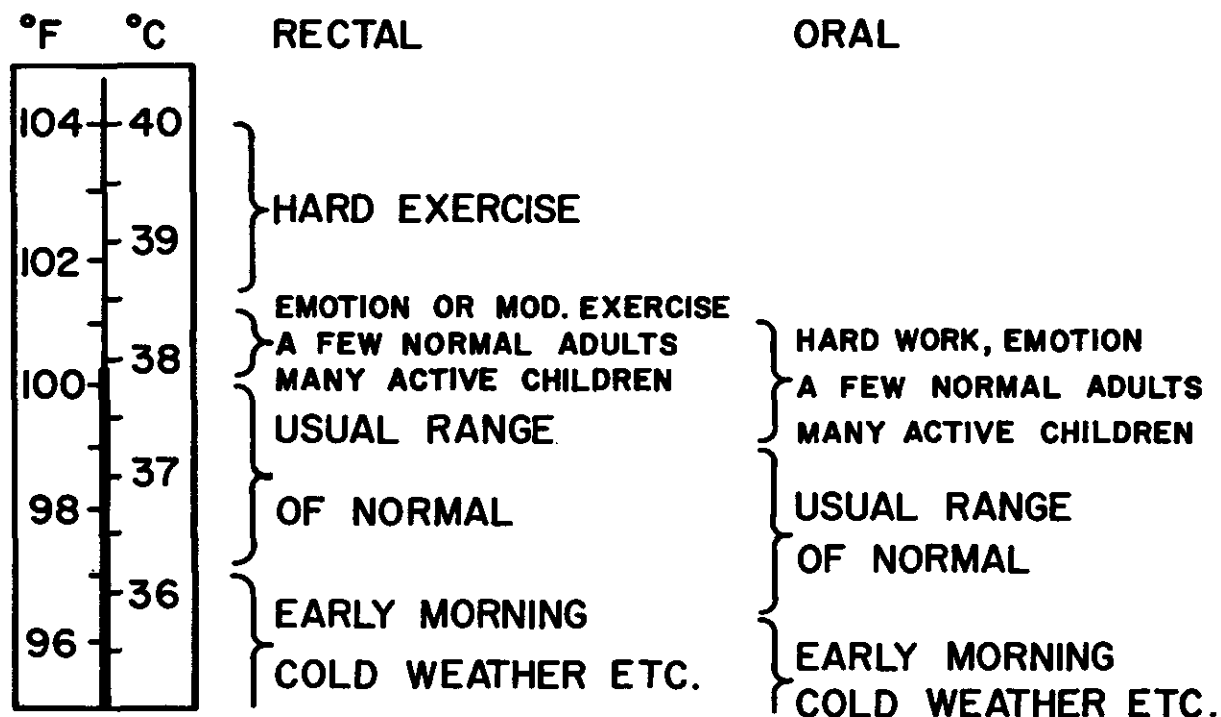
BODY TEMPERATURE REGULATION

Thermal Homeostasis

Man, and other homeotherms, regulate internal body temperature within narrow limits by physiologic control of blood flow from sites of heat production in muscles and deep tissues to the cooler body surface where heat is dissipated through physical channels of radiation, convection and evaporation to the environment. When heat loss is in balance with heat production, internal temperature is maintained at the regulated level. Homeostasis thus maintains a favorable and uniform internal temperature despite fluctuations in the thermal environment.

Normal Range

Figure 30-1' indicates the usual range in body temperature (rectal,oral) in normal persons as well as extreme upper and lower limits of normal. There are other sites in the lower esophagus and



DuBois, E. F.: Fever and the Regulation of Body Temperature. Springfield, Illinois, Charles C. Thomas, 1948.

Figure 30-1. Range of Normal Rectal and Oral Temperatures [from DuBois (1)]

in the ear canal for measuring internal temperature which reflect more promptly the responses to transient heating or cooling of the body. For present purposes central or "core" temperature, wherever measured, will be designated T_c .

Body Shell

This term refers to the cooler superficial tissues (skin, subcutaneous tissues, extremities) surrounding the warm core. Temperature of the shell tissues, particularly the distal extremities, varies more widely than the core under ambient heat and cold, as reflected in changes of mean temperature of the skin surface, \bar{T}_s , which is a weighted average taken at up to ten skin sites. The shell acts as a thermal buffer between the core and thermal environment. Under comfortable ambient conditions T_c is 37° and \bar{T}_s is normally 33-34°C, but may approach to within a degree or two of T_c under heat stress and decline to as much as 10-15°C below T_c in the cold.

These changes in core to surface gradient are accompanied by alterations in rate of blood flowing from the warm core to the cool surface to meet changing needs in heat conductance, which is defined as units of heat transferred through the skin per unit time to the environment per degree of temperature gradient. Under heat stress \bar{T}_s rises, and core to skin gradient narrows. A greater volume of blood must flow through the skin each minute to achieve the same rate of heat exchange as in a neutral environment. This is the basic cause for heat strain on the circulation, for which conductance is a useful index.

Heat Production

Energy required to sustain all body functions at rest and during work is derived by enzymati-

cally controlled oxidative combustion of fuel substrates (carbohydrate, fat, protein), with CO_2 , water and nitrogen wastes forming end products. These reactions are exothermic, the heat produced in the body being essentially equal to that measured when the same quantities of food substrates are oxidized at high temperature outside the body.

This is the basis of *indirect calorimetry* in which heat produced metabolically can be measured by the rate of oxygen uptake during rest or activity, one liter of O_2 being closely equivalent to a heat output of 5 kcal. Laboratory or field measurements of metabolic heat production are relatively simple, involving a system for measuring the volume of air breathed each minute and an instrument for measuring the difference in O_2 concentration between inspired and expired air.

Resting O_2 uptake in an average man (70 kg body weight; 1.8m² surface area) is about 0.3 l/min, equivalent to heat production at a rate of 1.5 kcal/min or 90 kcal/hr. In terms of surface area this is 50 kcal/m² hr, a unit referred to as *1 met*, the metabolic rate of a man sitting at rest in a comfortable environment.

There is little individual variation in resting metabolism when expressed in heat production per unit area. In terms of maximum capacity to perform work, however, there are wide differences, depending mainly on body size, muscular development, physical fitness and age. An important measure of work capacity is the maximum rate at which a man can take up oxygen during brief strenuous work effort. Maximum oxygen uptake (VO_2 max) among healthy workers ranges between about 2.0 and 4.0 l/min.

Table 30-1* lists examples of work activity, the O_2 requirement, the heat equivalent, and the

TABLE 30-1
Oxygen Uptake, Body Heat Production, and
Relative Energy Cost of Work in 70 kg Men

Activity	Oxygen* Uptake (l/min)	Body Heat** Production (M) (kcal/hr)	Maximum Oxygen Uptake (l/min)		
			Low 2.5	Medium 3.0	High 3.5
			Percent VO_2 max Required		
Rest (seated)	0.3	90	12	10	8.5
Light Machine Work	0.66	200	26	22	19
Walking (3.5 mph on level)	1.0	300	40	33	28
Forging	1.3	390	52	43	37
Shoveling (depends on rate, load and lift)	1.5-2.0	450-600	60-80	50-66	43-58
Slag Removal	2.3	700	92	77	66

*From Passmore and Durnin (See Figure 30-2).

**In lifting, pushing, or carrying loads, cranking, etc. the heat equivalent of the external work (W) is subtracted from the total energy output (O_2 uptake) to obtain heat produced in the body (M). Net efficiency of W, i.e., $\frac{W}{O_2 \text{ uptake (work)} - O_2 \text{ uptake (rest)}}$ is 20% or less for most work. Skill acquired by practice increases efficiency of work performance and thus reduces heat load of M.

TABLE 30-2
Heart Rate, Core Temperature, and Endurance Time
Corresponding to Relative Energy Cost of Work

	At Rest	Percent VO ₂ max				
		25	33⅓	50	75	100
Heart Rate (min)	60-80	90-100	105-110	120-130	150-160	180-190
Core Temperature (°C) at Equilibrium	37	37.4	37.8	38.2	38.8 (Unstable)	Continuous Rise
Endurance Time for Continuous Work	—	>8 hr	8 hr	1 hr	15-20 min	4-6 min

percent of VO₂ max required for this work in men of low (2.5 l/min), intermediate (3.0 l/min) and high (3.5 l/min) work capacity.

A comparative index for estimating maximum work capacity among men is the heart rate (HR) attained during steady work at less than the maximal effort (Table 30-2) which also indicates that

the rise in T_c is proportional to % VO₂ max.

At work rates at 50% VO₂ max and above the oxygen supply to the muscle fails to meet the O₂ demand, thus limiting endurance time. Successive increments in energy requirement for work are supported by progressively greater proportions of the energy being supplied by anaerobic (i.e.,

TABLE 30-3
Symbols and Their Meaning for Physical Factors in the Thermal Environment
and Physiological Factors in Heat Exchange

Physical Factors		Physiological Factors	
Symbol	Meaning	Symbol	Meaning
T _a	Air temperature using dry bulb thermometer.	\bar{T}_s	Mean skin temperature.
\bar{T}_r	Mean temperature of surrounding surfaces (wall temperature). In presence of radiant heat, T _r > T _a .	T _c	"Core" or central temperature (measured in the rectum, esophagus, or near the tympanic membrane).
V	Air velocity (fpm or m/s).	P _{wa}	Water vapor pressure of wetted skin at skin temperature.
T _g	Temperature of the 6" black globe. T _g exceeds T _a when T _r > T _a . Elevation of T _g in equilibrium with radiant heat varies inversely with convective cooling by V. With appropriate coefficients T _g represents R + C.	A	Total surface area of the body (m ²).
P _{wa}	Water vapor pressure of ambient air.	s	Area of wetted surface. $\frac{s}{A} \times 100 = \% \text{ of wetted body surface.}$
T _{wb}	Temperature of the wet bulb thermometer. Evaporative cooling under forced convection depresses reading of T _{wb} below T _a , the degree varying inversely with P _{wa} . In air fully saturated with water vapor (100% RH) T _{wb} = T _a .	M	Metabolic rate of body heat production (kcal/hr).
T _{ET}	Effective Temperature Scale. An empirical index combining T _a (or T _g), T _{wb} , and V into a single value based on sensory effect.*	met	Unit of M per m ² /hr. Resting M = 1 met or 50 kcal/m ² hr
°C _{ET}	Effective Temperature in degrees Centigrade.	VO ₂ max	Maximum oxygen uptake. Also called maximum aerobic work capacity.
		SR	Sweat rate (kg/hr).
		E	Body heat loss by evaporation (kcal/hr).
		BF _s	Blood flow to the skin (l/m ² min).
		C	Conductance = $\frac{M/A}{T_c - T_a}$ [kcal/m ² hr per degree of gradient]

*ET Scales in the form of nomograms (Basic Scale for men stripped to the waist and Normal Scale for men lightly clothed) were derived from tests on men moving between two climate chambers, a test chamber with T_a, T_{wb}, and V fixed in various combinations, and a reference chamber with still air fully saturated held at temperatures ranging in different tests from 0 to 43°C. All combinations of T_a, T_{wb}, and V producing immediate thermal sensations which were equivalent to those experienced in the reference chamber were assigned the same Effective Temperature, namely that of saturated still air at that temperature.

without O_2) splitting of muscle glycogen, the carbohydrate energy storehouse, into lactic acid, which accumulates in the muscle, impairs contraction and results in fatigue. During the rest period, the "oxygen debt" incurred during work is paid off, as indicated by O_2 uptake remaining elevated and declining exponentially to the resting level as the accumulated lactic acid is oxidized or resynthesized into glycogen. Under heat stress, the recovery period is longer to eliminate heat stored in the body during work.

Heat Loss

Under comfortable ambient conditions 25 percent of heat produced by metabolism (M) at rest is transferred from the skin surface to the cooler air by convection (C), 50 percent by radiative transfer to cooler surfaces in the surroundings (R), and the remaining 25 percent by warming inspired air, and by evaporation of 20 to 30 g/hr of moisture diffusing through the non-sweating skin. Res-

piratory heat loss (8-10% of resting M) plays little role in temperature regulation and only heat loss through the skin will be considered here.

Symbols and their meanings to designate the environmental and physiological variables used in this chapter are listed in Table 30-3.

The foregoing sections may be summarized in the heat balance equation as expressed for temperature equilibrium below and in Table 30-4.

$$M \pm R \pm C - E = 0,$$

in which R and C are rates of radiative and convective heat transfer. M and E are defined in Table 30-3. Table 30-4 indicates how the equation applies under three different conditions of the temperature and vapor pressure gradient between skin and environment. It should be noted that when $\bar{T}_s < T_g$ and P_{wa} approaches or equals P_{ws} , equilibrium is not possible either at rest or during work.

TABLE 30-4
Heat Balance under Different External Temperature Gradients
and Factors Limiting Endurance Time for Work

External Gradient	Example	Heat Balance	Endurance Time Limited by:	Representative Environments
$\bar{T}_s > T_g$ $P_{wa} >> P_{ws}$	$T_g = 25^\circ\text{C}$	$M = R + C + E$	Work Rate	Temperate climate. Also thermally neutral work places.
$\bar{T}_s = T_g$ $P_{wa} > P_{ws}$	$T_g = 35^\circ\text{C}$	$M = E$	Work rate and elevated P_{wa} and/or low V (Restricted evaporation)	Tropical climate. Also canning, textiles, laundries, deep metal mines.
$\bar{T}_s < T_g$ $P_{wa} > > P_{ws}$	$T_g = 45^\circ\text{C}$	$M + R + C = E$	Work rate and maximum capacity to sweat (Free evaporation)	Hot desert climate. Also manufacturing of primary metals, glass, chemicals, etc.

Hypothalamic Regulation of Body Temperature

There is convincing evidence based on animal experiments that the temperature regulating center in man lies in a region at the base of the brain called the hypothalamus. The anterior portion contains the "heat loss" center which responds to increases in its own temperature, as well as to incoming (afferent) nerve impulses from warm receptors in the skin. It activates heat loss through increased blood flow to the skin and sweating (man) or panting (other mammals).

A model of the thermoregulatory system for control of body temperature under heat stress is represented in Figure 30-2* as an analog of an engineering control system known as a proportional controller using negative feedback. Feedback is negative because the error signal is the difference between the set point of the thermostat (input) and T_c and/or T_s (output). It is a proportional controller because the central drive and effector responses (BFs and SR) are proportional to the error signal. In the absence of a heat load, central drive is zero, output and input being equal. The model predicts that when equilibrium is reached under a given heat load, the output of the

system (T_c , \bar{T}_s) will stabilize at a level above the set point by an amount also proportional to the load. This deviation from the set point is known as the "load error." In the presence of a load, a proportional controller does not restore the error signal to zero. These characteristics of the model are also seen in thermoregulatory control under heat stress in man. Finally, effectiveness of the controller in temperature regulation depends on its gain, or sensitivity to an error signal. The gain factor is high in individuals with high heat tolerance, and increases in acclimatization.

Subjective and Behavioral Responses to Heat Stress

Subjective sensations of heat, perceived as neutral, warm, or hot, depend primarily on skin temperature. *Heat discomfort*, however, is the subjective evaluation of the thermal environment in terms of unpleasantness and depends not only on sensations of heat but also on the level of physiological strain (SR, BF_s , T_c). Thermal comfort scales (e.g., Effective Temperature Scale) define limits of ambient temperatures, activity levels, and clothing under which heat balance can be maintained without thermal strain.

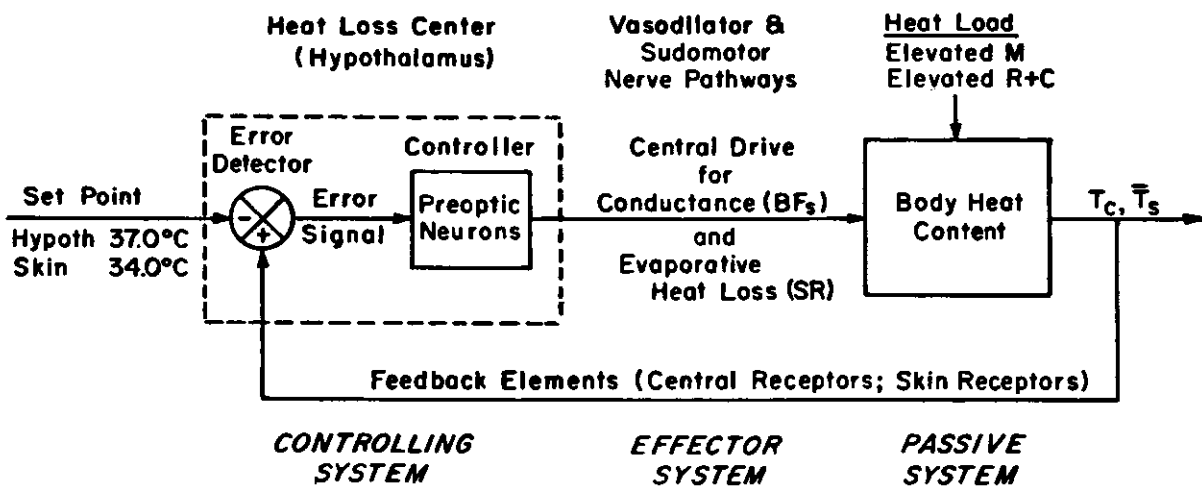


Figure 30-2. Model of the System for Thermoregulatory Control of Body Temperature.

*The model shown in Figure 30-2 is adapted from recent studies (Nadel *et al.*)³ indicating that the central drive for sweating is the summation of effects from the elevation of T_c and \bar{T}_s above their corresponding set points (37° and 34°C). The input from elevated T_c , however, is 10x greater in effect than that from elevated T_s . Moreover, local heating or cooling of the skin augments or suppresses local sweating from a temperature effect on the neuroglandular junction with a Q_{10} of 2.7 to 3.0. The summation model with the multiplicative factor for local skin temperature, T_{s1} , is given in the form

$$SR = [\alpha (T_c - 37) + \beta (\bar{T}_s - 34)] e^{(T_{s1} - 34)/10}$$

where $\frac{\alpha}{\beta}$ is about 10, and e is the base of natural logarithms.

These authors point out that SR is also inversely related to skin wetness and directly to degree of acclimatization.

Immediate sensations of heat or the subsequent discomfort from strain may lead to behavioral responses such as slowing or stopping work (reduced M), modifying clothing, or withdrawing to a cooler environment (reduced $R+C$). Such adaptive behavior, based on instinct or experience, serves as man's first line of defense against severe or incapacitating strain.

INDICES OF HEAT STRAIN

Sweat Rate

Under heat loads resulting in an error signal, effector outflow from the hypothalamus is transmitted via nerves to sweat glands of the skin which are activated by release of acetylcholine at the neuroglandular junction. Rate of secretion of individual glands, and the number of active glands recruited determines the total sweat rate. Under maximum central drive, the estimated 2½ million eccrine glands can secrete sweat at peak rates of more than 3 kg/hr for up to an hour in highly acclimatized men, and can maintain rates of 1 to 1.5 kg/hr for several hours.

When sweat can evaporate freely from the skin

(i.e., $SR=E$), evaporative cooling is regulated under steady state conditions of work and heat exposure to balance the heat load ($M+R+C$) up to the maximum rate of sweating (1 kg/hr). SR follows \bar{T}_s (Figure 30-3) which varies linearly with ambient temperature. Over a wide range of ambient temperatures from cool to moderately hot, Nielsen⁴ found that T_c is constant under steady state conditions of work, the elevation of T_c above 37°C depending solely on M . On the other hand, under constant ambient conditions SR varies with M , to which the elevation of T_c is proportional. The central drive for sweating is thus determined by work rate, M , but the actual sweat output is modulated by skin temperature to meet evaporative requirements under conditions from cool to hot up to the limits for sweating capacity.

Sweat Evaporation

The evaporation of 1 g of sweat from the skin eliminates 0.58 kcal of body heat. Efficiency of body cooling by sweat, however, depends on the rate of evaporation, which is determined by the gradient between vapor pressure of wetted skin (P_{wa}) and ambient air (P_{wa}) multiplied by a root function of effective air velocity at the skin surface ($V^{0.6}$) and s , the fraction of body surface, A , that is wetted.

When evaporation of sweat is restricted, \bar{T}_s rises above that observed under less humid conditions at the same T_a . The heat loss center responds by recruiting more sweat glands, thus increasing the extent of wetted body surface, s .*

If cooling needed to balance $M+R+C$ under these conditions is thereby met, core temperature remains essentially unchanged. At higher levels

*As a fraction of the total area of body surface, s cannot be measured directly. It is estimated from the ratio of the rate of evaporation required to balance $M+R+C$ (E_{req}) to the maximum rate at which sweat evaporation can occur (E_{max}) at a given \bar{T}_s , P_{wa} , and air velocity.

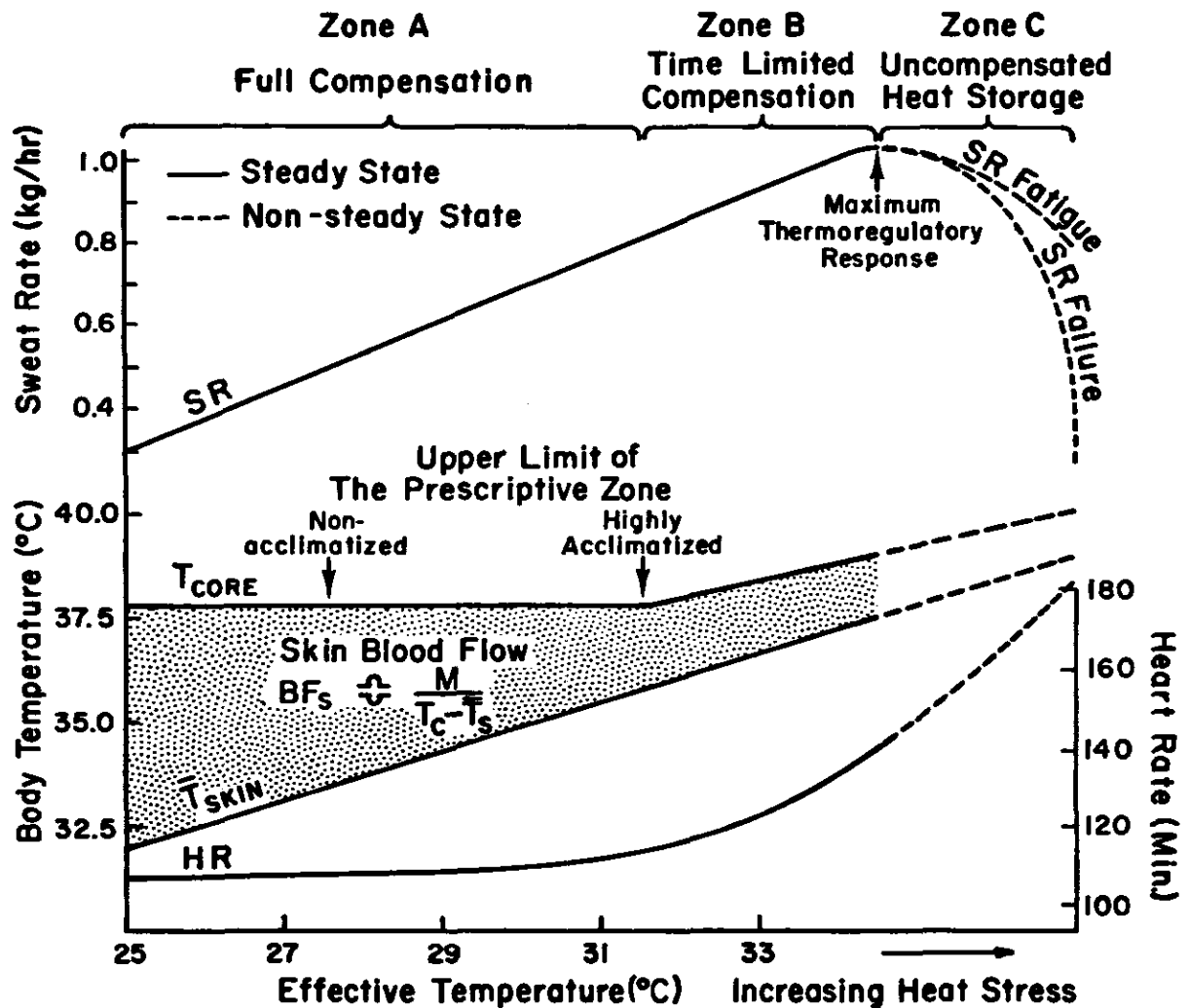


Figure 30-3. Thermoregulatory Responses to Heat Stress in Zone A (Full Compensation), B (Time Limited Compensation) and C (Uncompensated Heat Storage). Graph illustrates the effector responses (SR, BF_s), circulatory strain (HR) and the controlled variables (T_c, T_s) in a highly acclimatized man working at one-third VO₂ max (M=300 kcal/hr) at levels of heat stress up to his limits of tolerance. Responses under steady state conditions are linear with Effective Temperature in Zones A and B. In Zone C, the steady state is impossible. Dashed lines indicate continuous heat storage and show trends only of T_c, T_s, SR and HR with increasing heat stress. (Semi-schematic representation based on data from refs. 7, 8, 9, 10, 11, 12, and 13.)

of P_{wa} or lower air velocities, s approaches A (the total body surface area) and at the point when $s=A$, the body surface is 100% wetted. Any further increase in sweat production does not contribute to cooling, but drips off the body and is wasted. Under higher levels of P_{wa} with further restriction on E , body heat will be stored, raising both \bar{T}_s and T_c . The response is a greater central drive for sweating. But as \bar{T}_s rises, P_{wa} and evaporative rate increase also. As a result, a new steady state may be established but at a cost of increased thermoregulatory strain, as reflected in further elevation of SR, BF_s, and HR.

As seen above, sweat rate in the zone of free

evaporation varies linearly with heat load, and SR is proportional to $M+R+C$. In the zone of restricted evaporation when s/A approaches 1.0, $SR > E$ and is proportional to the increase in T_c and \bar{T}_s .

Sweat rate is, therefore, an index of heat stress over the entire range of compensation. It is also an index of heat strain in the zone of time-limited compensation, where its rise parallels T_c and HR.

Sweat rate serves as a time-weighted average of heat stress. It is measured by the difference in body weight over a given time period corrected for weight gain by water and food intake and weight loss by urine and feces.

A constraint on the use of SR as an index of heat stress (or strain) is that the level of sweating tends to decline with time of heat exposure, particularly under restricted evaporation when skin is extensively wetted.

As long as $SR > E$, the decline in sweat rate does not interfere with heat loss, and might be regarded as an adaptive mechanism to conserve body water and electrolytes under conditions in which more sweat is produced than is useful.

Circulatory Strain

Thermal conductance (C), referred to earlier as an index of BF_s , is defined as

$$C = \frac{M/A}{T_c - \bar{T}_s} \text{ [Kcal/m}^2\text{-hr per degree of gradient]}$$

The narrower the gradient for a given M, or the higher the M for a given gradient, the greater is the BF_s required to transfer metabolic heat from core to the environment (Figure 30-3).

In a thermally neutral environment, \bar{T}_s is lower during work than at rest, reflecting a redistribution of blood from skin blood vessels to those of active muscles. The reduced capacity and increased resistance of skin vessels and also of vessels in abdominal organs together with the pumping action of muscles maintain the return of venous blood to the heart whose output increases in proportion to the % VO_2 max required by work.

Under external heat loads both the central drive for increased conductance and the rise in local skin temperature dilate skin vessels, thereby increasing their blood capacity and reducing their resistance. BF_s increases but at the cost of reducing venous return of blood to the heart, resulting in less output per beat. To meet the oxygen requirements of working muscles, cardiac output can then be maintained only by further vasoconstriction in abdominal organs and an increase in heart rate (Figure 30-3).

Thermoregulatory requirements for BF_s thus compete for available cardiac output with energy requirements of active muscles. BF_s , as estimated by C, increases from a quarter of a liter per minute at rest in a neutral environment to over two liters per minute in men working at 3-4 *met* under heat stress.

Heart Rate as An Index of Circulatory Strain

Heart rate is responsive both to the increased cardiac output required by working muscles as well as the added circulatory strain imposed by heat exposure, and is a useful index of total heat load.

Measured either by counting the pulse at the wrist or by using electronic devices for monitoring, HR is a valuable guide in assessing hazards to health of workers exposed to heat stress. Brouha⁵ has used the term *cardiac cost of work* to indicate the total heart beats above the resting level during work, and the term *cardiac cost of recovery*, or "cardiac debt," to denote the total number of beats above the resting level during the recovery period following work.

The detrimental effect of heat stress on work performance is indicated by an increase in cardiac cost both of work and recovery. Reducing work

load, increasing time of recovery or providing cool rest areas are alternative measures which management may elect to prevent excessive heat strain on workers.

To ensure that men performing intermittent work in the heat will remain in thermal balance for the full shift without cumulative effects of strain, Brouha proposed a simple guide. *Pulse rate is counted for the last 30 seconds of the first three minutes after rest begins. If the first recovery pulse, i.e., from 30 to 60 seconds, is maintained at 110/min or below and deceleration between the first and third minute is at least 10 beats/min, no increasing strain occurs as the work day progresses.* Extensive testing to validate this guide in the management of health problems of industrial heat stress seems highly warranted.

The mean HR level observed during an entire work shift reflects sustained elevations and peak rates as well as recovery and resting rates and thus can also serve as a guide in assessing circulatory strain. Electronic devices for integrating total count or continuously recording individual heart beats are now generally available. Both methods were employed in a recent study of heart rate responses in steelworkers in a Pittsburgh steel mill.⁶ There was variance in the mean HR in five workers on the same shift depending on work capacity (VO_2 max) of the individual and in the same worker on different shifts depending on total heat load. HR in all workers ranged from 99 to 136/min. The two workers with mean HR's exceeding 120/min showed evidence of excessive strain as indicated by a high resting HR and impaired work performance during a standard exercise after the shift.

The heart rate of men working at one-third VO_2 max will be 105-110/min (Table 30-2). On the basis that the combined effects of heat stress and work should not impose a greater circulatory demand than from work alone, an upper value of 110/min as the mean HR for an 8-hour shift would appear to be a reasonable limit for work involving heat exposure. For men or women of lower work capacity (i.e., VO_2 max less than 3 l/min) the energy expenditure at this heart rate would be less, but the strain proportionally the same.

In order to adopt the limit of 110/min. expressed in Table 30-2 as a standard, extensive testing and validation in industry would be required. The aim would be to compare circulatory strain in workers performing jobs in which heat exposure and work rates vary in proportion, and in workers on jobs involving peak loads with those exposed to more uniform work stresses. Finally, it would be necessary to determine whether the level of 110/min is safe or should be lowered for male or female workers whose work capacity and heat tolerance is limited because of age, physical fitness, acclimatization, or general health status.

Core Temperature

In Zone A (Figure 30-3) SR and BF_s increase proportionally with the total heat load ($M + R + C$). T_c is maintained at a uniform level which is determined only by M, and is independent of

ambient temperatures at lower levels of external heat stress.⁴ Lind⁷ terms this the *prescriptive zone* to indicate the range of thermal environments in which men can work without strain on homeostatic control of core temperature.

The upper limits of this zone are lower at high work rates because T_c is higher (Table 30-2). By the same token, the limit would be similar for men differing in physical fitness but expending the same percent of their $\dot{V}O_2$ max (Table 30-1).

From data of Robinson⁸ and others^{9, 10, 11, 12} the upper limit of the prescriptive zone in highly acclimatized men working at 300 kcal/hr is 31-32°C_{ET}.

For non-acclimatized men varying in physical fitness Lind¹³ recommends 27.5°C_{ET} (Figure 30-3) as a realistic limit for this level of work. The wide latitude of heat stress between these limits clearly indicates the perplexing nature of the problem of setting rational standards for industrial heat stress which will both protect workers of low heat tolerance and not restrict unduly work performance of those with higher heat tolerance.

In a man performing steady work at 300 kcal/hr, T_c is higher in Zone B than in the prescriptive zone in proportion to heat stress up to a limiting value of 39°C (Figure 30-3). This represents the highest core temperature at which highly acclimatized men can attain a steady state of thermal balance, and then for only two hours or less. The upward inflection of T_c in Zone B serves to maintain the core to surface gradient as \bar{T}_s attains higher levels, but at a cost of thermoregulatory strain on T_c . In terms of the model (Figure 30-2), the load error of the control system as reflected in T_c increases in proportion to the load.

The maximum tolerable level of heat stress corresponding to the T_c limit of 39°C was found by Robinson and others to be 34 to 35°C_{ET}. Men less fit or less well-acclimatized for work at 300 kcal/hr would reach limiting levels for thermal balance at lower core temperatures and at correspondingly lower levels of external heat stress. As a practical guide, the average core temperature of men should not exceed 38°C for a work shift. Transient increases to 39°C should be permitted but only briefly, and with ample time for recovery in cooler areas.

The border between Zones B and C marks the upper limit of man's capacity to sweat, thus representing the maximum effector response of the thermoregulatory center. Hence, in Zone C, rates of heat loss fail to match rates of heat gain, leading to heat storage with T_c and \bar{T}_s , rising continuously at rates proportional to the heat load. Storage may be further accelerated by fatigue or failure of sweating. No steady state during continued work is possible. This is indicated by broken lines in Zone C which imply trends only and not the transient state. Under extreme heat (e.g., 40 to 45°C_{ET}) the core to surface gradient will be reversed, the blood returning from the skin heating the body core instead of cooling it. The rising body temperature accelerates metabolic processes (Q_{10} effect), further increasing the rate

of body temperature rise. Unless the man stops working and seeks relief, heat exposure in Zone C leads inevitably to his collapsing from circulatory failure or heat stroke. Voluntary tolerance time for work in Zone C ranges from a maximum of one hour to less than 20 minutes.¹⁴

Under intense radiant heat loads, skin temperature rises rapidly to the pain threshold (45°C). Under these conditions pain becomes the limiting factor in tolerance time rather than heat storage in deeper tissues.

FACTORS IN HEAT TOLERANCE

Heat Acclimatization

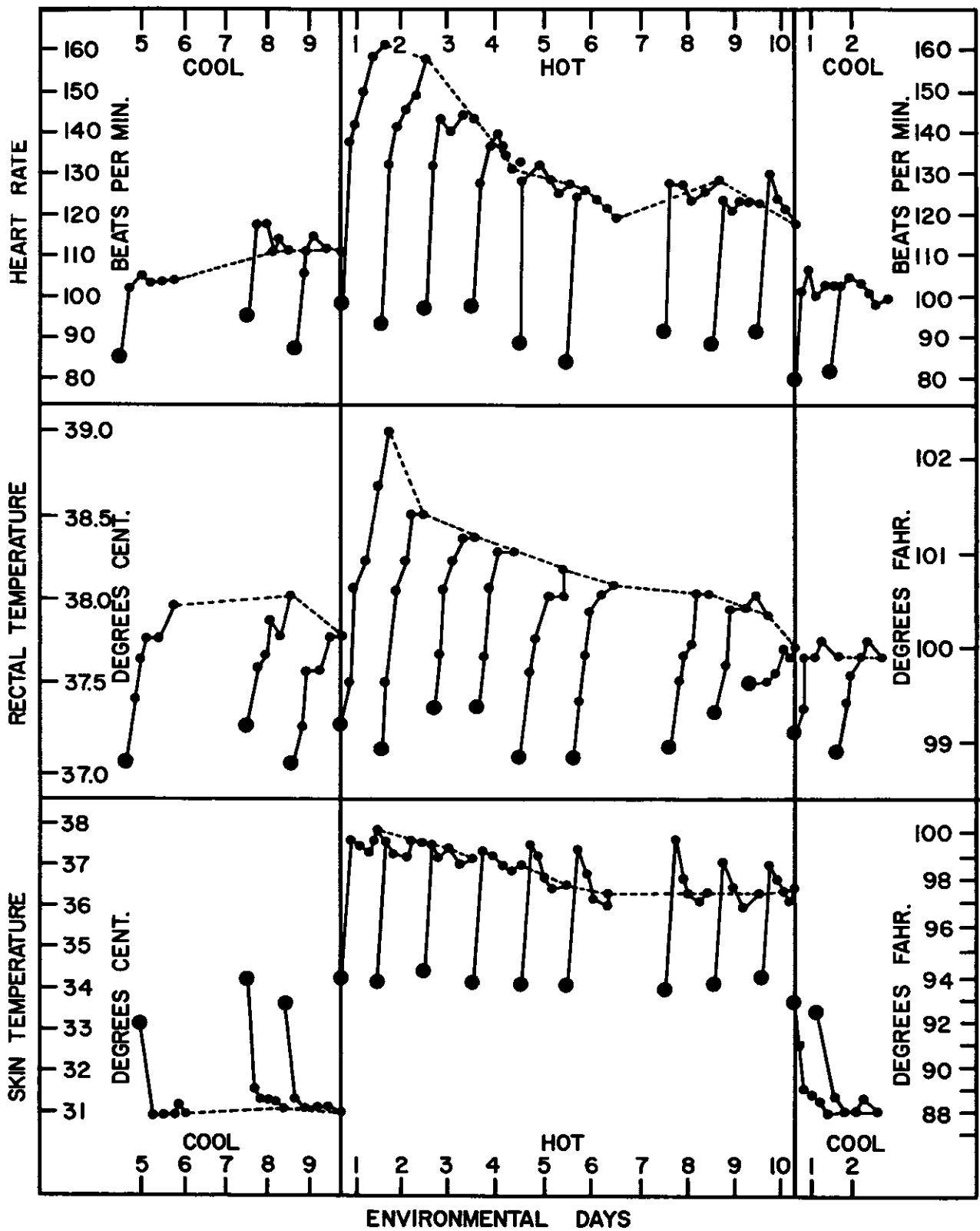
Any man, however healthy, well-conditioned and motivated, who works for the first time under heat stress will develop signs of severe strain with abnormally high body temperature, pounding heart, and other signs of heat intolerance. On each succeeding day of heat exposure his ability to work improves as signs of strain and discomfort diminish. After a week or two he can work without difficulty. The enhanced tolerance to heat acquired by working in a hot environment is called heat acclimatization.

Figure 30-4 from Eichna *et al.*¹⁰ illustrates the principal physiological adjustments in thermal balance which occurred in three highly conditioned young men with no previous heat exposure working for one hour/day for ten days at 300 kcal/hr (3 *met*) in dry heat (T_a , 50.5°C; T_{wb} , 26.5°C; V , 450 fpm). T_c , \bar{T}_s , and HR at rest in a cool environment (large dots) and at the end of each 10 min period of work in the heat (small dots) are shown, with control tests at rest and working under cool conditions before and after ten days of work in the heat. Table 30-5 summarizes the authors' data, including measurements of sweat rates and BF_s calculated from conductance.

The most significant change was a 10% increase in sweat output which was produced at a lower \bar{T}_s on hot day 10 compared with hot day 1. This increase in evaporative cooling with a steeper core to skin gradient was sufficient to compensate fully for the heat load, as indicated by the fact that core temperature was restored to within 0.1°C of that observed on cool day 1. In other words, conditions which had initially been nearly intolerable now fell within the "prescriptive zone" of full compensation, allowing the men to complete the work with no more difficulty than in the cool environment. Although BF_s remained elevated on hot day 10, acclimatization reduced the circulatory load by 32%.

Essential factors inducing acclimatization appear to be sustained elevations of T_c and \bar{T}_s , above levels for the same work in cool environments for an hour, or preferably more, per day for one or two weeks.

It seems well-established that acclimatization to wet heat increases tolerance to dry heat and vice versa. The reason why tolerance to wet heat is increased is not clear, because the increased sweat output, which may nearly double, is largely wasted. Heat conduction through the skin is enhanced,



Eichna, L. W., Park, C. R., Nelson, N., et al: Thermal regulations in a hot dry (desert type) environment. *Am. J. Physiol.* 163:585, 1950.

Figure 30-4. Thermoregulatory Responses to Heat Stress in Zone A (Full Compensation), B (Time Limited Compensation), and C (Uncompensated Heat Storage).

TABLE 30-5
Changes in Thermoregulatory Responses with Acclimatization (Eichna *et al.*¹⁰)

Condition	HR (min)	SR (kg/m ² hr)	T _c °C	\bar{T}_s °C	T _c - \bar{T}_s	BF _s (l/m ² ·min)
Initial cool day	111	0.079	37.8	30.9	6.9	0.35
Hot day 1	162	0.621	39.0	37.8	1.2	2.58
Hot day 10	118	0.692	37.9	36.4	1.5	1.76
Final cool day	103	0.083	37.7	31.1	6.6	0.37

Reprinted from American Journal Physiology, 163:585, (1950).

however, which suggests a change in distribution of blood to the skin.¹⁵

Whether the underlying change in acclimatization is greater sensitivity of the center to thermal inputs from skin or central receptors, a lower threshold of skin receptors to heat, an enhanced response of the sweat glands to the central drive, or some combination of these factors is still the basic problem of thermal physiology which remains under active study.

Men who work at hot industrial tasks acquire levels of acclimatization commensurate with their average heat exposure. Unusual demands for work effort or sudden spells of hot weather may, however, overload their thermoregulatory capacity, leading to signs of overstrain. Heat acclimatization needs periodic reinforcement, such as occurs daily during the work week. Men may show some loss of acclimatization on the first day of the new shift after being idle for two days or over a weekend. After vacations of two weeks or longer, the loss of acclimatization is substantial, several days at work elapsing before heat tolerance is fully restored. Some traces of acclimatization may be evident, however, as long as eight weeks following the last heat exposure.

Seasonal changes in outside weather are reflected in heat tolerance of workers,¹⁶ the lower level during cooler seasons owing largely to milder heat stress on the job, which parallels changes in outside weather temperature.

Physiologic adjustments in acclimatization also include changes in sweat composition. Sweat is a dilute solution of electrolytes, principally sodium chloride. In unacclimatized subjects, sodium chloride concentration in sweat (3 to 5 g/kg) is about half the concentration in blood plasma. In acclimatized subjects, sweat is not only more abundant but more dilute, the salt concentration falling to levels of 1 to 2 g/kg, reflecting an adaptive change in hormonal balance through secretion of aldosterone which acts to conserve body salt both by the kidneys and sweat glands.

Surface Area to Weight Ratio

In obese individuals as well as in those with stocky build the body surface area (A) to body weight (Wt) ratio is relatively low. Because heat loss is a function of A and heat production a function of Wt, a low A/Wt is a handicap for men performing sustained work in the heat. If lacking in acclimatization, physically unfit and obese men are at greater risk of succumbing to heat stroke.

Age and Degenerative Diseases

The healthy older worker (40-65 yrs) performs well on hot jobs if allowed to work at his own pace. Under demands for sustained work output in the heat, he is at a double disadvantage compared with younger men. First, VO₂ max declines 20-30% between ages 30 and 65, leaving the older worker with less cardiocirculatory reserve capacity and second, under levels of heat stress above the prescriptive zone, the older worker compensates for the heat loads less effectively than the younger man, as indicated by his higher core temperature and peripheral blood flow for the same work output.¹⁷ This has been attributed to a delay in onset of sweating, and a lower sweat rate in older men, resulting in greater heat storage during work and longer time for recovery.

Degenerative diseases of the heart and blood vessels intensify the age effect on heat tolerance by limiting the circulatory capacity to transport heat from body core to surface. Elderly men and women with chronic diseases of aging account for much of the excess in mortality reported in large northern cities during sustained heat waves.¹⁸

Men with long work experience in hot industries, on the other hand, seem to be less at risk of dying from cardiovascular and other diseases than workers of similar age without a work history of heat exposure. In a recent unpublished biostatistical study of 12,946 open hearth steel workers,¹⁹ the mortality rate for arteriosclerotic heart disease, and respiratory disease, as well as overall mortality rate were significantly less in this group than in the entire population of 58,829 steel workers. A self-selection process which eliminates those of low physical fitness and heat tolerance from jobs on the open hearth could not be ruled out.

Water Balance

Effective work performance in the heat depends on replenishing body water and salt lost in sweat. A fully acclimatized worker weighing 70 kg can secrete 6-8 kg of sweat per 8-hr shift. If water lost in sweat is not replaced by drinking, continued sweating ultimately draws on water both from tissue spaces and body cells as well, leading to the picture of shriveled skin, dry mouth and tongue, and sunken eyes recognized as extreme dehydration.

Sweat loss of 1 kg of body water (1.4% of body weight) can be tolerated without serious effect. Water deficits of 1.5 kg or more during work in the heat deplete the volume of circulating blood, resulting in signs and symptoms of in-

creasing heat strain (elevated HR and T_{re} ; thirst and severe heat discomfort), resembling those seen in unacclimatized men. With water deficits of 2 to 4 kg (3 to 6% of body weight) work performance is impaired. Continued work leads to incipient signs of *heat exhaustion*. Therefore, to avoid excessive depletion of body water, sweating men should drink frequently at intervals of 30 min or less.

Unacclimatized men should be encouraged to drink somewhat more than thirst dictates to avoid "voluntary" dehydration. Well-acclimatized men succeed much better in balancing water losses, even when sweating at high rates. Dehydration of more than 1 to 2% of body weight in acclimatized workers during a shift may signify greater heat loads than usual, or lack of access to water.

Salt Balance

Salt (NaCl) losses in sweat during work can usually be replaced at mealtime. The average American diet, which contains 10 to 15 g/day of salt, would meet the needs of an acclimatized worker producing 6-8 kg of sweat containing 1 to 2 g of salt per kg during a single shift. For the period of acclimatization supplementary salt during hot work might be needed by workers with no previous heat exposure. Although maximal sweating rates in unacclimatized men are lower (4-6 kg/shift), salt concentrations are higher (3 to 5 g/kg sweat) than after acclimatization. At the higher sweat rate, an unacclimatized man may lose 18 to 30 grams of salt. Supplements in the form of 0.65-g salt tablets (preferably impregnated to avoid gastric irritation) may be taken if ample water is available. Better practice is to use salted water (0.1% or 1 tsp/gal) or to advise increased salt on food at mealtime.

Salt supplements should be reduced or discontinued after several days of heat exposure because salt loading suppresses normal hormonal mechanisms regulating salt and water metabolism under heat stress.

Depletion of body salt may occur in unacclimatized men exposed to heat who replace water losses without adequate salt intake in food. This leads to progressive dehydration because homeostatic controls are geared to maintain a balance between electrolyte concentration in tissue fluids with that in the cells. Deficient salt intake with continued intake of water tends to dilute tissue fluid, which suppresses the antidiuretic hormone (ADH) of the pituitary gland. The kidney then fails to reabsorb water and excretes dilute urine containing little salt.

Thus homeostasis maintains the electrolyte concentration of body fluids but at the cost of depleting body water with ensuing dehydration. Under continued heat stress, symptoms of heat exhaustion develop similar to those resulting from water restriction, but with more severe signs of circulatory insufficiency and notably little thirst. Absence of chloride in the urine (< 3 g/l) is diagnostic of salt deficiency.

On a short-term basis, sweating men drinking large volumes of unsalted water may develop *heat cramps* which are excruciatingly painful spasms of

those muscles used while working (arms, legs, or abdominal). Dilution of tissue fluid around the working muscle results in transfer of water into muscle fibers, causing the spasms.

Treatment of the various clinical syndromes of water and salt depletion is similar; namely, replacement of depleted body water and/or salt by oral ingestion of salted liquids in mild cases or intravenous infusion of saline in more serious ones. An excess of salt or water over actual needs is readily controlled by kidney excretion. These and other clinical entities resulting from failure to adapt to heat stress are described in Table 30-6, which is based on a nomenclature prepared jointly by committees representing the U.K. and the U.S.²⁰ For further details on etiology, signs, symptoms, treatment and prevention of heat illnesses, the reader is referred to Leithead and Lind.¹⁴ (See Table 30-6).

Alcoholic Habits

Many authors have noted an excessive alcohol intake by patients within hours or a day or two prior to onset of *heat stroke*. Others have described striking reductions in workers' heat tolerance on the day following an alcoholic "binge." It is known that alcohol suppresses ADH, leading to loss of body water in urine. Hence dehydration may be a primary factor.

Physical Fitness

Physical conditioning alone does not confer heat acclimatization. The subjects of Eichna *et al.*, (Figure 30-4) were all highly conditioned before the test. Physical training without heat exposure, however, does improve heat tolerance, as indicated by somewhat lower heart rates and core temperatures in men exposed to heat after conditioning as compared with before. Sweat rates do not increase and skin temperature remains high. Physical conditioning enhances heat tolerance by increasing functional capacity of the cardiocirculatory system. Two important changes are first, an increase in number of capillary blood vessels to muscle, thus providing a larger interface between blood and muscle for exchange of oxygen and waste products and second, increased tone of small veins from tissues other than muscle so as to reduce their capacity during exercise, thus increasing pressure in large central veins returning the blood to the heart. Cardiac output per minute during work can increase with less need to accelerate the heart. These factors combine to increase VO_2 max of the physically conditioned man, giving him a wider margin of safety in coping with the added circulatory strain of work under heat stress. The extent to which men might gain in heat tolerance by acclimatization is not easily predictable, but those with a high level of physical fitness have the advantage.

Selection and Periodic Examination of Workers

Past performance in heat is perhaps the only reliable criterion on which to predict effectiveness of a worker's future performance under heat stress. For new employees without previous heat exposure, screening procedures should include standard tests of physical fitness and heat tolerance. Heart rates attained during a stepping exercise at 332

TABLE 30-6.
Classification, Medical Aspects, and Prevention of Heat Illness

Category	Clinical Features	Predisposing Factors	Underlying Physiological Disturbance	Treatment	Prevention
1. Temperature Regulation					
<i>Heat Stroke and Heat Hyperpyrexia</i>	Heat Stroke: 1) <i>Hot dry skin</i> : red, mottled or cyanotic. 2) <i>High and rising</i> T_e , 40.5°C and over. 3) <i>Brain disorders</i> : mental confusion, loss of consciousness, convulsions, coma as T_e continues to rise. Fatal if treatment delayed. Heat Hyperpyrexia: milder form. T_e lower; less severe brain disorders, some sweating.	1) Sustained exertion in heat by unacclimatized workers. 2) Lack of physical fitness and obesity. 3) Recent alcohol intake. 4) Dehydration. 5) Individual susceptibility. 6) Chronic cardiovascular disease in the elderly.	<i>Heat Stroke</i> : Failure of the central drive for sweating (cause unknown) leading to loss of evaporative cooling and an uncontrolled accelerating rise in T_e . <i>Heat Hyperpyrexia</i> : Partial rather than complete failure of sweating.	<i>Heat Stroke</i> : Immediate and rapid cooling by immersion in chilled water with massage or by wrapping in wet sheet with vigorous fanning with cool dry air. Avoid overcooling. Treat shock if present. <i>Heat Hyperpyrexia</i> : Less drastic cooling required if sweating still present and $T_e < 40.5$.	Medical screening of workers. Selection based on health and physical fitness. Acclimatization for 8-14 days by graded work and heat exposure. Monitoring workers during sustained work in severe heat.
2. Circulatory Hypostasis	Fainting while standing erect and immobile in heat.	Lack of acclimatization.	Pooling of blood in dilated vessels of skin and lower parts of body.	Remove to cooler area. Recovery prompt and complete.	Acclimatization. Intermitent activity to assist venous return to heart.
3. Salt and/or Water Depletion	<i>Heat Exhaustion</i> 1) Fatigue, nausea, headache, giddiness. 2) Skin clammy and moist. Complexion pale, muddy or hectic flush. 3) May faint on standing with rapid thready pulse and low blood pressure. 4) Oral temperature normal or low but rectal temperature usually elevated (37.5-38.5°C). <i>Water restriction type</i> : Urine volume small, highly concentrated. <i>Salt restriction type</i> : Urine less concentrated, chlorides less than 3 g/l.	1) Sustained exertion in heat. 2) Lack of acclimatization. 3) Failure to replace water and/or salt lost in sweat.	1) Dehydration from deficiency of water and/or salt intake. 2) Depletion of circulating blood volume. 3) Circulatory strain from competing demands for blood flow to skin and to active muscles.	Remove to cooler environment. Administer salted fluids by mouth or give I-V infusions of normal saline (9%) if unconscious or vomiting. Keep at rest until urine volume and salt content indicate that salt and water balances have been restored.	Acclimatize workers using a breaking-in schedule for 1 or 2 weeks. Supplement dietary salt only during acclimatization. Ample drinking water to be available at all times and to be taken frequently during work day.
b) <i>Heat Cramps</i>	Painful spasms of muscles used during work (arms, legs, or abdominal). Onset during or after work hours.	1) Heavy sweating during hot work. 2) Drinking large volumes of water without replacing salt loss.	Loss of body salt in sweat. Water intake dilutes electrolytes. Water enters muscles, causing spasm.	Salted liquids by mouth, or more prompt relief by I-V infusion.	Adequate salt intake with meals. In unacclimatized men, provide salted (0.1%) drinking water.
4. Skin Eruptions	<i>Heat Rash</i> (miliaria rubra; "prickly heat") Profuse tiny raised red vesicles (blister-like) on affected areas. Pricking sensations during heat exposure. <i>Anhidrotic Heat Exhaustion</i> (miliaria profunda) Extensive areas of skin which do not sweat on heat exposure, but present goose flesh appearance, which subsides with cool environments. Associated with incapacitation in heat.	Unrelieved exposure to humid heat with skin continuously wet with unevaporated sweat. Weeks or months of constant exposure to climatic heat with previous history of extensive heat rash and sunburn. Rarely seen except in troops in wartime.	Plugging of sweat gland ducts with retention of sweat and inflammatory reaction. Skin trauma (heat rash; sunburn) causes sweat retention deep in skin. Reduced evaporative cooling causes heat intolerance.	Mild drying lotions. Skin cleanliness to prevent infection.	Cooled sleeping quarters to allow skin to dry between heat exposures. Treat heat rash and avoid further skin trauma by sunburn. Periodic relief from sustained heat.
5. Behavioral Disorders	a) <i>Heat Fatigue - Transient</i> Impaired performance of skilled sensorimotor, mental, or vigilance tasks, in heat. b) <i>Heat Fatigue - Chronic</i> Reduced performance capacity. Lowering of self-imposed standards of social behavior (e.g., alcoholic indulgence). Inability to concentrate, etc.	Performance decrement greater in unacclimatized, and unskilled men. Workers at risk come from homes in temperate climates, for long residence in tropical latitudes.	Discomfort and physiological strain. Psychosocial stresses probably as important as heat stress. May involve hormonal imbalance but no positive evidence.	Not indicated unless accompanied by other heat illness.	Acclimatization and training for work in the heat. Orientation on life abroad (customs, climate, living conditions, etc.)

kg.m/min are now being used in selecting men for further acclimatization before assigning them to mining ore under high heat stress in the deep gold mines of South Africa.²¹ Those of low work capacity, as indicated by a heart rate of over 140/min, are eliminated for these tasks. Those with lower exercise heart rates, particularly if below 120/min, are considered the best candidates and undergo graded acclimatizing exercises for 4 hours/day for 8 days in hot rooms ($T_{wb} = 31.7^{\circ}\text{C}$). A second screening at this stage eliminates those with oral temperatures persistently above 38.3°C . Through screening, acclimatization, and selective placement based on heat tolerance, together with careful supervision of workers, serious heat casualties from heat stroke among the 100,000 or more men recruited yearly in this industry have been greatly reduced and productivity substantially increased.

Operations of this magnitude do not exist in the United States, but the same principles are applicable. On pre-employment examination, the physician can readily assess physical fitness using stepping exercises, or a bicycle ergometer to estimate VO_2 max. In terms of O_2 uptake per kg, a VO_2 max of 28 ml/kg min or less should be disqualifying. A standard test for heat tolerance is desirable but requires special facilities.

Older workers, including both new applicants and those undergoing periodic evaluation, should be examined with particular attention to chronic impairments of the heart, circulation, and vascular system but also of the kidneys, liver, endocrines, lungs and skin. Significant disease of any of these systems should be disqualifying for new employment on jobs involving severe heat exposure, or for those previously employed in such jobs if the disease is progressive despite treatment. Careful inquiry should be made on use of drugs, particularly hypotensive agents, diuretics, antispasmodics, sedatives, tranquilizers, and anti-depressants, as well as the abuse of drugs, particularly amphetamines and alcohol. Many of these drugs impair normal physiological responses to heat stress, and others alter behavior, exposing the patient or fellow workers to safety hazards. Toxic agents in the work environment which reduce heat tolerance, notably carbon monoxide, must also be considered. History of repeated accidents on the job, poor work performance, emotional instability, or frequent sick absence should alert the physician to possible heat intolerance of the employee.

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THERMAL STANDARDS AND MEASUREMENT TECHNIQUES

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INTRODUCTION

The Industrial Revolution brought with it undeniable benefits to mankind, but not without certain costs. The opportunities for injury and sudden death that emerged included hazards unknown to the craftsmen in home-centered manufacturing activities. Among the more dangerous pursuits were those involving the production of basic materials, glass, metals, etc.: in short, the hot industries. Not only was there the ever-present danger of splashes, explosions and spills of molten material, but injuries and deaths mounted as the result of hard physical work in excessively hot environments. With the more enlightened current attitudes, one would assume that deaths and heat-illnesses are rare in the United States, but accurate data are not available on the frequency of heat casualties.

Other chapters in this volume provide information related to the physiologic consequences of heat stress (Chapter 30) and possible measures which may be taken to reduce stresses caused by the thermal environment (Chapter 38). It is the purpose of this chapter to outline the philosophy and development of indices for rating severity of the thermal environment, to outline the methods of assessment of the several parameters involved in the indices, and to provide guidelines for application and interpretation of the indices.

MEASUREMENT OF THE THERMAL ENVIRONMENT

Measurement of the thermal environment requires selection and placement of instrumentation such that the data acquired will be meaningful in terms of heat exchanges between the worker and the environment. For this to be achieved effectively, the investigator must (a) understand the fundamental physical laws governing thermal exchanges and (b) become familiar with the operating principles and procedures of the instruments. Such understandings will help to avoid inappropriate applications of instrumentation.

Thermal Exchanges with the Environment

The modes of heat exchange between man and the environment — evaporation, convection, radiation — have been covered qualitatively in Chapter 30, as have the environmental parameters which influence the rate of exchange. Quantitative relationships are developed in this chapter.

Convection (C) is a function of (1) the temperature gradient between the skin and the ambient air (or outer clothing), and (2) the movement of air past the surface. Stated algebraically:

$$C = f (T_a - T_s), V^n$$

In the Newtonian form and with the "Fort Knox" coefficients as revised by Hatch,^{1,2} the expression becomes

$$C = 1.0 V^{0.6} (T_a - T_s)$$

where C = Convection, kcal/hr

V = Air speed, meters/min

T_a = Air temperature, °C

T_s = Skin surface temperature, °C.

The empirically obtained exponent of 0.6 applies to forced convection over vertical cylinders,³ the geometric configuration that best corresponds to man in the working environment.

The sign convention has been chosen such that when T_a is higher than T_s, C will be positive; thus heat *gain* to the man will be positive, and heat *loss*, negative.

The coefficient includes the surface area for an "average" man (= 1.8 m²). For a particular individual whose surface area may differ from average, the value of C may be adjusted by multiplying by the ratio: actual area/1.8. The "Fort Knox" coefficients were developed on men essentially nude; the influence of clothing is considered by Belding in Chapter 38.

Radiation, R, is a function primarily of the gradient from the mean radiant temperature of the solid surroundings to skin temperature. While radiative exchange, in reality, is a function of the fourth power of absolute temperature, a first order approximation is sufficiently accurate for estimating R in the application outlined here.⁴ [Note that the value of the coefficients in reference (4) also have been modified.²]

$$R = 11.3 (T_w - T_s)$$

where R = Radiation, kcal/hr

T_w = Mean radiant temperature of the solid surroundings, °C.

and T_s = Skin surface temperature, °C.

Evaporation, E, is a function of air speed, and the difference in vapor pressure between the perspiration on the skin (vapor pressure of water at skin temperature) and the air. In hot, moist environments, evaporative heat loss may be limited by the capacity of the ambient air to accept additional moisture, in which case,

$$E_{max} = 2V^{0.6} (PW_s - PW_a)$$

where V = Air speed, meters/minute

PW_s = Vapor press. of water on skin, mmHg

PW_a = Vapor press. of air, mmHg.

In hot, dry environments E may be limited by the amount of perspiration which can be produced by the worker. The maximum sweat production that can be maintained by the average man throughout an eight-hour shift is one liter per hour, which is equivalent to an evaporative heat loss of 600 Kcal/hr. or (2400 Btu/hr).

From the above, it is evident that four environmental factors define the thermal exchanges: T_a , T_w , PW_a and V . Physiological factors, e.g., T_b , metabolism (M), are dealt with elsewhere (Chapters 30 & 38).

NOTE: Equations for C , R , and E_{max} in English units ($^{\circ}F$, ft/min, Btu/hr) are $C = 1.08 V^{0.6} (T_a - T_b)$, $R = 25 (T_w - T_b)$ and $E_{max} = 4.0 V^{0.6} (PW_a - PW_b)$, respectively.

Instruments

Thermometry. Air temperature may be measured by a variety of instruments, each of which may have advantages under certain circumstances.

1. *Mercury (or alcohol)-in-glass thermometers.* The common glass thermometer is often used for determining air temperature. But because of its very common nature, sometimes the simplest of precautions are overlooked.

Calibration. Thermometers may be in error by several degrees. Each should be calibrated over its range in a suitable medium (usually a temperature-controlled oil bath) against a known standard, e.g., Bureau of Standards certified thermometer. Only thermometers with the graduations marked on the stem should be used. Those with scale markings on a mounting board can be off by 10° ; further the stem can shift relative to the mounting board.

Range. It seems superfluous to specify that the range of the thermometer should be selected to cover the anticipated environment. But if one is careless, a $0-50^{\circ}C$ thermometer can be easily carried into a $60^{\circ}C$ environment where the mercury will break the capillary glass tube; this is not an unusual occurrence in practice.

Separation of columns. Sometimes the liquid column in a thermometer will separate. Before readings are taken, the continuity of the column should be checked. Separated columns may be rejoined by shaking, or by heating in hot water (never a flame!).

Type. If the thermometer is totally "immersed" in the air being measured, a total immersion instrument should be selected. A partial immersion thermometer will be the instrument of choice for wet bulb and globe thermometers and for the aspirated psychrometer. The depth of submersion for which a partial immersion thermometer is calibrated is usually indicated by a mark on the stem.

Breakage. Glass thermometers are the simplest to use, most readily available and cheapest of the temperature instruments considered. Yet their fragility may prove to be a hazard in certain applications. The

mercury spilt from a broken thermometer may not be of consequence in a large, well-ventilated shop, but would certainly require careful cleanup in an enclosed space, e.g., underwater chamber.

2. *Thermoelectric thermometers.* When two dissimilar metals are joined, and the temperature of the junction is changed, a small voltage is generated (Seebeck effect)⁵. Two junctions in a circuit, with one held at a known temperature ("reference junction"), form the basic elements of a thermocouple. The current flowing in the circuit resulting from the electromotive force (e.m.f.) generated may be measured directly by a galvanometer, or the e.m.f. balanced by a known source potentiometrically. The latter technique is preferred, as the length of the thermocouple (hence its resistance) becomes of no consequence when current flowing becomes zero. Each thermocouple used with a current-measuring device must be calibrated individually. With a potentiometer, only samples from the spools of wire need be calibrated, and only then if extreme precision is required. Figure 31-1 provides a schematic arrangement of the components in a thermocouple system.

Thermocouples of copper and constantan (a copper-nickel alloy) are commonly used for most environmental temperature ranges. They are easy to construct, and the wire for an individual couple costs only a few cents. However, the potentiometer will cost several hundred dollars.

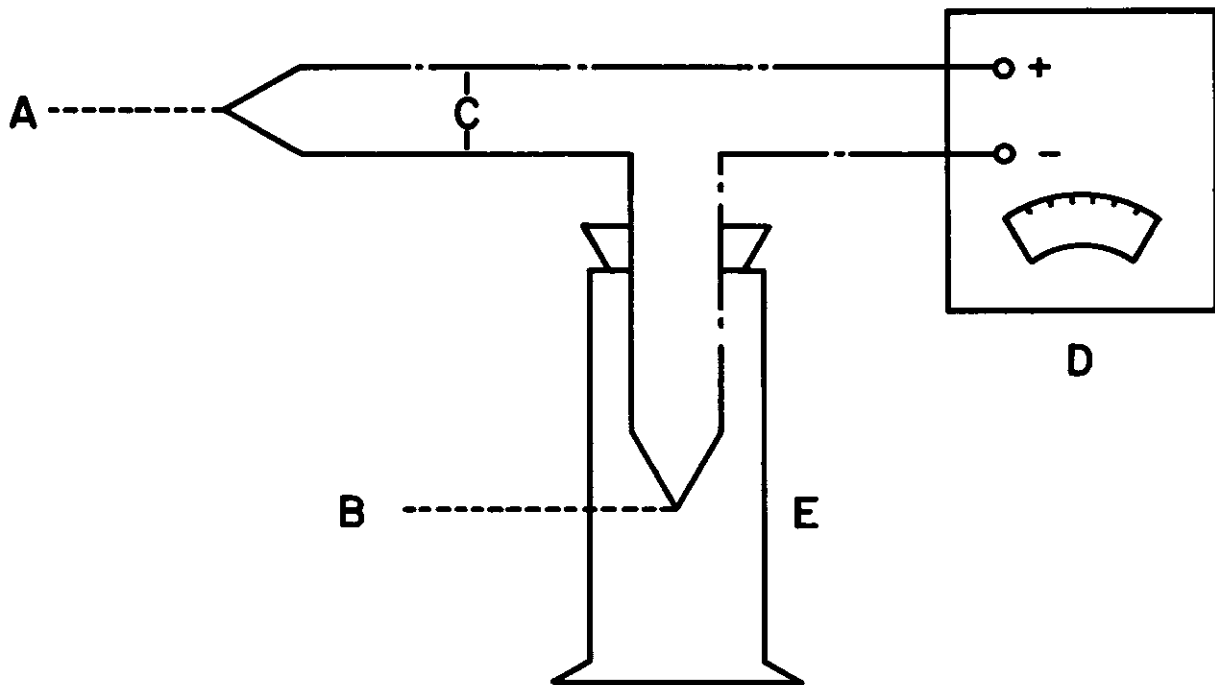
The availability of small thermocouple wire, as fine as 40 gauge, makes the technique useful for measuring physiological temperatures, e.g., skin, ear canal, rectal, with the same recording or readout equipment as used for environmental temperatures. To prevent shorting out between junctions in the saline milieu of the body, thermojunctions used for physiological measurements should be electrically insulated.

Thermocouples have these advantages over mercury-in-glass thermometers:

- (1) Adaptability to specific placement. Small junctions may be placed where the bulb of the thermometer would not be appropriate, e.g., skin surface.
- (2) Remote reading. Thermojunctions may be placed at the measurement site, and read remotely — hundreds of meters away, if necessary.
- (3) Simultaneous readings from several stations may be read at one place with one potentiometer with a rotary selector switch in the circuit.
- (4) Low cost of thermocouples, once potentiometer is purchased.
- (5) Adaptability to continuous recording.
- (6) No hazards from breakage.
- (7) Equilibrium time with changing temperatures is almost instantaneous, whereas mercury-in-glass thermometers may require several minutes to reach a steady reading.

On the other hand, disadvantages include:

- (1) High initial cost of potentiometer.
- (2) Bulk of potentiometer.



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Figure 31-1. Components in a Thermocouple System.

- (3) Requirement for reference junction (usually ice bath in Thermos bottle).
- (4) Requirement to run wires to measurement site.
- (5) Some technical skill required to construct thermocouples and use equipment. Laboratory training in techniques highly recommended.

3. *Thermistor thermometry.* One of the "space age" gadgets is the thermistor: thermal resistor. Thermistors are semiconductors which exhibit substantial change in resistance in response to a small change in temperature. As the resistance of the thermistor itself is measured in thousands of ohms, the resistance imposed by lead wires up to 25 meters or so is immaterial, permitting remote readings, as with thermocouples. Readout equipment is battery-powered and relatively light and portable which is convenient for field studies.

Advantages:

- (1) Simple to use with minimum training.
- (2) Less bulky and complicated to use than thermocouples.
- (3) Requires no reference junction.
- (4) Output signal may be recorded.
- (5) Variety of probes available for special applications.

Disadvantages:

- (1) Cost of readout equipment about the same as potentiometer, but thermistor probes cost about \$25.00 each. If the lead breaks,

it is not easily repaired, as are thermocouples.

- (2) Thermistor probes, though they are called "interchangeable," require individual calibration before use. Calibration of thermistor beads will shift somewhat with age, requiring annual or biennial recalibration. *Comment:* The advantages of the thermistor thermometer make it the instrument of choice for field use when mercury-in-glass thermometers are inappropriate. Regardless of the type of thermometer used, shielding of the sensor against radiant exchange may be required where walls are cooler or warmer than the air, or in direct sunlight. Heavy aluminum foil fastened loosely around the bulb provides effective shielding; however, it should not restrict the free flow of air around the sensor element. And finally, in asymmetric thermal fields readings at several locations in the occupied space may be required to provide an adequate estimate of average air temperature.

Anemometry. As noted above, heat transfer by convection and by evaporation are functions of movement of the ambient air. While the units associated with air motion — distance per unit time — suggest movement of the mass of air past a point, turbulent air with little net mass movement will be as effective in heat transfer as linear movement.

Directional instruments, useful in ventilation engineering or meteorology, are usually not applicable for assessment of heat stress. On the other hand, instruments which depend upon rate of cooling of a heated element provide readings meaningful in terms of "cooling power" of the moving air, and are thus the instruments of choice.

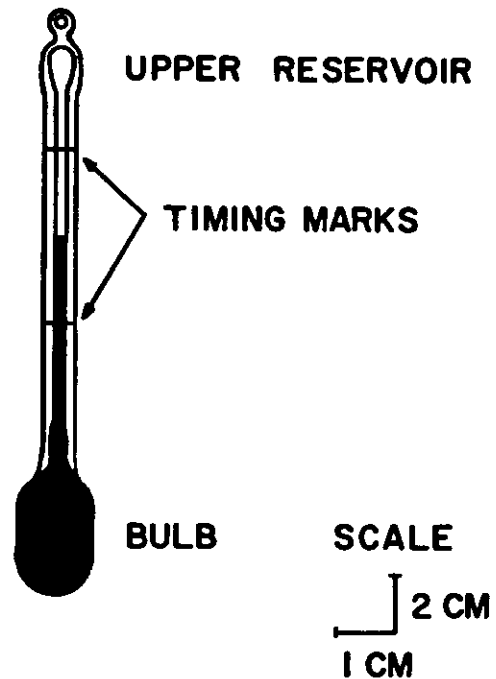
1. Thermoanemometers.

Willson thermoanemometer. In use, two matched thermometers are mounted about 5 cm. apart in the environment. One of the thermometer bulbs is wrapped with a fine resistance wire. Current from a battery passing through the wire heats the bulb. The second thermometer is bare. The temperature differential between the heated and the unheated thermometers depends on the current through the wire (adjustable), and the air speed. The voltage is set between 2 to 6 volts, depending on the range of air speed encountered. At high air speeds, greater heat input is required to obtain sufficient differential between the thermometers for reliable readings. Knowing this temperature differential and the voltage, the operator may find the air speed from the calibration curves supplied with each instrument. Achieving equilibrium requires 2 to 5 minutes. On the one hand, this provides an integrating effect in turbulent air, but on the other hand makes determination of air speed at many locations tedious. Its design, however, assures relatively non-directional response.

Alnor thermoanemometer. This instrument measures air motion by the rate of cooling of a heated thermocouple at the tip of the probe. One thermojunction is heated by a constant current supplied to a heater wire; the other junction is located in the air stream. The air speed governs the rate of heat removal from the heated thermocouple, which in turn determines its millivolt output. The scale is calibrated directly in feet per minute. The low mass of the thermocouple permits almost instantaneous response of the instrument. An area may be surveyed quickly, but rapid fluctuations in air motion make mean speed estimates difficult. Batteries supply the power, making the instrument portable and self-contained. The thermocouple and heater supports restrict airflow somewhat; the probe should be slightly rotated to obtain the maximum reading.

Anemotherm. The principle of operation of the Anemotherm is similar to the Alnor, though a heated resistance wire is used as one leg of a Wheatstone bridge instead of the heated thermocouple circuit.⁶ The Anemotherm also may be used to measure temperature and static pressure.

Kata thermometer. Hill⁷ developed the Kata thermometer to determine cooling power of the air, as a measure of efficiency of ventilation in factories, mines, etc. (Figure 31-2). It is essentially an alcohol-filled thermometer with an out-sized bulb. The bulb is heated in warm water until the column rises into the upper reservoir and is then wiped dry. The instrument is suspended in the air stream (it may be hand held, provided the body of the operator does not interfere with the flow of air); the fall of the column from the upper



Hill, L.: The Science of Ventilation and Open Air Treatment. Part I, Med. Res. Count. Spec. Dept. No. 32, London, 1919.

Figure 31-2. Kata Thermometer.

to the lower mark etched on the stem is timed with a stopwatch. The cooling time of the Kata is a function of air speed and air temperature; the air speed is determined from nomograms accompanying the instrument.

Katas are made in several ranges for high temperature environments, as well as the standard instrument for the comfort range (upper mark 38°C, lower mark 35°C). The bulb of the Kata must be silvered to reduce the effect of radiant heat exchange. The Kata is a good instrument for estimating accurately the cooling power of air motion at low speeds, <15 meters/min. The requirements for heating above ambient make it somewhat awkward for field work, though a Thermos of hot water may be carried.

2. *Estimation of air motion.* For investigators frequently called upon to make heat stress studies, it is well worth the effort to learn to judge air motion by "feel." This permits a gross estimate of air movement without instruments on a survey or "walk through." If no motion is felt, the air speed is below 10 to 15 meters/min (30-50 ft/min). If a light breeze is felt, the speed will be about 15 to 30 meters/min. Breezes strong enough to cause movement of clothing, tousling of hair, etc., are in the range of 30-90 meters/min. Winds stronger than these are not often found within buildings, except in front of fans.

Psychrometry. The amount of water vapor in the air (humidity) controls the rate of evaporation of

water from skin surface and from other moist tissues, e.g., lungs, respiratory passages, conjunctiva of the eyes, etc. To understand the process of evaporation from these tissues into the ambient air, certain properties of liquid-vapor interfaces should be reviewed.

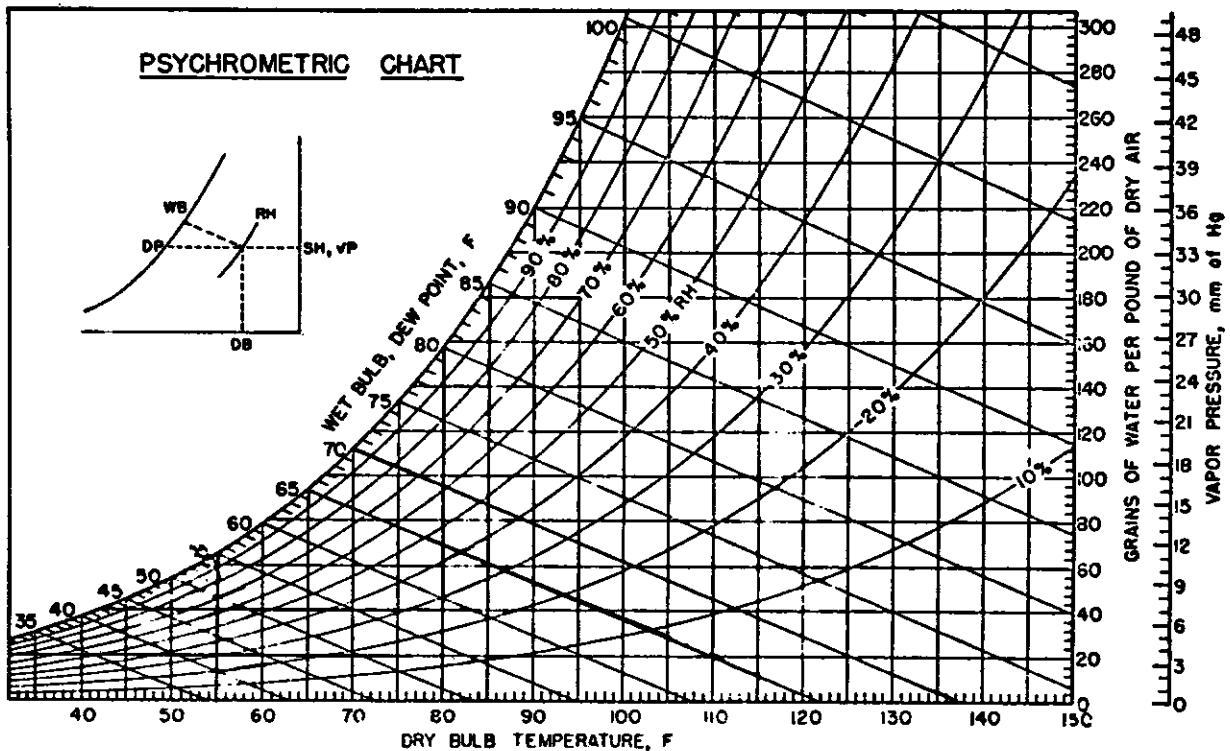
Water, like other liquids, will tend to saturate the surrounding space with vapor. In an enclosed vessel, the amount of water vapor per unit volume in the space above the water is dependent only on the temperature of the system (assuming constant total pressure). In accordance with Dalton's law of partial pressures, presence or absence of other species of gases in the space will have no effect on the amount of water vapor present. If all other gases are evacuated, the pressure developed is termed the true vapor pressure (or saturation pressure) of the liquid at the existing temperature. If the temperature is raised, saturation vapor pressure will increase. When the vapor pressure equals total atmospheric pressure, boiling occurs. In an open vessel where ambient air currents carry away the water vapor, continuous evaporation takes place.

"Relative humidity" (RH) is defined as the amount of moisture in the air as compared with the amount that the air could contain at saturation at the same temperature. It is usually expressed as a percentage. Thus, the amount of moisture in the air at, say, 50% RH will vary depending on the air temperature. Since it is the *amount* of

water vapor in the air ("absolute" humidity) which influences evaporation, the relative humidity cannot be used directly to compute evaporative loss.

To illustrate this point: water vapor in air saturated at 0°C exerts a vapor pressure of about 5 mm Hg. This condition might prevail on a winter's day with freezing drizzle. When this air is inhaled into the lungs, it passes over mucous membranes coated with liquid water at 37°C, corresponding to a vapor pressure of about 45 mm Hg. With this gradient of 40 mm Hg, evaporation occurs, quickly saturating the air, now warmed to 37°C. Thus, air at 100% RH enters at 0°, and air at 100% RH leaves at 37°, yet evaporation has occurred, and the moisture content differs greatly from inhaled to exhaled air. On exhalation, the air cools and the new moisture burden condenses out, creating a visible cloud.

Given the relative humidity and the temperature, the water vapor pressure may be determined. In fact, any two properties (temperature, total heat content, dew point, relative humidity, etc.) completely define the thermodynamic state of the air-water vapor mixture.⁶ The psychrometric chart is a convenient graphical representation of the mathematical interrelationships of these parameters (Figure 31-3 inset). The saturation line (100% relative humidity) marks the upper limit of moisture holding capacity of the air (Figure 31-3). Note that at saturation, the dry-bulb, wet-



Powell, C. H., Hosey, A. D. (eds): The Industrial Environment — Its Evaluation and Control, 2nd Edition. Public Health Services Publication No. 614, 1965.

Figure 31-3. Psychrometric Chart and Vapor Pressure Nomograph.

bulb, and dew-point temperatures are equal.

Sling psychrometer. This instrument consists of two thermometers clamped in a frame which in turn is fastened to a swivel handle. A cotton wick dipped in distilled water covers one thermometer; the other is bare. The terms "wet bulb" and "dry bulb" temperatures originated from this type of instrument. When it is rapidly whirled, water evaporates from the wick, cooling the bulb. The rate of evaporation from the wick is a function of the vapor pressure gradient, determining in turn the depression of the wet bulb thermometer reading below the dry bulb. The vapor pressure can be read directly from the psychrometric chart, or tables.⁹

A few simple precautions should be observed in the use of the sling psychrometer. Usually one minute of swinging adequately cools the wet bulb to its lowest reading. It is advisable to check the reading, and then swing again for a few seconds. (Repeat if the temperature continues to fall.) There should be no obstructions in the path of the swinging thermometers. The use of distilled water prolongs the usefulness of the wick. When dirty, it may be restored by washing with detergent and thorough rinsing. It should also be noted that thermal radiation can cause rather large errors in both dry- and wet-bulb temperatures taken with a sling psychrometer.

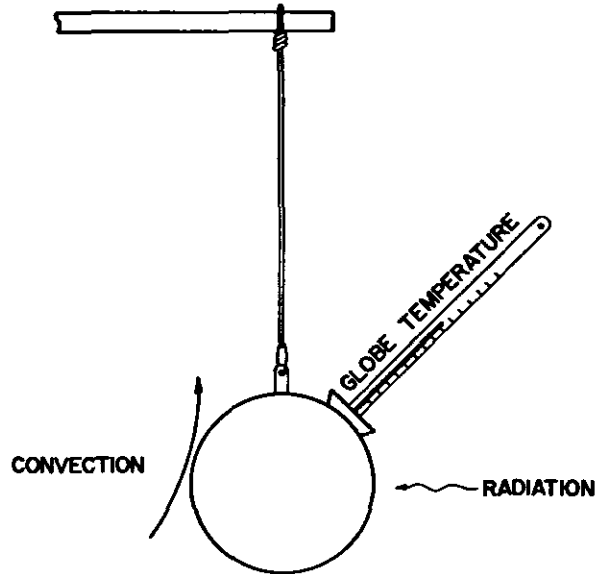
Motor-driven psychrometer. Several types of aspirated psychrometers are available, battery-powered for field use, as well as conventional laboratory instruments. These accomplish the same end as the sling psychrometer; air motion across the thermometer bulbs is created mechanically rather than whirling by hand.

Hair hygrometer. Human hair absorbs and desorbs moisture with changes in atmospheric humidity. The length of hair under tension changes in turn with its moisture content. This motion is transmitted through a system of levers to a pointer indicating the relative humidity. Fitted with a pen, the pointer records the relative humidity on a revolving drum.⁶

Radiometry. Measurement of the mean radiant temperature of the solid surroundings (T_r) for evaluation of thermal stress is most often effected by means of a blackened sphere, or Vernon globe.¹⁰ More precise measurements of the radiant field may be made by radiometers of various designs, or by surface pyrometry. For these more precise techniques, refer to other sources, such as Fanger,¹¹ Gage,¹² or Longley *et al.*¹³

Vernon Globe (Black Globe). The Vernon Globe, or Black Globe, consists of a copper sphere about 15 cm. in diameter, the exterior of which is painted flat black. A hole for a thermometer (thermojunction or thermistor may be used) and a tab for a wire by which to hang it, complete the instrument (Figure 31-4). Copper toilet floats have been used with success, but spun spheres are usually preferred.

To estimate the mean radiant temperature at some given point in an enclosure, the globe is placed at the desired location. The temperature of the globe is measured by the thermometer after



Vernon, H. M.: The measure of radiant heat in relation to human comfort. *J. Physiol.* 70, Proc. 15, 1930.

Figure 31-4. Vernon Globe (Black Globe).

thermal equilibrium has been established, usually about 15 to 20 minutes. At equilibrium, heat loss (or gain) of the globe by convection is balanced by heat gain (or loss) by radiation.

The mean radiant temperature at the globe location may be calculated by the equation:

$$T_w^* = 100 \sqrt{\left(\frac{T_r}{100}\right)^4 + 2.48 V (T_r - T_a)}$$

T_r^* = Vernon globe temp, °Kelvin

V & T_a = as before.

where T_w^* = mean radiant temp, °Kelvin ($273 + ^\circ\text{C}$)

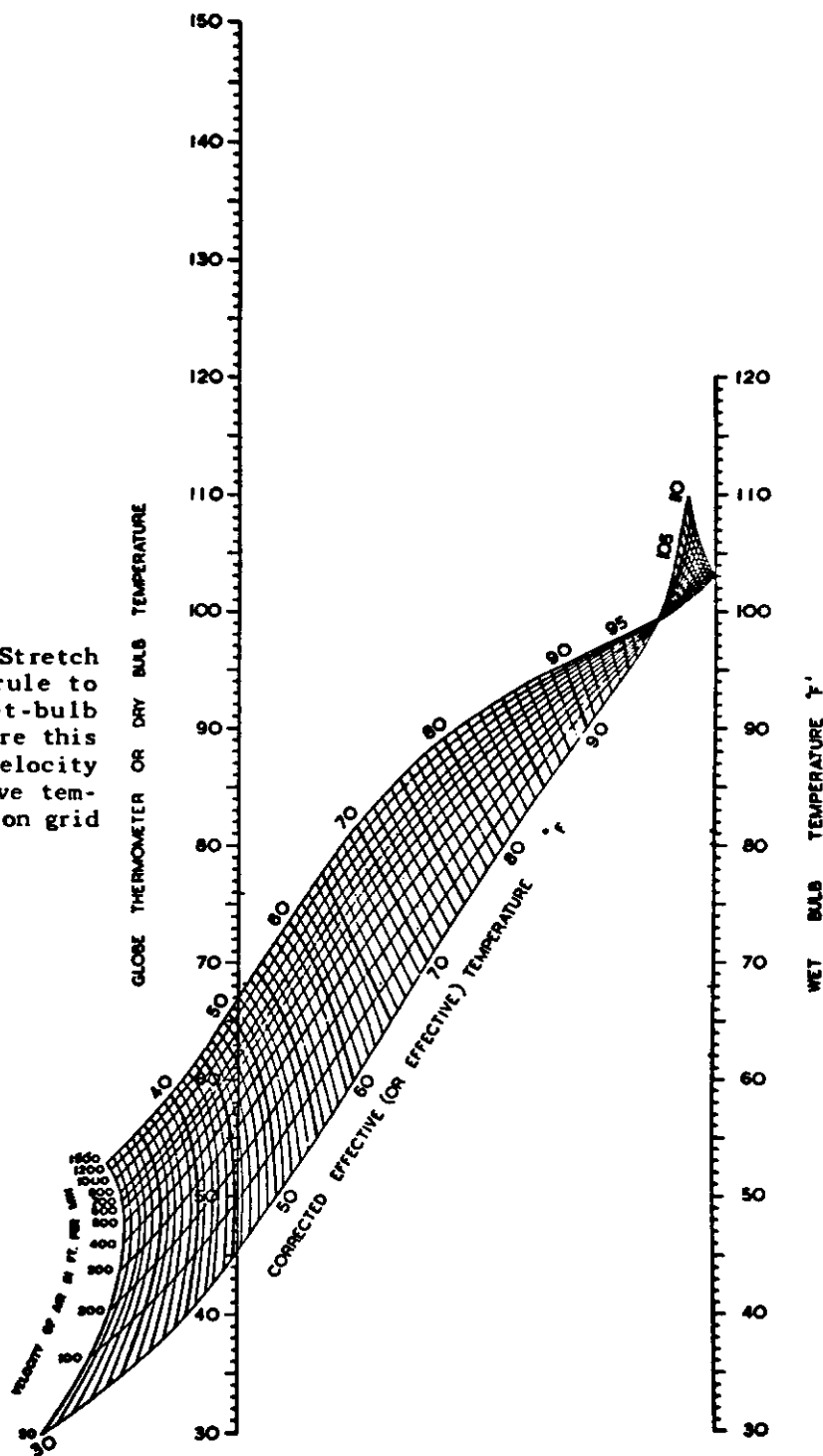
T_w^* as calculated from this expression is an effective wall temperature (absolute). It represents the temperature of a "black" enclosure of uniform wall temperature which would provide the same heat loss or gain as the environment measured.

INDICES OF THERMAL STRESS

The search for a scheme to integrate the several environmental, physiological and behavioral variables affecting heat transfer from man to the environment into a simple index has occupied scores of engineers and physiologists for decades. Recent reviews provide breadth and depth for analyses of the many rating scales which have been proposed.^{14,15} The purpose here is to outline those which have emerged as the most commonly encountered in evaluation and control of industrial heat stress.

Effective Temperature. The search for design criteria for thermal comfort in occupied spaces led to the development of the "Effective Temperature" scale (E.T.). This concept was introduced in 1923 by Houghten and Yaglou;¹⁶ their work was

Instructions for use: Stretch a thread or place a rule to join dry-bulb and wet-bulb temperatures. Note where this cuts appropriate air velocity line and read effective temperature at this point on grid lines.



Powell, C. H., Hosey, A. D. (eds): The Industrial Environment — Its Evaluation and Control, 2nd Edition. Public Health Services Publication No. 614, 1965.

Figure 31-5. Chart Showing Normal Scale of Corrected Effective (or Effective) Temperature. Instructions for use: Stretch a thread or place a rule to join dry-bulb and wet-bulb temperatures. Note where this cuts appropriate air velocity line and read effective temperature at this point on grid lines.

sponsored by the American Society of Heating and Ventilating Engineers. Briefly, the objective was to define the various combinations of dry-bulb temperature, air motion, and humidity which would provide the same thermal sensation to the occupants. Subjects were exposed first to one combination and then another of the parameters (wall temperature was the same as air temperature $T_w = T_a$). On the basis of a large number of trials, nomograms were developed which characterized equivalent environments, expressed in terms of the temperature of a still, saturated environment.

Through the years, the original concept has been refined and modified by many investigators; among other things, methods of correcting for radiant heat exchange have been included. The early nomograms were psychrometric charts with lines of E.T. superimposed (see earlier editions of ASHVE Guide, e.g., 34th ed., 1956, for these forms of the E.T.). A separate nomogram was required for each air velocity. The present form of the scale incorporates the modifications into a single chart. Figure 31-5 shows the "normal" E.T. scale which relates to people wearing light weight summer clothing, similar to workers' uniforms. There is another E.T. scale for seminude men called the "basic" scale.

Example: Given dry bulb = 76°F, wet bulb = 55°F, air speed = 100 ft/min (English units used in the Chart), find E.T. = 67. That is, the given environment would provide the same thermal sensation as one with dry- and wet-bulb temperatures of 67°F, and no air motion. (In reality, "still" air approximated 25 ft/min, or 8 m/min.)

In spite of its widespread use, the E.T. has serious limitations, particularly as an index of heat stress:

- It was developed on transient thermal sensations. This tended to neglect the importance of sorption or desorption of moisture in the subject's clothing.
- The scale was developed using clothed subjects in dress of that day.
- The subjects were sedentary. Later modifications were made to include the effect of metabolic rate.
- The scale was designed primarily for environments reasonably near the comfort zone. Extrapolation to thermally stressful environments is tenuous.

Heat Stress Index (HSI). The Heat Stress Index was developed by Belding and Hatch at the University of Pittsburgh during the mid-1950's.¹⁷ Their index combines the environmental heat (radiation and convection, R and C) and metabolic heat (M) into an expression of stress in terms of requirement for evaporation of sweat (E_{req}).

Stated algebraically:

$$M \pm R \pm C = E_{req}$$

The resulting physiologic strain is determined by the ratio of the stress (E_{req}) to the maximum evaporative capacity of the environment, E_{max} (see above). Thus, the HSI is calculated:

$$HSI = \frac{E_{req}}{E_{max}} \times 100$$

E_{req} and E_{max} may be computed by means of the equations given on pg. 274. A more convenient means is offered by a nomogram developed by McKarns and Brief¹⁸ (Figure 31-6). This nomogram is based on further revisions of the Fort Knox coefficients, which provide a 30 percent reduction in R, C, and E_{max} for the average man wearing light work clothing. The following equations were used in the nomogram development:

$$R = 17.5 (T_w - 95)$$

$$C = 0.756 V^{0.6} (T_a - 95)$$

$$E_{max} = 2.8 V^{0.6} (42 - PW_a)$$

where R = Radiant heat exchange, Btu/hr

C = Convective heat exchange, Btu/hr

E_{max} = Max evaporative heat loss, Btu/hr

T_w = Mean radiant temp. °F

T_a = Air temp. °F

V = Air velocity, ft/min.

PW_a = Vapor press, mmHg.

Caution: The original nomogram of Belding and Hatch is being widely reproduced in texts and handbooks even today, in spite of the availability for more than a decade of these revised coefficients.

The sample solution outlined below and shown in Figure 31-6 illustrates the use of the nomogram.

Example: Given $T_g = 130^\circ\text{F}$, $T_a = 100^\circ\text{F}$, $T_{wb} = 80^\circ\text{F}$, $V = 50$ ft/min, and $M = 2000$ Btu/hr.

Step 1. Determine convection. Connect 50 fpm (column I) with $T_a = 100^\circ\text{F}$ (column II). Read C = 40 Btu/hr (column III).

Step 2. Determine E_{max} . From the psychrometric chart (Figure 31-3), read dew point of 73°F from dry and wet bulb temperatures. Connect column I and column IV from $V = 50$ to dew point = 73 (line 2). Read $E_{max} = 620$ (column V).

Step 3. Determine constant, K. Connect $V = 50$, column I, with $T_g - T_a$ (130-100) = 30, Column VI. Read K = 22 (column VII).

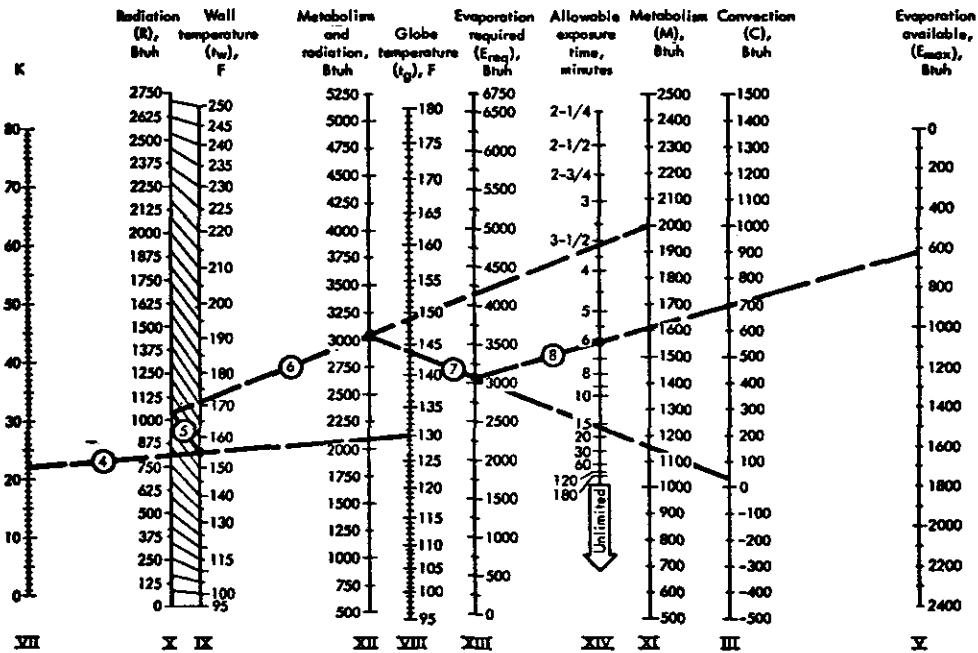
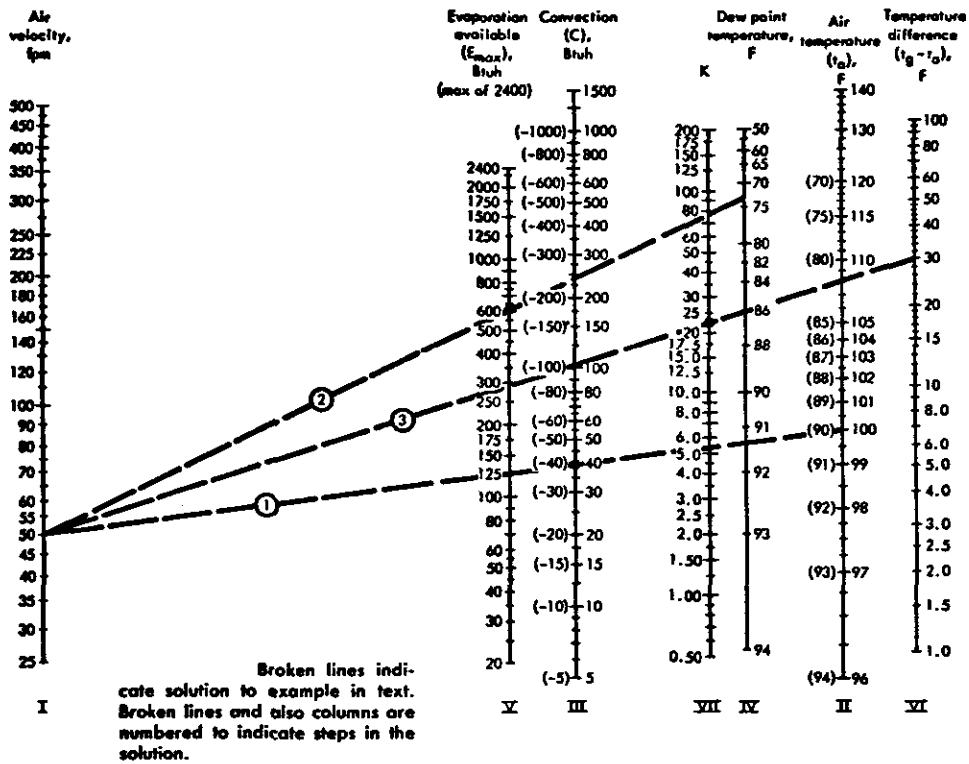
Step 4. Determine T_w . Enter K = 22 in lower diagram, column VII. Connect this to $T_g = 130$, column VIII. Read $T_w = 155$, column IX.

Step 5. Follow the slanting line to column X, read R = 1050 Btu/hr.

Step 6. Connect R = 1050 with M = 2000 (column XI); read R + M = 3050 on column XII.

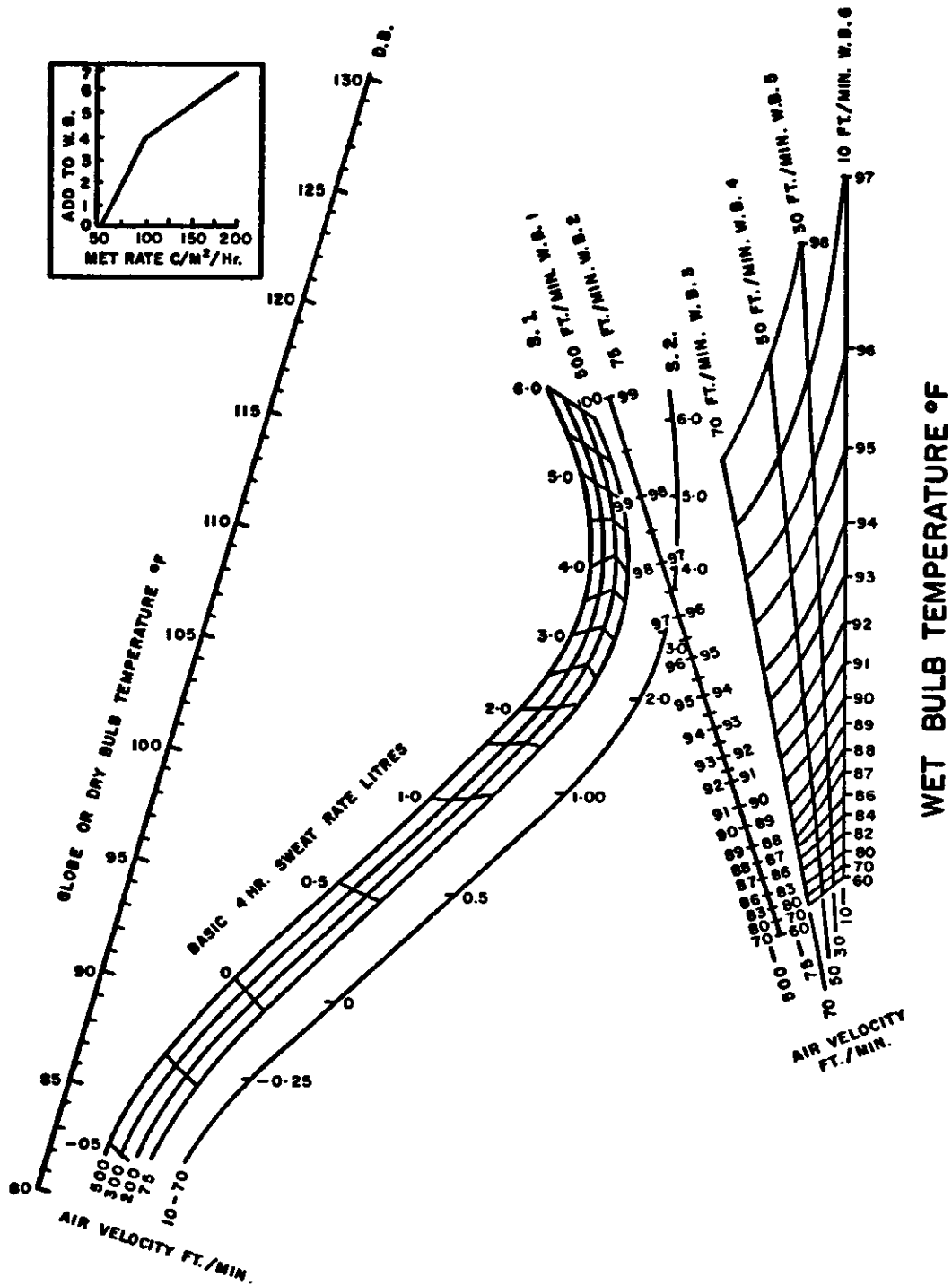
Step 7. Enter C = 30 in column III of lower figure; connect with R + M = 3050, in column XII, read $E_{req} = 3090$ Btu/hr on column XIII.

Step 8. Enter $E_{max} = 620$ (step 2) on column V of lower diagram, and connect with $E_{req} = 3090$ Btu/hr, column XIII. Read allowable exposure time = 6 min.



McKarns, J. S., Brief, R. S.: Nomographs give refined estimates of heat stress index. Heat Pip. Air Condit. 38:113, 1966.

Figure 31-6. Nomograph Developed by McKarns & Brief Incorporating the Revised Fort Knox Coefficients.



McArdle, B., Dunham, W., Holling, H. E., et al: Med. Res. Coun. R.N.P. Rep. 47:391, 1947.
 Figure 31-7. Nomogram for the Prediction of the 4-Hour Sweat Loss of Fit, Acclimatized Young Men, Sitting in Shorts. The small inset chart gives the degrees F to be added to the wet bulb for metabolic rates between 50-100K Cals/m²/Hr.

Computation of the HSI value yields:

$$\text{HSI} = \frac{3090}{620} \times 100 = 500.$$

In their original paper, Belding and Hatch presented physiologic interpretations for various levels of HSI (Table 31-1). As can be seen, 500 greatly exceeds the maximum strain tolerable. The addition by McKarns and Brief of tolerance times for HSI's in excess of 100 is a valuable contribution.

Predicted Four Hour Sweat Rate (P₄SR). McArdle *et al.*¹⁹ developed a heat stress rating scheme based upon the sweat loss (in liters) that different environmental conditions would evoke: hence, the name "Predicted Four Hour Sweat Rate." Figure 31-7 is the latest version of the nomogram, incorporating the effects of clothing and level of activity.

TABLE 31-1.

Evaluation of Values in Belding and Hatch HSI.

Index of Heat Stress (HSI)	Physiological and Hygienic Implications of 8-hr. Exposures to Various Heat Stresses
-20	Mild cold strain. This condition frequently exists in areas where men recover from exposure to heat.
-10	
0	No thermal strain.
+10	Mild to moderate heat strain. Where a job involves higher intellectual functions, dexterity, or alertness, subtle to substantial decrements in performance may be expected. In performance of heavy physical work, little decrement expected unless ability of individuals to perform such work under no thermal stress is marginal.
20	
30	
40	Severe heat strain, involving a threat to health unless men are physically fit. Break-in period required for men not previously acclimatized. Some decrement in performance of physical work is to be expected. Medical selection of personnel desirable because these conditions are unsuitable for those with cardiovascular or respiratory impairment or with chronic dermatitis. These working conditions are also unsuitable for activities requiring sustained mental effort.
50	
60	
70	Very severe heat strain. Only a small percentage of the population may be expected to qualify for this work. Personnel should be selected (a) by medical examination, and (b) by trial on the job (after acclimatization). Special measures are needed to assure adequate water and salt intake. Amelioration of working conditions by any feasible means is highly desirable, and may be expected to decrease the health hazard while increasing effi-
80	
90	

ciency on the job. Slight "indisposition" which in most jobs would be insufficient to affect performance may render workers unfit for this exposure.

100 The maximum strain tolerated daily by fit, acclimatized young men.

Adapted from Belding and Hatch, "Index for Evaluating Heat Stress in Terms of Resulting Physiologic Strains," Heating, Piping and Air Conditioning, 1955.

Example: Given Globe temperature = 105°, wet bulb = 80°, air speed = 70 fpm, and metabolic rate (*M*) = 100 kcal/m² = hr. From the small chart, find 4°F to be added to wet bulb to compensate for *M* above resting. Enter right side of chart at *T_{wb}* = 84 (80 + 4). Follow 84 *T_{wb}* line to intersection with 70 ft/min line. Connect this point with thread or straightedge to *T_g* = 105. Read *P₄SR* where this transverse line cuts air speed = 70; read *P₄SR* = 1.2. This would result in relatively mild physiologic strain, as the upper limit of tolerance for fit, young men is about *P₄SR* = 4.5.

Note that the chart is for men dressed in shorts. The index becomes less accurate in predicting strain as the upper level of tolerance is reached. Extrapolation to populations other than the standard "fit, young, acclimatized male" must be done with caution.

Wet Bulb Globe Temperature Index (WBGT). This index was developed originally to provide a convenient method to assess, quickly and with minimum of operator skills, conditions which posed threats of thermal overstrain among military personnel.²⁰ Because of its simplicity, it has been adopted as the principal index for a tentative Threshold Limit Value (TLV) for heat stress (Figure 31-8) by the American Conference of Governmental Industrial Hygienists (ACGIH)²¹ Fundamentally, the WBGT index is an algebraic approximation of the E.T. concept. As such, it has all the built-in limitations of the E.T., but has the advantage that wind velocity does not have to be measured for calculating its value.

WBGT is computed by appropriate weighting of Vernon Globe (*T_g*), dry bulb (*T_a*), and natural wet bulb (*T_{nwb}*) temperatures. The natural wet bulb is depressed below air temperature by evaporation resulting only from the natural motion of the ambient air, in contrast to the thermodynamic wet bulb, which is cooled by an artificially produced fast air stream, thus eliminating the air movement as a variable.

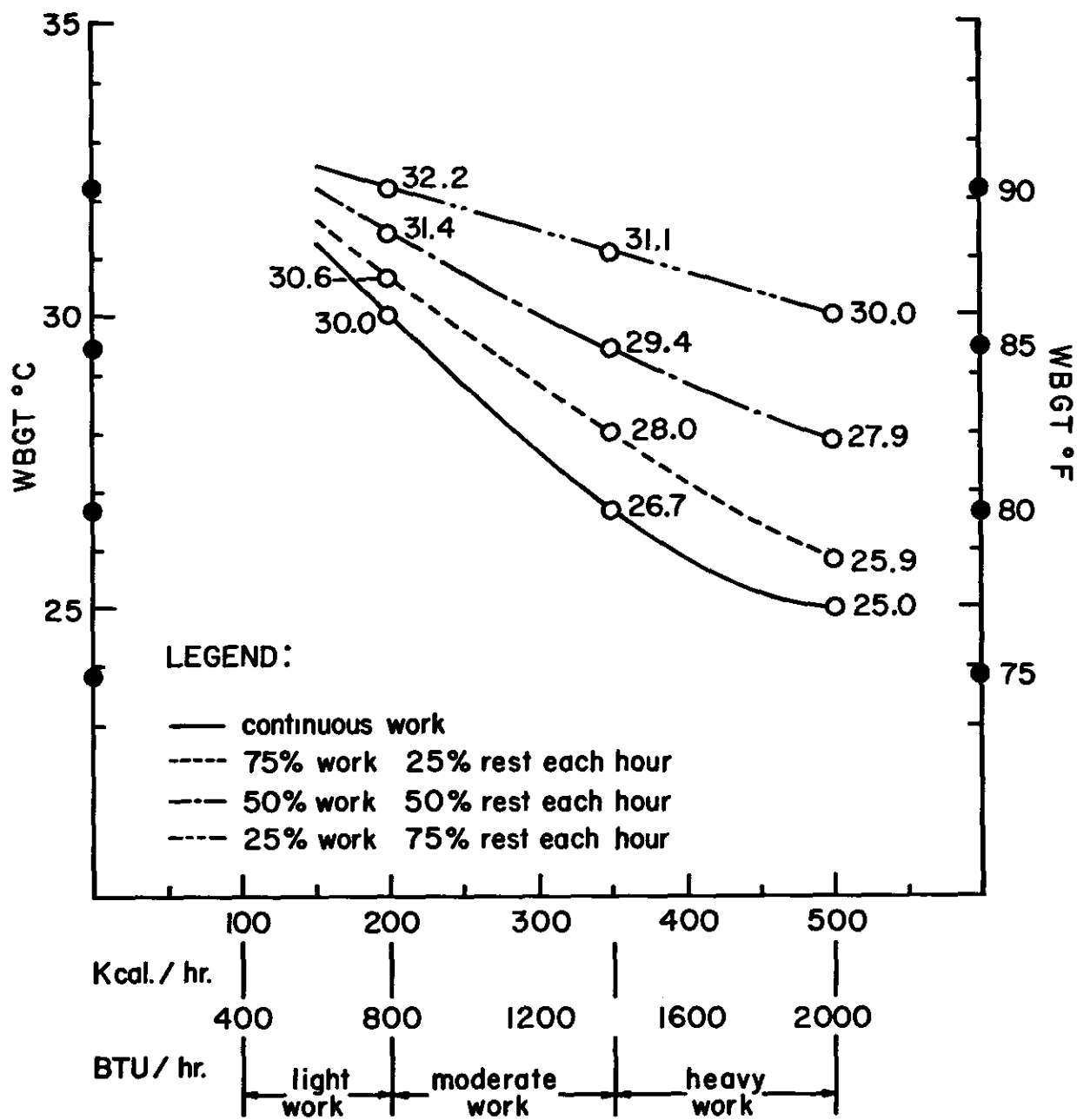
For outdoor use (in sunshine) the WBGT is computed:

$$\text{WBGT} = 0.7 (T_{nwb}) + 0.2 (T_g) + 0.1 (T_a).$$

For indoor use, the weighting becomes:

$$\text{WBGT} = 0.7 (T_{nwb}) + 0.3 (T_g).$$

Originally the interpretation of the levels of WBGT was for military activities of recruits in the following manner: above 30°C (86°F) WBGT, activities to be curtailed; above 31°C (88°F) WBGT, suspended entirely. For those in the latter stages of training, and hence acclimatized to



American Conference of Governmental Industrial Hygienists: Cincinnati, Ohio, 1971.

Figure 31-8. Permissible Heat Exposure Threshold Limit Value.

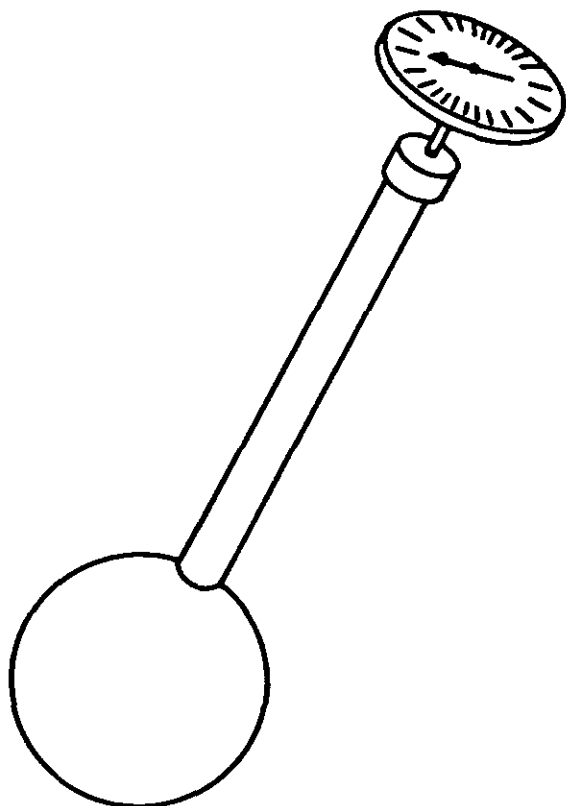
the heat, the levels are 31.0° and 32.2°C (88° and 90°F), respectively.²²

INTEGRATING INSTRUMENTS

Many attempts through the years have been made to devise instrumentation for assessing simultaneously the four environmental factors of air temperature, air speed, humidity, and radiant temperature.

One unit of this type, the modified Envirec was developed under a NIOSH contract. This instrument senses, indicates, and records on either magnetic tape or strip chart, the dry-bulb, thermodynamic wet-bulb and globe temperatures, and air velocity.

Another useful instrument, the WBGT integrator was developed under another NIOSH contract. This instrument senses and indicates dry-bulb, natural wet-bulb, and globe temperatures. It will also integrate these measurements and give a direct readout of the WBGT Index for either sunlit or inside conditions in accordance with the previously stated equations. Instruments for integrating two or more parameters into a single reading include the Vernon globe discussed above; the globe temperature is used directly in the Corrected Effective Temperature of Bedford.²³ Also, the globe temperature, in conjunction with natural wet



Botsford, J. H.: A wet globe thermometer for environmental heat measurement. *Amer. Ind. Hyg. Assoc. J.* 32:1-10, 1971.

Figure 31-9. Botsford — A Wet-Globe Instrument "Botsball".

bulb temperature, forms the basis of the WBGT Index discussed above.

More recently, Botsford²⁴ has developed a wet-globe instrument based on a small (6-cm diameter) copper sphere fitted with a black cotton wick and water reservoir (Figure 31-9). While the Vernon globe integrates the effects of air temperature, mean radiant temperature and air motion, wetting of the sphere introduces the fourth parameter. The device is maintained completely wet; man is not 100% wet unless E_{max} is low (see Chapter 38). The objective desired is that the stress readings obtained with the "Botsball" will correlate sufficiently well with physiologic strain that a given "Botsball" reading will have the same physiologic meaning in all combinations of environmental parameters. The instrument has not been available long enough to determine whether this objective will be achieved, although, replacing the WBGT with the "Botsball" would be desirable because of its simplicity.

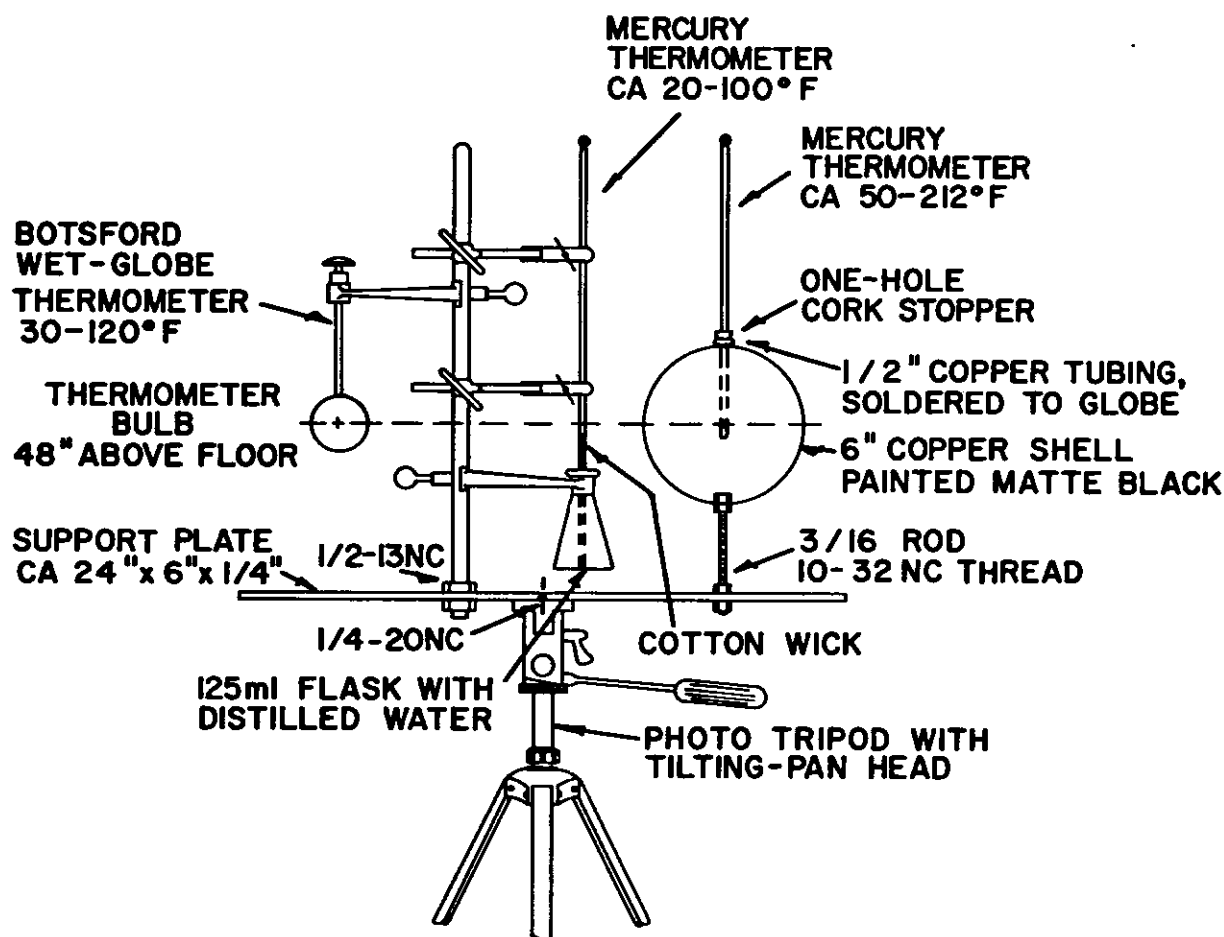
The "Botsball" has a more advanced variant: the Botsball Cooling Capacity Meter. By addition of a heat source in the wet ball a constant 35°C surface temperature is maintained, to simulate human skin temperature. The associated electronics translate the current required to maintain this temperature into a meter readout, either in terms of Cooling Capacity Index, with a range from 0 to 100, or in terms of cooling power expressed in watts or Btu/hr. Battery-powered or 110 AC models are available (see Appendix for manufacturer). This sophistication exacts a price: an order of magnitude greater in cost and loss of simplicity. The physiological meaning of the cooling power values obtained with this instrument will have to be established before its applicability can be evaluated.

GUIDE FOR ASSESSING HEAT STRESS AND STRAIN

For purposes of validating the applicability of the ACGIH TLV for heat stress as an index for establishing thermal standards NIOSH sponsored a symposium. The participants of this symposium were asked to gather data in industry by using a standard methodology based on the TLV requirements and described in *the Guide for Assessing Heat Stress and Strains* as prepared by Minard and Belding.²⁵ Several industries agreed to follow the procedures outlined to provide a substantial body of data for evaluating the tentative TLV.

An instrumentation package consisting of the following instruments was recommended:

- 2 Bendix Hygro Thermographs Model 594; range +10° to +110°F
- 1 Bendix Psychron; range +30° to +120°F
- 1 Botsford Wet-Globe Thermometer
- 1 Six-inch Globe Thermometer; range about 50° to 212°F
- 1 Natural Wet Bulb Thermometer; range about 20° to 100°F
- 1 Hot Wire Anemometer for measurement of air velocity.



Minard, D., Belding, H. S.: Guide for Assessing Heat Stress and Strains. Industrial Health Foundation, Inc., Engineering Ser. Bull. No. 8-71, 1971.

Figure 31-10. Suggested Instrument Arrangement for Environmental Measurements.

One Hygro Thermograph records weather conditions outside the plant; the other is used as a reference monitoring station at a representative area within the plant.

The Vernon globe and natural wet bulb are mounted together on a tripod for stationing at selected work sites (Figure 31-10). The Botsball is also shown in this arrangement, to encourage comparability studies.

The psychrometer is used to take spot measurements of dry and (thermodynamic) wet bulb temperatures so that HSI or P_sSR may be calculated as well as WBGT. Sample data sheets are also provided so that information submitted by the diverse industries participating will be in comparable form. The outcome of the pooled data will provide validation and/or modification of the tentative TLV so that an effective and fair standard for heat stress may be written.

WINDCHILL INDEX

In recent years, it has become fashionable for weather reporters on radio and television to in-

clude the Windchill factor. This index was devised by Siple²⁶ to assess the relative discomfort of cold in relation to the air temperature and wind speed. The basic concept recognizes that convection is the most important single avenue of heat loss under cold conditions. The Windchill effect can be read from Table 31-2 where it is expressed in equivalent air temperatures which achieve the same rate of cooling at different wind velocities.

Example: Given $T_a = 45^\circ\text{F}$ and wind of 20 mph, read equivalent temperature = -27°F (at 0 mph). Note that equivalent temperatures are given for exposed flesh. Windchill values around 30°F are "cool;" -10°F , "cold;" below -40°F , exposed flesh freezes quickly and "travel is dangerous."

SUMMARY

The philosophy and development of indices for rating severity of the thermal environment has been discussed. The methods of assessment of the several parameters involved in the indices and guidance for their application and interpretation have been provided.

TABLE 31-2.
Equivalent Temperatures on Exposed Flesh at Varying Wind Velocities†

Temperature, °F	Wind velocity, mph								
	0	1	2	3	5	10	15	20	25
23	47.5	53.5	57	60	65	67	68	69.5	
-11	20	34.5	39	44.5	52	55	57	59	
-27	0	11	18.5	28	38	42.5	45	47	
-38	-23.5	-9	0	11	25	30.5	34	36	
-40*	-40*	-40	-16.5	-5	11	18	23	25	
		-40*	-40	-19	-2	6	11	14	
			-40*	-35	-15	-6	0	3	
				-40	-29	-18	-12	-8	
				-40*	-40	-30	-23	-18	
					-40*	-40	-35	-30	
						-40*	-40*	-40*	

†Adapted from Consolazio, Johnson and Pecora, *Physiologic Measurements of Metabolic Functions in Man*, McGraw-Hill Book Company, New York, 1963.

*Less than value.

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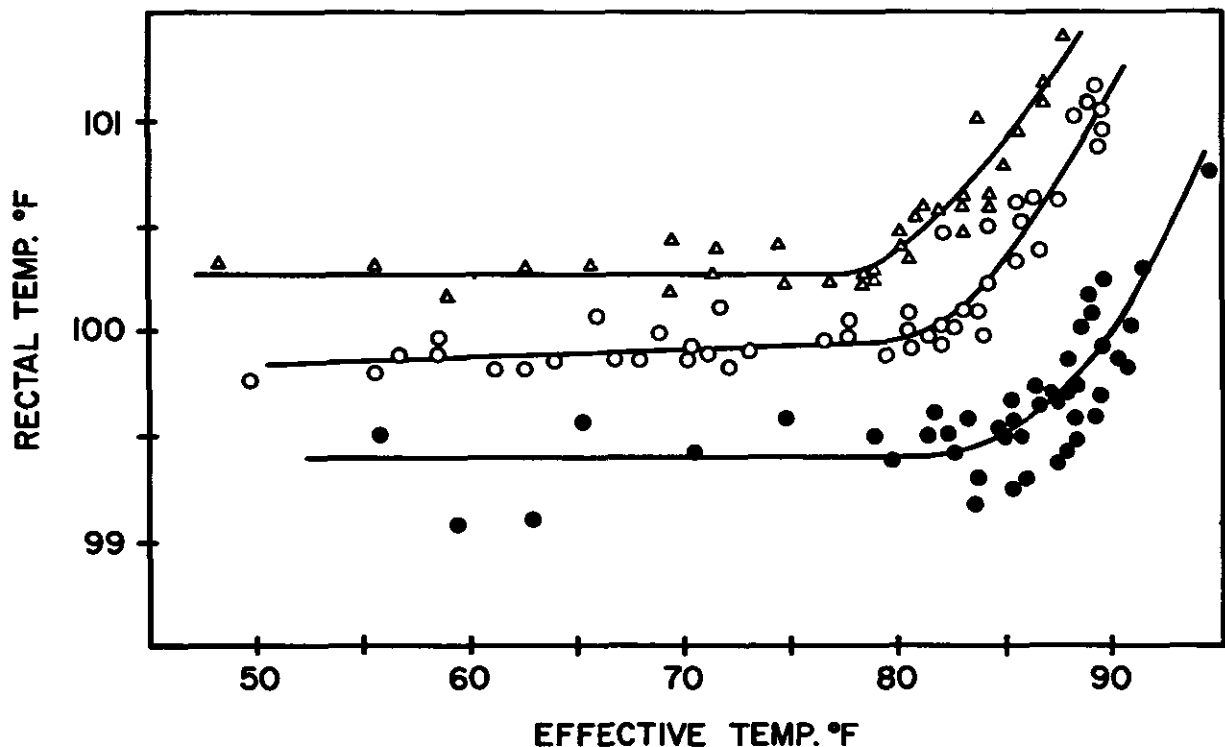
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NIOSH Note

The TLV diagram (Figure 31-8) combines three basic parameters: metabolic demands of the task (abscissa), an index of severity of the en-

vironment (WBGT), and percentage of time that the individual may be permitted to perform the task. For example, a task requiring light to moderate light work of 200 kcal/hr, could be performed continuously in environments up to about $WBGT=30^{\circ}C$, but only 25% of the time at $WBGT=34^{\circ}C$. A heavier task, say 400 kcal/hr, could be performed in environments of WBGT only up to about $26^{\circ}C$. This recognizes the role played by metabolic heat production in the heat balance equation (see Chapter 30); a simple method for assessing this parameter can be found in the TLV text.²¹ The basis for development of the TLV has been on the one hand the experiences of the services in protecting troops in training against heat illness,²² and on the other hand, consideration of combinations of environments which do not cause deep body temperatures (T_{core}) to rise above $38^{\circ}C$ ($100.4^{\circ}F$); these were determined by Lind and were identified as the "Prescriptive Zone."²³ As is evident in Figure 31-11, the equilibrium level of deep body temperature is dependent on the intensity of exercise, and independent of environment — up to a point. This effect was first noted by Nielson.²⁴ The family of curves suggest that at the inflection points the environmental stress has taxed the thermoregulatory system to its limit of thermal equilibrium at acceptable levels is no longer possible. The philosophy applied in the TLV is that the environmental



Lind, A. R.: Tolerable limits for prolonged and intermittent exposures to heat in Hardy, J. D. (ed): *Temperature: Its Measurement and Control in Science and Industry*. New York, Reinhold, 1963, vol. 3, p. 337.

Figure 31-11. Levels of Rectal Temperature during Continuous Work at 100 Kcal/m²/hr (●), 167 Kcal/m²/hr (○) or 233 Kcal/m²/hr (▲). At each rate of work there is a wide range of conditions in which the level of rectal temperature equilibrium is constant or nearly constant.

stress should not create a rise in deep body temperature over that in response to the work itself. This concept was also considered as most appropriate for the protection of the workers' health by an international scientific panel of the World Health Organization.

Others have argued that daily demands on the body for temperature increases above the Prescriptive Zone have no deleterious effects. Indeed, in some industrial uses the upper limits of thermal stress are based on elevations of body temperatures rather than on environmental parameters.²⁹

Application of the heat stress indices to hot industries has been attempted, not without some difficulties. Where the heat exposure is relatively uniform and lasts for prolonged periods e.g., military marching, driving an earthmoving vehicle, tending a weaving machine, the assessment of climatic and metabolic parameters is relatively simple. However, industries where duration of specific tasks may be measured in seconds, requiring maximal effort one minute, and minimal the next, and the environment may switch from intense radiant heat next to hot metal to ambient conditions of winter a few feet away, the assessment of the workers' actual heat exposure becomes quite cumbersome. Under such conditions, a detailed time and motion analysis of the work has to be performed and time weighted averages have to be calculated both for the climatic exposure and work load.

Research is currently underway at NIOSH to provide simpler and more accurate methods for assessing WBGT values, as well as the metabolic demand of the task.

APPENDIX

Sources of Environmental Instrumentation

Thermocouple wire: Driver-Harris, N.J., Leeds and Northrup, 4901 Stenton Ave., Philadelphia, Pa.; Revere Corp. of America, Wallingford, Conn.

Thermistor thermometer: Yellow Springs Instrument Company, Yellow Springs, Ohio (Manufacturer. Available only through scientific apparatus supply houses.)

Sling psychrometer: Taylor Instrument Company, 95 Ames St., Rochester, N.Y.

Motor-driven psychrometer: The Bendix Corp., Environmental Science Division, 1400 Taylor Ave., Baltimore, Md.; C. F. Casella Company, Ltd., Regent House, Fitzroy Square, London W.1, England.

Hair hygrometer, recording: The Bendix Corp., Environmental Science Division, 1400 Taylor Ave., Baltimore, Md.

Thermoanemometers: Alnor Instrument Co., 420 N. LaSalle St., Chicago, Ill.; Anemostat Corp. of America, P.O. Box 2128, Hartford, Conn.; Willson Products Div., The Electric Storage Battery Co., Reading, Pa.

Kata thermometer: C. F. Casella and Co., Ltd., Regent House, Fitzroy Square, London, W.1, England.

Vernon globe: (6-inch hemispherical spun copper blanks) Arthur Harris and Co., 212 N. Aberdeen St., Chicago, Ill.

Bottle thermometer: Howard Engineering Co., Box 3164, Bethlehem, Pa.

ERGONOMIC ASPECTS OF BIOMECHANICS

Erwin R. Tichauer, Sc.D.

INTRODUCTION

Biomechanics is the discipline dedicated to the study of the living body as a structure which can function properly only within the confines of both the laws of Newtonian Mechanics as well as the biological laws of life. Biomechanics is by no means a new pursuit. The mechanics of locomotion of many animals and birds were researched in depth as early as during the 17th century by Borelli.¹ In the course of the next century, Bernoulli² published a treatise on the "physiomechanics" of muscle movement. A contemporary of Bernoulli, Bernardino Ramazzini,³ the father of occupational medicine, discussed in his book "De Morbus Artificum" (about the diseases of workers) in remarkable detail the ill effects of poor posture and poorly designed tools on man. In the preface to the 1700 edition of his text he writes ". . . Manifold is the harvest of diseases reaped by certain workers from the crafts and trades that they pursue; all the profit they get is injury to their health. That stems mostly I think, from two causes. The first and most potent is the harmful character of the materials that they handle, noxious vapors and very fine particles, inimical to human beings, inducing specific diseases. As the second cause I assign certain violent and irregular motions and unnatural postures of the body, by reason of which the natural structure of the living machine is so impaired that serious diseases gradually develop therefrom . . ." For nearly two centuries industrial hygiene and related disciplines limited their scope of interest to the first set of occupational disease vectors as discussed by Ramazzini. They were easily identified and in many instances amenable to control by procedures already then available to industrial hygienists. Simultaneously, however, positive and aggressive steps were taken to develop energetically other fields of scientific endeavor basic to the maintenance of occupational safety and health. An unbroken chain of endeavors by physicists and physiologists since Lavoisier⁴ provided the basic data necessary to develop metabolic studies and ergonomometry into reliable procedures, applicable to the measurement of effort expended by man at work.

The publications of Benedict and Cathcart⁵ in 1913 and of Amar⁶ in 1917 are among the first acquainting practitioners in industry with the application of ergometry to work measurement. Towards the end of World War I, the general interest in work physiology widened and deepened in the United States, Britain, France and Germany. Dire manpower needs forced the women of

these countries to forego their rather sheltered victorian style of life and to accept employment in ammunition factories and other occupations that up to then had been considered distinctly unfeminine. They performed jobs strange to them in an environment they had never known before; emotional and physiological considerations caused problems in efficiency, hygiene and safety, which in turn stimulated research, especially as related to the effects of heat⁷ as well as light on both output and physical comfort of workers.

By the end of the hostilities, both work physiology as well as industrial psychology had become firmly established albeit quite separate disciplines.

The events of World War II and their social and economic after-effects gave impetus to the consolidation of a number of narrow specialties into a broad, unified and generally accepted separate discipline dedicated to the academic as well as the applied study of man at work: Ergonomics. Also, the Ergonomics Research Society was founded in England. Its membership developed rapidly on a world-wide basis. However, in the immediate post-war years the practice of ergonomics was of prime importance to European countries where, as a matter of economic survival, consumer goods industries had to be rebuilt fast. Their working population was still untrained in the use of modern technology that had meanwhile developed in the United States. Workers were also generally undernourished and worn out from years of struggle and many of them were physically handicapped. Thus, ergonomics was first applied to overcome the serious and general problems involved in fitting jobs to the physical and behavioral operating characteristics of individual workers. This involved a broader study of the relationship between man and his environment, the design of equipment and particularly the application of anatomical, physiological and psychological knowledge to the solution of problems arising from equipment and environment. This new systems approach to problems common to occupational safety and health as well as industrial efficiency required new and deeper understanding of the mechanics of the living body at work.^{8, 9}

Occupational Biomechanics was added as a new tributary to the pool of general knowledge essential to the understanding of the complex mechanisms of interaction between the worker and the industrial environment.

The industrial environment as opposed to work environment (including, e.g., farming) is unique in several aspects. Firstly, it is entirely

man-conceived, man-made and purposefully designed with one objective in mind: to maximize economic efficiency of human performance. Physiological performance and comfort of the working population, at least until recently, were only considered inasmuch as they were conducive to higher levels of productivity. Thus, by implication, those who are responsible for the maintenance of occupational safety and health have to overcome many biomechanical, physiological and behavioral hazard vectors likely to be overlooked in the design of the industrial environment.

It is the purpose of this chapter to describe occupational biomechanics as a subdiscipline of ergonomics which can be applied by professionals

active in the health as well as technological sciences for the purpose of achieving maximal physiological and emotional well-being of the working population, while at the same time enhancing the economic efficiency of industrial undertakings as a whole. In our modern industrial environment efficiency is a by-product of comfort. The enterprise that manufactures no sore backs, shoulders, wrists or behinds is at a competitive advantage over one with suffering workers.¹⁰

The information provided in this chapter will be adequate for a general biomechanical evaluation of workplaces, machinery, handtools, chairs, lifting tasks and industrial work situations in general.



The Ergonomics Research Society: The Origin of Ergonomics. Loughborough, England, Echo Press, 1964.

Figure 32-1. Illustration symbolizes the concept of modern ergonomics (biomechanics). Worker is surrounded by external physiological and mechanical environments which have to be matched to his internal physiological and biomechanical environments.

THE ANATOMY OF FUNCTION

Anatomy is concerned with the description and classification of biological structures. Systematic anatomy describes the physical arrangement of the various physiological systems (e.g., anatomy of the cardiovascular system); topographic anatomy describes the arrangement of the various organs, muscular, bony and neural features with respect to each other (e.g., the anatomy of the abdominal cavity); and functional anatomy focuses upon the structural basis of biological function (e.g., description of the heart valves and ancillary operating structures, description of the anatomy of joints). As distinct and different from the aforementioned, the anatomy of function is concerned with the analysis of the operating characteristics of anatomical structures and systems when these interact with physical features of the environment such as is the case in the performance of an industrial task. Modern occupational biomechanics considers the worker as the monitoring link of a man-equipment-task system. In such a situation, man is enveloped by the "external mechanical environment" (Figure 32-1) which is an array of machinery, levers, pushbuttons, and such other equipment as may pertain to the immediate working environment of the individual. Located inside of the human skin is the "internal biomechanical environment" which may be presumed, at the risk of oversimplification, to be identical with the neuro-musculo-skeletal system. If the "motions and reactions inventory" demanded by the external environment is not compatible with the one available from the internal biomechanical environment, then discomfort, trauma and inefficiency may ensue.

The anatomy of function is the structural basis of human performance and thus provides much of the rationale by which the output measurements derived from work physiology and engineering psychology can be explained.

Lever Systems Within the Human Body

The musculo-skeletal system is an array of bony levers connected by joints and actuated by muscles. With few exceptions, lever classifications and taxonomy in both anatomy and applied mechanics are identical. Each class of anatomical lever is specifically suited to perform certain types of movement and postural adjustments efficiently and without undue risk of accidents while it may be less suited to perform other equally specific maneuvers. Therefore a good working knowledge of location, function and limitation of anatomical levers involved in specific occupational maneuvers is a prerequisite essential for the ergonomic analysis and evaluation of most man-task systems.

First Class Levers have force and load located on either side of the fulcrum acting in the same direction but opposed to any force supporting the fulcrum (Figure 32-2). This is exemplified by the arrangement of those musculo-skeletal structures as are involved in head movement in looking up and down. Then the atlanto-occipital joint acts as the fulcrum of a first class lever because the muscles of the neck provide the force necessary to extend the head. This is counteracted by gravity

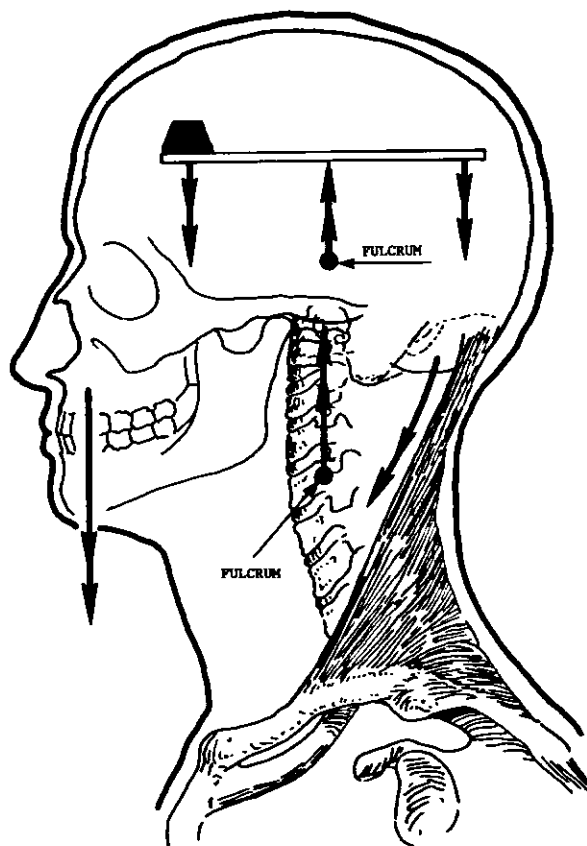
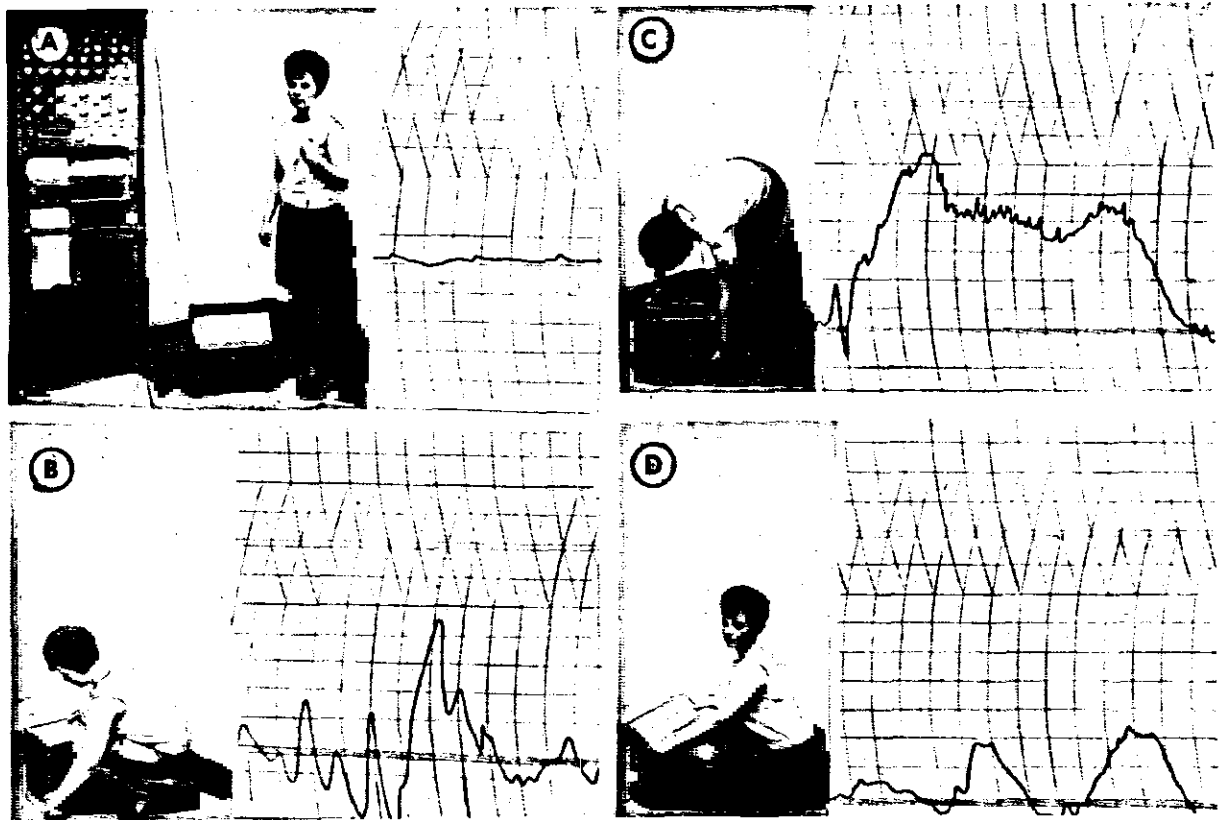


Figure 32-2. The action of the muscles of the neck against the weight of the head is an example of a first class lever formed by anatomical structures. The atlanto-occipital joint acts as a fulcrum.

acting on the center of mass of the head which is located on the other side of the joint, and hence constitutes an opposing flexing weight. First class levers are often found where fine positional adjustments are required. In standing or the static holding of bulky loads, head movement in the midsagittal plane produces the fine adjustment of the position in the center of mass of the whole body necessary to maintain upright posture (Figure 32-3). Individuals suffering from impaired head movement (e.g., arthritis of the neck), should not be exposed to tasks where inability to maintain postural equilibrium constitutes a substantial hazard. Likewise, workplaces where free and unrestricted head movement is difficult should be provided with either chairs or other means of postural stabilization.

Second Class Levers have the fulcrum located at one end, the force acts upon the other end but in the same direction as the supporting force of the fulcrum. The weight acts upon any point between fulcrum and force in a direction opposed to both of them. Second Class Levers are optimally associated with ballistic movements requiring some force and resulting in modifications of stance, posture or limb configurations. The muscles in-



Tichauer, E. R.: Ergonomics: The state of the art. Amer. Ind. Hyg. Assoc. J. 28:105-16, 1967.

Figure 32-3. Myograms of the Sacrospinalis Muscle during a Lifting Task. It can be seen how activity in this muscle varies according to posture. (A) upright posture showing electro-silence in muscle. (B) failure to hold head upright in straight-back, bent-knee lift results in strong postural reactions recorded by the myogram. (C) straight-knee, bent-back lift, showing high strain in sacro-spinalis muscle. (D) straight-back, bent-knee, head-up lift, showing less stress in sacro-spinalis muscle.⁸

served into the heel by way of the achilles tendon (i.e., force), the weight of the body transmitted through the ankle joint, and the base of the big toe (i.e., fulcrum) are a good example of a second class lever system used in locomotion (Figure 32-4).

Third Class Levers have the fulcrum at one end, the weight acts upon the other end, in the same direction as the supporting force of the fulcrum. The "force" itself acts upon any point between weight and fulcrum but in a direction opposed to both of them. Tasks which require the application of strong but voluntarily graded force are often best performed by this type of anatomical lever system. Holding a load with forearm and hand when the brachialis muscle acts upon the ulna with the elbow joint constituting the pivot is a typical example (Figure 32-5).

Torsional Levers are a specialized case of the Third Class Lever (Figure 32-6). Here the axis of rotation of a limb or long bone constitutes the fulcrum. The force-generating muscle of the system is inserted into a bony prominence and produces rotation of the limb whenever the muscle contracts. The "weight" is constituted by the in-

ertia of the limb plus any external torque opposing rotation. An example is the supination of the flexed forearm. Here the fulcrum is the longitudinal axis of the radius, the force is exerted by the biceps muscle inserted into the bicipital tuberosity of the radius while the opposing load may be the inertia of forearm and hand plus the resistance of, for example, a screw driven home. Tasks to be performed with strength and precision and at variable rates of speed are best assigned to torsional lever systems.

An inexpensive anatomical atlas for artists constitutes a useful aid in task analysis and design whenever an evaluation of the effectiveness of the anatomical lever systems employed is under consideration.

Range and Strength of Limb Movement

The absolute range of limb movement is limited by the mechanical configuration of the joints. For example, due to interference of the olecranon, it is impossible to extend the angle between forearm and upper arm beyond 180°. Likewise, the location of the point of insertion of the brachialis tendon into the ulna makes it impossible to flex the joint to an angle of less than 15°. This re-

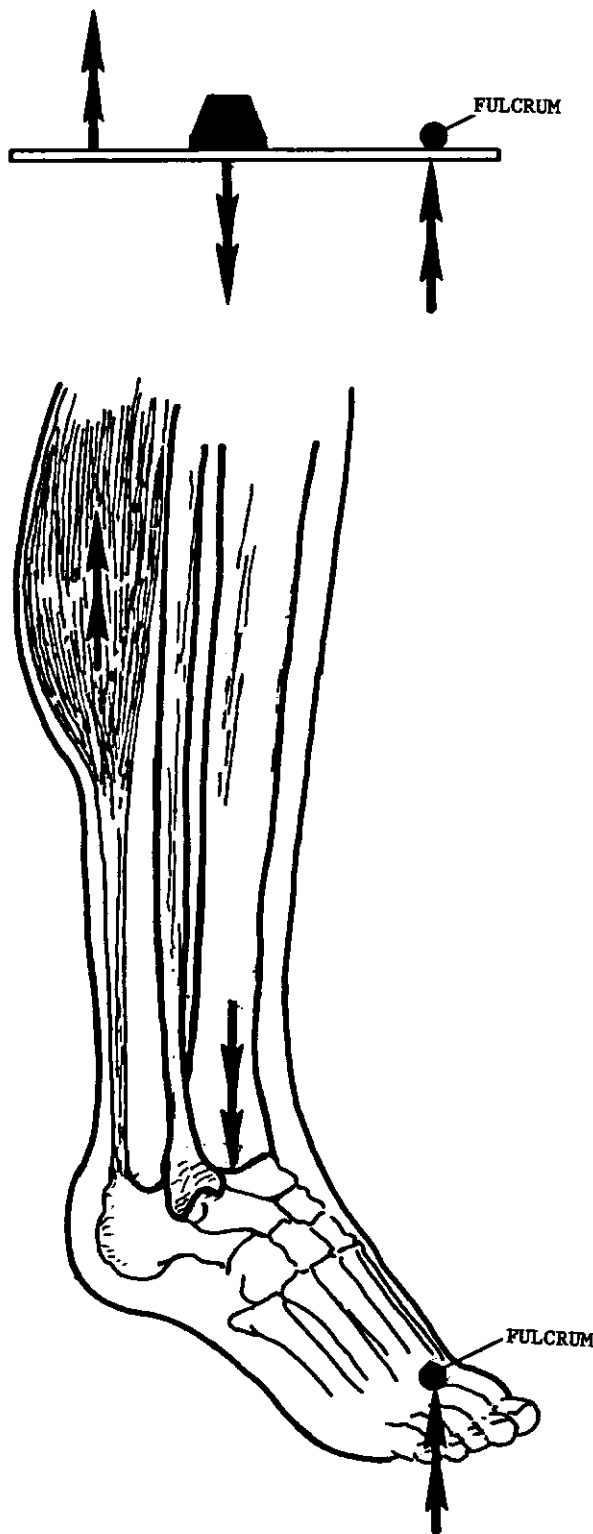


Figure 32-4. The Ankle Joint, as an Example of an Anatomical Second Class Lever System. The fulcrum is located at the base of the big toe.

sults in a total range of 165°. In occupational biomechanics, however, not the total but only the

effective range of movement is of significance (Figure 32-7). Muscles behave like extension springs. They can exert no force when fully contracted and exert maximal force when fully extended. Between these two states, potential force varies linearly as a degree of extension. Further complexities are introduced into the system because the "mechanical advantage" to which it can be applied varies with the degree of joint flexion. In physics "mechanical advantage" is defined as "... ratio of the weight of the actual load raised to the force input required to perform," [paraphrased from (11)]. Therefore, the mechanical advantage with which the potential force of the muscle can be applied does not vary linearly, but changes in proportion to the sine of the angle between the bony elements of the lever system. This results in a narrow angular range within which limb movement is strong as well as precise and outside of which not only effectiveness of motion decreases, but individual differences increase to such an extent that performance becomes virtually unpredictable. There are many compilations in tabular form available, useful in estimating range and strength of limb movement for a given work situation.^{12, 13, 14} Partial recapitulation of the comprehensive data presented in the references mentioned would not only be redundant but could also tempt readers to rely on fragmentary and insufficient information as a basis for decision making. Most anthropometric reference works, however, were developed as aids in the design of specialized man-task systems such as the operation of motor vehicles,¹⁵ or military aircraft, and therefore some information might not be applicable without a degree of modification to generalized work situations. Also many references state range of joint movement over the full angle and strength of movement in terms of maximum and therefore these data, with the help of an anatomical atlas or, better, an articulated plastic skeleton, should always be reduced to the "effective range" for a specific task or for a specialized working population (Figure 32-8).

Kinetic Elements

The functional aggregate of all anatomical structures involved in producing a simple movement of a joint about one of its axes is called a "kinetic element" (Figure 32-9).

The basic structure of each kinetic element is a lever system consisting of at least two bones connected by a joint. The levers are moved by the contraction of muscles inserted into the bones. These muscles are arranged to oppose each other. The action muscle is termed "protagonist;" the opposer, "antagonist." Contraction occurs in response to stimuli from the specific nerve supplying each muscle. The oxygen required for the energy release needed to bring about muscular contraction is provided by arterial branches supplying protagonists as well as antagonists with blood. The waste products of the physiological combustion process incidental to energy release are carried away by venous or other drainage mechanisms. Thus, each kinetic element is made up of the following constituents:

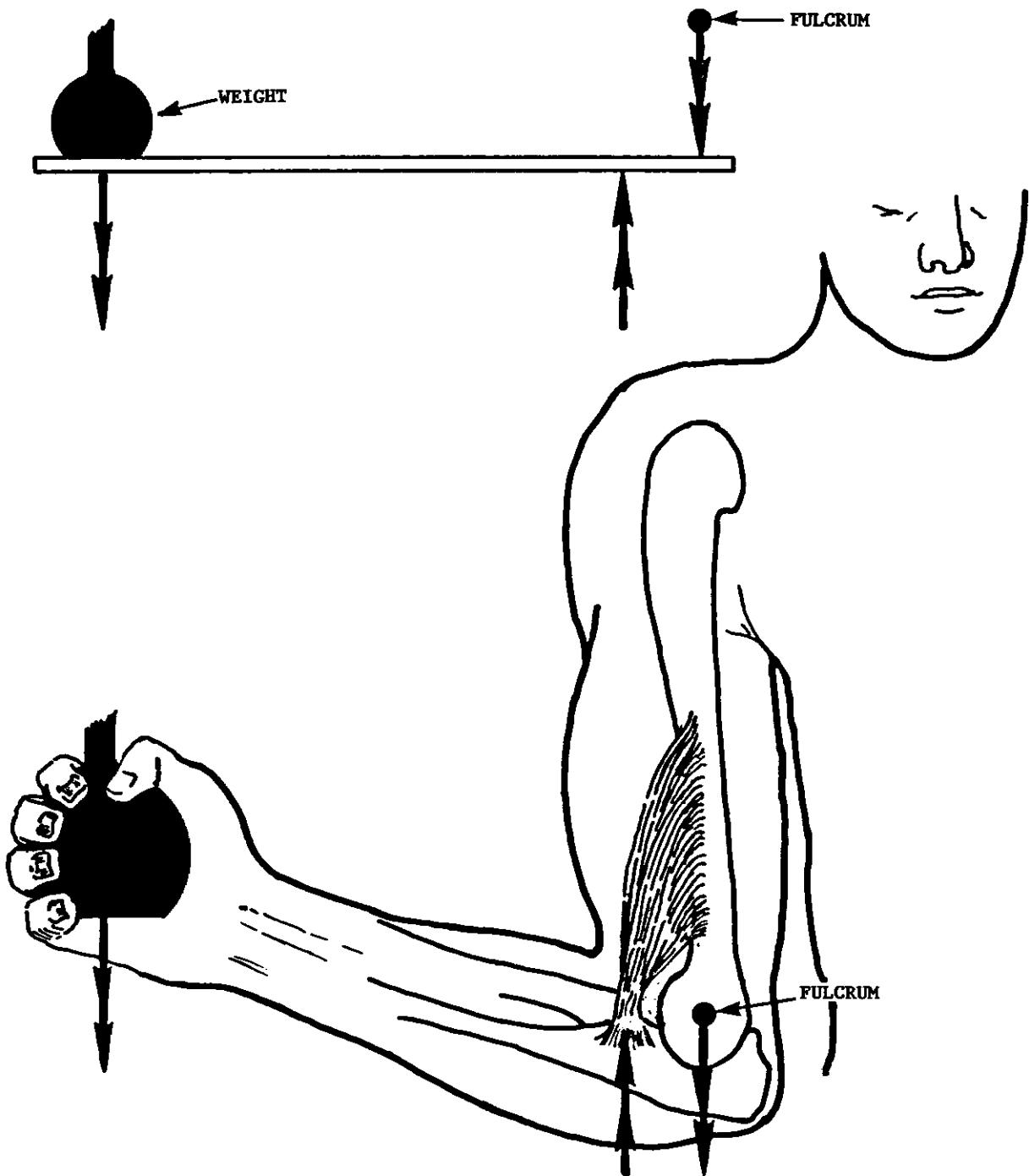
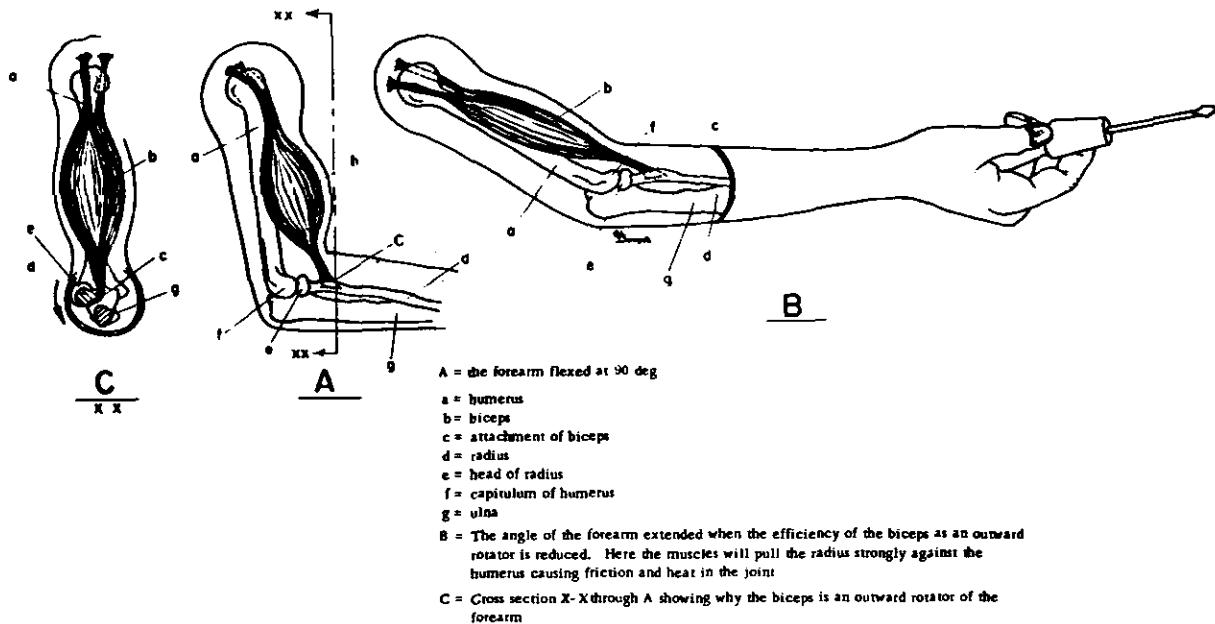


Figure 32-5. An anatomical third class lever is formed between ulna and humerus. The brachialis muscle provides the activating force, the fulcrum is formed by the center of the trochlea of the humerus.



Tichauer, E. R.: The Biomechanics of the Arm-Back Aggregate under Industrial Working Conditions. New York, American Society of Mechanical Engineers, 1965.

Figure 32-6. A Torsional Lever System Exemplified by the Kinetic Element Made Up of Humerus, Radius and Biceps.

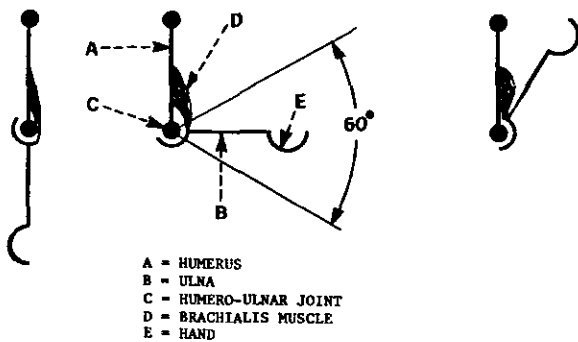
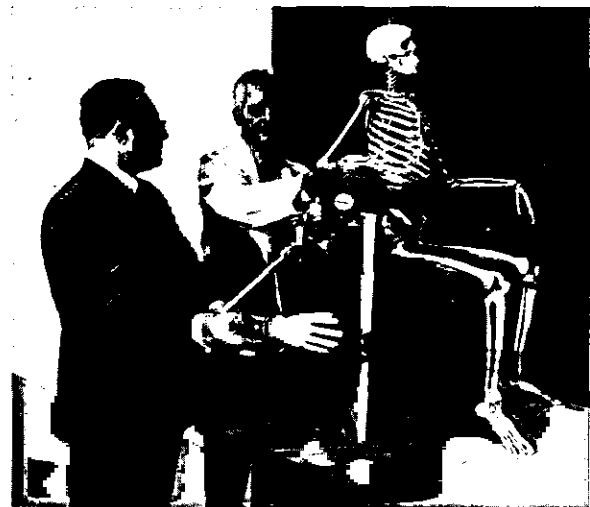


Figure 32-7. The kinetic element formed between humerus, ulna and brachialis muscle can operate at best mechanical advantage only within a relatively narrow angle of forearm flexion.

1. bony;
2. articular;
3. muscular;
4. nervous; and
5. vascular.

Only the simplest and most basic of all motions such as, for example, reflex reactions, involve only one kinetic element. In the industrial environment, manipulative as well as locomotive maneuvers are normally performed by a "kinetic chain."



Western Electric News Features, New York, 1965.

Figure 32-8. The Use of a Plastic Skeleton for the Objective Analysis of Biomechanical Advantage of a Specific Working Posture. Possible stresses in the shoulder joint are measured with the mechanical analog along side.

Kinetic Chains

A kinetic chain consists of a number of serially interacting kinetic elements reacting to inputs and

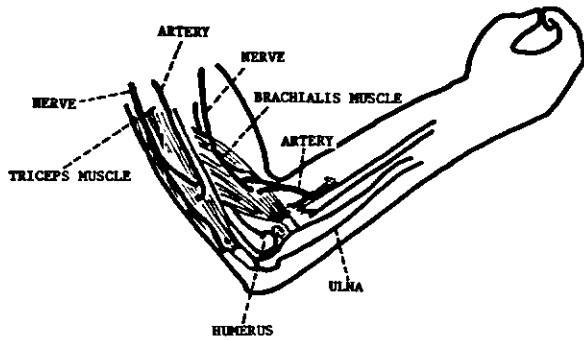
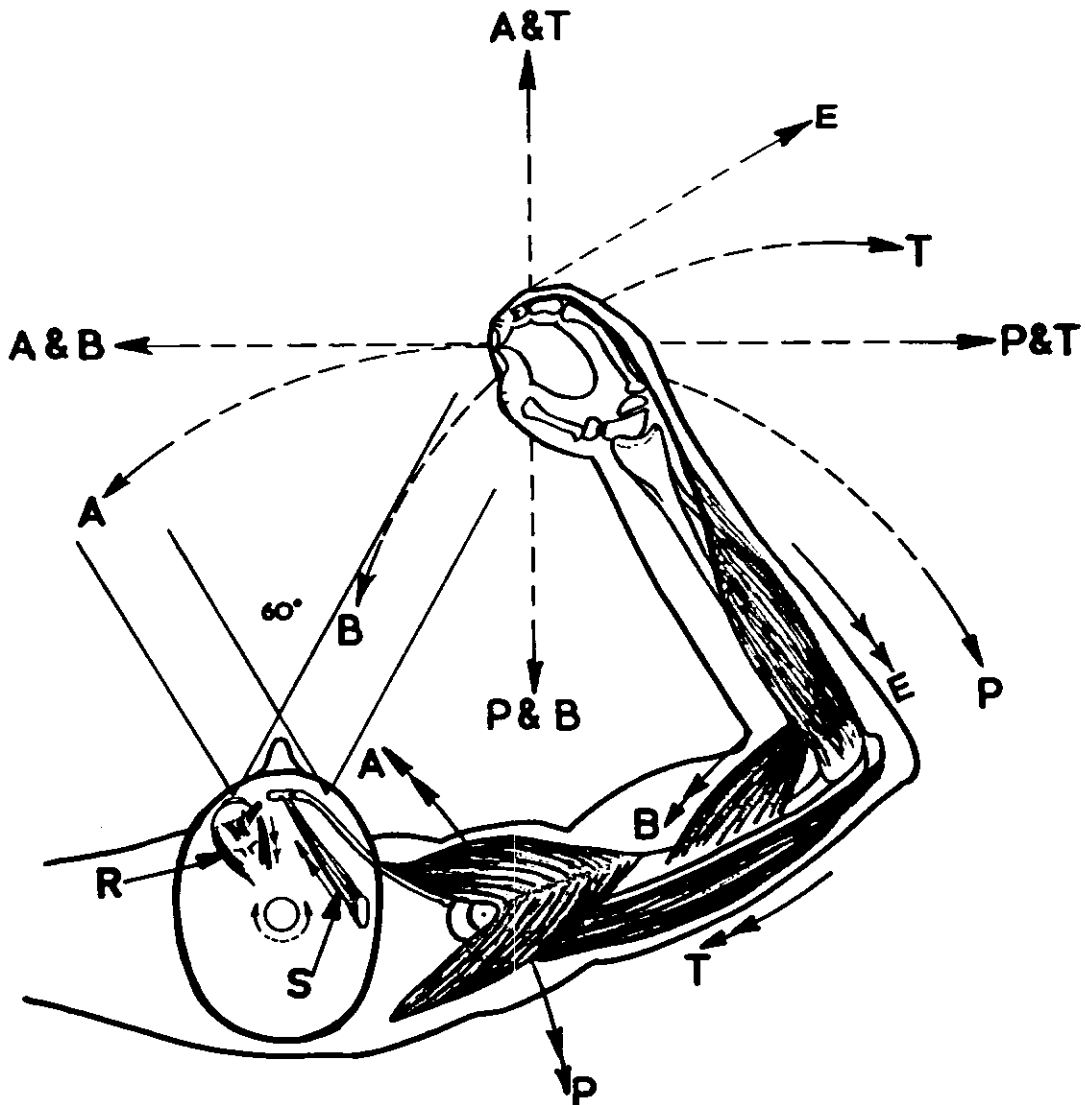


Figure 32-9. The Kinetic Element of Fore-arm Flexion and Extension.

feedbacks perceived from within and without the body by sensory organs connected with the kinetic element in such a manner as to form a cybernetic, or self-regulating system. The first step in the biomechanical evaluation of a workplace is normally the identification of that kinetic chain which links sensory inputs or feedbacks from the workplace with the muscular output required to perform a specific task.¹⁶ To enumerate all anatomical structures of a kinetic chain is not only cumbersome, but often unnecessary. Therefore, in industrial practice the description of a kinetic chain includes only major sensory organs and key kinetic elements.

The kinetic chain of "eye-hand coordination" is perhaps the most frequently used one in most industries (Figure 32-10). Here the main sensory input is perceived by the eyes. These track the visual target when moved by the small muscles



Tichauer, E. R., Gage, H., Harrison, L. B.: The Use of Biomechanical Profiles in Objective Work Measurement. J. Ind. Eng. IV:20-27, 1972.

Figure 32-10. The Kinetic Chain of Eye-Hand Coordination.

(Figure 32-10/R.) which rotate the eyeball. However, binocular vision and thus, depth perception, exists only within the binocular visual cone of 60°. To bring binocular vision to bear upon an object positioned outside of this cone, it becomes necessary to rotate the head and thus the next kinetic element in the chain is formed by the sternomastoid muscle (Figure 32-10/S) and its connection with the skull and the breastbone. Subsequent to visual evaluation of the work situation, a forward movement of the arm about the shoulder is produced by the anterior belly of the deltoid muscle (Figure 32-10/A) which is antagonized and controlled by activity of the posterior belly (Figure 32-10/P) of the same muscle. To reach out, the triceps inserting into the ulna functions as protagonist and this action is opposed and controlled by the brachialis, (Figure 32-10/T and 32-10/B) which, in turn, originates from the humerus and inserts into the ulna. Fine positioning of the wrist is governed by, among others, a complex group of extensor muscles (Figure 32-10/E), originating from the elbow region and inserted into the phalanges of the fingers. Identification of such a kinetic chain makes it possible to compare, without physical experimentation, the anatomical complexity of motions performed under visual control in various directions, and to eliminate those which are likely to be the most fatiguing motions. In Figure 32-10 motion pathway B would be very easy to perform, requiring only the use of the brachialis muscle while motion pathways A & B and P & T would very likely lead to early fatigue as such action demands the use of every element, sensory as well as motor, in the kinetic chain.

Likewise, correct identification of the kinetic chain permits the spotting, and often the elimination, of potential anatomical failure points in a man-task system.

Anatomical Failure Points in Man-Task Systems

Whenever, in a man-task system, an element in a kinetic chain is structurally overstressed so that the maintenance of economically acceptable production rates or product quality becomes impossible without impairing the worker's physiological or emotional well-being, then the kinetic element under consideration becomes an actual or potential anatomical failure point.

Quite frequently, workplace design in accordance with established industrial engineering principles is conducive to the generation of such failure points. The principles of work simplification and other work measurement and design techniques did not change at the same pace as the development of modern industrial technologies. Many reputable industrial engineering texts¹⁷ still recognize only five different classifications of motion:

1. finger;
2. fingers and wrists;
3. fingers, wrists and forearm;
4. fingers, wrists, forearm and upper arm; and
5. all of the above (1-4) plus a body motion or a change of posture.

These texts or common usage¹⁷ further stipulate "... required motions should be performed

within the lowest classification possible . . . any motion beyond the maximum for 4th class should be avoided if at all possible. The shorter the motion, the less time and effort it will take to perform it . . ." This approach has simply become untenable in this age of pushbutton-operated machinery and miniaturization.

Even the simplest of man-task systems, unless screened while still in the planning stage, for potential anatomical failure points, can adversely affect health as well as performance of large numbers of workers.¹⁸ For example, the ergonomic efficiency and safety of a screwdriving task depends primarily on the magnitude of the included angle between forearm and upper arm in habitual working posture. If workers are permitted to position themselves only a few inches too far away from the workplace, then the incidence of sore elbows at the workplace, be they classified as epicondylitis, bursitis, or by any other name, will increase dramatically (Figure 32-11). This can be explained and avoided by biomechanical analysis of the relevant kinetic element. The biceps is not only a flexor of the forearm but also, due to the mode of its attachment to the radius, the most powerful lateral rotator of the wrist (Figure 32-11/c). Whenever working posture is such that the angle between forearm and upper arm approximates 90° (Figure 32-11), then this muscle operates at mechanical advantage. However, if a posture is assumed which increases this angle (Figure 32-11), then the biceps also jams the head of the radius against the capitulum of the humerus generating friction, heat, and ultimately conditions commonly classified as epicondylitis. This example is typical of the numerous work situations where effective occupational hazard control can be exercised through identification of anatomical failure points in a man-task system.

A kinetic element is a potential failure point when:

- a. the degrees of freedom of movement required exceed those available from the lever system employed;
- b. the lever system has to perform for extended periods of time at mechanical disadvantage or under conditions of high stress concentration at the joint surfaces;
- c. the muscles employed are too small to maintain performance for prolonged intervals of time;
- d. the blood supply to the muscles is impaired; and
- e. sensory feedback is defective or equivocal.

ANTHROPOMETRY

Industrial Anthropometry is the discipline concerned with the body measurements of man as they relate to the maintenance of occupational efficiency, safety and health. A number of excellent reference works containing complete sets of numerical data are available in this field,^{19, 20} so that partial recapitulation of numerical material here would not only be redundant but, due to the necessary oversimplification in presentation, dangerously misleading.

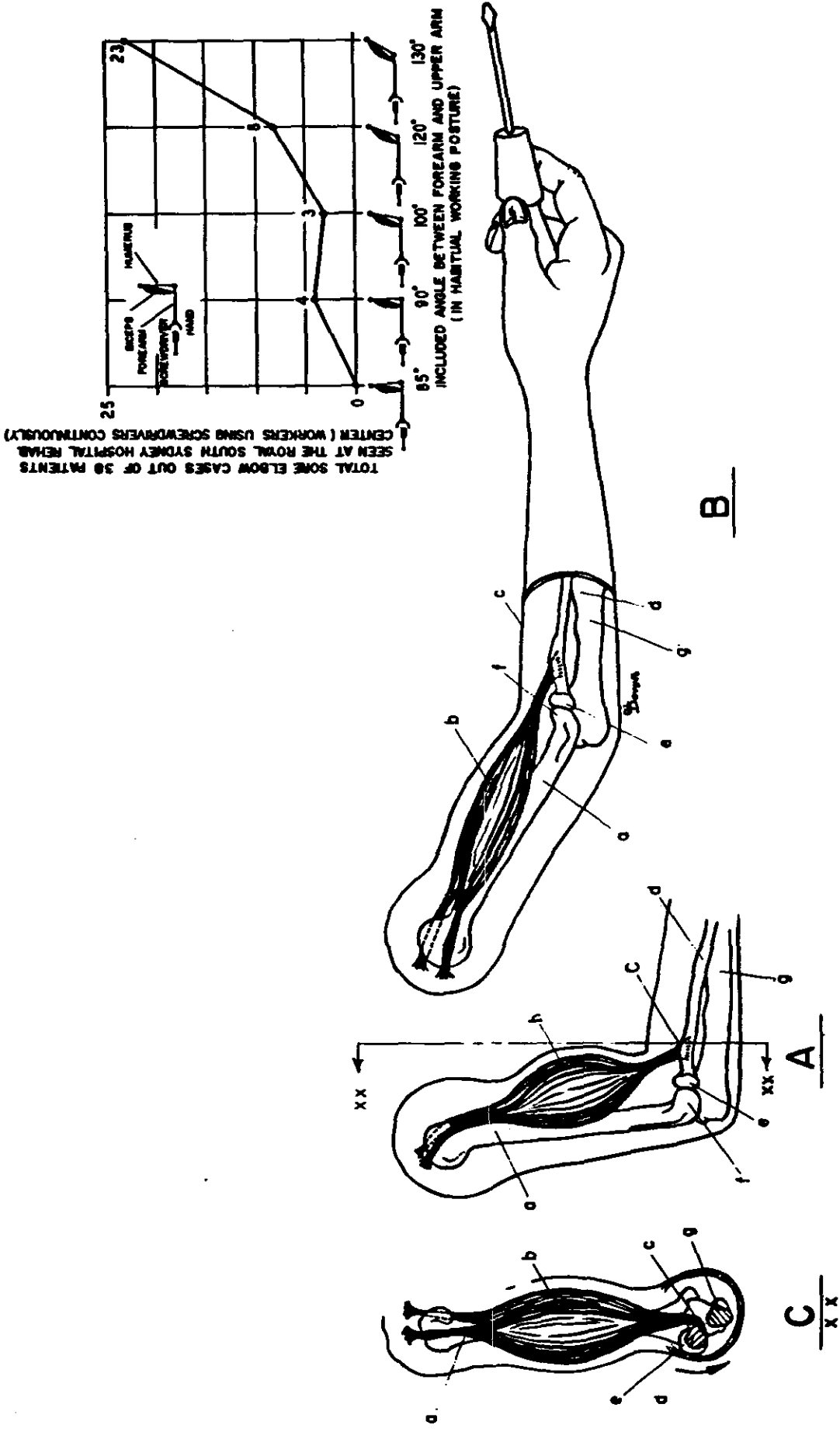


Figure 32-11. THE MECHANICAL ADVANTAGE OF THE BICEPS DEPENDS ON THE ANGLE OF FLEXION OF THE FOREARM. This muscle is not only a flexor, but also, due to the mode of attachment, the most powerful outward rotator of the limb. The worker who sits too far away from his work place has to overexert himself when using a screwdriver because the biceps operates at mechanical disadvantage. Some muscles and excessive friction between the bony structures of the elbow joint are the results.¹²

In most cases anthropometry is concerned with the measurement of relationships between visible anatomical surface landmarks. In industrial practice, most data are obtained by direct caliper measurement. The data gathered are statistically evaluated and made representative of the range of body measurements typical for the working population under study. To substitute means in lieu of ranges is a dangerous practice. Often a piece of equipment of a workplace dimensioned for average man will be too small for one-half of the working population, and too large for the other half. Likewise, due consideration should be given to the substantial differences in body di-

mensions as well as skeletal geometry of movement between males and females.

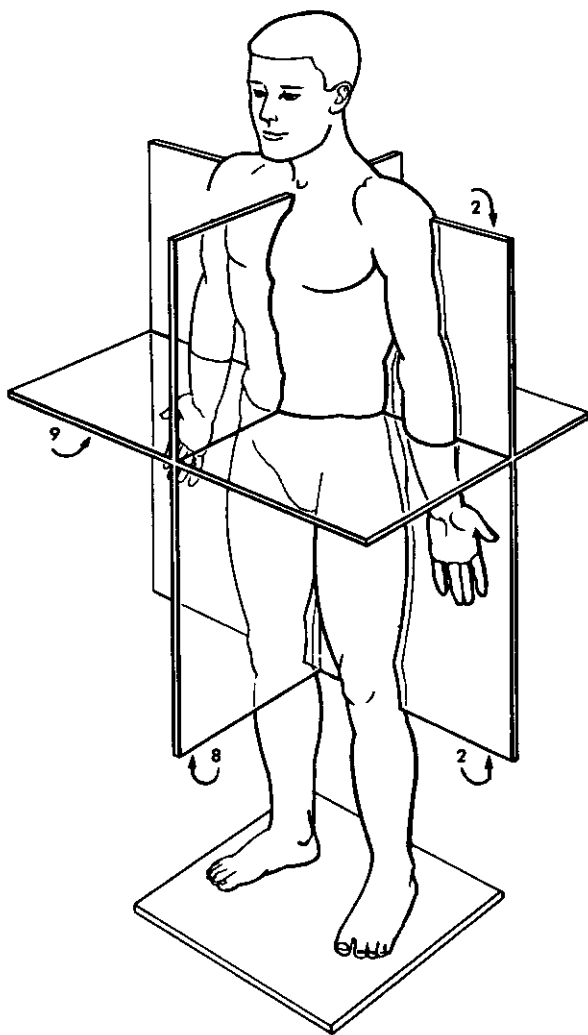
Industrial Seating

Many jobs require performance in seated posture. Therefore, chairs are among the most important devices used in industry. They determine postural configuration at the workplace. Poorly designed seating accommodations represent frequent and definitive occupational hazards. Well-designed working chairs do not only contribute to the physical well-being of the working population but also may add as much as approximately 40 productive minutes to each working day. Optimal dimensions for working chairs and benches are well established and can be obtained with ease from standard reference works (Fig. 32-12).^{21, 22} Numerical dimensions are of but limited value to the designer or user of industrial seating, unless they are supplemented by adequate knowledge of the relevant anatomical facts and biomechanical considerations.

To facilitate description of seated as well as other work situations based on anthropometric considerations, a uniform nomenclature of planes of reference suitable for the description of postures has been agreed upon by convention.^{13, 23} A line in the coronal plane passing through the point of contact between the ischial tuberosities and the seating surface constitutes the "axis of support" (Figure 32-13) of the seated torso. This produces a "2-point support." Therefore, all coronal sections of the seating surface of the chair should be straight lines. A coronally contoured seating surface may restrict postural freedom at the workplace severely and, when poorly matched to the curvatures of the buttocks, may cause discomfort. Likewise, improper contouring may interact with sanitary napkins and other devices worn by women during the menstrual period with the ensuing further reduction in physical well-being during an already trying time of the month.

Working chairs should be "cambered" in the sagittal plane. The term "camber" describes the backward slant of the seating surface. A properly cambered seat prevents forward sliding of the buttocks and encourages the use of the backrest. A rough texture of the seating surface further helps to prevent undesirable and fatiguing sliding. The frontal end of the seating surface should terminate in a "scroll" edge which does not cut into the back of the leg. Finally, the seating surface should be preferably porous or else constructed in such a manner as to permit adequate conduction of heat away from the contact area between buttocks and chair. Especially undesirable are interacting combinations of multiple layers of loose garments made from synthetic fabrics and solid synthetic seat covers of, for example, vinyl plastic which will definitely affect female workers detrimentally due to a considerable damming up of heat at the body surface.

At the back of the leg, in the hollow of the knee, a sharp and easily distinguishable crease is located which is termed the "popliteal crease." The distance from the popliteal crease to the floor when standing in a relaxed upright posture and



- 2 = CORONAL PLANE
- 8 = MID-SAGITTAL PLANE
- 9 = TRANSVERSE PLANE

Jacob, S. W., Francone, C. A.: Structure and Function in Man. Philadelphia, W. B. Saunders Co., 1970, p. 8.

Figure 32-12. The Basic Planes of Reference for Biomechanical and Anatomical Description²².

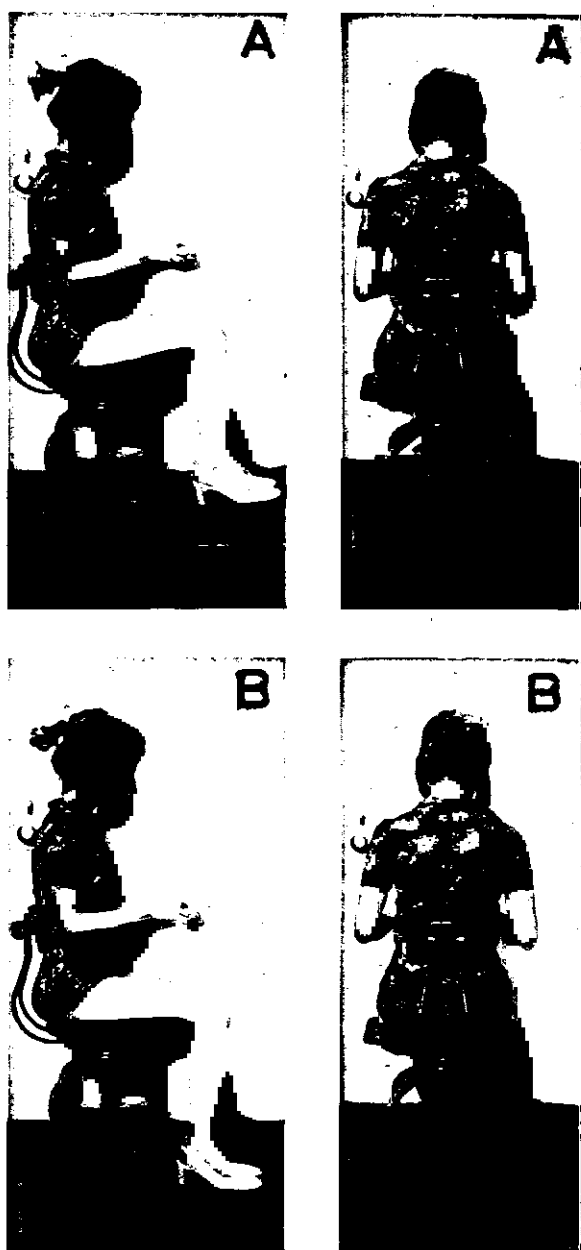


Figure 32-13. A biomechanically — correct seating posture (A) contributes substantially to health, well-being and efficiency of the working population. When the popliteal height of the worker is less than the popliteal height of the chair (B) discomfort will ensue. Note deformation of thigh and buttocks in situation (B).

while normal working shoes are worn is termed the “popliteal height of the individual.” The height of the highest point of the seating surface above the floor is the “popliteal height of the chair.” If the popliteal height of the chair is equal or greater than the popliteal height of the individual concerned, then undesirable pressures may be exerted upon the back of the thigh. To

be comfortable, the popliteal height of the chair should be approximately 2-inches lower than the popliteal height of the individual. The seating surface should be short enough so that the distance between the front edge of the seat and the popliteal crease is about 5 inches. This dimension is called “popliteal clearance.” In some industrial chairs, the depth of the seat can be regulated by adjustment of the backrest. If the backrest is moved forward, then the seat becomes shorter. This is a very desirable design feature contributing both to productivity as well as physical well-being.

The lower border of the backrest should clear the iliac crest. Preferably the upper edge or the highest point of contact with the back of the seated individual should be at a level lower than the inferior margin of the rib cage. At least the top of the backrest should clear all but the “false” ribs. Many work situations require continuous and rhythmic movement of the torso in the sagittal plane, and then a backrest which is too high will produce bruises on the backs of a considerable portion of the working population. The best designed backrests are small, kidney shaped, and can swivel freely about a horizontal axis located in a coronal plane. Thus, they fit well into the hollow of the lumbar region and provide the needed support for the lower spine without detrimental interference with soft tissues. It is often desirable, especially when much movement of the torso during work must take place, that the area of contact with the backrest does not extend beyond that region of the back which overlays the tough and fibrous plate which constitutes the origin of a large muscle; the latissimus dorsi. A backrest which is overly wide, under circumstances when much materials-handling and twisting of the torso in the seated position takes place will make frequent and repeated contact with the breasts of female workers.²⁴ This can produce great pain, especially during the premenstrual period when the breasts of many individuals are quite tender. Whenever backrests produce either bruising or only slight discomfort, workers protect themselves. The painful effects of excessive interaction between chair and torso are commonly reduced by ad hoc devices such as pillows, brought from home and strapped to the backrest. Work sampling studies show that several hours every week may be wasted in an effort to keep such improvised cushioning devices in place. Properly designed backrests are much cheaper than improvisations, both in the long as well as in the short run.²⁵

A frequent and sometimes dangerous response to chair-generated discomfort is temporary absenteeism from the workplace. When the level of personal tolerance has been exceeded, workmen simply “take a walk.” It is found occasionally that individuals involved in accidents are at the place of injury without authorization. Since no accident is possible unless victim and injury-producing agent meet at the same spot and at the same time, temporary absenteeism from the workplace may result in unnecessary exposure to potentially hazardous situations.⁷

Some working chairs are equipped with coasters. These facilitate limited locomotion and materials-handling without abandoning the seated posture. In many work situations, coasters help to reduce unnecessary torsional moments acting on the lumbar spine. In other circumstances, especially in some cases of circulatory disturbance in the lower extremity, a chair equipped with coasters may stimulate muscular activity and consequently improve circulation in the leg. However, coasters should only be used when they either contribute to the well-being of an individual or the efficiency of an operation. They constitute some hazard to safety. There is always the risk that the chair rolls accidentally away or is inadvertently removed while the user gets up for a brief interval of time. Where possible, a cheap restraining device such as a nylon rope, a chain, or, in some circumstances, a rigid linkage between chair and workbench should be considered.

Supervisors as well as workers should receive brief but formal instruction in the proper adjustment of working chairs. First, the height between seating surface and top of the workbench is adjusted so that an optimal angle of abduction of the upper arms during activity can be maintained. The chairs should have design features permitting easy adjustment in discrete steps. A 3-step height adjustment is adequate for most populations and in most situations. Secondly, after the height of the seat with respect to the top of the worktable has been fixed, correct popliteal height is then established by means of an adjustable footrest. Footrests, because they cannot be easily adjusted, are less desirable, and may traumatize anatomical structures around the ankle joint and may interfere with the ease of access to foot pedals. Occasionally drawers located underneath workbenches may interfere with proper seat height adjustment and should then be removed. There should be no need for adjustment of the camber in a well-designed working chair. Third, seating surfaces should be wide enough to permit some postural freedom. Arm rests are sometimes useful but in some situations, support for only one arm is needed. In such case, a chair with detachable arm rests should be provided.

No one single chair design can possibly fit all work situations. Seating analysis should always be conducted in a thorough fashion, giving due weight to all relevant features of the task under consideration. It is highly desirable that standard reference works^{19, 21, 22} be available during consultation.

In addition to the analysis of the seated posture with respect to physical comfort and biomechanical correctness, it is also necessary to consider the changes in kinesiology of the lower extremity resulting from seated posture. The seated leg and foot can rotate only with difficulty and unless the popliteal height of the chair is extremely low, such as is the case in motor vehicles, operation of foot pedals may become cumbersome and fatiguing. On the other hand, the seated "leg and thigh aggregate" can abduct and adduct voluntarily, precisely and strongly without fatigue for long intervals of time. It is therefore frequently

advantageous to make use of this kind of movement in the design of machine controls (e.g., the knee switch of the sewing machine). In the seated posture, knee switches are generally superior to foot pedals.

The Physical Dimensions of the Workplace

In most industrial enterprises, productive activities are organized according to certain principles of division of labor and thus broken down into a series of relatively simple and specific operations; each one assigned to a different employee. Therefore, most members of the working population do spend practically the entirety of their productive time confined to a quite small area of the manufacturing plant which is termed "the workplace." Thus, in many instances the term "workplace" is synonymous with "working environment" and includes everything except man himself. Thus, regular as well as protective clothing, climate, illumination, chairs, machines, tools, and the product worked upon must be considered in the ergonomic analysis of the industrial environment. Within the narrower framework of biomechanics, the physical relationship, in terms of distances and other linear dimensions is often of paramount importance to production efficiency as well as to physical and emotional well-being of the worker. Even small changes in the dimensions of the workplace may have large effects on occupational safety and health as well as on the economics of the productive process.

In practice, the designer of workplaces must often operate within the constraints of accepted industrial standards. These aim at the attainment of maximal levels of production efficiency. Most of these standards were developed between 1917 and 1936.^{26, 27} Unfortunately, the development of industrial standards relating to the dimensions of the workplace lags behind the development in workforce and technology which has so radically altered the industrial environment during the last few years. Acceptance of recommended changes in workplace layout will normally depend on the ability of the analyst to convince all parties concerned that higher levels of efficiency accompanied by increased well-being are a normal "by-product" of work situations dimensioned to suit the anthropometric and kinesiological capabilities of the workforce.

Perhaps the most commonly used set of "norms" for workplace layout are the "Principles of Motion Economy" which were first enunciated by the Gilbreths,²⁸ improved by subsequent researchers and accepted today generally in the format developed and presented by Barnes²⁹ who uses as a subheading for that table the words "A Checksheet for Motion Economy and Fatigue Reduction" (Table 32-1). Many of these principles of motion economy are still applicable in the form in which they were originally enunciated. However, others have become either redundant or, in some instances, outright hazards to safety and health. They were devised to optimize the interaction between man and the workplace within the framework of technologies and industrial furniture available at the time of their conception. They aim principally at an increase of produc-

TABLE 32-1
Principles of Motion Economy

A Check Sheet for Motion Economy and Fatigue Reduction

These twenty-two rules or principles of motion economy may be profitably applied to shop and office work alike. Although not all are applicable to every operation, they do form a basis or a code for improving the efficiency and reducing fatigue in manual work.

<i>Use of the Human Body</i>	<i>Arrangement of the Work Place</i>	<i>Design of Tools and Equipment</i>
1. The two hands should begin as well as complete their motions at the same time.	10. There should be a definite and fixed place for all tools and materials.	18. The hands should be relieved of all work that can be done more advantageously by a jig, a fixture, or a foot-operated device.
2. The two hands should not be idle at the same time except during rest periods.	11. Tools, materials, and controls should be located close to the point of use.	19. Two or more tools should be combined wherever possible.
3. Motions of the arms should be made in opposite and symmetrical directions, and should be made simultaneously.	12. Gravity feed bins and containers should be used to deliver material close to the point of use.	20. Tools and materials should be pre-positioned whenever possible.
4. Hand and body motions should be confined to the lowest classification with which it is possible to perform the work satisfactorily.	13. Drop deliveries should be used wherever possible.	21. Where each finger performs some specific movement, such as in typewriting, the load should be distributed in accordance with the inherent capacities of the fingers.
5. Momentum should be employed to assist the worker wherever possible, and it should be reduced to a minimum if it must be overcome by muscular effort.	14. Materials and tools should be located to permit the best sequence of motions.	22. Levers, crossbars, and hand wheels should be located in such positions that the operator can manipulate them with the least change in body position and with the greatest mechanical advantage.
6. Smooth continuous curved motions of the hands are preferable to straight-line motions involving sudden and sharp changes in direction.	15. Provisions should be made for adequate conditions for seeing. Good illumination is the first requirement for satisfactory visual perception.	
7. Ballistic movements are faster, easier, and more accurate than restricted (fixation) or "controlled" movements.	16. The height of the work place and the chair should preferably be arranged so that alternate sitting and standing at work are easily possible.	
8. Work should be arranged to permit easy and natural rhythm wherever possible.	17. A chair of the type and height to permit good posture should be provided for every worker.	
9. Eye fixations should be as few and as close together as possible.		

From "Motion and Time Study", R. M. Barnes, John Wiley & Sons, Inc., New York, 1963.

tive output per unit of time with fatigue reduction and maintenance of product quality a secondary, albeit important, consideration.

A second set of universally used, as well as misused, schemes of "normal" and "extended" reach and work areas²⁹ must be considered limited in application as the schemes neglect anthropometric considerations necessary due to different ethnic compositions of diverse working populations. They also neglect age and are based on an incorrect conception of the kinesiology of the upper limb.

However, there is still very much substance in the "Principles of Motion Economy," the concepts of work areas, predetermined motion-time systems as well as other current industrial standards; they are still useful and, when properly applied, of great potential value for the promotion of economic efficiency as well as occupational health. To adapt the above-mentioned industrial systems, standards and practices to current needs, the dimensions of the workplace should comply with the following set of rules:³⁰

Rule 1: The dimensions of the workplace are determined by body measurement as well as range and strength of movement of the kinetic elements involved in a task. These should be obtained from reference works specifically aiming at the industrial environment.³¹

Rule 2: Workplaces should always be dimensioned to suit the full range of body measurements of that specific working population likely to be assigned to the task under consideration.³²

Rule 3: Differences of sex, ethnic origin and educational or social background often express themselves in specific types of musculo-skeletal configurations as well as specific motion inventories and/or manipulative skills. Therefore, both dimensions as well as geometry of the workplace should take these characteristics into consideration if maximal efficiency and physical well-being are to be obtained in competitive situations.

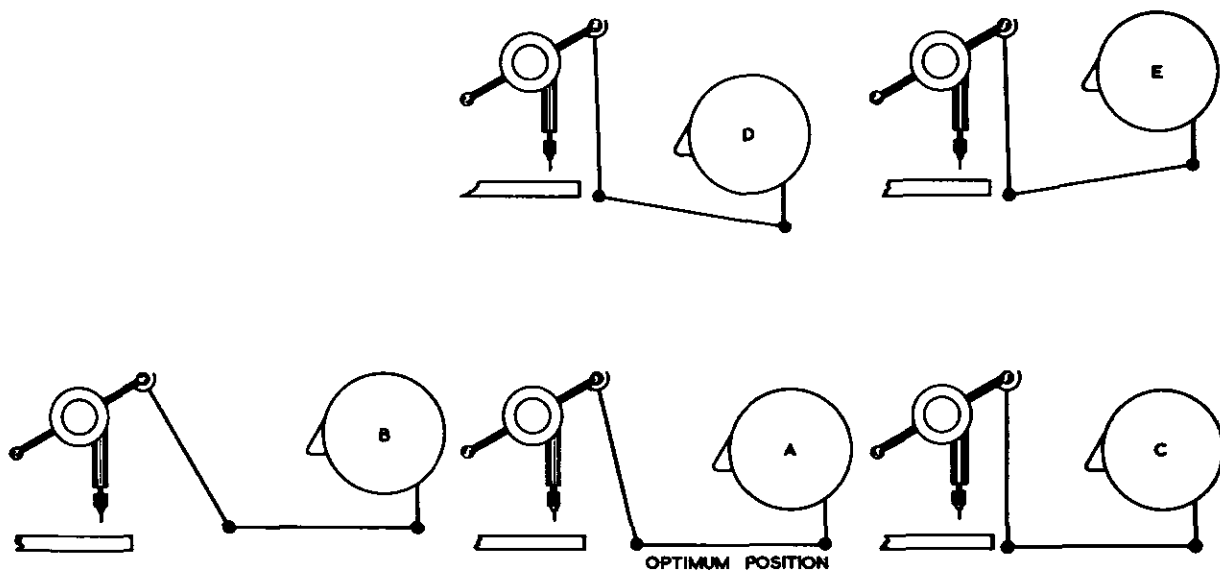
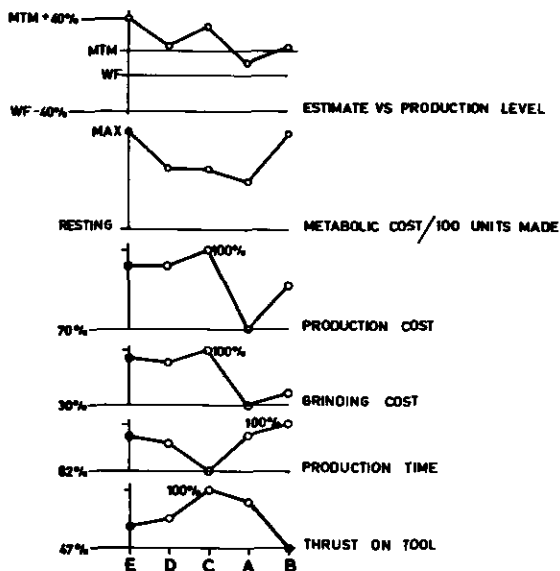


Figure 32-14. If the dimensions of equipment do not suit the body measurements of workers, then displacement by as little as 2 inches from the optimum position of the operator may modify performance levels of man and/or equipment considerably.

- Rule 4:** Optimal position of operator with respect to equipment controls should be ascertained by biomechanical analysis. Relatively small deviations from the optimum may produce drastic productive as well as physiological responses from the equipment operator (Figure 32-14). Therefore, both operator and supervisor should receive instructions about proper positioning of individuals with respect to the physical features of the workplace.
- Rule 5:** In repetitive work situations, task design should aim at maximal postural freedom.

Wherever feasible, a task should be equally well-performable in the seated as well as the standing posture. Such occasional changes during the working day are beneficial and therefore measurements of workbenches, chairs, trays, equipment, etc., should be selected in such a manner as to permit individuals to stand up or sit down without changing the angle of abduction of the upper arm, the angle of forward flexion of the upper arm, or the included angle between forearm and upper arm (Figure 32-15).

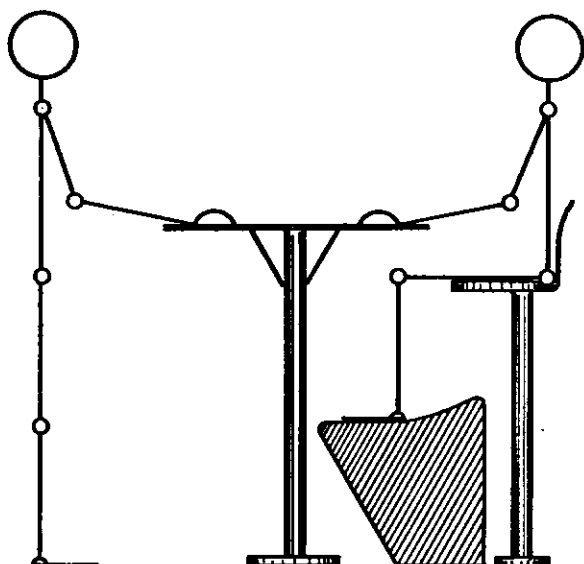


Figure 32-15. When work is possible in either seated or standing position, then workbench and seating design should permit change of posture without change of musculo-skeletal configuration.

Rule 6: In work situations demanding a standing posture, all tasks, including materials-handling operations, should be performable without standing on the toes, torsion or sideways bending of the trunk.

Rule 7: No work should be performed on a strip 3" wide from the border of the workbench which is closest to the operator. The proximity of this area to the operator's body demands excessive retraction or abduction of the upper arm to bring the hands into position. In addition, excessive forward flexion of head and neck are needed to achieve effective eye/hand coordination (Figure 32-16). Under such conditions, users of spectacles or individuals afflicted with slight arthritic conditions of the neck, who are frequently found in middle-aged and other working populations, can suffer considerable physical discomfort. Likewise, in many women, the position of the breasts interferes with ease of visual scanning in this area.

Rule 8: Whenever workplaces must be designed on the basis of already accepted standardized normal and extended reach areas (Figure 32-17), then this information should be supplemented by charts which display optimal directions within each area and identify such points as may be difficult to reach due to anatomical or kinesiological reasons.³³



Tichauer, E. R.: Industrial Engineering in the Rehabilitation of the Handicapped. J. Ind. Eng. XIX:96-104, 1968.

Figure 32-16. (A & B) Visual problems combined with bad postural habits might cause a typist to sit too close to the typewriter. This may put great strain on a neck with arthritic lesions (a). To educate the patient to sit eight inches further away from the typewriter helps to reduce stress on the cervical spine and assists with problems caused by farsightedness (b). Compressive stress between the sixth and seventh cervical vertebrae in "a" is approximately three times the force computed for "b."

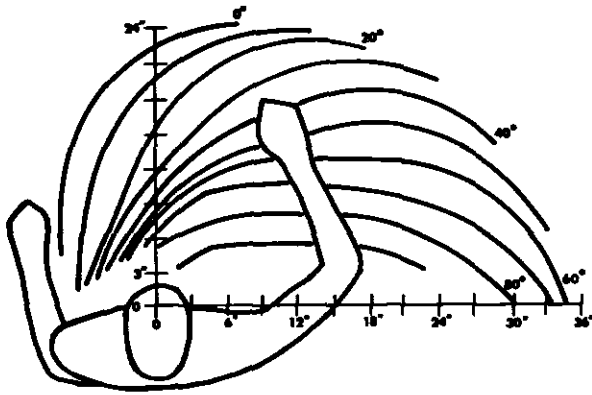


Figure 32-17. The natural motions pathway of the wrist changes with the angle of abduction. Adapted from (33).

Rule 9: The dimensions of areas for temporary holding or storage of products in process should be computed on the basis of queuing theory. Frequently the following formula can be used to advantage:⁸

$$N = \frac{\text{Log } P}{\text{Log } R}$$

where N = the required capacity of the area

P = the greatest acceptable probability that the area will become temporarily overloaded. This number is normally determined on the basis of a subjective management decision.

R = the mean arrival rate of units per time divided by the mean processing rate. These values are normally available from the Motion and Time Studies Department.

Rule 10: Source of incident or reflected light should be located in such a manner as not to produce visual discomfort due to glare (Figure 32-18).

WORK TOLERANCE

Within the context of Ergonomics, *work stress* is defined as any action of an external vector upon the human body while *work strain* manifests itself as the physiological response to the application of stress.³⁴ Stress and strain need not occur at the same points. An increase in environmental temperature above normal is correctly called "heat stress" and the resulting increase in sweating rate is then identified as "heat strain." Likewise, when lifting loads, the force exerted upon the musculo-skeletal system is termed "work stress" and the resulting increases of cardiac and metabolic activity are each examples of "work strain."

The performance of any task, no matter how

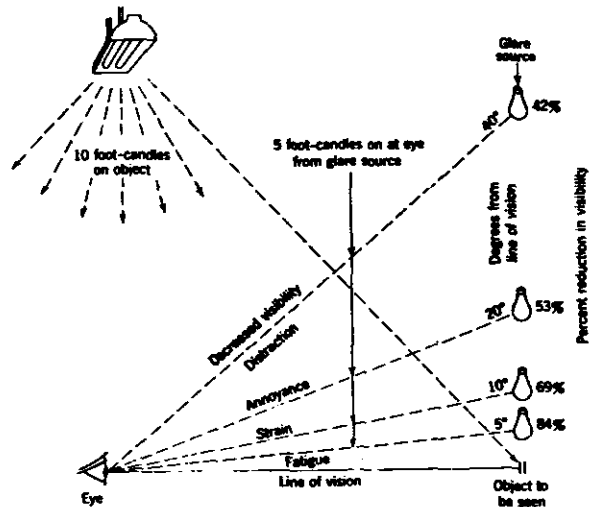


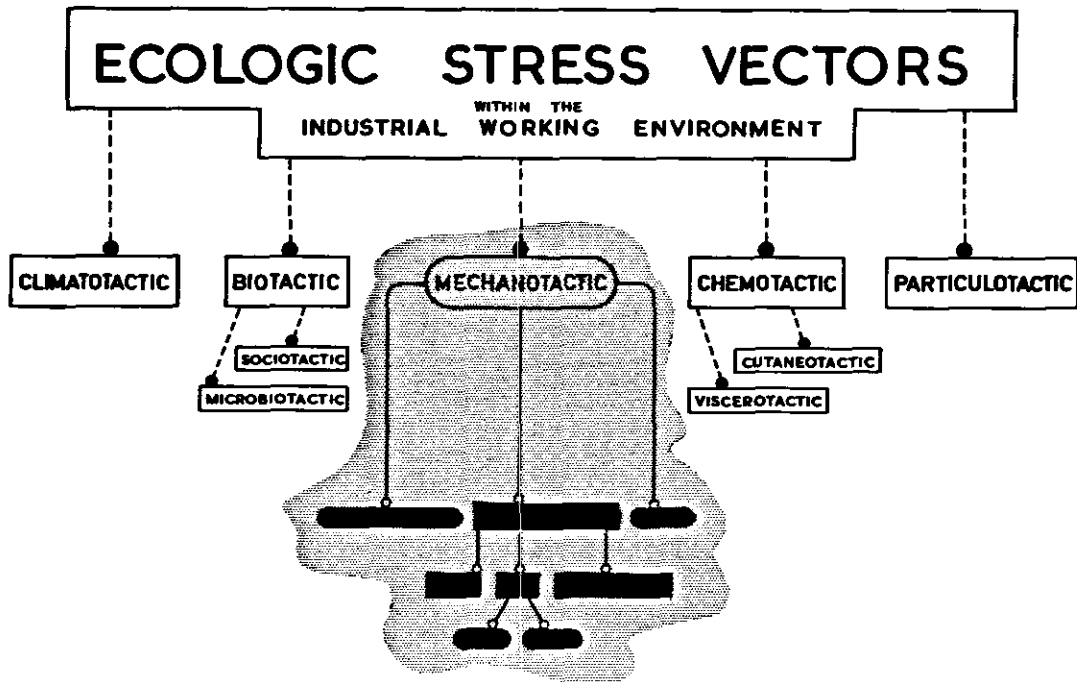
Figure 32-18. Glare becomes worse as it comes closer to the direct line of vision. From M. Luckiesh, *Light, Vision and Seeing*, copyright 1944, D. Van Nostrand Co., Princeton, New Jersey.

light, will impose some work stress and consequently by needs elicit physiological responses characteristic of work strain. Thus, neither work stress nor work strain per se are undesirable; unless they become excessive and produce work-induced disease or diminished work tolerance. The general field of Ergonomics is concerned with five basic environmental stress vectors (climatotactic, biotactic, mechanotactic, chemotactic, particulo-tactic) (Figure 32-19).³⁵ All but mechanotaxes are treated comprehensively elsewhere in this book. Therefore, only mechanotaxes, contact with things mechanical, is discussed in this chapter.

Mechanotactic stress results in three types of strain (Fig. 32-20):

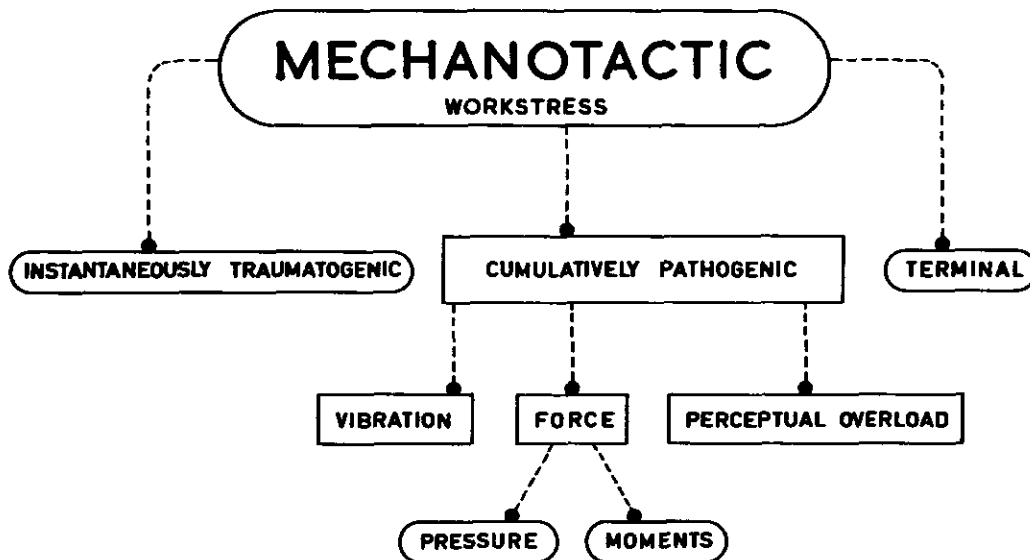
1. Terminal Strain: Death.
2. Instantaneous Trauma: An immediately apparent physical injury.
3. Cumulative Pathogenesis: The gradual development of ergogenic disease by repeated mechanotaxis applied for sufficiently long intervals of time; where each individual application of stress may be quite harmless in itself, but produces lesions through frequency and repetition of application.

Contact with things mechanical, even light contact, may result in trauma. A long enough stay in bed may produce a very intractable lesion, the bed sore. Writer's cramp and the calluses on the hands of surgeons are other well-known examples of strain resulting from mechanotactic stress. Often excessive environmental stress leads to a reduction in work tolerance, long before injury or disease have become manifest. The establishment of conditions conducive to high levels of work tolerance is of utmost importance for the maintenance of occupational health.



Tichauer, E. R. Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

Figure 32-19 The Scheme of Ecologic Stress Vectors Common to All Working Environments. Workstress is derived from contact with climate, contact with living organisms such as fellow man or microbe, contact with things chemical, contact with hostile particles such as silica, or asbestos and finally, contact with things mechanical.²⁵



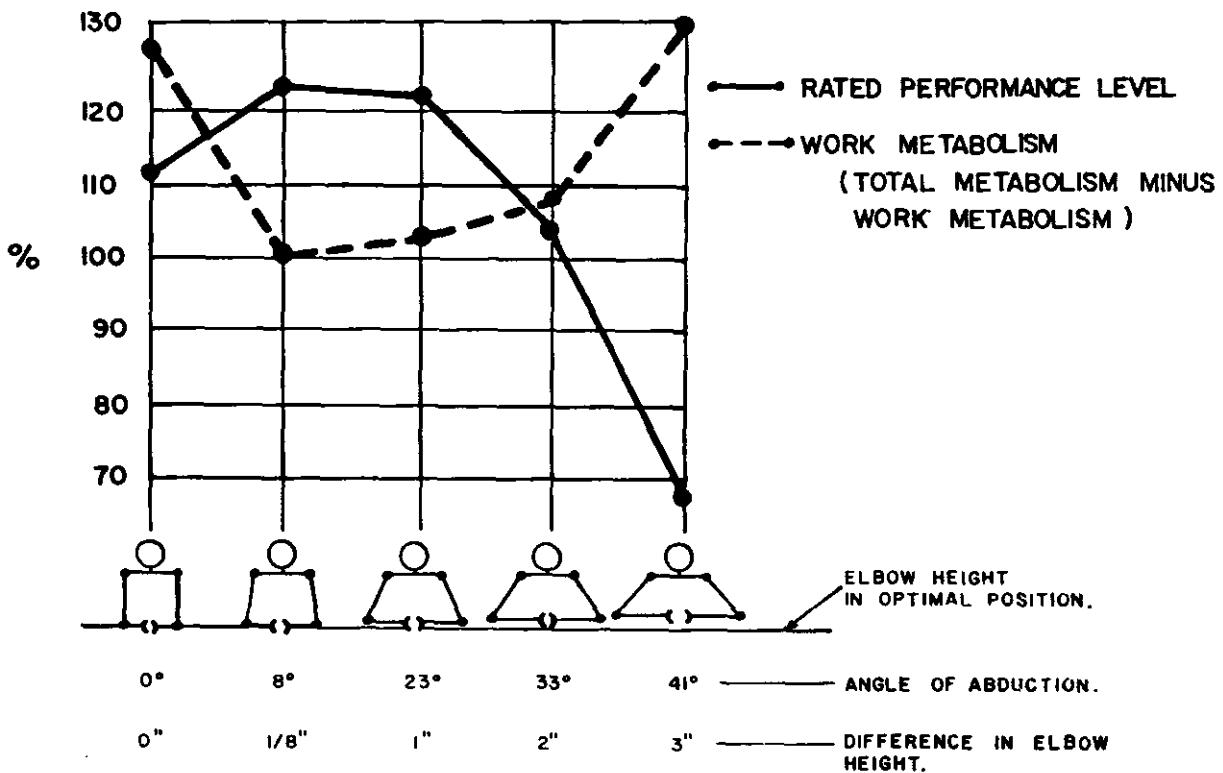
Tichauer, E. R. Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

Figure 32-20. Mechanotactic Stress Vectors Leading to Hazard Exposure in the Industrial Environment: A. Instantaneous Traumatogenesis (e.g. an arm is torn off). B. Terminal (e.g. death occurs immediately). C. Cumulative Pathogenesis. This term describes the gradual development of disability or disease through repeated exposure to Mechanical Stress Vectors over extended periods of time.²⁵

TABLE 32-2
Prerequisites of Biomechanical Work Tolerance
 by E. R. Tichauer

<i>Posture:</i>	<i>Man-Equipment Interface:</i>	<i>Effective Kinesiology:</i>
(P1): Keep the elbows down.	(E1): Do not restrict circulation.	(K1): Avoid deviation of the wrist while moving or rotating the forearm.
(P2): Keep moments acting on the vertebral columns low.	(E2): Vibrations transmitted at the man-equipment interface should not lead to somatic resonance reactions.	(K2): Avoid forward reaches exceeding 16 inches.
(P3): Avoid Covert Lifting Tasks.	(E3): Moving parts of the body should not be constrained by rigid supports.	(K3): When the motion element "transport loaded" has to be performed in the sagittal plane, then the movement should be directed towards the body and not away from it.
(P4): Scanning should require eye movement only and not necessitate simultaneous head motion.	(E4): Stress concentration on small skin areas or small joints should be avoided.	(K4): Holding and manipulation are mutually exclusive operations.
(P5): A musculo-skeletal configuration conducive to maximal biomechanical efficiency should be maintained.	(E5): Ergonomic check-lists should always be consulted whenever handtools are designed, modified, selected or evaluated.	(K5): Motions should be terminated by positive external stops rather than by voluntary muscular action.

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Tichauer, E. R. Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

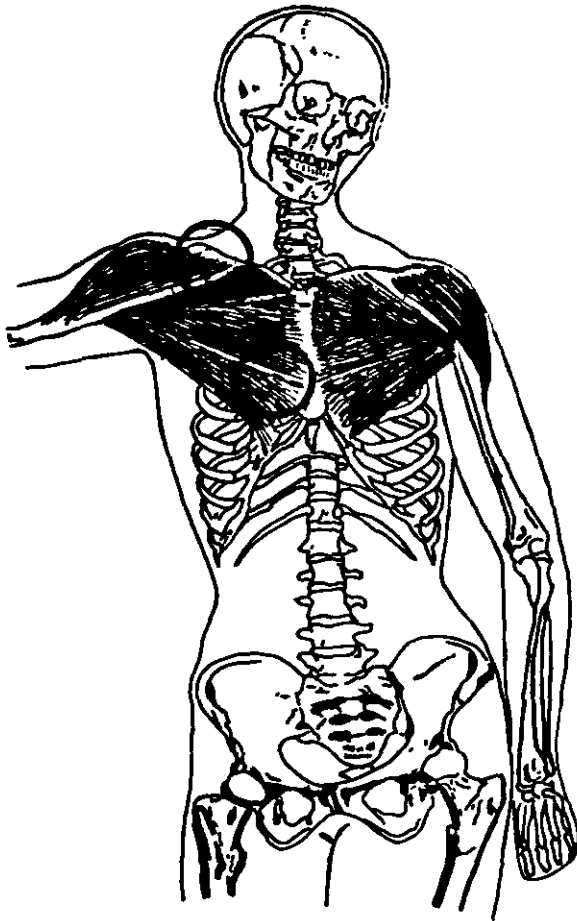
Figure 32-21. Effect of Angle of Abduction on Physiological As Well As Economical Working Efficiency of 12 Female Workers 20 to 32 Years of Age Engaged in Food Packing. Stick figures indicate elbow height in relation to optimal position (horizontal line); first line of numerals, angle of abduction, in degrees; bottom line, difference in elbow height, in inches, from optimal position, statistically tested means are reduced to arbitrarily fixed "benchmarks" of 100 percent. Work metabolism (total metabolism minus work metabolism, dashed line) measured by Wolff's method and instrument Performance levels (solid line).³⁶

Work Tolerance

Work tolerance is defined as the ability to perform a task at acceptable economic levels with respect to both quality as well as quantity of output, while, at the same time, enjoying a full measure of physiological and emotional well-being.

The most important prerequisites of Biomechanical Work Tolerance are presented in tabular form (Table 32-2), arranged into three sets each consisting of five "Prerequisites":

- P: Five prerequisites relating to the maintenance of postural integrity and safety.
- E: Five prerequisites relating to the development and maintenance of nontraumatogenic man/equipment interfaces.
- K: Five prerequisites relating to the production of an effective as well as nonfatiguing kinesiology.



Tichauer, E. R. Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

Figure 32-22. Keeping the arm abducted brings large muscles into play. This, during protracted periods of work, may cause soreness over chest and shoulder in some untrained individuals and therefore occasionally induce fear of heart disease or even an impending heart attack. Areas of potential soreness are circled.³⁵

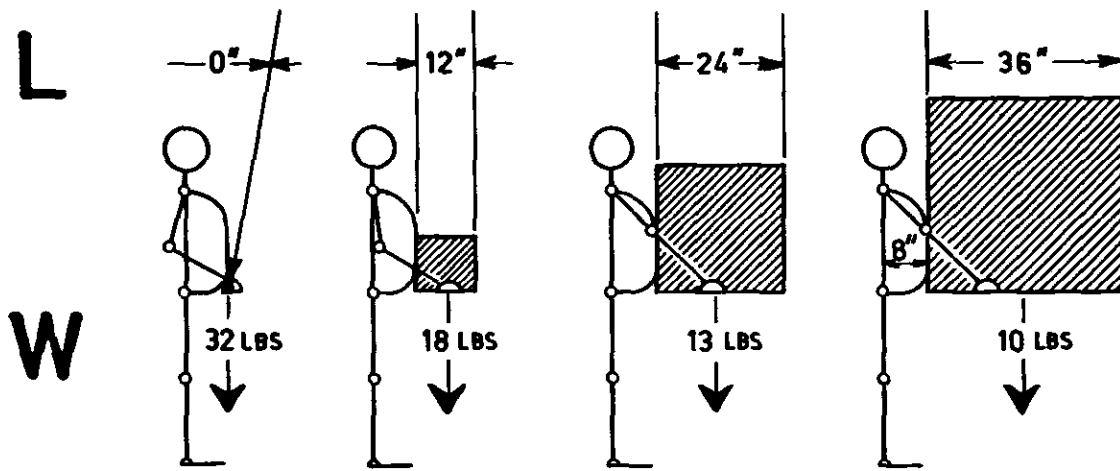
Posture

P1: Keep the elbows down. Unnecessary abduction of the upper arm, especially if maintained for extended periods of time, may have several undesirable side effects. It may also be produced through carelessness in workplace design in several different ways. For instance, if chair height is poorly policed, then a seat height only three inches too low with respect to the work surface will produce an angle of abduction of the upper arm of approximately 45° (Figure 32-21).^{36, 37} When this is the case, then a wrist movement at the workplace normally performed by rotation of the humerus would require a physically demanding shoulder swing. The resulting fatigue over several hours may reduce the efficiency rating by as much as 50%. Also when the seat is too low, especially in assembly operations, the left arm is frequently used as a vise, and the right hand to manipulate objects. Then after an hour or two, particularly under incentive conditions, some vague sense of discomfort over the origin of the left pectoralis and deltoid muscles, which stabilize the abducted arm, may be felt. This can lead especially in elderly and overweight workers, or those with heart conditions, to an unjustified fear of an impending heart attack and all the ensuing undesirable emotional difficulties (Figure 32-22).

P2: Keep moments acting on the vertebral column low. Lifting stress is not solely the result of the weight of an object handled. Its magnitude must be expressed in terms of "Biomechanical Lifting Equivalent" in the form of a "moment." This relationship, when holding a load upright, can be roughly estimated by taking 8 inches as the thickness of the human body plus half the length of the load, again in inches. The sum will approximate the distance of the center of mass of the load from the lumbar spine. Very often a light but bulky object (Figure 32-23) may impose a heavier lifting stress than a heavy load of great density.

P3: Avoid covert lifting tasks. Physiologically a lifting task exists when, for any reason whatsoever, a moment is applied to the vertebral column. This frequently includes situations where only body segments are moved but no object is lifted (Figure 32-24). Then man becomes an analog of the crane and the same mechanical considerations with respect to load supporting capacity apply to both. When bending over, the weight of the body segment moved — in this case, the trunk — may impose a far greater lifting stress than the load itself. Likewise, there are work situations where everything is stacked high and closely arranged in semicircular fashion around the worker. This requires holding up of the arm and thus applying a torque on the shoulder joint for extended periods of time. This may produce pain in the lumbar region because the torque is transmitted through the stabilized shoulder via the vertebral column onto the lumbo-sacral joint. Other examples will be discussed in a separate section on back problems.

P4: Scanning should require eye movement only and not necessitate simultaneous head motion. Only under conditions of binocular vision is it possible to estimate correctly and/or easily true



$$\left(8 + \frac{1}{2}L\right) (W) = M_e \approx 250 \text{ INCHPOUNDS}$$

Tichauer, E. R.: Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

Figure 32-23. The "Moment Concept" Applied to the Derivation of Biomechanical Lifting Equivalents. All of the loads represented in the figure produce approximately equal bending moments on the sacro-lumbar joint (approximately 250 inch pounds). 8=approximate distance in inches from the joints of lumbar spine to front of abdomen (i.e., a constant for each individual). L: length in inches of one side of a cube of uniform density lifted during the standard task. W: the weight in lbs the cube handled. M_e : the biomechanical lifting equivalent (here approximately 250 inch pounds).³⁵

or relative distances or sizes of objects. Binocular vision without head movement can take place only within a cone of 60° included angle, the axis of which is originating from the root of the nose and is located in the midsagittal plane of the head (Figure 32-25). Often head movement at the workplace constitutes a "protective" reaction necessary to reestablish binocular eyesight whenever the visual target is located outside of the cone. Simultaneous eye and head movements take much time, and this may produce a hazard whenever fast-moving equipment (motor vehicles, airplanes, conveyors) are operated. Furthermore, whenever head movement is restricted (e.g., eyeglasses or arthritic lesions in the neck), then if objects of manipulation are located outside the visual cone of 60°, problems of eye-hand-head coordination will ensue.

P5: A musculo-skeletal configuration conducive to maximal biomechanical efficiency should be maintained. Unless the individual members of a kinetic chain involved in the performance of a task are optimally positioned and aligned, with respect to each other as well as with any equipment controls employed, considerable work strain may result, even under conditions of light work. Of especial importance in this respect are angles formed between long bones (Figures 32-11 & 32-14).

Man-Equipment Interface

E1: *Do not restrict circulation.* Both the designer as well as the evaluator of tools and equipment should be familiar with the location of the principal and vulnerable blood vessels. Otherwise circulation may be inadvertently impaired and localized ischemia can result. Of especial importance is the protection of the blood vessels in the hand. For example, a poorly designed or improperly held scraping tool (Figure 32-26) may squeeze an important blood vessel, the palmar arch, between handle and the hamate bone. Numbness and tingling of the fingers will follow.

E2: *Vibrations transmitted at the man-equipment interface should not lead to somatic resonance reactions.* White Finger Syndrome, or intermittent blanching and numbness of the fingers, sometimes accompanied by lesions of the skin, has been identified for many years as an occupational disease associated with the operation of pneumatic hammers and other vibrating tools.^{38, 39} Vibrations of low frequency and quite low intensity can make the whole body, body segments or individual viscera vibrate at harmonic resonance frequencies.⁴⁰ The resulting symptoms may simulate a wide range of musculo-skeletal and organic diseases such as back pain, respiratory difficulties, cardiac distress or minor ailments such as visual disturb-

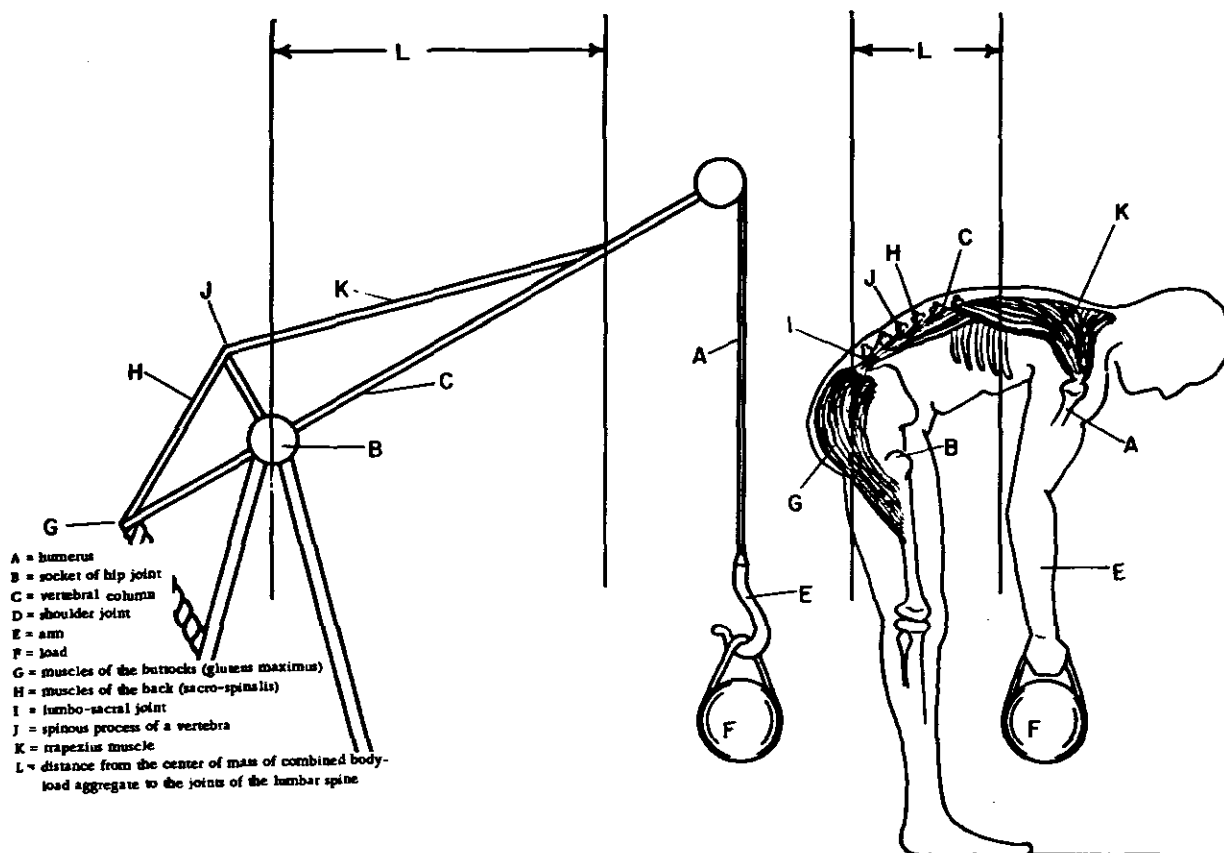


Figure 32-24. IN LOAD-LIFTING, THE STRUCTURAL ELEMENTS OF MAN ARE ANALOGOUS TO THE STRUCTURAL ELEMENTS OF A CRANE. The same mathematical techniques can be applied to predict performance of either of them.¹⁸

ances.⁴¹ Reliable literature⁴² and experienced expert advice should be consulted whenever vibration transmittal between equipment and the human body is a possible cause of manifestations of ill health.

E3: Moving parts of the body should not be constrained by rigid supports. Where extensive movement of the trunk in the sagittal plane is required, an improperly located backrest will produce bruises. Likewise, a firm arm rest supporting a moving elbow will lead to swelling and inflammation.

E4: Stress concentration on small skin areas or small joints should be avoided. In many industries a trend towards miniaturization, mechanization and automation is conducive to the ever-increasing introduction of highly localized work stress. Often simple remedies will help to prevent penetration of the skin, calluses, or the aggravation of joint disease. The tailor's thimble is one good example. Often the introduction of simple cushioning devices such as foam rubber or springs underneath pushbuttons can reduce or eliminate trauma to the distal interphalangeal joints of the fingers. Even the prevention of soreness of the fingertips may facilitate or accelerate training programs for the technologically obsolescent in a

pushbutton-oriented society. Finally, formfitting handtools or equipment handles often fit only one hand perfectly: the hand of the designer. When used by individuals with larger or smaller hand dimensions, contour features may cut into the body surface and produce localized stress concentrations.

E5: Ergonomic checklists should always be consulted whenever handtools are designed, modified, selected or evaluated. The most frequent, as well as most intense, contact between man and equipment occurs normally at the handtool interface. The design features of a nontraumatogenic handtool are complex and an ergonomic checklist is presented as a separate section of this chapter.

Effective Kinesiology

K1: Avoid deviation of the wrist while moving or rotating the forearm. Tools are occasionally designed in such a manner as to demand deviation of the wrist towards the ulna or the radius during operation (Figure 32-27). This affects both health as well as efficiency. The principal flexor and extensor muscles of the fingers originate in the elbow region and are connected with the phalanges by way of long tendons. The extensor tendons are held in place by a confining transverse ligament on the dorsum of the wrist while the

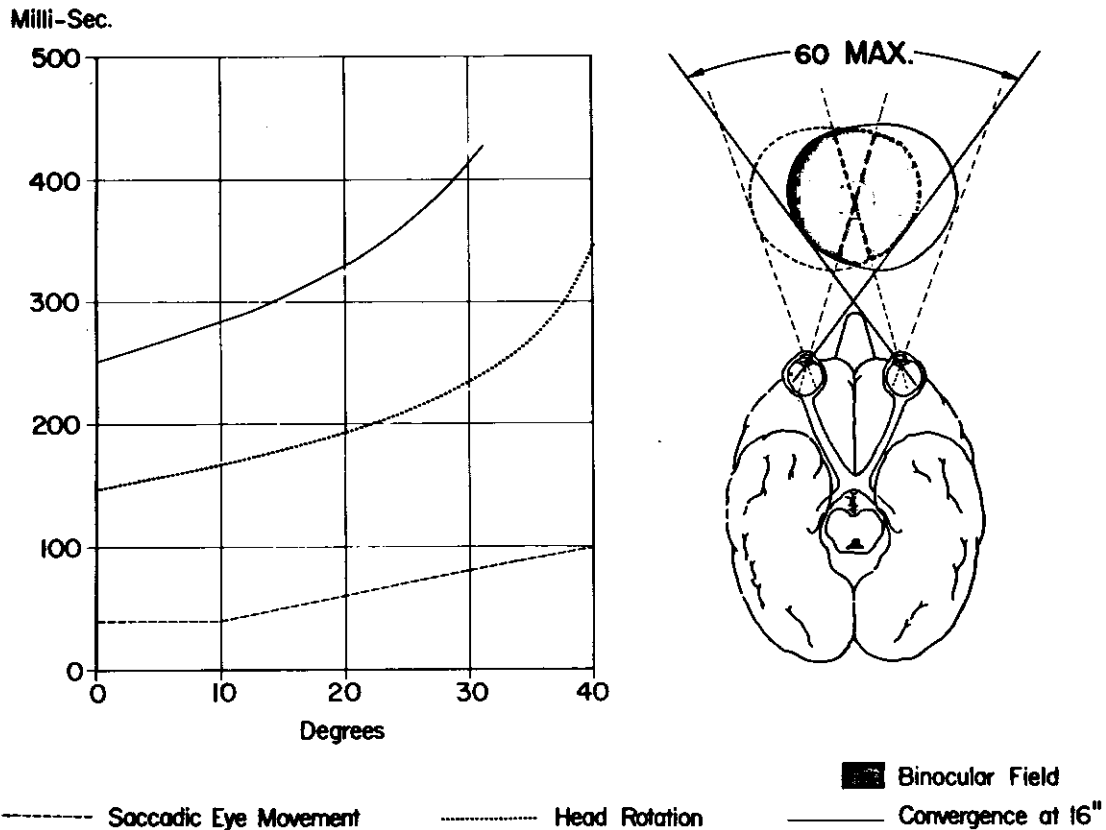


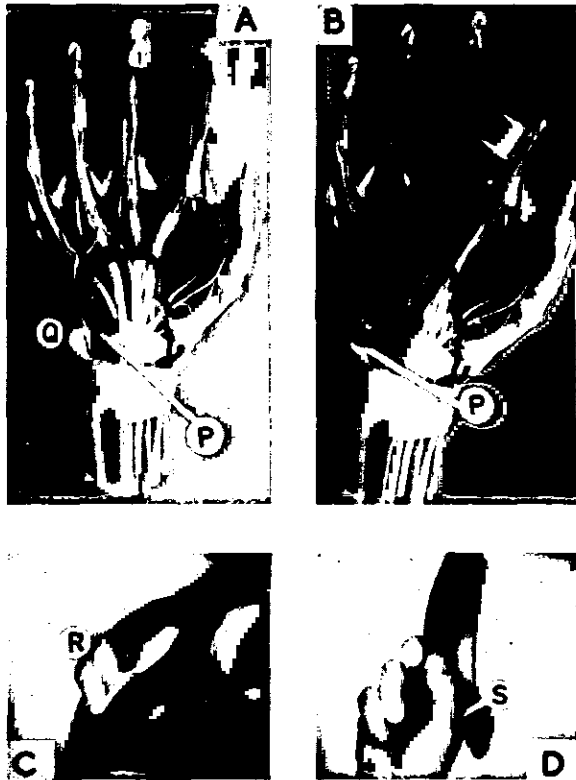
Figure 32-25. "EYE TRAVEL AND BINOCULAR VISION" (RELATED TO SPEED AND QUALITY OF PERFORMANCE).

flexor tendons on the palmar side of the hand pass through a narrow carpal tunnel which contains also the median nerve. Deviation of the wrist towards the ulna causes these tendons to bend and to become subject to mechanical stress underneath the ligament and in the tunnel. This is conducive to tenosynovitis. Likewise, this skeletal configuration favors ulnar drift of the extensor tendons which is highly undesirable when a hand is already afflicted with even very light arthritis. When such a tool is used in jobbing operations for only a few minutes every working day, then generally no ill effects are experienced. However, when continuous operation under production conditions is demanded, ulnar deviation constitutes a hazard to the health of the working population, and it should be remembered that it is much safer to bend the tool than to bend the wrist. If, however, ulnar deviation is overcompensated so that the wrist becomes deviated towards the radius, then the hazard of "tennis elbow" is introduced. This risk is particularly high when a work situation demands the simultaneous dorsiflexion and radial deviation of the wrist. Furthermore, deviation of the wrist reduces the range of rotation of the forearm and hand (Figure 32-28). As much as 50% of the useful range of motion may be lost through wrist deviation. Whenever screws have to be inserted or panels wired, the number of wrist movements necessary to perform that task will

have to be doubled because of the lost range of motion. This is conducive to early fatigue and difficulties during training.

K2: *Avoid forward reaches exceeding 16 inches.* Most systems of predetermined motion times in common use in industry for the purposes of workplace layout postulate that reach time is a linear function of reach length.⁴³ This, however, applies only to young individuals with a high degree of physical fitness. In a middle-aged working population, where the vertebral column exhibits already the signs of the normal wear and tear of life, in woman during the premenstrual and menstrual period, and in individuals afflicted with light arthritic conditions of the vertebral column, a reach in the sagittal plane exceeding 16" constitutes a severe covert lifting task and causes reach time to increase proportionally to the square of the reach length (Figure 32-29). Under such conditions, certain groups of workers will not only be at a competitive disadvantage, but will suffer severe physical discomfort when trying to keep up with younger and more physically-fit workers. It is often easy to arrange the workplace in such a manner as to obviate excessive reach length.

K3: *When the motion element "Transport Loaded" has to be performed in the sagittal plane, then the movement should be directed towards the body and not away from it.* The protagonist muscles of forward flexion of the upper arm oper-



Tichauer, E. R.: Ergonomics: The state of the art. Amer. Ind. Hyg. Assoc. J. 28:106-16, 1967.

Figure 32-26. Ergonomic Considerations in Hand Tool Design. A, the relations of bones, blood vessels, and nerves in the dissected hand. B, a paint scraper is often held so that it presses on a major blood vessel (P) and directs a pressure vector against the hook of the hamate bone (Q). C, in the live hand, this results in a reduction of blood flow to, among others, the ring and little fingers, which shows as a darkening on infrared film (R). D, a modification of the handle of the paint scraper causes it to rest on the robust tissues between thumb and index finger (S), thus preventing pressures on the critical areas of the hand.⁷

ate at biomechanical disadvantage. Their antagonists are the large and powerful muscles of the back and this, in balance within the kinetic element, makes a sagittal forward reach per se an undesirable motions element. The transport of even a relatively light object, by means of the hand away from the body in the direction of the sagittal plane leads to early fatigue, loss of precision of movement and ultimately great discomfort in the shoulder region. Such disposal movements are best performed at an angle of 45° to the sagittal plane or in the coronal plane (Figure 32-30). K4: *Holding and manipulation are mutually exclusive operations.* The arrangement of muscles, tendons and ligaments which make possible the

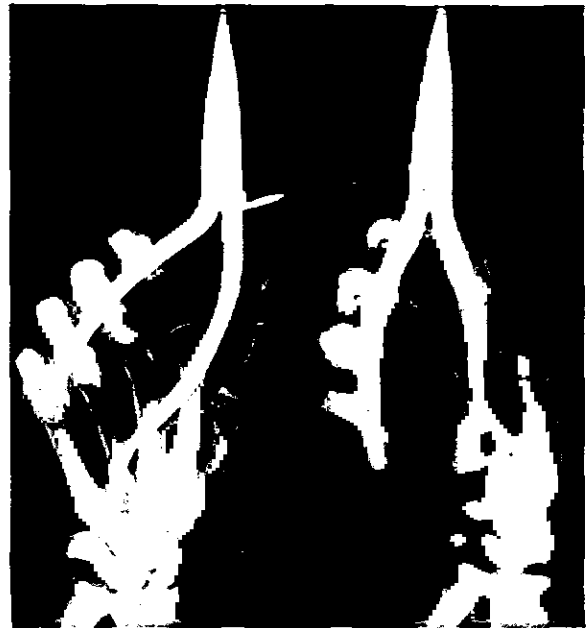


Figure 32-27. STRAIGHT-NOSE PLIERS PRODUCE STRONG BENDING MOMENTS IN THE WRIST. Neither the axis of rotation nor the axis of thrust correspond with the corresponding axes of the limb. A tool with a bent nose eliminates these faults.¹⁸

use of the hand for "work" is complex. The fully flexed wrist, among other reasons because of pre-tensing of the extensors of the fingers, does not permit an effective wraparound grasp (Figure 32-31).⁴⁴ Under opposite conditions, when the wrist is fully hyper-extended, the configuration of the wrist joint, tension in the flexor muscles of the fingers, and the mechanical disadvantage of the small intrinsic muscles of the hand, do not permit the effective use of the distal phalanges for fine manipulative movements.

When the wrist is fully extended, but not hyper-extended, there is 100 percent grasping power, 50 percent holding power, and 50 percent manipulative effectiveness. In full flexion of the wrist, the hand is 100 percent effective in manipulation but has almost no holding power.

The strong dependence of the effectiveness of the hand on skeletal configuration may produce situations where a machine control can be tightened or loosened effectively by a right-handed person, but can be completely unmanageable by a left-handed one. Often such job difficulties for left-handed people may be eliminated by creating a work situation without postural restraint as far as the wrist is concerned. Whenever a task requires a mixture of both holding and manipulation such as is frequently the case in the operation of vises, fixtures, dials to be adjusted, then these controls should be located so that they can be operated effectively by both the right as well as the left hand. Often a simple bend in a lever or the positioning of a dial at an angle will accom-

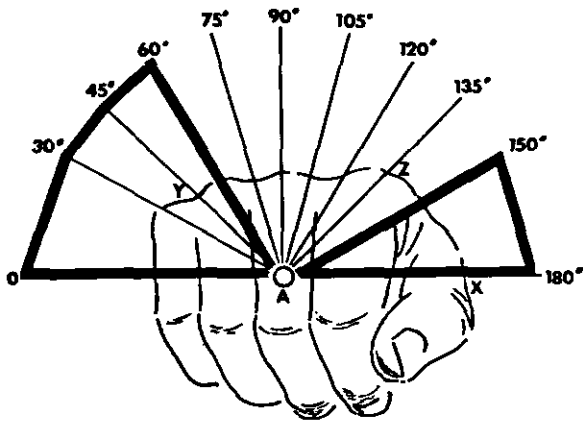


Figure 32-28. Ulnar deviation of the wrist reduces normal range of pronation-supination from 180 degrees to 90 degrees, thus doubling the number of movements necessary to perform a pronation-supination task. Fatigue or, even worse, occupational trauma may ensue. (Adapted from *Industrial Engineering Handbook*: H. B. Maynard, editor, McGraw Hill Book Co., 1963. p. 5-23).

plish this. About 25% of the working population are left-handed.

K5: Motions should be terminated by positive external stops rather than by voluntary muscular action. It is well-known that termination of hand movement with precision, especially when high speed is demanded or incentive conditions are involved, can lead to performance difficulties. Well-known systems of predetermined motion times make allowance for a "positive stop work factor," recognizing the need to facilitate the precise termination of hand movements by positive contact with an external stop. This important sensory facilitation can be achieved through diverse, physically quite different devices (Figure 32-32). In each and every case it will reduce the need for voluntary control over precision of movement and often will reduce performance times. This is of especial importance to the young worker who is inexperienced, those with little innate manual dexterity and the elderly who are developing tremors or show the beginnings of not yet clinically important bone and joint disease. Especially under incentive conditions, or where the possibility of dismissal because of failure to meet efficiency demands exists, these working populations may develop emotional reactions such as nervousness, or abrasiveness, in contact with fellow workers unless sensory facilitation produced at positive stops enables them to perform again at competitive levels. Not infrequently the absence of positive stops produces intense nervousness, especially when the job security of a worker depends on his ability to maneuver a fragile object into a narrow space. Such physiological responses

may include fluctuations and increases of heart rate and variations in respiratory parameters.

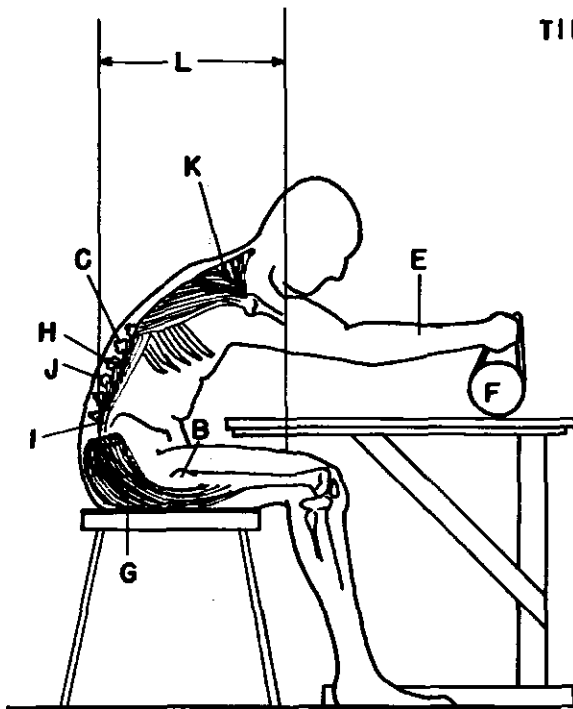
Not all of the above-listed "Prerequisites of Work Tolerance" are applicable to all work situations and all individuals. They provide, however, a convenient checklist for the analysis of existing or planned work situations in order to insure that human needs for peace of mind, physical comfort, occupational safety and health have not been sacrificed for the sake of short-term expediences such as the need to maintain high performance speed over short periods of time. Where the majority of prerequisites of work tolerance are applied (Table 32-2), there is a better labor-management relationship. Likewise, improvement of the general physical and emotional health of the working population as well as an increment in economic efficiency, and higher levels of product quality will be observed.

HANDTOOLS

The basic tools used today by man as well as the basic machines were invented in the dawn of the prehistoric age and evolved over many thousands of years. However, the contemporary and very rapid rate of industrial and technological development demands frequently "instant" creation of new and specialized implements through efficient design rather than by evolution. This section considers both hand tools as well as equipment controls since the latter are merely the "tools" which permit the operation of machinery. Also, the functions of tools are varied and their shapes diverse. There are many principles of biomechanics and ergonomics which need to be considered in the selection and evaluation of almost all kinds of tools, no matter how different their fields of application. Some of the material presented here has been mentioned elsewhere in this chapter. It is, however, by no means redundant, as such repetition where it occurs, emphasizes the relevance of ergonomic and biomechanical factors upon the selection and evaluation of the most commonly used implements in industry, tools and equipment controls.

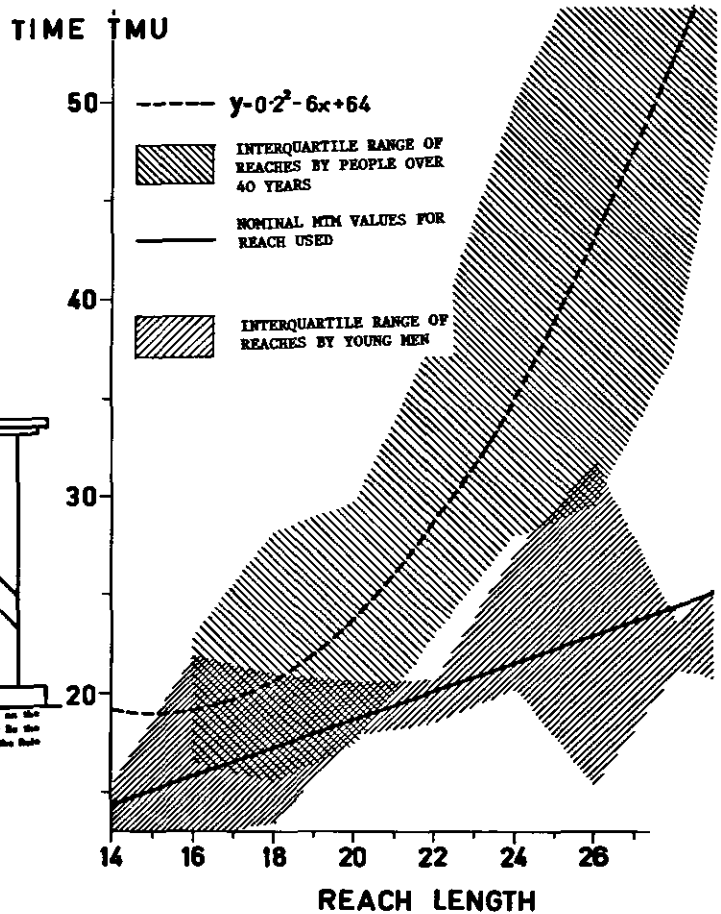
Force Optimization

The prime purpose of primitive tools was to transmit forces generated within the human body onto a material or workplace. In the course of artisanal and industrial development, this purpose was widened so that tools should now be designed to extend and reinforce range, strength, and effectiveness of limbs engaged in the performance of a given task. The term "extend" as used here is not restricted to the meaning of magnification and amplification because often a tool makes possible a far finer movement than the unarmed hands would be capable of performing (e.g., tweezers, screwdriver) and sometimes it enables the application of a grip or grasp soft enough so as not to injure a workpiece as is the case in a suction tool so often used to transport small and fragile components. A micromanipulator of the "master-slave" type is another good example of a tool which serves as an attenuator rather than as an amplifier of human force and motion.



Awareness of the "Hidden" Lifting Task Should Exist, Because of Higher Torques Exerted on the Lumbar Spine, a Seated Job, Instead of Being "Light Work." Here Is the Physiological Equivalent of a Severe Lifting Task, in Seated Work, the Rule Is: "Get the Job Close to the Worker." (Adapted from [43])

- A = Humerus
- B = Socket of Hip Joint
- C = Vertebral Column
- D = Shoulder Joint
- E = Arm
- F = Load
- G = Stool
- H = Muscles of the Back (Rhomboid Muscles)
- I = Lumbo-Sacral Joint
- J = Spinous Process of a Vertebra
- K = Trapezius Muscle
- L = Distance from the Center of Mass of Combined Body-load Aggregate to the Joints of the Lumbar Spine



Tichauer, E. R.: Industrial engineering in the rehabilitation of the handicapped. J. Ind. Eng. XIX:96-104, 1968.

Figure 32-29. The Interquartile Range of 1200 Reaches in Sagittal Direction Performed by Individuals above 40 Years of Age Fitted Well to a Quadratic Equation. A control experiment where a like number of reaches was performed by young men showed agreement with MTM data. A system of predetermined motion times for the elderly worker remains still to be developed.

In an endeavor to provide maximum mechanical advantage, equipment designers frequently maximize through effective use of the principle of the lever, the ratio of force output from the tool divided by the force input from the hand. This, however, can be easily overdone, because the force output should also provide sufficient sensory feedback to the muscular-skeletal system in general and the tactile surfaces of the hand in particular. In a thread-tapping job, for instance, if this ratio is too large, the force applied may be excessive resulting in either stripped threads or broken taps and bruised knuckles. If, on the other hand, the ratio of force output over force input is too small, then an unduly large number of work elements will have to be repeated to complete a job such as is the case in the pounding of a large nail with too small a hammer. A tool should also produce an optimal stress concentration at a desired location on the workpiece. Thus, up to a certain limit,

an axe should be as finely honed as possible to fell a tree with the minimum number of strokes, but the edge should not be so keen as to require frequent sharpening or to be fragile.

Finally, the shape of the tool should be such as to insure that it is automatically guided into a position of optimal mechanical advantage where it will do its job best without bruising either hand or workpiece. The Phillips Screwdriver as compared with the ordinary flat blade tool is a good example of such efficient design.

Distribution of Pressures and Stresses

The use of handtools causes generation of a large variety of stress vectors at the man-equipment interface. These may be mechanical, thermal, circulatory or vibratory and have a tendency to be propagated to other points within the body. Thus, awareness that work strain and the resulting trauma often show up at points quite remote from the locus of work stress application must be

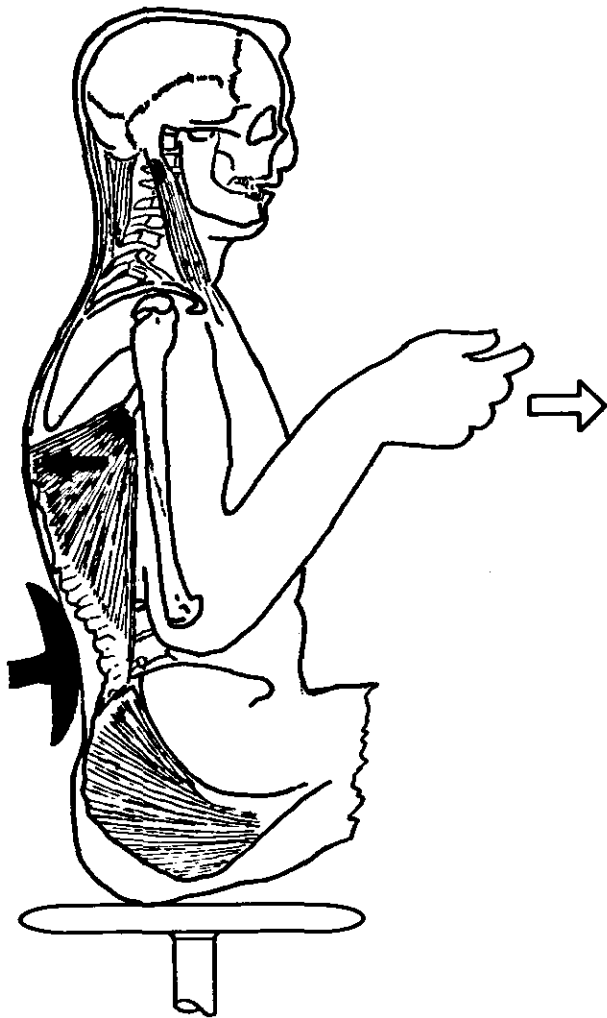


Figure 32-30. The disposal of objects in a direction away from the body and in the mid-sagittal plane is conducive to discomfort and early fatigue because of the strong antagonist activity in the latissimus dorsi muscle.

kept constantly in mind.⁴⁵ Contact surfaces between the tool and the hand or other live tissues should be kept large enough to avoid concentration of high compressive stresses. Pressures should be distributed over sufficiently large skin areas so that both ischemia as well as mechanical trauma to nerves are avoided. Care should be exercised to avoid all but the mildest possible compression against those areas of the hand which overlie particularly vulnerable blood vessels and nerves (Figure 32-33). "Form-fitting" should be a feature employed only sparingly in the design of handles and all anthropometric factors of relevance should be considered so that the handle does not fit only the hands of the designer properly. Likewise, it is advantageous to use the tough tissue located at the vertex of the angle formed between the spread thumb and index fingers as one of the skin areas capable of supporting large pressure and other physical stress.⁴⁶ Whenever

finger grooving is employed as a device to facilitate firm gripping of a tool, then it should be shaped in such a manner as not to lead to stress concentration on the interphalangeal joints when oversized or undersized hands must hold the implement (Figure 32-34). Therefore, the selector and evaluator of handtools should be provided with and trained in the use of an atlas of the anatomy of the hand and be fully familiar with shape and location of those anatomical structures which relate to the long term and short term safety of handtool usage.

Consideration of Working Gloves

Many undesirable results may stem from improper fit and/or design of working gloves. These may lead to low efficiency and certain health hazards; but a false impression may be generated that these discomforts, poor workmanship and increased tendency towards injuries, could be due to poor tool design. Unsuitable working gloves are likely to be associated with one or more of the following areas of concern resulting in hand-tool usage:

1. *Loose gripping of tools.* It is impossible to close the hand without causing the interphalangeal surfaces of the fingers to abut against each other (Figure 32-35). The skin between the fingers is particularly richly endowed with nerve end organs which transmit sensory feedback to the central nervous system. Strength of grip may well be dependent upon pressure between the fingers. If the working glove is too thick in this region, high pressures at the interdigital surfaces may be generated before the hand is firmly closed about the tool handle or equipment control and these may then be insecurely grasped. Awareness of this lack of firmness of hold may cause many individuals to grip unnecessarily tightly and firmly which results in increased fatigue and other undesirable side-effects. Also, if a working glove is too thick, the fingers may not be able to wrap around the handle sufficiently for a firm hold. The detrimental effect of overdesigned working gloves becomes most apparent when pulling cables or holding firmly onto smooth rods.
2. *Carpal tunnel considerations.* The carpal tunnel is a channel in the wrist through which important nerves, blood vessels and tendons pass into the hand (Figure 32-36). Pressure, generated by overly tight or too stiff cuffs of working gloves, on the tunnel itself or on the areas immediately proximal or distal to it may result in one or more of the following: ulnar tenosynovitis; impairment of blood supply to the hand and, consequently, coldness, numbness and tingling of the fingers. The fit of working gloves should be checked before tool design or workload are considered as a possible cause for the aforementioned symptoms. There is a well-known disease entity, the "carpal tun-

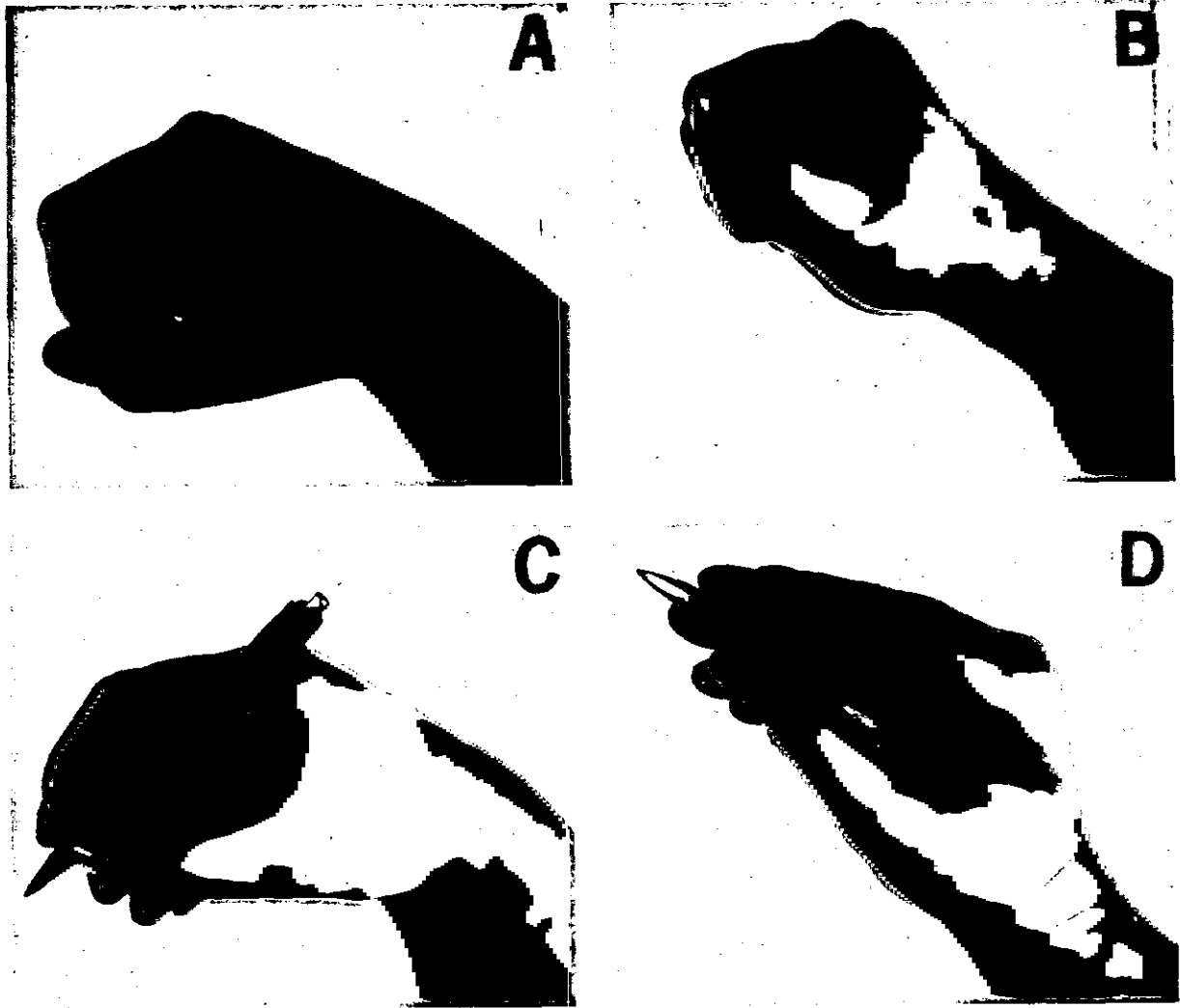


Figure 32-31. The flexed wrist (A) cannot grasp a rod firmly, while the straight wrist (B) can grip and hold firmly. Conversely the flexed wrist (C) is well positioned for fine manipulation, but when extended (D) freedom of finger movement is severely limited.

nel syndrome." This can be aggravated through poorly designed working gloves; but may not have been caused by either gloves, tools or workplace design.

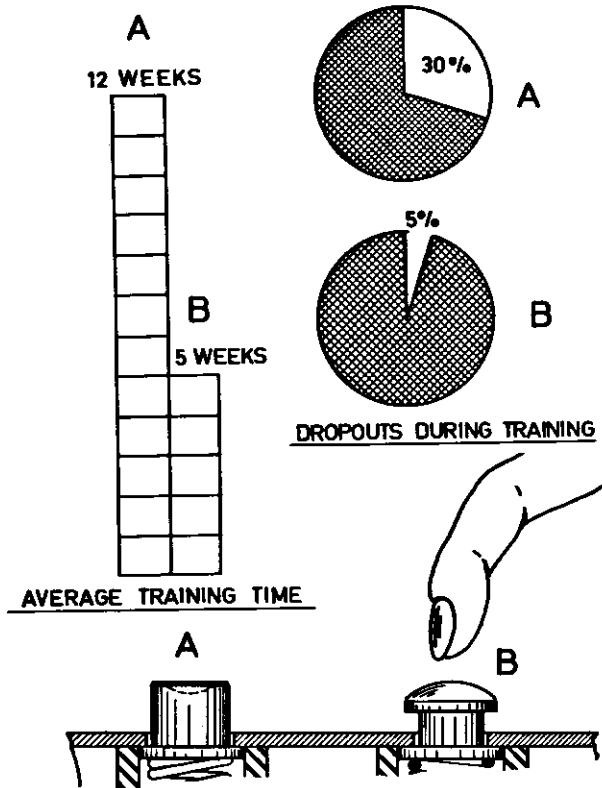
Selection and Evaluation of Tools Based on Biomechanical Design Considerations

Repetitive maneuvers and the resulting cumulative work stress are far more frequent causes of occupational trauma than spontaneous overexertion.

Frequently observed in this connection is tenosynovitis. This may be due to biomechanical overstress or an infectious process. Both overuse of the hand as well as unaccustomed usage are associated with tenosynovitis and some consider it a "training disease." Industrial physicians often resort to a medically-imposed restriction of performance levels once the disease has been diagnosed.⁴⁷

Tenosynovitis is most frequently observed on

the back of the hand where it involves the extensor tendons. It is not a "training disease," but a definite sign of overstress which should be corrected by changes in tool design or workplace layout. Whenever changes in the design of the working environment and implements are not feasible, then reduction in task demands such as lowering the required output or changes in work rhythm should be considered as possible means to reduce tenosynovitis. As another alternative, "job enlargement"⁴⁸ may be tried. Then members of the exposed working population will not be performing the "suspect task" throughout the entire working day, but will be rotated periodically to workplaces which are less conducive to excessive cumulative work stress imposed upon the wrist. Equipment used under circumstances where repetitive rotation of the wrist against resistance is required should allow the task to be performed without ulnar deviation. Ulnar deviation favors



Tichauer, E. R.: Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

Figure 32-32. Sensory facilitation of positioning can be achieved in many ways, be it by enlargement of contact surfaces "B", or sometimes by the flaring of inlet holes. Such facilitation will result in the reduction of training time as well as in an increased number of individuals capable of learning a new operation without fatigue or discomfort. Adapted from (35).

"drift" towards the ulna of the extensor tendons, exposing these and the surrounding tendon sheath to compressive stresses. Likewise, on the palmar side of the wrist, those tendons, nerves and blood vessels which pass through the carpal tunnel are subjected to similar stresses in ulnar deviation (Figures 32-27 & 32-36).

A pre-existing risk of tenosynovitis, be it due to the anatomy of the operator, or due to working conditions, may be enhanced whenever strong palmar flexion of the wrist is demanded concurrently with ulnar deviation. Since tool-wrist-forearm configuration is often a function of the proximity of the worker to the workbench, or the location of the chair, close attention should be paid to these extraneous potential causes of handtool imposed work stress.

Dorsiflexion of the wrist while the forearm is pronated should be avoided. This combination predisposes to radio-humeral bursitis (i.e., "tennis elbow"). To exert excessive stress on the el-

bow joint by this configuration, repetitive pronation and supination of the forearm need not be part of the task. Stresses on the radio-humeral joint, which may be potentially pathogenic, can be imposed also while the forearm is stabilized in pronation, such as when hammering overhead in an awkward position.

Generally speaking, tool-hand configurations which are conducive to motions like "laundry wringing," insertion of screws, looping of wires using pliers, or repetitive manipulation of switches or controls rotating coaxially with long rods, such as those found on the steering handles of motorcycles, require careful biomechanical analysis in order to avoid damage to forearm, wrist, and hand.

Many of those strong muscles which flex and extend the fingers come from the elbow region and are connected by tendons to the phalanges. Because of the peculiar construction of the tendon-tendon sheath system, a potential risk of "trigger finger" is imposed when any finger other than the thumb must be frequently flexed against resistance. This is true for both dynamic as well as isometric flexion. The level of exposure is increased when a tool handle is so large that the distal phalanx must be flexed before the more proximal phalanges can be flexed and repositioned (Figure 32-37). "Trigger Finger" is the vernacular term for two different conditions, both having the same effect. Either overwork may result in the impression of a groove on the tendon where it enters a guiding tunnel in the hand, or alternatively a nodule may arise on sheath or tendon and lock the mechanism when it is squeezed within the sheath.

In either case, the flexor muscles are able to flex the finger against the resistance of the trigger mechanism, but the extensors are too weak to straighten it out after locking. The finger must then be extended by external manipulation and this extension is usually accompanied by a small click caused by the sudden release of a groove or nodule.

All trigger-controlled hand or power tools should be subject to careful biomechanical analysis. Often triggers can be replaced by push-buttons which can be operated easily by the thumb. Unlike the other fingers, the thumb is flexed, abducted and opposed by strong short muscles located within the palm of the hand. It can therefore actuate pushbuttons and triggers repeatedly and strongly without fatigue.

The handles of rotating tools should be positioned at an angle of roughly 120° with the longitudinal axis of the tool. This angle is desirable because the axis of rotation of the forearm runs from the lateral side of the elbow through a point located roughly at the base of the ring finger (Figure 32-38). However, the optimal axis for transmission of thrust runs from the base of the index finger through the center of the capitulum of the humerus. It runs parallel with the longitudinal axis of the forearm and at an angle of approximately 10° with the axis of rotation, while the "axis of grip" of the closed fist runs at an

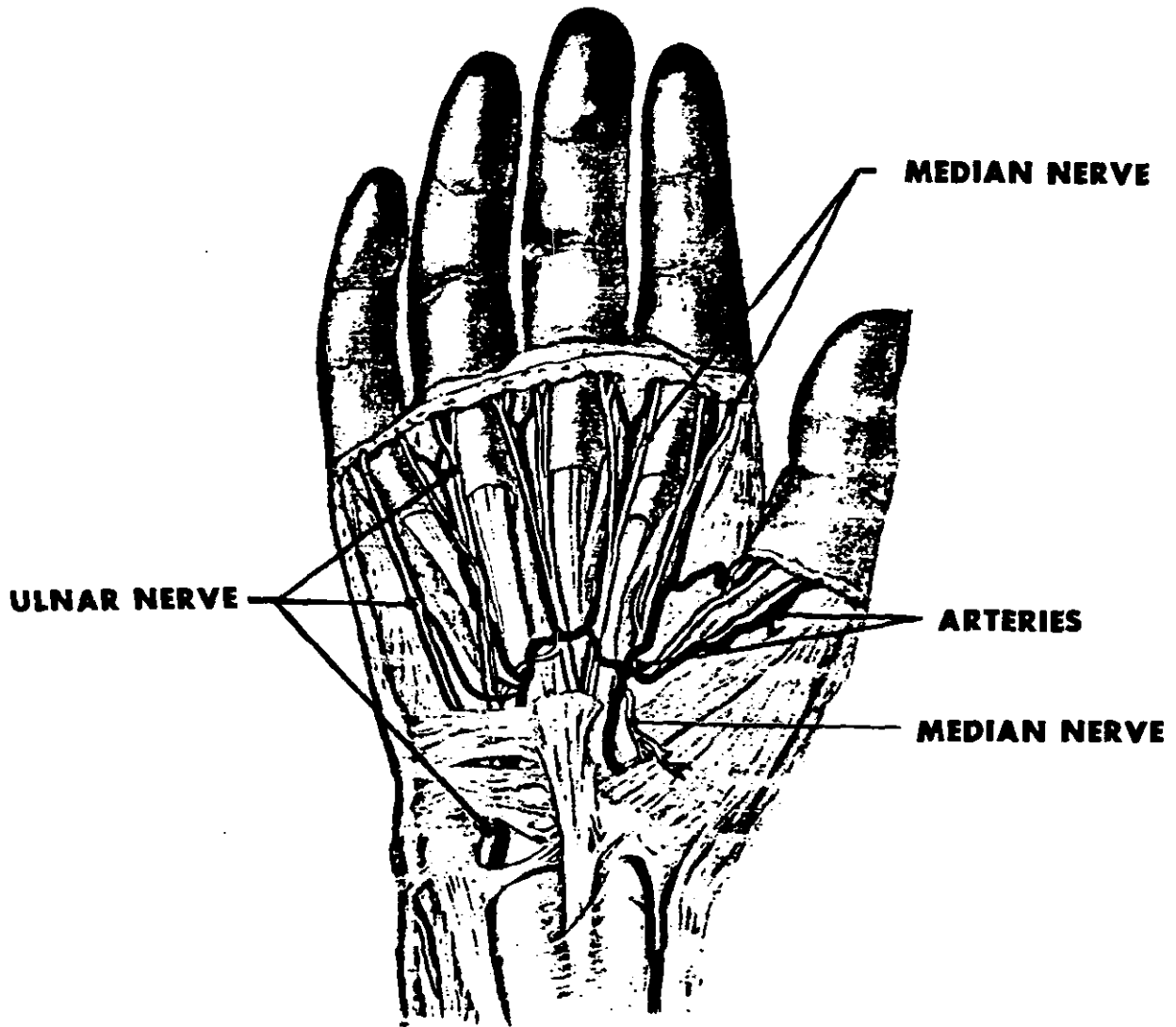


Figure 32-33. Position of the Most Important Arteries and Nerves in the Palm of the Hand.

angle of 70° with respect to the best line of thrust transmittal.

If thrust is required for the effective operation of a tool, then the implement should be designed so that this force vector is directed towards the base of the thumb and the broad distal end of the radius (Figure 32-38). Thrust should never be applied so that it acts against the heel of the little finger because this would produce a bending moment on the wrist which could cause fatigue, discomfort and, in extreme cases, trauma to nerves, tendons or blood vessels.

It is often possible to design a rotating tool so that its tip emerges from the hand between the middle and the ring finger, or if thrust is required, between the index and the middle finger. This, in spite of its occasionally awkward appearance, produces excellent results from the point of view of working comfort and endurance.

Optimal musculo-skeletal configuration of the forearm may frequently be achieved by bending the tool instead of flexing the wrist.

Materials and Weights for Tools and Handles

Tool weight should be determined according to the nature of the task to be performed. A tool housing vibrating components, especially pneumatic and power tools, should be sufficiently heavy to possess inertia adequate to prevent transmission of excessive vibration onto the human body. If this requires excessive weight, then recourse should be taken to suspension mechanisms and counterweights. The center of mass of heavy tools should be located as close as possible to the body of the operator in working posture and preferably on a transverse plane passing through the umbilicus (Figure 32-39). Materials for tool handles to be operated by the ungloved hand should be poor conductors of heat and electricity. All handles should have a surface texture rough enough to permit secure gripping and avoid slipping in operation. Handles should be hard enough so that they will not allow chips, small components, grit or injurious materials to be imbedded. They

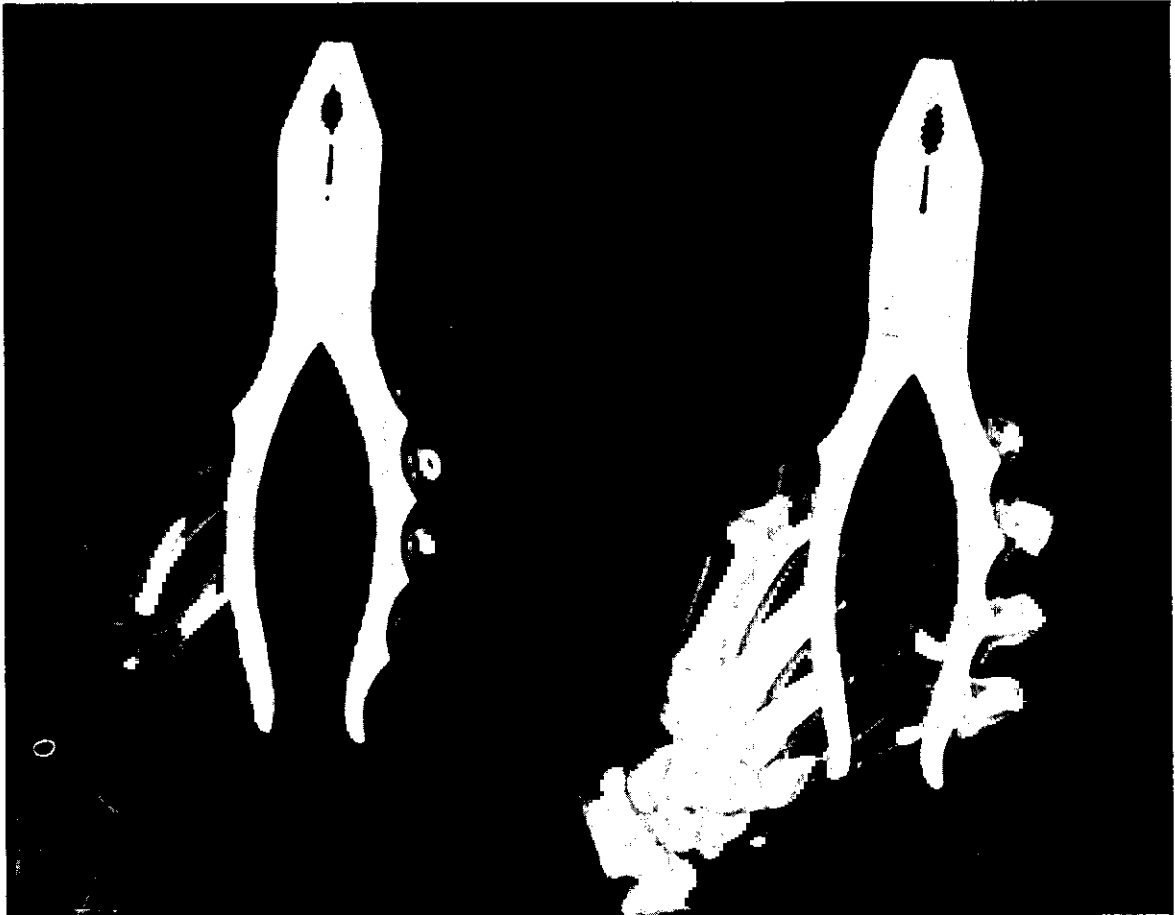


Figure 32-34. Form-fitting hand tools often fit only the hands of the designer. When an oversized or undersized hand grips a finger grooved handle, then undesirable pressure upon the surfaces of the joints may be exerted.⁴⁹

should also be made of nonporous materials so that they will not soak up or retain oils or other liquids.⁴⁹

Power Tools

The operating mechanism of most power tools are either reciprocating (i.e., vibratory) or rotary. They are operated by either compressed air or by electricity.

When selecting reciprocating or vibratory tools, the frequency and amplitude spectrum of the vibrations transmitted onto man should be evaluated.⁴⁰ The risk of somatic resonance response is highest when amplitude exceeds 100 microns within a frequency band between 3 to 125 Hertz. This has already been discussed in general terms under the heading of "Man-Equipment Interface." With respect to the operation and selection of hand tools, Raynaud's Syndrome (i.e., White Fingers) provoked at critical frequencies or potential exacerbation of developing bone and joint disease, deserves careful consideration.

When tools are activated by a rotating mech-

anism, the maximum torque transmitted upon the axis of rotation of the forearm should be below 12 inch-lbs. A 2-handed power tool should be designed with an angle of 120° between the gripping axes of both hands (Figure 32-40) for optimum operation when firmly held.

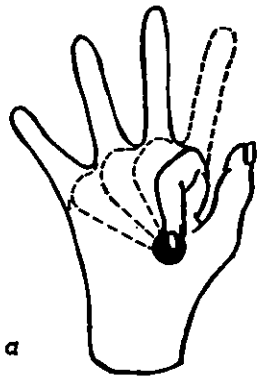
Tools powered by electricity should not be operable without a ground line which uses the third or middle prong of the power plug. Make-shift conversion from 3-prong to 2-prong adaptors should be prevented by appropriate plug and socket design.

MANUAL MATERIALS-HANDLING AND LIFTING

Almost one-third of all temporarily disabling injuries at work are related to the manual handling of objects.⁵⁰ Many of these are avoidable and are the consequence of inadequate or simplistic biomechanical task analysis.

The Elements of a Lifting Task

Relative severities of materials-handling operations and differences in lifting methods can only



Basmajian, J. V.: *Muscles Alive: Their Function Revealed by Electromyography*, 2nd Edition. Baltimore, The Williams & Wilkins Co., 1967.

Figure 32-35. The fingers buttress against each other when flexed.⁷⁷

be evaluated when all elements of a lifting task are considered together as an integral set (Table 32-3).

All these elements are of different mechanical dimensions (Table 32-4) but, nevertheless, have one basic property in common. Any change in

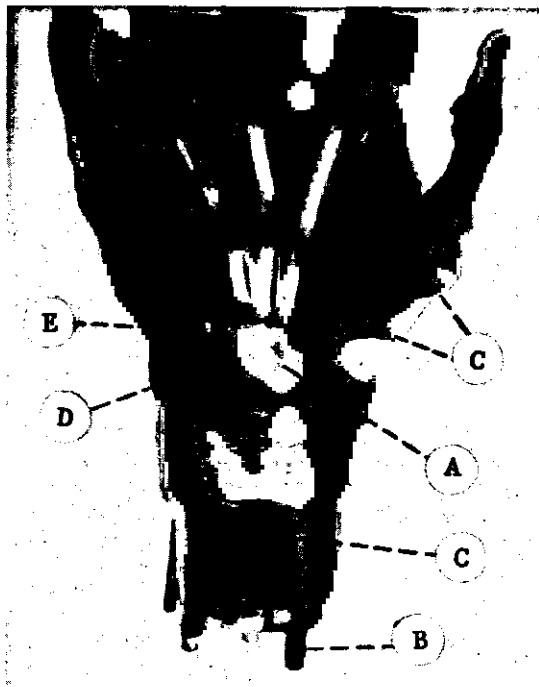
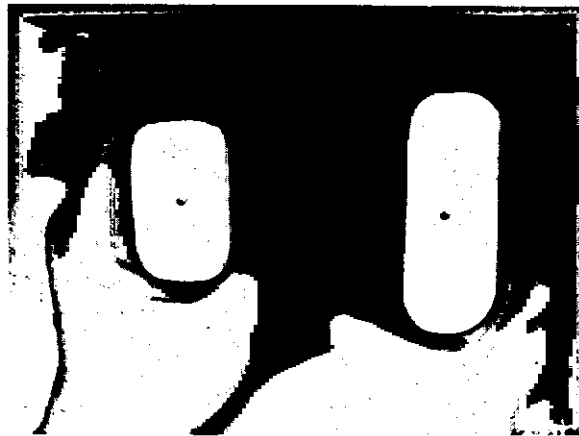


Figure 32-36. Through the carpal tunnel (A) pass many vulnerable anatomical structures: blood vessels (B) and the median nerve (C). Outside of the tunnel, but vulnerable to pressure are: the ulnar nerve (D) and a major artery, the palmar arch (E).



Tichauer, E. R.: *Gilbreth Revisited*. New York, American Society of Mechanical Engineers, 1966.

Figure 32-37. Too wide a pistol grip on an electric hand drill prevents a firm grasp because distal phalanx of a finger cannot be flexed strongly unless middle phalanx has been prepositioned by bending. A grasp around a handle which is too wide will produce large compressive forces on joints and may lead to joint disease or trigger finger if tool is used often enough and long enough.⁷⁸

magnitude of any element of a lifting task produces a change in magnitude of metabolic activity. Thus, no matter what the dimensions of mechanical stress imposed upon the human body during materials-handling are, the physiological response will result in increased energy demand and release, conveniently measured in "calories." Therefore, physiological response to biomechanical lifting stress has always the dimensions of work. Hence, the measurement of metabolic activity through computation of oxygen uptake per unit of time provides a convenient experimental method for the objective measurement of the relative severity of materials-handling and other chores. The current consensus⁵¹ assumes on the basis of an 8-hour working day, that the limit for heavy continuous work has been reached when oxygen uptake over and above resting level approaches 8 kilo-calories per minute. 6 kilo-calories per minute seems to be the upper limit for medium heavy continuous work while an increment of 2 kilo-calories per minute appears to be the dividing line between light and medium-heavy work (Table 32-5).

However, application of metabolic measurement is often not possible. The procedure requires expensive equipment, great expertise and is often difficult to perform on the shop floor. Furthermore, the objective assessment of work stress through the analysis of respiratory gases is an ex post facto procedure. The job exists already and its energy demands are computed so that possible corrective action may be considered. It is, of course, much better to analyze a task objectively while both job as well as workplace layout are

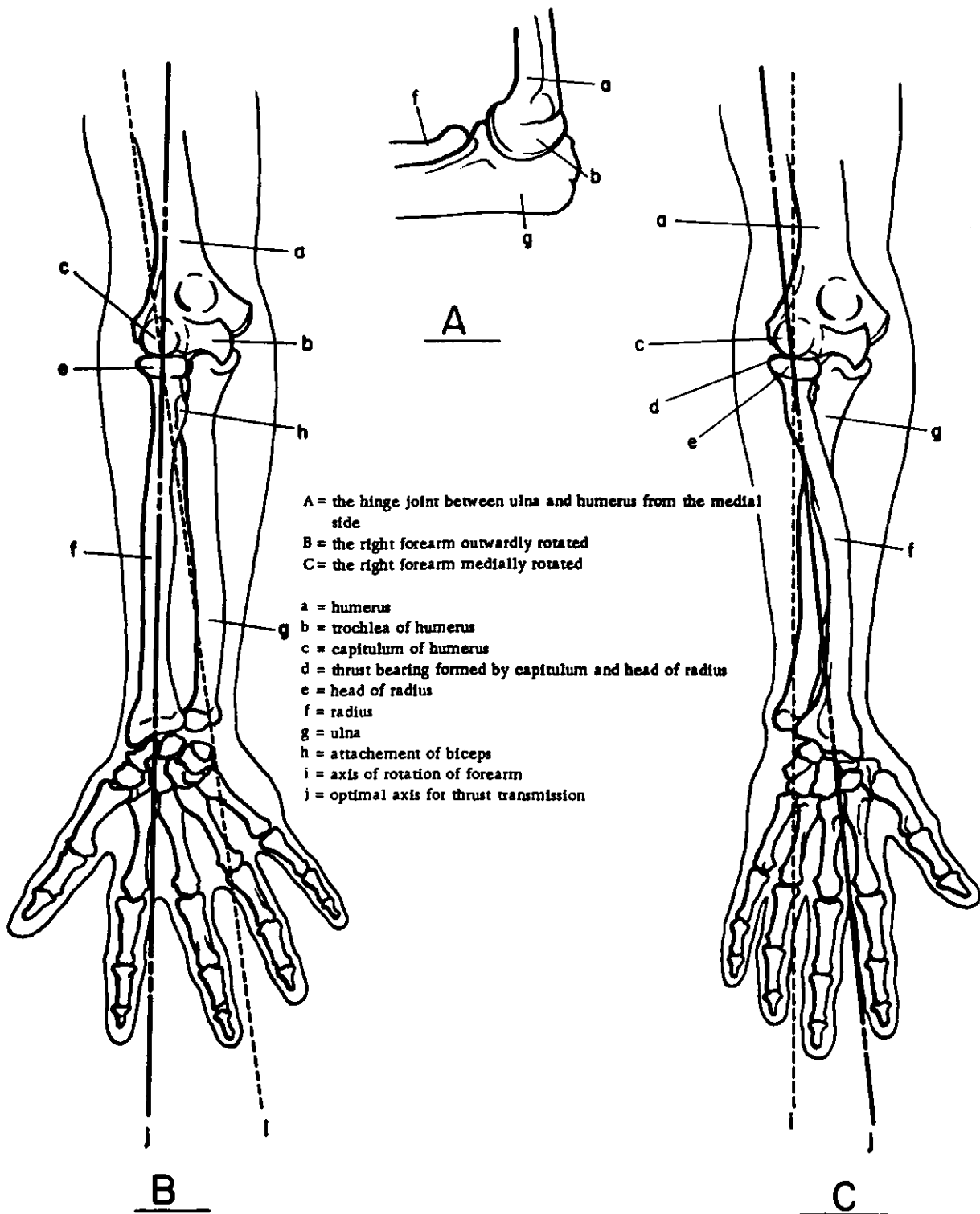


Figure 32-38. THE CONSTRUCTION OF THE SKELETON OF THE FOREARM.

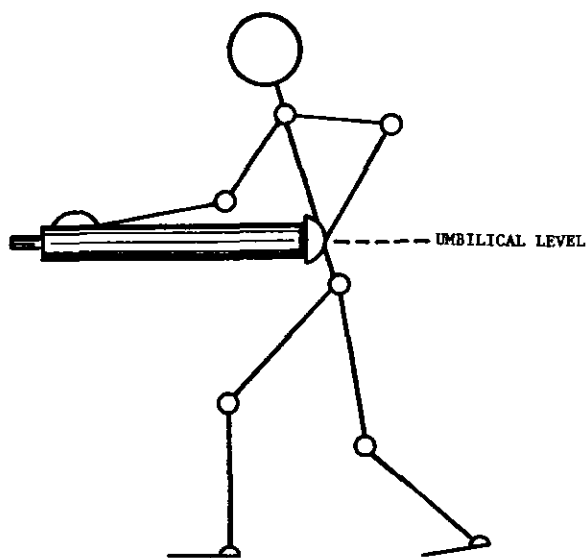


Figure 32-39. The axis of action as well as the center of mass of a heavy two-handed powertool should be located in that transverse plane which passes through the umbilicus.

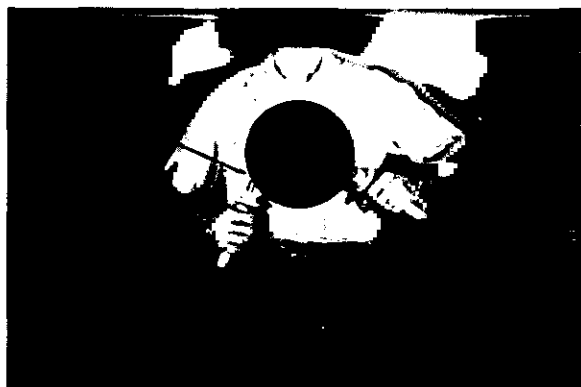


Figure 32-40. The included angle between the axes of the handles of a two-handed power tool should approximate 120 degrees to achieve optimal biomechanical posture.

still in the design stage. Recourse must then be taken to elemental analysis.

By definition, a state of lifting exists whenever a moment — no matter in which direction — acts upon the vertebral column. A “moment” is defined as magnitude of the force times distance of application. The three “static moments” (Table 32-3/a) are easy to compute, either from drawings, from photographs, or by speculative analysis. Moments are conveniently expressed in foot-pounds, multiplying the force acting upon an anatomical structure with its distance from the point of maximal stress concentration. The heaviest article normally handled by man at work is his

own body. Only rarely do workers handle objects weighing 150 lbs., and, in most instances, the mass of an object moved is quite insignificant when compared to the weight of the body segment involved in the operation. For example, the majority of handtools or mechanical components in industry weigh considerably less than $\frac{1}{2}$ lb., but an arm, taken as an isolated body segment, weighs 11 lbs.^{52, 53}

The sagittal lifting moment is the one easiest to compute and is of greatest severity when lifting loads and putting loads down right in front of the body. It is most conveniently derived by graphical methods. First, the weights of the body segments involved in a specific task are obtained from reliable tables.⁵⁴ Then a “stick figure” of proper anthropometric dimensions (Figure 32-41) is drawn and the location of the center of mass for each body segment as well as for the load handled is marked. Finally, the sum of all moments acting upon a selected anatomical reference structure (in this case the lumbo-sacral joint) is computed and becomes the sagittal biomechanical lifting equivalent of the specific task under consideration.

The estimation of sagittal lifting equivalents is of great practical usefulness in the comparison of work methods. It is often necessary to decide if a task is better performed sitting as opposed to standing (Figure 32-42). A schematic sketch or a photograph is then a convenient aid to decision making. The masses involved, i.e., the torso above the lumbo-sacral joint plus neck, head, upper limb and the object manipulated are identical for each individual, in both the seated and standing postures. According to data by Abt,⁵⁵ the body mass in the case of a 110-lb. female would be 45 lbs. To this, the weight of the object handled, in this case, 20 lbs., is added. Then computing moments,^{56, 57} the distance from the lumbo-sacral joint to the center of mass of body segments and load combined equals approximately $1\frac{1}{2}$ ft. (Figure 32-42/L). However, in the case of a seated individual, value “L” becomes approximately 2½ feet. This is due to the forward leaning posture of trunk and the outstretched arm. Therefore the torque exerted on the lumbar spine now is increased to 146 ft.-lbs. or nearly 50% more than when standing. This explains why, in so many instances, when unnecessary chairs are introduced in the work situation, workers, instead of being overjoyed, complain rightly about much increased work stress.

Analyzing lifting tasks routinely in terms of moments tends to develop in supervisors a healthy and critical attitude toward cut and dried “cook-book rules of lifting.” The principle of “knees bent-back straight-head up” is well enough known. However, a simple diagram (Figure 32-43) shows that in many work situations sensible concessions must be made to the influence of body measurements on work stress. In Figure 32-43 “Mr. X,” long legs, short torso shows the anthropometric configuration of a typical male; while “Ms. Y,” relatively long torso and fairly short legs, has female body characteristics. It can be

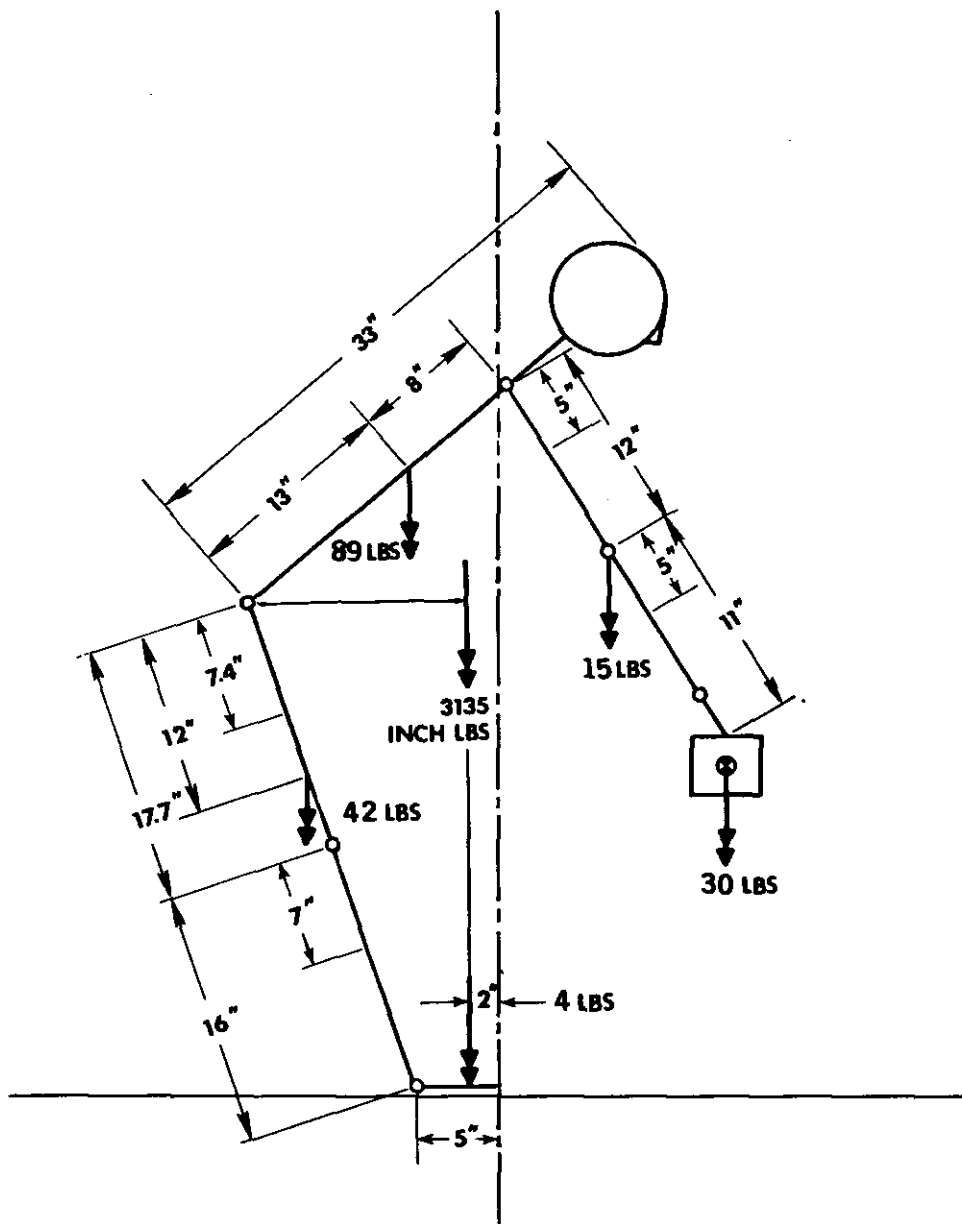
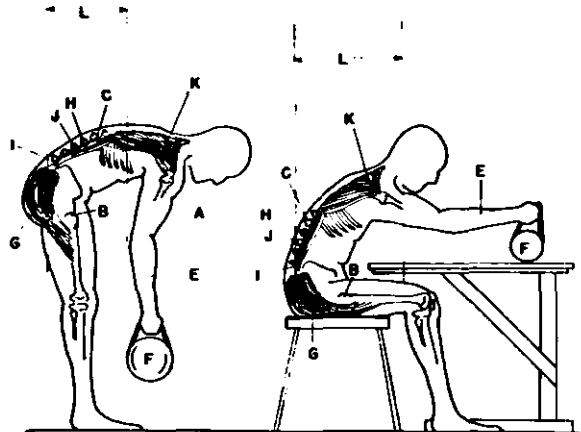


Figure 32-41. Graphic computation of the location of center of mass of whole body and body segments as well as of the sagittal moment acting upon the lumbo-sacral joint can be conveniently accomplished through the use of stick figures. This example shows that an improper working posture, a load weighing only 30 lbs., combined with the mass of the various body segments involved in a lifting task, may produce a torque exceeding 3000 inch-lbs., which is the lifting equivalent of a very severe task.

readily seen that "Mr. X" does not benefit at all from application of the standard lifting rule simply because his body build prevents him from getting under and close to the load. Therefore, distance "L" in Figure 32-43/b is no shorter than distance "L" in Figure 32-43/a; therefore, the moments acting on the lumbar spine are the same in both cases. Ms. "Y," however, due to a differently proportioned body, can get under the load and close to it. Thus, distance "L" now becomes much shorter and the moments on the lumbo-sacral joint

and therefore, also work stress, are approximately halved. Under such circumstances, provided that the height of the workbench cannot be changed, the standard lifting rule may be applied to the female, while in the case of the male, no benefit is derived. To the contrary, working in the "approved lifting posture" may lull a male worker into a sense of false security.

It has already been described earlier (Figure 32-33) how a light but bulky object will often impose a lifting stress much greater than the one



- A = Humerus
- B = Socket of Hip Joint
- C = Vertebral Column
- D = Shoulder Joint
- E = Arm
- F = Load
- G = Muscles of the Buttocks (Gluteus Maximus)
- H = Muscles of the Back (Sacro-Spinalis)
- I = Lumbo-Sacral Joint
- J = Spinous Process of a Vertebra
- K = Trapezius Muscle
- L = Distance from the Center of Mass of Combined Body-Load Aggregate to the Joints of the Lumbar Spine

Tichauer, E. R.: Ergonomics of Lifting Tasks Applied to the Vocational Assessment of Rehabilitees. Rehabilitation in Australia, Oct. 1967, pp. 16-21.

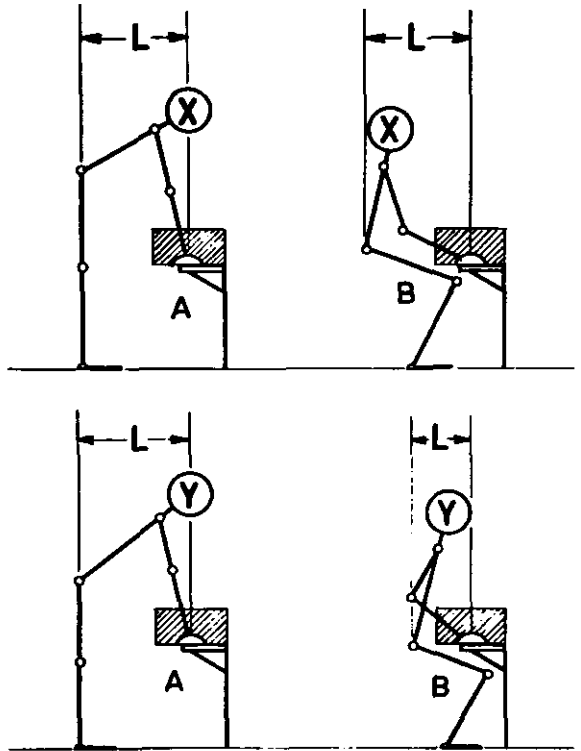
Figure 32-42. A change from standing to seated working posture may move the centre of mass of the combined body load aggregate away from the lumbar spine and thus increase stress there. When changing from standing to seated work, reach length should be kept as short as possible.⁵²

exerted by a heavier article of greater density. Indeed, the ergonomic problems resulting from recent trends in miniaturization and containerization have added a serious and perhaps sinister overtone to the age-old jocular question: "Which is heavier — one pound of lead or one pound of feathers?" The feathers, of course; they are so much bulkier!

In many instances, however, other moments in addition to the sagittal one must be considered. Lateral bending moments assume importance whenever a job calls for "side-stepping" (Figure 32-44) or the handling of materials on trays. Likewise, consideration of torsional moments becomes necessary when materials are transferred from one surface or workbench to another (Figure 32-45).

All moments like the other elements of a lifting task add up, not algebraically but vectorially. The magnitude of lateral and torsional moments is computed by procedures similar to the one described for the sagittal moment. Often a mathematical computation becomes unnecessary because trained ergonomists soon develop the knack to "guesstimate" rather correctly the magnitude of all three moments by looking at the worker, motion pictures or a drawing of the workplace layout.

It may be assumed that, when the vector sum of all three moments is 350 inch-lbs. or less, the



A "WRONG" POSTURE
B "APPROVED" POSTURE

Tichauer, E. R.: Ergonomics of Lifting Tasks Applied to the Vocational Assessment of Rehabilitees. Rehabilitation in Australia, Oct. 1967, pp. 16-21.

Figure 32-43. Postural corrections in training for lifting should be aimed at reducing torques acting on the spine. "X," an anthropometric male, does not benefit materially from the "approved" lifting posture because "L," the distance from the center of mass of load to the fourth lumbar vertebra, does not shorten materially. "Y," an anthropometric female, does benefit from the "bent knees, straight back" rule because she can get under the load. When matching worker and task, the measurements of the individual worker as well as the dimensions of the workplace should be considered.⁵²

work is light and can be performed with ease by untrained individuals, male as well as female, irrespective of body build. Moments above this level but below 750 inch-lbs. put a task into the classification of "medium-heavy" requiring good body structure as well as some training. Tasks above this but below 1200 inch-lbs. are considered to be heavy requiring selectivity in the recruitment of labor, careful training and attention to rest pauses. Whenever the vector sum of moments exceeds those stated before, then the work is very heavy in nature, cannot always be performed on a continuing basis for the entire working day and requires great care in recruitment and training.

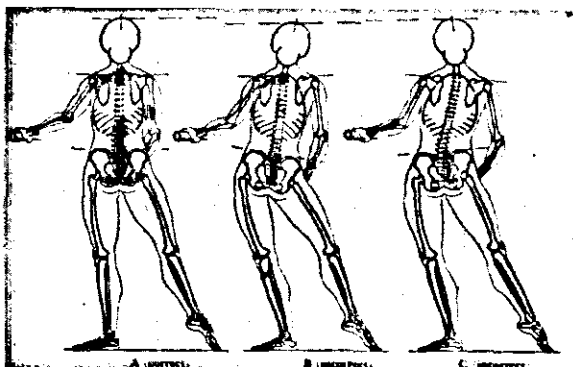


Figure 32-44. Side stepping induces heavy lateral bending moments acting on the spine. (from: SPARGER, C.—Anatomy and Ballet-by A. and C, Black Ltd., London, 1960).

The gravitational components are elements of a lifting task which are always present.

In physics work is defined as a product of force and the distance through which this force acts. Thus, lifting 10 lbs. against gravity to a height of 5 feet will constitute 50 foot-lbs. of work. Likewise, pushing an object horizontally for a distance of 5 feet when 10 lbs. of pushing force are required to perform this task throughout this distance will also result in 50 foot-lbs. of work.

This definition, however, is not always applicable from the standpoint of work physiology. For example, if an individual pushes with all his force against the wall and moves neither his body nor the wall, he has not accomplished any work in the sense of physics. Nevertheless, during the entire time while his muscles are under tension, his metabolic activities have increased, and the added energy demands of the living organism manifest themselves in the expenditure of additional calories which, in physics, are assigned the dimensions of work. The event which causes such physiological work to be performed is called "isometric activity." Isometric "work" is performed whenever a muscle is under tension, but produces no visible motion. Another kind of "physiological work" is "tension time."⁵⁸ This also results in an increased expenditure of calories and is performed whenever muscle is under tension for an interval of time. Tension time is always present and must always be taken into consideration whenever a materials-handling task is performed. It can be estimated simply by taking the weight of the object handled plus the weight of the body segment involved in the task, and multiplying this by the time the musculature is under tension.

Both "isometric work" and "tension time" are assigned the dimensions of "impulse" which equal force multiplied by time. For the practical purposes of work stress estimation, "isometric work" and "tension time" are added algebraically together, and their sum, named the "isometric component"

(as distinct from "isometric work") is in turn added vectorially to the other gravitational components (Table 32-3).

A vector defined by the dimensions of impulse is obviously not additive with other vectors carrying the dimensions of work. To overcome this difficulty, a simple mathematical transformation is useful.⁵⁸

Dynamic work is defined as the product of the weight of an object handled multiplied by the vertical distance through which it is lifted upwards against gravity. It has the dimensions of work as defined by physics.

Negative work¹ is performed whenever an ob-

TABLE 32-3
The Elements of a Lifting Task

(a) Static Moments	(b) Gravitational Components	(c) Inertial Forces
sagittal	isometric	acceleration
lateral	dynamic	aggregation
torsional	negative	segregation

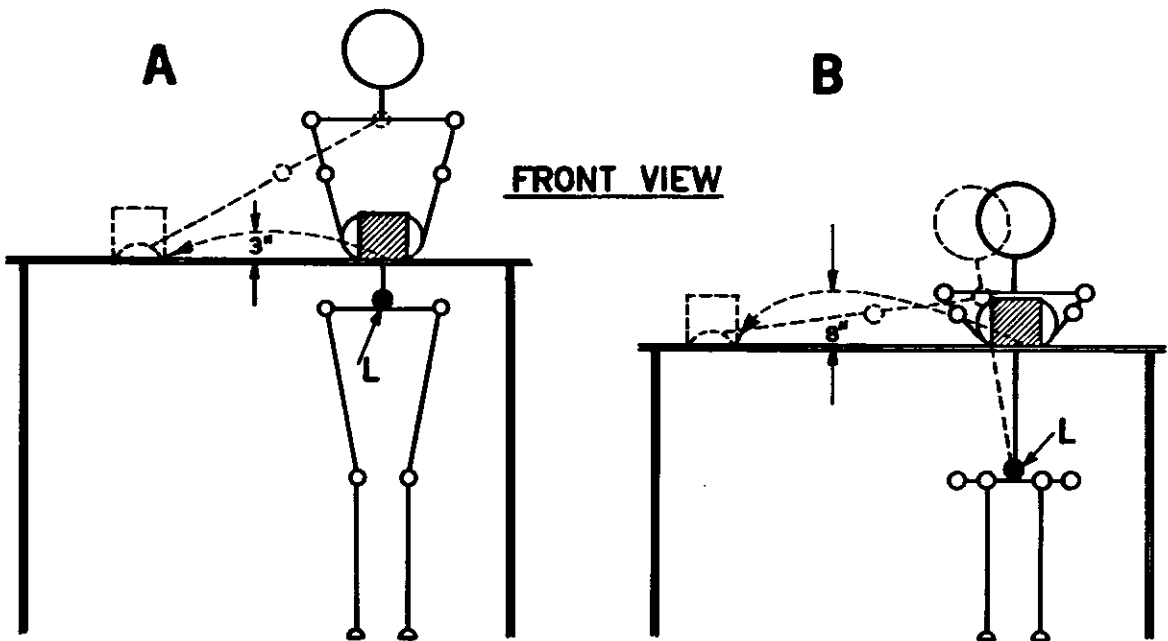
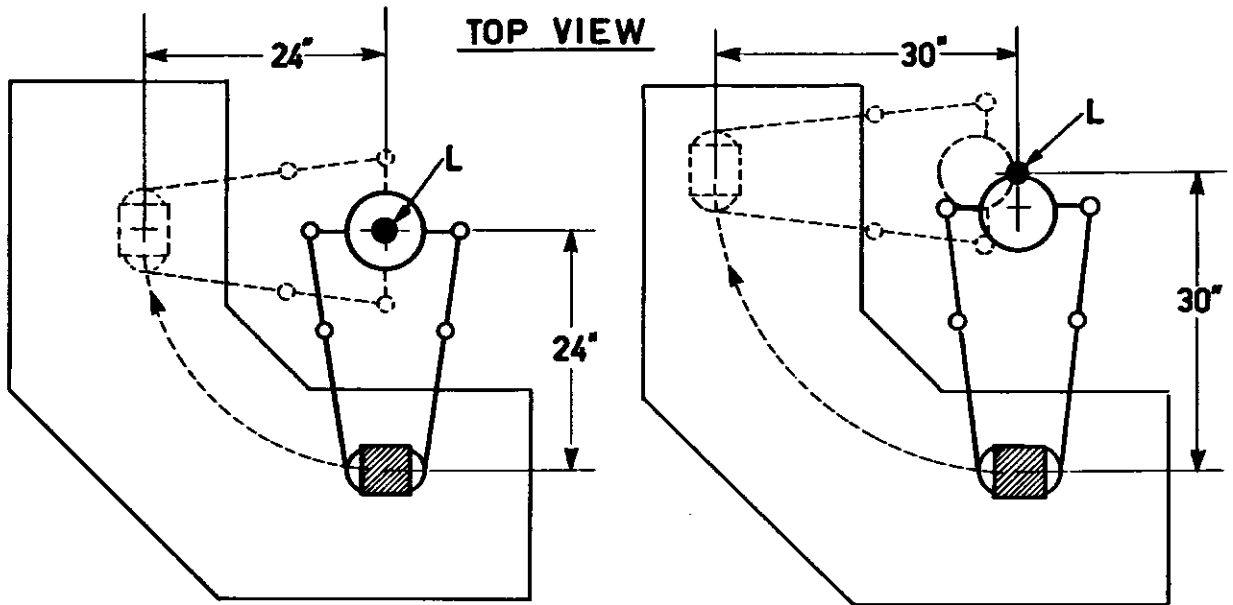
(d) Frequency of Task

ject is lowered at velocities and accelerations of less than gravity so that work against the gravity vector is performed. To avoid complex computations, it is practical under industrial working conditions to accept the recommendation by Karpovich⁵⁹ to assume that one-third of that work which would have been expended when lifting the same object over the same distance in an upward direction is approximately equal to the dynamic work equivalent of the task.

Finally, the inertial forces have to be considered. Often acceleration over several inches of distance is too insignificant to demand numerical evaluation of this vector, provided that isometric activity is given due consideration. However, the forces involved in the aggregation and segregation of man and load do affect work stress to a high degree.

In order to maintain equilibrium in upright posture, it is necessary that the center of mass of the body be located above a line passing through the sesamoid bones of the big toes. Whenever a load is lifted, then object and human body become one single aggregate and during the act of aggregation, the combination of load and body and the formation of a single center of mass exert forces upon vulnerable anatomical reference points. Likewise, during segregation the displacement of the center of mass of the body exerts forces on diverse anatomical structures.

Inertial forces have the dimensions of mass multiplied by acceleration (i.e., force). Objects such as are commonly handled in industry are lifted (i.e., aggregated) over approximately three seconds, while release (i.e., segregation) is much faster requiring only a time interval of somewhat less than 1/25th of a second. Therefore the severity of a lifting task is greatest at the instant of



L = lumbo-sacral joint

Figure 32-45 & 46 (A & B). Schematic Drawing of the Lifting Task Evaluated Quantitatively in the Text of Standing (A) and Seated (B) Position. Solid lines describe posture at beginning, broken lines posture at end of task.

load release.

It was already mentioned that the severity of a lifting task can be reliably evaluated by theoretical analysis. Under such circumstances, all the elements of a lifting task as listed in Table 32-3 are described quantitatively and the values then added as vectors. The addition of vectors, however, demands that the quantities involved in the computation are of identical dimensions. Therefore it is necessary, prior to final computation, to reduce the elements of a lifting task to values with compatible dimensions. It was already established by the pioneers of work physiology^{60, 61} that the basic activity of the musculo-skeletal system leading to increased energy demands, expressed in terms of calories (dimensions of work) would be isometric effort (dimensions of impulse).

Work with rehabilitees caused researchers in the immediate period following World War II to assume that for computational purposes it would be desirable to reduce all elements of physical work to quantities having the dimensions of impulse (i.e., force \times time). The soundness of this approach was validated by Starr.⁵⁸ To make all elements of a lifting task dimensionally compatible with isometric effort, the following operations are performed:

1. The vector sum of the three moments is divided by distance (moment arm) and multiplied by performance time.

2. The total physiological effort equivalent of isometric dynamic and negative work is obtained from the formula:

physiological effort equivalent =

$$\int_0^t m | a + g | dt;$$

where t is performance time and a is acceleration other than gravity, while g is the acceleration due to gravity and m equals mass.

3. The inertial forces of acceleration, aggregation and segregation are multiplied by their time components. This converts all elements into equivalents of physiological effort with the isometric dimensions of 1bF sec or Force lbs. multiplied by time.

The following practical example will illustrate in step by step fashion the mode of application of this approach to lifting problems.

Solved Problems

The lifting and transfer of a box weighing 30 lbs. from a table to a sideboard without side-stepping can be performed either seated or standing (Figure 32-46).

When standing the object is picked up from a point in the midsagittal plane two feet in front of the midcoronal plane. It is put down in the midcoronal plane two feet to the right from the midsagittal plane. Operation time amounts to two seconds per box and maximum height of lift is 3 inches. Frame by frame film analysis shows aggregation and segregation times to be 0.5 seconds and 0.04 seconds respectively, while segmental analysis (Figure 32-41) permits the assumption that the displacement of the center of gravity of the body in aggregation and segregation equals 2 inches.

When the worker is in a seated position, and the workbench interferes with knees and other anatomical features, the worker must move further away from the task, and now the distances from the coronal and sagittal plane respectively will equal 30 inches. Performance, aggregation and segregation times are now 4 seconds, 0.6 seconds and 0.05 seconds respectively. The changed postural configuration increases the displacement of the center of mass during aggregation and segregation from 2 inches to 3 inches and the maximum height of lift from 3 inches to 8 inches.

For the purposes of comparative work stress evaluation, the following assumptions are made:

1. Accelerations and decelerations are constant and equal in magnitude for all displacements.
2. The path of the center of mass of the box approximates a straight line from pick-up point to the maximum height of lift.
3. Peak velocity of displacement is attained midway between aggregation and segregation points, and is assumed to be twice the average velocity.
4. The load accelerates from 0 to peak velocity and decelerates back to 0.

Sagittal and lateral moments are obtained in 1bF ft, by multiplying the weight of the box by its distance from the midcoronal and midsagittal plane respectively. To compute the torsional moments, the mass of the box is multiplied by its acceleration and the resulting force multiplied by the distance. The weight of trunk and arms was neglected in these calculations because they are constant for both postures, and their inclusion would have increased the complexity of computation considerably without materially increasing the accuracy for the purposes of estimation.

The following symbols will be used throughout calculations:

w = weight of the load

m = mass of the load

W = weight of the man

M = mass of the man

1bF = pounds force

l = reach of arm in ft.

t = operating time in seconds.

a = acceleration and deceleration during the operation

b = acceleration and deceleration during aggregation

c = acceleration and deceleration during segregation

S = total path travelled during the operation in ft.

h = height to which the load is lifted in ft.

t' = aggregation time in seconds.

t'' = segregation time in seconds.

x = distance through which the center of gravity moves in aggregation and segregation.

Subscript 1 denotes standing position.

Subscript 2 denotes sitting position.

The numerical values of those parameters which describe adequately both lifting tasks, the standing and the seated one, for the purposes of quantitative analysis, are stated in Table 32-4. On the basis of these values, the elements of both lifting tasks are now computed as represented in Table 32-5. Now the values obtained are made isodimensional with physiological isometric effort for the purposes of computation as derived in Table 32-6. Finally, the total level of physiological effort for standing and seated work while performing the lifting task is computed by the methods shown in Table 32-7. The results of this analytical exercise, provided that the frequency of lift is the same in both cases, shows clearly that in this case a standing working posture requires far less effort and that the provision of seating accommodations far from making the task easier, would require almost twice the effort expanded by a standing worker.

As this chapter addresses itself specifically to biomechanics proper, a comprehensive treatment of lifting and materials-handling would exceed the boundaries of the section and lead to overlap with other chapters. Nevertheless, occupational safety and health problems stemming from manual materials-handling are numerous and complex. Therefore, wide cross-reading on all aspects of manual materials-handling is recommended. By way of illustrative examples, culled from a larger number of equally excellent publi-

cations, Astrand⁶² and others⁶³ are cited as a good source of reference on work physiology. McCormick⁶⁴ deals in a comprehensive fashion with the human factors aspects of lifting and back problems while Snook⁶⁵ and Snook and Irvine⁶⁶ treat the psycho-physiological aspects of the problem extensively. Finally, the publications of the National Safety Council,⁶⁷ Himbury⁶⁸ and Grimaldi⁶⁹ are recommended as general references which place the problem of manual materials-handling into proper perspective with respect to the overall problem of occupational safety and health.

MEASUREMENT AND EVALUATION IN BIOMECHANICS

Americans have always been a nation of problem solvers. The history of this country in fields economical and social, as well as technological, bears ample witness to this. Thus it is but logical that all industrial, as well as technological development in this country stems from the need to overcome and solve problems of design, production, distribution and use of manufactured articles. However, the very concept of "problem solving" implies that an existing situation is unsatisfactory and must be improved. Therefore American industry traditionally has subscribed to the "improvement approach" as the principal avenue towards economic efficiency and viability of private enterprise. This, in many instances, has led to

TABLE 32-4
Numerical Values of Parameters
Describing Lifting Example

Symbol	Values	
	Standing	Sitting
t	$t_1 = 2.00$ secs	$t_2 = 4.00$ secs
t'	$t'_1 = 0.50$ secs	$t'_2 = 0.60$ secs
t''	$t''_1 = 0.04$ secs	$t''_2 = 0.05$ secs
l	$l_1 = 2$ ft.	$l_2 = 2.5$ ft.
h	$h_1 = 1/4$ ft.	$h_2 = 2/3$ ft
x	$x_1 = 1/6$ ft.	$x_2 = 1/4$ ft.
$S = 2 \sqrt{\frac{l^2}{2} + h^2}$	$S_1 = 2 \sqrt{2^2 + \left(\frac{1}{4}\right)^2}$ $= 2.8722$ ft.	$S_2 = 2 \sqrt{\frac{(2.5)^2}{2} + \left(\frac{2}{3}\right)^2}$ $= 3.7784$ ft.
$a = \frac{4S}{t^2}$	$a_1 = \frac{4(2.8722)}{2^2}$ $= 2.8722$ ft/sec ²	$a_2 = \frac{4(3.7784)}{4^2}$ $= .9446$ ft/sec ²
$b = \frac{4x}{(t')^2}$	$b_1 = \frac{4(1/6)}{0.5^2}$ $= 2.6664$ ft/sec ²	$b_2 = \frac{4(1/4)}{0.6^2}$ $= 2.7777$ ft/sec ²
$c = \frac{4x}{(t'')^2}$	$c_1 = \frac{4(1/6)}{0.04^2}$ $= 416.6250$ ft/sec ²	$c_2 = \frac{4(1/4)}{0.05^2}$ $= 400.0000$ ft/sec ²

TABLE 32-5
Values of Elements of Lifting State in
Their Proper Dimensional Units

Elements	Values	
	Standing	Sitting
Sagittal Moment = wl	$wl_1 = 30(2) = 60$ lbF ft	$wl_2 = 30(2.5) = 75$ lbF ft
Lateral Moment = wl	$wl_1 = 30(2) = 60$ lbF ft	$wl_2 = 30(2.5) = 75$ lbF ft
Torsional Moment = ma_l	$ma_1 l = .9316(2.8722)2$ = 5.3514 lbF ft	$ma_2 l_2 = .9316(.9446) (2.5)$ = 2.1997 lbF ft
Isometric + Dynamic + Negative Work = $\int_0^t m a + g dt$	$\int_0^t .9316(2.8722 + 32.2) dt$ = (.9316) (35.0722) (2) = 65.3464 lbF sec	$\int_0^t .9316(.9446 + 32.2) dt$ = (.9316) (33.1446) 4 = 123.5100 lbF sec
Acceleration Force = ma	$.9316(2.8722) = 2.6757$ lbF	$.9316 (.9446) = 0.8799$ lbF
Aggregation Force = $(m + M)b$	= (.9316 + 6583) (2.6664) = 14.9049 lbF	(.9316 + 4.6583) (2.7777) = 15.5270 lbF
Segregation Force = $(m + M)c$	= (.9316 + 4.6583) (416.6250) = 2328.8920 lbF	= (.9316 + 4.6583) (400) = 2235.96 lbF
Vector Sum of Moments = $\{(\text{sagittal moment})^2$ + $(\text{lateral moment})^2$ + $(\text{torsional moment})^2\}^{1/2}$	= $\sqrt{60^2 + 60^2 + (5.3514)^2}$ = 85.3514 lbF ft	= $\sqrt{(75)^2 + (75)^2 + (2.1997)^2}$ = 106.0888 lbF ft

TABLE 32-6
Values of Elements of Lifting in Physiological
"Work" Units with Their Calculations

Element	Standing	Sitting
<i>Work</i> due to Moments = $\frac{\text{vector sum in lbF ft} \cdot t}{l}$	= $\frac{85.3514 (2)}{2}$ = 85.3514 lbF sec	= $\frac{106.0888 (4)}{2.5}$ = 169.7420 lbF sec
Isometric + Dynamic + Negative <i>Work</i>	= 65.3464 lbF sec	= 123.5100 lbF sec
Acceleration <i>Work</i> = $ma \cdot t$	= 2.6757 (2) = 5.3514 lbF sec	= (0.8799) (4) = 3.5196 lbF sec
Aggregation <i>Work</i> = $(m + M) b \cdot t'$	= (14.9049) (.5) = 7.4524 lbF sec	= (15.5270) (.6) = 9.3162 lbF sec
Segregation <i>Work</i> = $(m + M) c t''$	= (2328.8920) (0.04) = 93.1556 lbF sec	= (2235.96) (0.05) = 111.7980 lbF sec

uneconomic product design and manufacturing methods. Particularly prior to the development of rational methods of workplace design as are available today, it was accepted procedure to conceive products hastily, establish manufacturing processes intuitively, and then, on the shop floor, during actual production runs to review gradually deficiencies in product design or manufacturing methods. Such improvement normally takes place over several months or years. This approach was not only feasible, but also highly desirable during past decades when, for example, the "T" model of the Ford remained in full production for ap-

proximately 30 years. In the past, this very same classical process of gradual improvement of products as well as method was also applied successfully to the reduction of health hazards and the redesign of stressful work situations.

First evidence of work-induced trauma and occupational disease was obtained then the causes were identified and eventually removed.

The effectiveness of "improvements" in both fields economical as well as occupational health are customarily measured in terms of "cost reduction." In many industries "cost reduction" is expected as a matter of course from supervisory

TABLE 32-7
Physiological "Work" in LbF sec

Description	Physiological "Work" in 1bF sec	
	Standing	Sitting
Moments (Vector Sum)	85.4	169.7
Work (Isometric + Dynamic + Negative)	65.3	123.5
Acceleration	5.4	3.5
Aggregation	7.4	9.3
Segregation	93.2	111.8
Total	256.7	417.8

and engineering personnel during the first months or years of production of a new article. This helps produce a strong temptation among those who are responsible for "efficiency" to design products and work methods initially imperfect to provide opportunities for later cost reduction. This, of course, is false economy which may well lull management into a sense of false security while a competitive position is being lost. The trait of viewing "cost reduction" as the only index of managerial effectiveness is especially strong in enterprises which maintain effective cost accountability systems. There cost avoidance is occasionally actively discouraged because it is not easy to measure in terms of dollars and cents, while cost reduction shows up clearly in the ledger.

Often the practitioner in ergonomics is challenged to justify his activities in terms of savings accrued by the improvement of existing operations.

There are three main areas of evaluation of activity which are of prime interest to the practitioner in industry:

- (1) historical evaluation:
- (2) analytical evaluation: and
- (3) projective evaluation.

Historical Evaluation

The improvement and cost reduction approaches outlined above are so firmly ingrained in industrial practice that quite often interest of manufacturing enterprises in biomechanics is initially triggered by a patently obvious breakdown in occupational safety and health resulting in increased manufacturing expense, poor personnel relationships, and a distorted image of corporate objectives, projected to consumers. The result is normally a request for historical evaluation of past activities and events. Such study is normally conducted within the framework of reference of the "four big C's" of any investigation of a breakdown in occupational safety and health:

1. Cause.
2. Consequence.
3. Cost.
4. Cure.

In most instances, the consequence and the cost are known; what remains to be discovered is the true cause and the cure.

In any such study, theoretical analysis is the most powerful tool available to the investigator. Experimental methods are often not only expensive and lengthy, but also quite superfluous when applied to a critique of events of the past. In addition, the procedures of theoretical analysis offer a depth of scope and a degree of privacy and confidentiality not available whenever experimentation with man as a subject is conducted.

The investigation is normally initiated by identifying the environmental stress vectors (Figures 32-19 & 32-20) which may be implicated. Whenever mechanotaxis could be one of the possible vectors involved, then the next step would be to ascertain if the principles of motion economy (Table 32-1) or the prerequisites of biomechanical work tolerance (Table 32-2) were to some extent disregarded in the design of products or work methods. Step by step, to check out procedures with the aforementioned tables in hand is the best approach. At this juncture, it is often possible to suggest possible causes for the observed anatomical, physiological or behavioral failure and frequently, an inexpensive and easily applied corrective action may be suggested.

It should however be constantly borne in mind that too simplistic an approach may prevent the detection of the actual anatomical failure points. The locus of observation of evidence of work strain is frequently quite remote in terms anatomical as well as in time from the point of application of work stress mechanism. This is, in fact, very often the case when less than due attention has been paid to the biomechanical prerequisites of work tolerance. Then the following questions should be asked:

1. Are the muscular constituents of the kinetic element involved large enough to perform the task without undue fatigue?
2. Do hand tools, machine controls, or other mechanotactic vectors evident at the workplace interfere with adequate blood supply to the muscle masses performing the actual work?
3. Are all kinetic chains working at adequate levels of mechanical advantage?
4. Are the sensory feedback mechanisms in the kinetic chain adequate to elicit some protective response by the worker to excessive stress?

Whenever the frequency of incidence of occupational ill health or accidents increase, after a manufacturing process has been in safe operation for some time, then the following questions should be asked: **WHAT CHANGES IN EQUIPMENT DESIGN, TOOLS USED, WORKING POPULATION EMPLOYED OR WORK METHOD APPLIED HAS TAKEN PLACE IMMEDIATELY PRIOR TO THE BREAKDOWN OF HAZARD CONTROL?**

A case study will illustrate the power of theoretical analysis.

A case study in historical evaluation of the biomechanical causes of a series of accidents. In a factory producing basic chemical materials, a sudden and dramatic increase of "pedestrian acci-

dents" was observed. Workers crossing aisles were hit by fork-lift trucks transporting materials on pallets. Common human-factors engineering approaches were explored, the trucks made more visible and zebra-striped, the aisles better lit and automatic warning horns were installed on some of the vehicles. However, none of these measures was of any avail. Then the question was asked: Why were so many workers crossing the aisles and walking around instead of being seated in comfort and safety at the workplace? Work sampling studies⁷⁰ revealed two things: firstly, that the accident frequency was proportional to the density of pedestrian traffic in the aisles and, secondly, that from a certain date onwards brief periods of absenteeism from the workplace had increased dramatically in number and, consequently, more people were walking in the aisles at any instant. The time of this change of workmen's behavior coincided with the introduction of a new tool. A rather expensive electrical brush used to clean trays was replaced by a much cheaper and apparently far more effective paint scraper (Figure 32-26). As stated under the "Prerequisites of Biomechanical Work Tolerance" (Table 32-2) I-1, the new and cheaper tool interfered with the blood supply to the ring and little finger. The resulting numbness and tingling caused the individuals afflicted to lay down their tools at frequent intervals and to seek relief by exercising their hands. First, line supervisors tried to counteract the decrease in productivity by frequent admonitions. Now, in order to avoid arguments with their supervisors, workers simply made use of every conceivable opportunity for brief absences from the job. Trips to the washroom, the tool room, the store, etc., became rather frequent, and this was the true cause of the rapid increase in accidents unjustly ascribed to the fork-lift trucks. The first of the four big C's, the true cause of the accidents, had been identified as absence from the workplace produced by an ergonomically incorrect designed tool. It only remained to develop a cure. The handle of the paint scraper was redesigned (Figure 32-47). As a result, workers spent more time per day in productive activity and thus output and economy of operation increased, while at the same time, due to diminished exposure to vehicles in the aisles, accident rates returned to normal.

Analytical Evaluation

The procedures of analytical evaluation are most often called for when an already existing manufacturing operation is generally satisfactory but has to be improved, either in order to make it more competitive or to reduce training time, to eliminate operator discomfort and to enhance the health and well-being of the working population.

Theoretical analysis applied as described in the foregoing paragraph is the initial step in all analytical evaluation. However, very often this will not suffice and certain experimental measures must be employed. The simplest and perhaps most effective aid in this kind of study is cinematography and subsequent frame-by-frame analysis. This will permit a detailed evaluation of



Figure 32-47. Redesigned Paint Scraper, Eliminating Interference with Blood Supply in the Fingers as Described in Figure 26.

the worker's reaction to each event at the workplace, and to each contact with tool, machine, or manufactured article. Very often slow-motion viewing of the manufacturing operation will reveal biomechanical or ergonomic defects as well as reflex reactions which cannot be detected with the naked eye because of the brief duration of many such events. The fact that the "hand is quicker than the eye" is well known to stage magicians who wish to deceive the spectators in the audience. The movie camera prevents self-deception by the work analyst. There is currently a strong trend towards the use of videotape for such purposes. This should be discouraged because the evolution of videotape is not adequate for the detection of fine details of expression, blanching of the skin, or frame-by-frame analysis. Furthermore, color videotaping is exorbitantly expensive while color film, especially in the Super-8 size, is economical and tells much more than a black-and-white picture.

Finally, manufacture of a videotape from movie film is very inexpensive while the converse, i.e., the manufacture of a movie film from a videotape, is a very expensive operation. Furthermore videotape, being magnetic in nature, requires more careful storage and is sensitive to magnetic fields, and often gets accidentally erased.

Motion picture analysis of the work situation

should allow the viewing of the workplace at least in two different planes, if a realistic appreciation of all the parameters of the layout is to be obtained (Figure 32-48).⁷¹ When movie analysis alone is not adequate as a basis for process evaluation, then recourse to other experimental technologies must be taken.

a. *Dynamometry.* This is a technique concerned with the measurement of the force-time relationship of strength of joint movement. It is employed with advantage in fatigue measurement when a lever system intrinsic to a specific kinetic element, made, by means of a mechanical device, to act against a measured force for a fixed number of cycles or a fixed interval of time. Magnitude of excursion of joint movement as well as magnitude of force developed during the activity are both plotted against time. The ergograph commonly employed for the measurement of finger fatigue in industry (Figure 32-49)⁷² is one of the

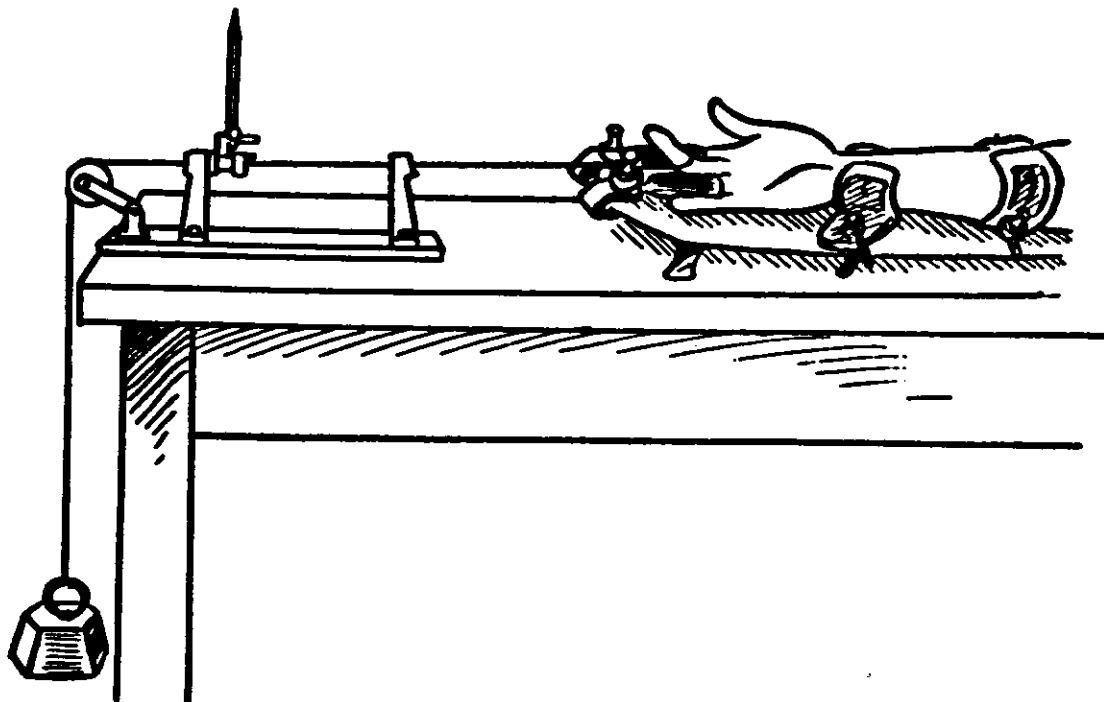
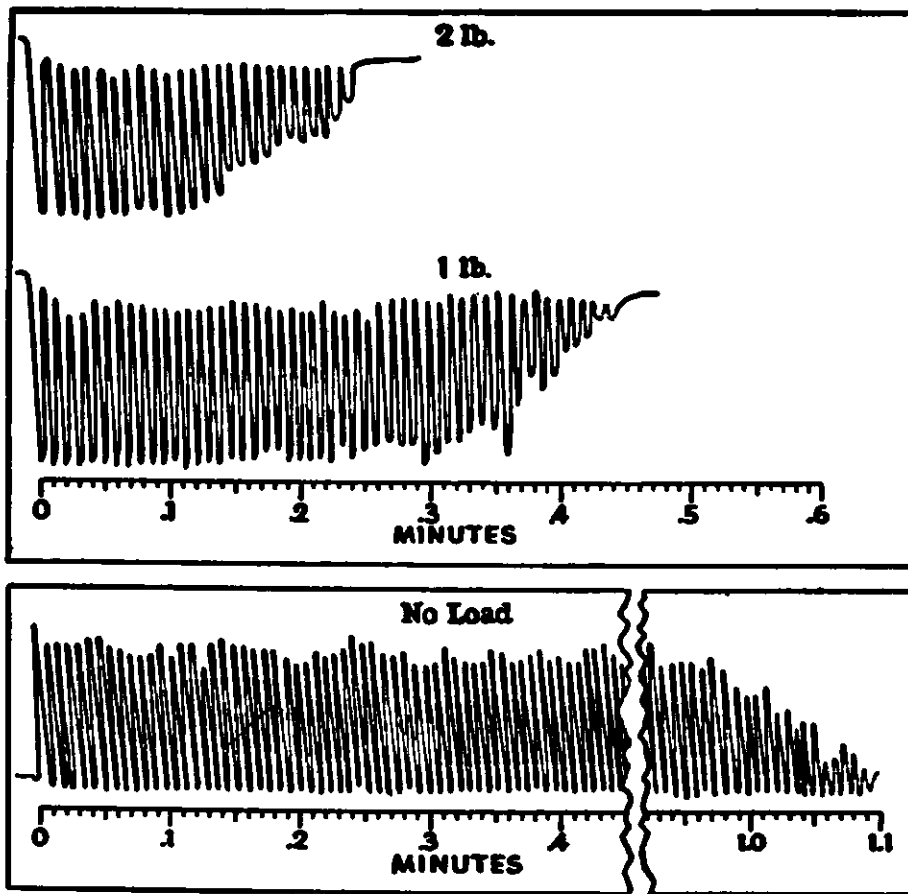
many useful types of dynamometers. The squeeze dynamometer (Figure 32-50)⁷³ is applicable for the objective measurement of fatigue and work tolerance in squeezing operations of the whole hand, such as are demanded by wraparound grasps of power grips, must be evaluated. The mechanical form of dynamometer used in rehabilitation medicine or physiotherapy is not commonly applicable to industrial circumstances as it is only an indicator of maximal force developed under conditions of a single squeeze.

b. *Myography.* Techniques of ergonomy and dynamometry permit the objective diagnosis of whether an individual is fatigued or incapacitated with respect to the specific job under analysis. Often, however, it is necessary to make a projective prediction about the likelihood of fatigue developing sometime in the future, the possibility of overexertion of a single kinetic



Tichauer, E. R.: Industrial Engineering in the Rehabilitation of the Handicapped. J. Ind. Eng. XIX:96-104, 1968.

Figure 32-48. A realistic impression of the three-dimensional nature of a task can best be obtained by "mirror-box" photography. This chronocyclegraph shows changes in the angle of abduction which influence effort levels in three coordinates.⁴³



Munn, N. L.: Psychology — The Fundamentals of Human Adjustment, 3rd Edition. Boston, Houghton Mifflin Co., 1955.

Figure 32-49. FINGER ERGOGRAPH AS DESIGNED BY MOSSO. The pointer at upper left traced a record of movements upon a smoked drum. The first and third fingers are held stationary by being inserted into metal cylinders. Lifting is done by the second finger.



Figure 32-50. An Instrumented Hand Dynamometer Permitting to Explain Subject's Performance Decay as a Function of Fatigue Due to Shape of Tool Handles. (a) 1½-in. handle starting performance, normal pattern. (b) Fatigue pattern after 12 min. of activity. (c) Starting performance in subject with inflamed tendon sheaths resulting in pronounced decay after 2 min. of performance. (d) After 8 min. a complete performance drop in subject c. (e) Subject with damage to nervous system. Original performance pattern showing early decay. (f) Same subject as in e, improved performance pattern after work tolerance training.⁷³

element, reduced work tolerance or other hazards to occupational safety and health. Then it is necessary to establish muscular input — biomechanical output relationships. Muscular effort involved in the performance of a specific task can conveniently be demonstrated by electromyography. A myogram is an electrical signal obtained from a contracting muscle. Under laboratory conditions, it may be advantageous to insert needle electrodes directly into the muscle investigated and record the potentials developed during exertion. This is the type of myogram preferred by physicians for the purpose of clinical investigation of neuromuscular disease. In occupational biomechanics, however, bioelectricity is "assumed to be" merely the by-product of a muscular event which makes it possible to measure strength and sequencing of muscle utilization through techniques non-invasive with respect to the human body. This limits industrial biomechanical procedures to surface electrodes which are adhesive conductive discs similar to those employed in electrocardiography. Before application, the skin is cleansed with alcohol or a similar solvent and good electrical conductive contact between the human body and the electrode is insured by the application of a conductive jelly between electrode and skin. The electrodes are placed so that they "triangulate" the

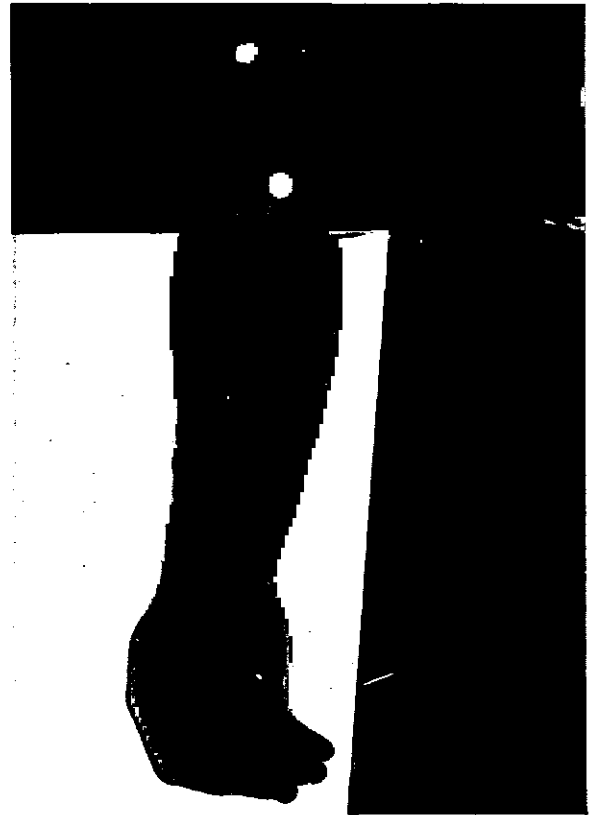


Figure 32-51. Electrodes for Surface Myography "Triangulating" the Biceps Muscle to Obtain a Maximal Integrated Myographic Signal.

individual muscle or muscle group under study (Figure 32-51).⁷⁴ A differential amplifier is then employed to magnify the action potentials so that they can be read on oscilloscopes or paper recorders. A differential amplifier uses three electrodes, one ground and two active electrodes. It augments only the difference between the two active electrodes. As any interference is common to all three electrodes, it is not amplified. This "common mode" rejection makes imperative the use of differential amplifiers in an industrial setting where electrical interference from fluorescent tubes and all kinds of other apparatus is abundant.

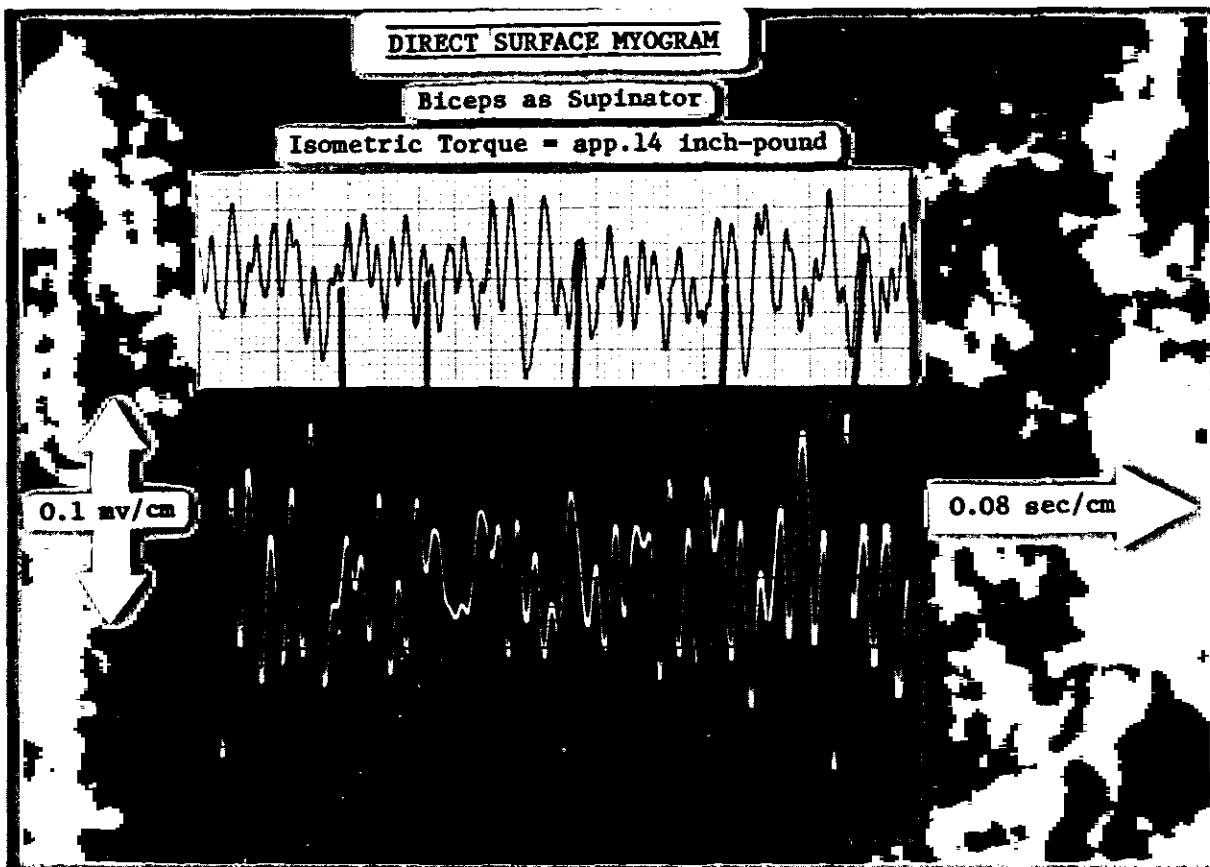
Due to the nature of the procedure, surface electrode myography records the summed signal from a number of action potentials simultaneously, depending upon the placement and size of the electrodes. Because of the brief intervals of time elapsing between individual action potentials, which is sometimes on the order of a few microseconds only, readout devices and recorders may be "overdriven" with respect to speed

and time. The signal is then not representative of the nature of the action potential but is conditioned and distorted as a function of the quality of the recording device (Figure 32-52). Even a change in the viscosity of the ink may produce a drastic change in the pattern of the tracing from the same amplifier reproduced on the same recorder. Therefore, in biomechanics, a conditioned type of myogram is employed. It records the sum total of the peaks of the action potentials counted over a sampling interval of time. If the rate at which individual muscle fibers contract is twice as fast, the deflection of the recorder pen will be twice as large. This type of myogram, which is representative of the total number of muscle fibers contracting at any instant, is erroneously but nevertheless commonly referred to as an "integrated myogram."

Due to the physiological "all or none law," it is also representative of the effort expended at any instant. As the signal pro-

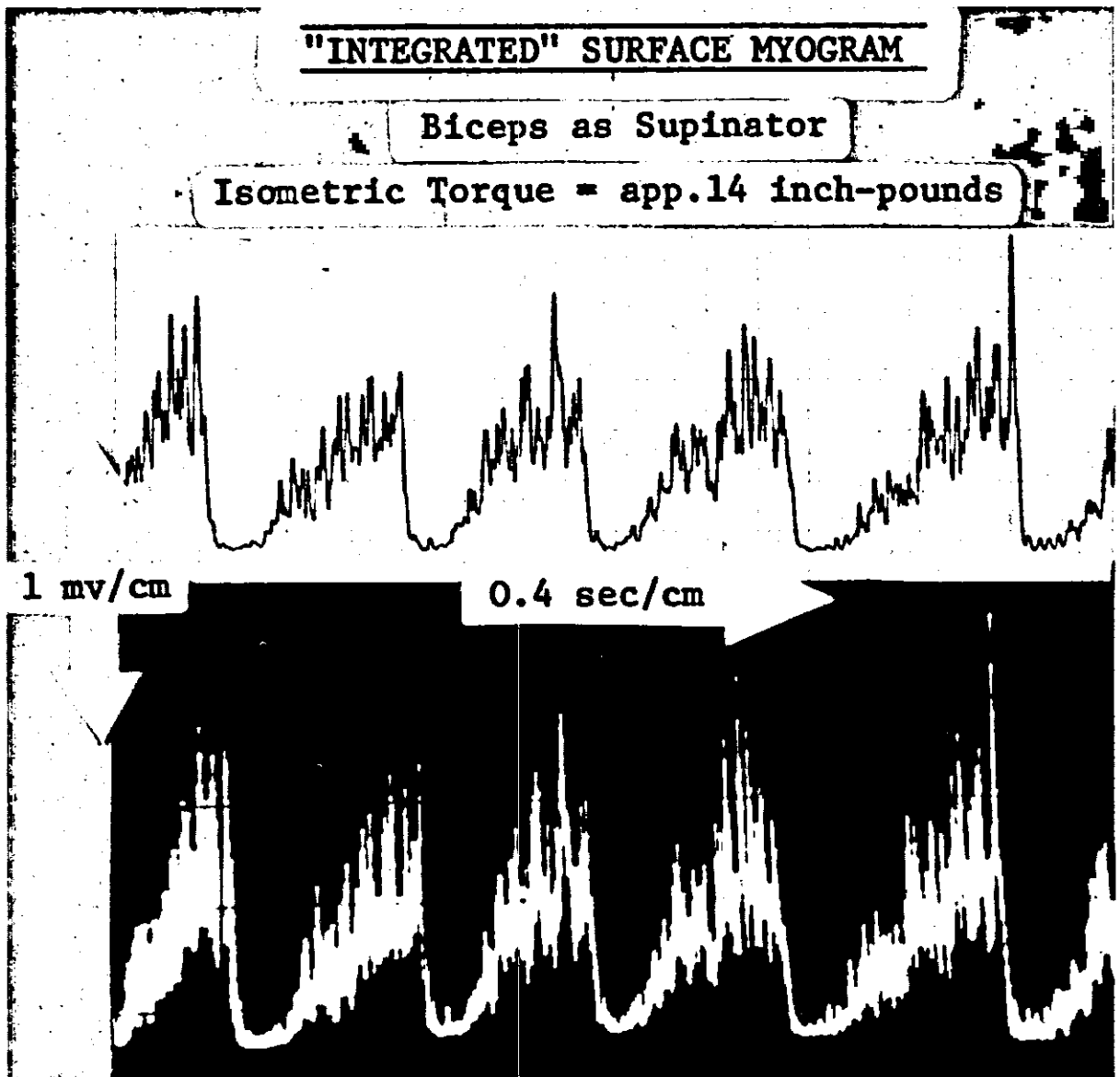
duced requires only a rather slow response capacity of the recorder, it is repeatable and easily obtained with relatively inexpensive equipment (Figure 32-53). It is thus possible to ascertain under field conditions if an undue amount of effort is expended in the performance of a specific maneuver. Likewise, the integrated myogram shows if there is proper sequencing between muscles involved in an operation. There should always be a "peak and valley" relationship between protagonist and antagonist muscles (Figure 32-54).

It cannot be too strongly emphasized that the industrial myogram is employed not to detect pathology, but to detect fatigue indicated by changes in the pattern of the myogram; to establish whether muscles function in the most desirable sequence and whether a specific muscle is actually involved in a specific productive operation. When the areas of application which define also the limits of usefulness of an integrated sur-



Tichauer, E. R., Gage, H., Harrison, L. B.: The Use of Biomechanical Profiles in Objective Work Measurement. J. Ind. Eng. IV: 20-27, 1972.

Figure 32-52. A Simultaneous Recording of the Biceps Muscle Firing Pattern Displayed on a Chart Recorder (Upper Half) and an Oscilloscope (Lower Half) at Exactly the Same Sensitivity and Speed. Only five points of similarity are evident, because the signal speed of the myogram exceeds the rise time and slew rate of commercial chart recorders.¹⁶



Tichauer, E. R., Gage, H., Harrison, L. B.: The Use of Biomechanical Profiles in Objective Work Measurement. *J. Ind. Eng.* IV: 20-27, 1972.

Figure 32-53. The Same Biceps Contraction Pattern as Shown in Fig. 52 Chart Recorder (Upper Half), Oscilloscope (Lower Half). However the signals here have been conditioned by summing all action potentials over time so that the trace now represents the analog of the firing rate, which is indicative of the total activity of the muscle mass at any instant during the sampling period. The signals are fully compatible with the frequency response of the chart recorder. The integrated myogram produces repeatable and very reliable measurements of muscular activity levels.²⁶

face myogram are kept clearly in mind, then this electrophysiological signal will be found to be an eminently useful tool in the objective analysis of work situations.

There are, of course, other and perhaps even more precise approaches to electromyography in fatigue study,^{76, 76-77} but many of these require the true laboratory setting of a clinical or research institution.

Preferred fields of application of electromyography are the comparative evaluation of handtool designs, of lifting stress when objects of different weight or shape are to be handled, etc. It is often a more convenient and reliable means of work and effort measurement than metabolic investigations.

c. *The Biomechanical Profile.* It is often de-

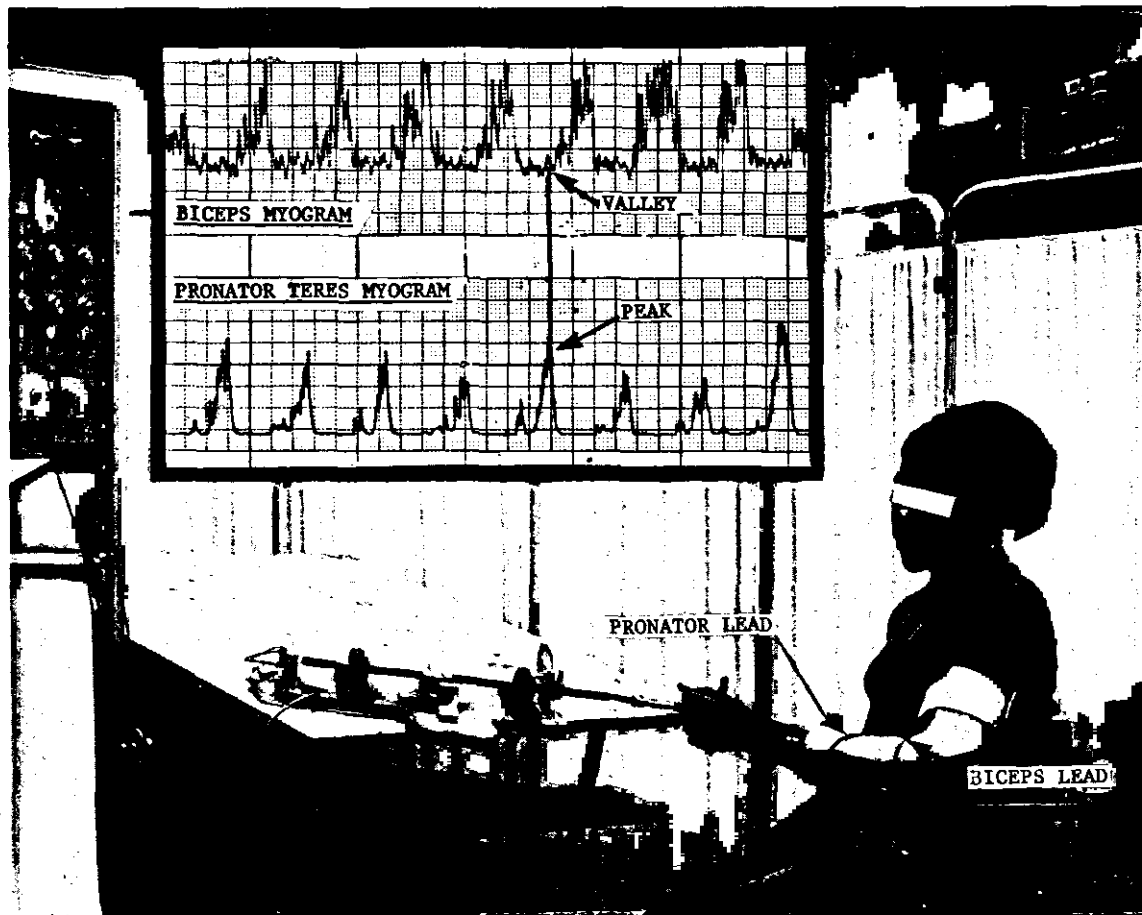


Figure 32-54. Simultaneously recorded integrated myograms of biceps (supinator) and pronator teres (antagonist) show peak and valley phasing indicative of proper sequencing of muscle conducive to high work tolerance.

sirable to record simultaneously myograms and the readouts from dynamometers. The resulting tracing constitutes a "Biomechanical Profile" indicative of the nature of muscular effort-work output-work tolerance relationships. Such Biomechanical Profile permits the objective evaluation and prognostication of changes in functional capacity resulting from modifications of man-equipment interfaces.

Figures 32-55 and 32-56 illustrate the comparative evaluation of two machine controls. First a T-handle was attached to a rotating dynamometer, and subjects were asked to pronate the supinate against a set resistance. A biceps myogram, as indicative of the main supinatory effort, was recorded simultaneously with an electrical signal proportional to the amplitude of the rotation of the shaft. This then constituted a Biomechanical Profile in simplest form (Figure 32-56). Then a straight handle was substituted. This straight handle

forced the wrist into ulnar deviation (Figure 32-55). The resulting Biomechanical Profile (Figure 32-56) now shows that, when a machine control requires the wrist to be rotated while in ulnar deviation, that the operator must expend twice the force to obtain half the output because the myogram is now twice as high while the displacement signature shows only half the amplitude. In other words the operator, when using the straight handle instead of the T-handle, would have to apply twice the effort to produce rotation. As the range of excursion of the shaft is halved, he would also have to perform twice as many maneuvers to achieve the same output. Clearly the T-handle is much superior and less injurious to operator health (Figure 32-57).

Projective Evaluation

Whenever possible, a job should be ergonomically evaluated while it is still in the planning phase. This makes it possible to "design out" of

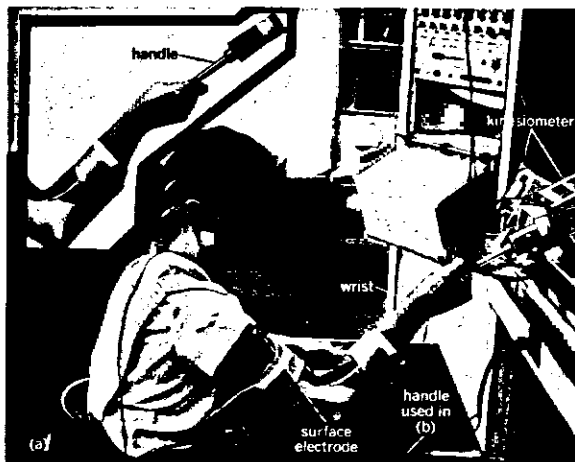


Figure 32-55. Kinesiometer Measuring Rotation of the Forearm Using (a) a Tool Handle Which Permits the Wrist To Be Kept Straight. A surface electrode simultaneously picks up a myogram of the biceps, which is one of the muscles rotating the forearm, and a potentiometer attached to the end of the tool shaft measures rotation of tool. (b) A tool handle which forces the wrist into deviation, which is uncomfortable and fatiguing.³⁶

the task, features, equipment and maneuvers which are potentially traumatogenic. It also makes it possible to make reliable predictions with respect to the work tolerance of a specific industrial population, duration of training, and counselling procedures which should be employed while training is in progress.

All projective evaluation, be it theoretical or experimental, must include an analysis which shows how sensory input from the workplace is transferred by the musculo-skeletal structure into manipulative output. The ergonomist, under such circumstances, should direct his efforts towards the development of the optimal kinetic chain for the performance of a given task.

If projective evaluation demands experimentation, then the results of laboratory or field work should be presented in the form of a Biomechanical Profile, which, however, is far more complex than the one described in Figure 32-56. Also, unless the task studied is physically heavy, the dynamometer will only be rarely used in projective evaluation. Instead the kinesiometer is employed.

The kinesiometer measures the biomechanical parameters of manipulative movements. These are output measurements describing quantitatively the performance elements of a man-task system. In manipulative movement, most commonly displacement, velocity and acceleration of the object handled, are used as measures of output efficiency.

Displacement is indicative of range and pattern of motion. Velocity serves as an index of both speed as well as strength. Finally, acceleration reflects control over precision and quality of motion.¹⁶ Abnormal acceleration and deceleration "signatures" are invariably associated with im-

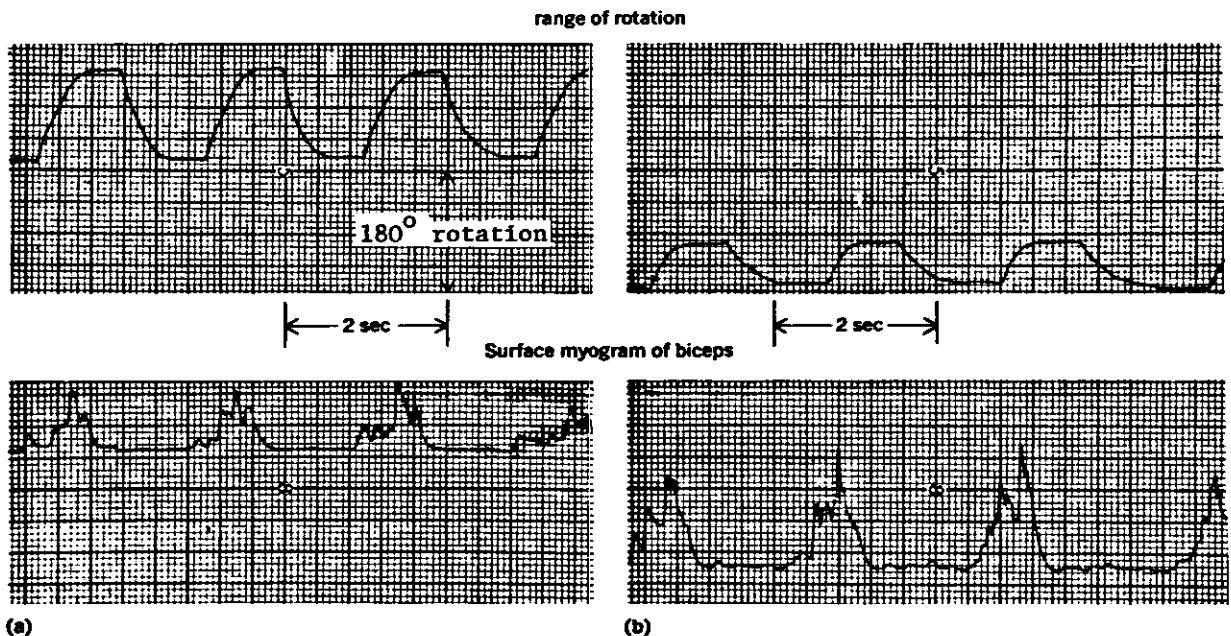
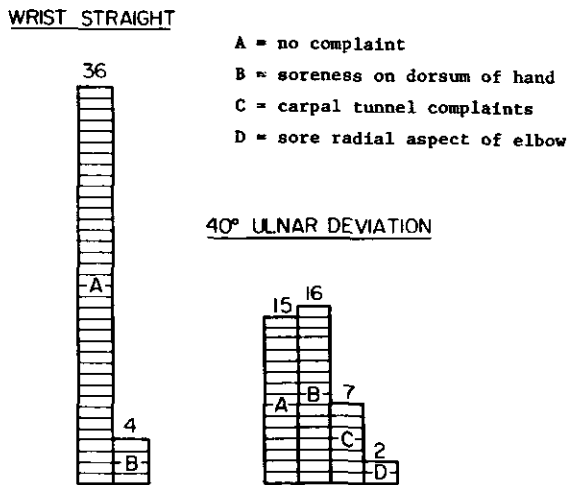


Figure 32-56. Biomechanical Profile of Forearm Rotation Using Tracing of Tool Rotation and Surface Myogram of Biceps. (a) Wrist straight. (b) Wrist deviated.³⁶



Tichauer, E. R.: Potential of Biomechanics for Solving Specific Hazard Problems. Proc. 1968 Professional Conference, American Society of Safety Engineers, Park Ridge, Illinois, 1968, pp. 149-187.

Figure 32-57. Subjective Physical Response Obtained from a Sample of 40 Volunteers Performing the Task Described in Fig. 56.³⁵

precise and unsafe movements due to the inability to terminate a motion at the correct place and time. A kinesiometer is described in Figure 32-58. It comprises a task board with lights installed on it and wired so that only one light is on at a time. A metal-tipped "tool" is mounted on a lightweight rod. As soon as the light is touched by the tool, it is extinguished and another bulb automatically switches on. With the help of a programming board, it is possible to generate a sequence of motions simulating an actual job closely, thus avoiding an expensive mock-up of a workplace which may exist at that stage only on the drawing board. The rod attached to the tool is connected to a set of potentiometers so that the movement of the tool in space generates voltage signals which are converted into electrical analogs of the vector sums of each displacement, velocity and acceleration of the "tool tip" at any instant. Motion inventories can be programmed through interchangeable patchboards to simulate occupational motion patterns for a wide range of industries, such as food processing, electronic assembly, or the needle trades.

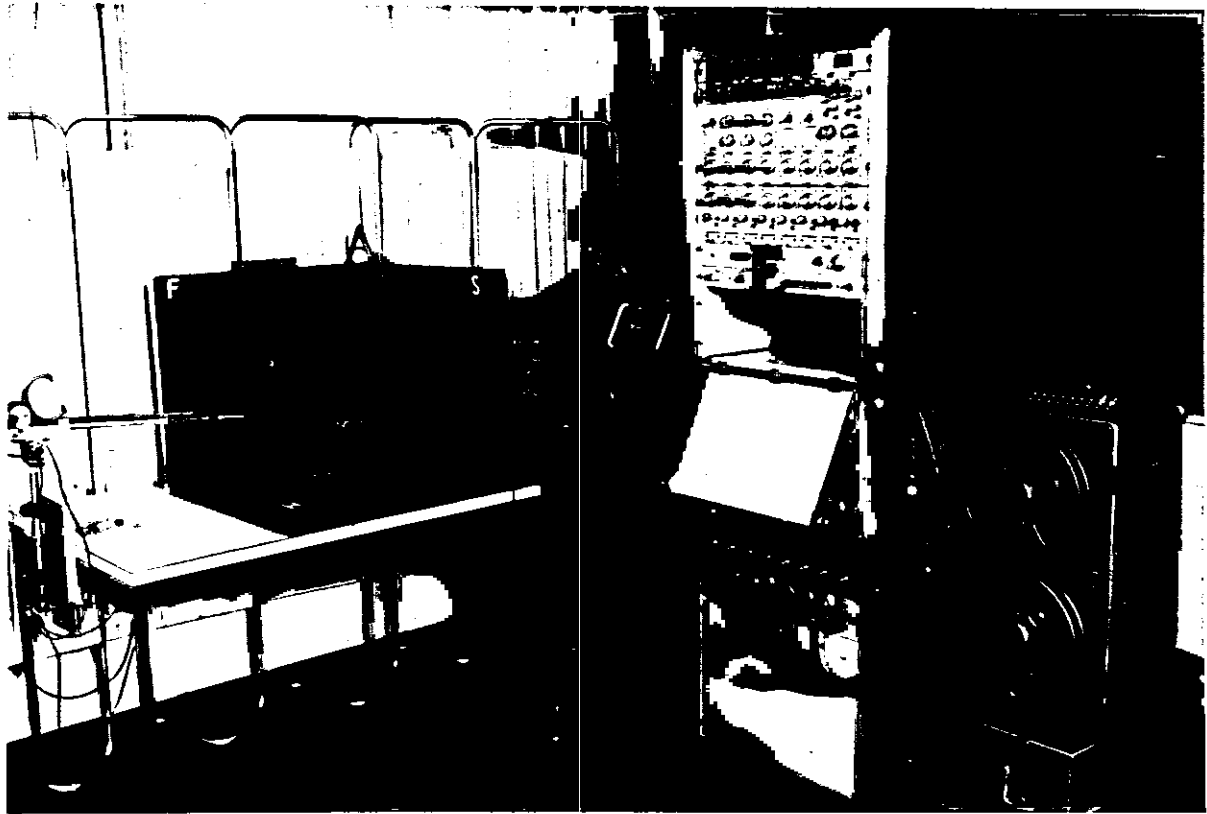
These biomechanical parameters are recorded simultaneously with the electrophysiological parameters of the kinetic chain of the task (Figure 32-59). These represent activity of the muscles moving the eyes, the head and neck, the shoulder and

the extensors of the wrist. These tracings — altogether seven in number — displaced on the chart recorder constitute the complete Biomechanical Profile for this task. Figure 32-60 shows a subject completely electroded for testing. Optimal positioning of electrodes can be easily obtained when consulting standard reference works.^{78, 79}

The profile makes it possible to distinguish between individuals likely to develop either low or high work tolerance (Figure 32-61). In the example shown in Figure 32-61, two workers performed exactly the same task, a number of forward reaches in identical sequence. Although their production times were approximately equal, the effort required to produce these outputs was markedly different. The activity rate in the deltoid muscle, particularly at low velocity, was generally far higher in the individual with low work tolerance while, at the same time, the wrist extensor signal remained unstructured. This is indicative of high effort, but disproportionately low output, and predictive of early fatigue. Also, it was seen from the tracings of neck muscle activity that too much scanning was done by the head instead of by the eyes. The lack of purposeful anticipatory eye scanning following a single head movement is also indicative of inferior performance and great discomfort when performing the task over lengthy periods of time. The remedy, of course, is training for proper motion habits, after potentially discomfort-causing performance features have been identified.

The Biomechanical Profile can also establish status and quality of the individual's training as well as identify many improper work mannerisms which can be eliminated through proper instruction. Figure 32-62 shows "before practice" and "after practice" performance of the same individual reaching sideways away from body and back. The untrained worker lacks coordination between scanning and wrist movements; the deltoid muscle is in constant tension, indicating that there is a violation of one of the basic prerequisites of work tolerance: Keep the Elbows Down (Table 32-2). The worker was counselled to look straight at the target, then to proceed to reach for it without further dependence upon further visual correction, reserving the strongest activity of the wrist for the end of the sequence when time positioning takes place. In the "after practice" profile recorded, eye and wrist movement are now in proper sequence. Deltoid activity has declined; thus, the level of effort has substantially decreased, work tolerance has increased, and productive output has nearly doubled.

A kinesiometer can take many forms and can be adapted to a wide variety of jobs, from hand-tool operation to the measurement of the potential traumatogenic effects of equipment displays, and to the measurements of lifting operations. This bridges the gap which since the beginnings of scientific management, industrial psychology and work physiology has plagued most practitioners in industry. Workers as early as the Gilbreths had already fully established the scientific rationale behind the disciplines of ergonomics and biome-



Tichauer, E. R., Gage, H., Harrison, L. B.: The use of Biomechanical Profiles in Objective Work Measurement. *J. Ind. Eng.* IV: 20-27, 1972.

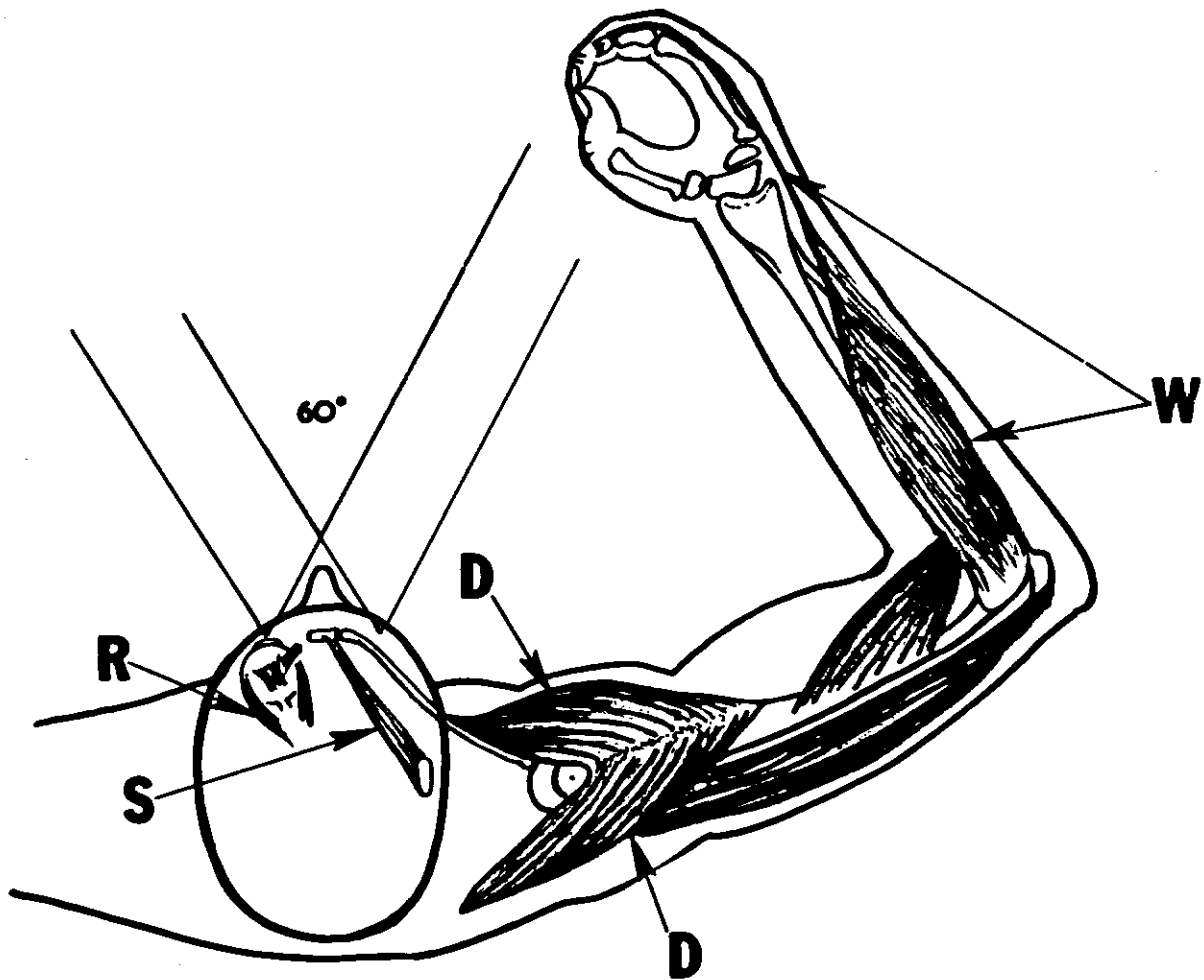
Figure 32-58. The kinesiometer used in this experiment consists of a task board (A) and a metal-tipped tool (B). When any of the 19 lights on the task board is touched by the tool it is extinguished and another bulb switches on. The tool movement generates voltage signals in three potentiometers (C). The output of this kinesiometer is converted by an analog computation module (D). Also at (D) are the interchangeable patch boards which program the light patterns to simulate any occupational motion pattern. The chart recorder (E) displays the complete Biomechanical Profile. Signals are stored in analog form on a multi-channel tape recorder (F) for computer processing.¹⁶

chanics as practiced today. Nevertheless, they lacked instrumentation adequate to conduct experimental investigations into the physical effort expended by individual muscles in the performance of a specific task. Likewise, the sequencing of action and effort levels of the various muscles involved in manipulative and other maneuvers were beyond the investigative technologies available then. These pioneers were simply fifty years ahead of their time. True enough, the second industrial revolution, due to the fact that the worker in industry is no longer a "free roaming animal" but is constrained to a relatively rigid posture and repetitive motion pattern throughout a long working day, has produced, or aggravated, numerous known and previously unknown industrial ailments and complaints. However, the new technologies, as a by-product, also produced the means of disability prevention. The solid-state technologies perfected during recent years and the ensuing miniaturization and improvements of in-

strumentation have made it possible to develop kinesiometers and biomechanical techniques which are effective tools of disability prevention raising both the levels of physiological and emotional well-being of the working population as well as the productive levels and the competitive posture of American enterprise.

ACKNOWLEDGEMENTS

Much of the research leading to the technologies described in this chapter was supported by a grant from the National Institute for Occupational Safety and Health, and to some degree by the Social and Rehabilitation Service of the Department of Health, Education and Welfare, under the designation of New York University as a Research and Training Center. Dr. Howard Gage helped with the review, and redrafting of the section on Ergonomic Evaluation of Handtools; while Dr. Ch. Saran assisted with the mathematical mechanics in the section on Materials — Handling.



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Figure 32-59. The kinetic chain constructed for industrial practice links the major sensory organs and key muscles required to perform a task. In Eye-Hand coordination, sensory input to the eyes is inferred by monitoring the small muscles (R) which rotate the eyeball. To see objects outside a binocular visual cone of 60 degrees, the head must be moved, using (S) the sternomastoid muscles of the neck. Arm movement at the shoulder is produced by (D) the deltoid muscle. Wrist movement is produced by (W) the extensor muscles of the forearm.^{1a}

C. Gold designed much of the electronic instrumentation described. My wife, Mrs. Helen Tichauer, was of great help in literature search and in the drawing and development of illustrations. Finally, the subsection on Projective Evaluation is based upon a paper^{1a} "The Use of Biomechanical Profiles in Objective Work Measurement" by Tichauer, Gage and Harrison. The painstaking care of Miss E. Schipper in preparation and revision of the manuscript is gratefully acknowledged.

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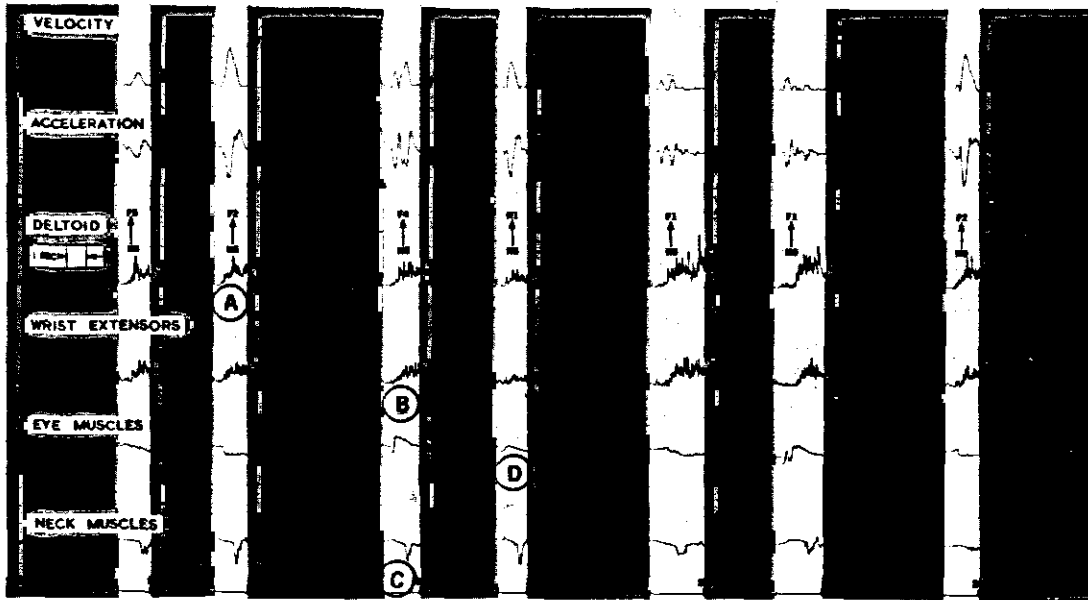
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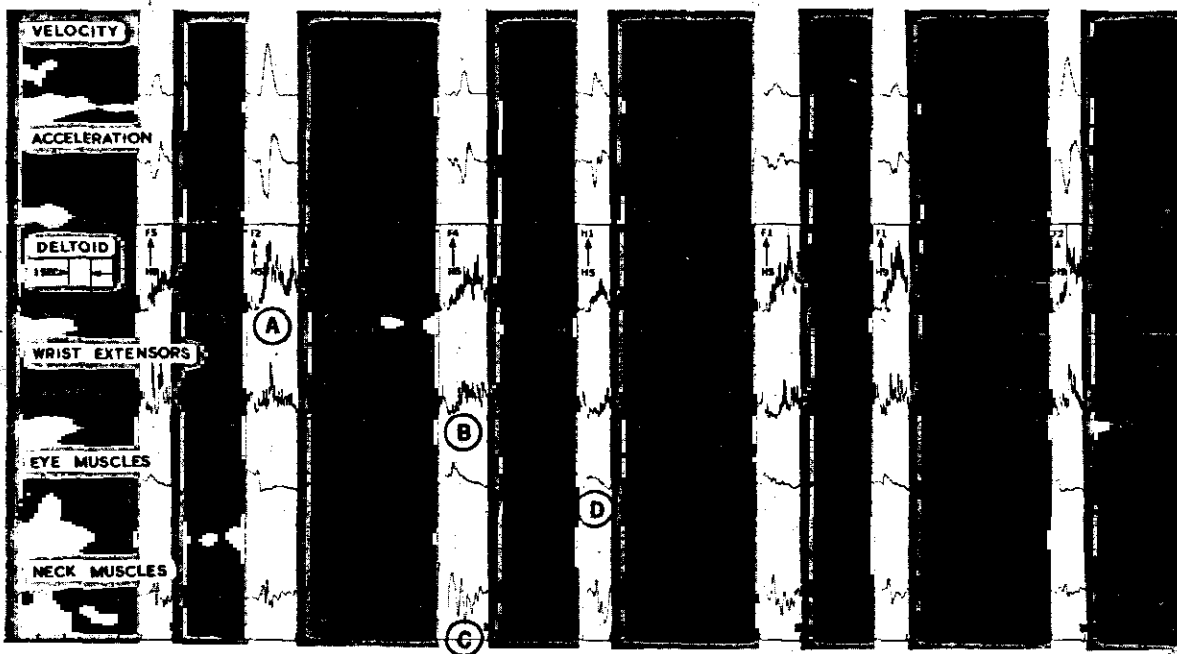
Figure 32-60. Four sets of surface electrodes were placed on each subject, over the muscles comprising the kinetic chain, as pictured in Fig. 59. In each set, the third electrode acts as the ground. Electrodes were positioned according to standard muscle testing procedures, so that each myogram obtained represented a maximum amount of contracting muscle mass. All subjects were representative of the female working population commonly found performing manual production work in industry.¹⁶

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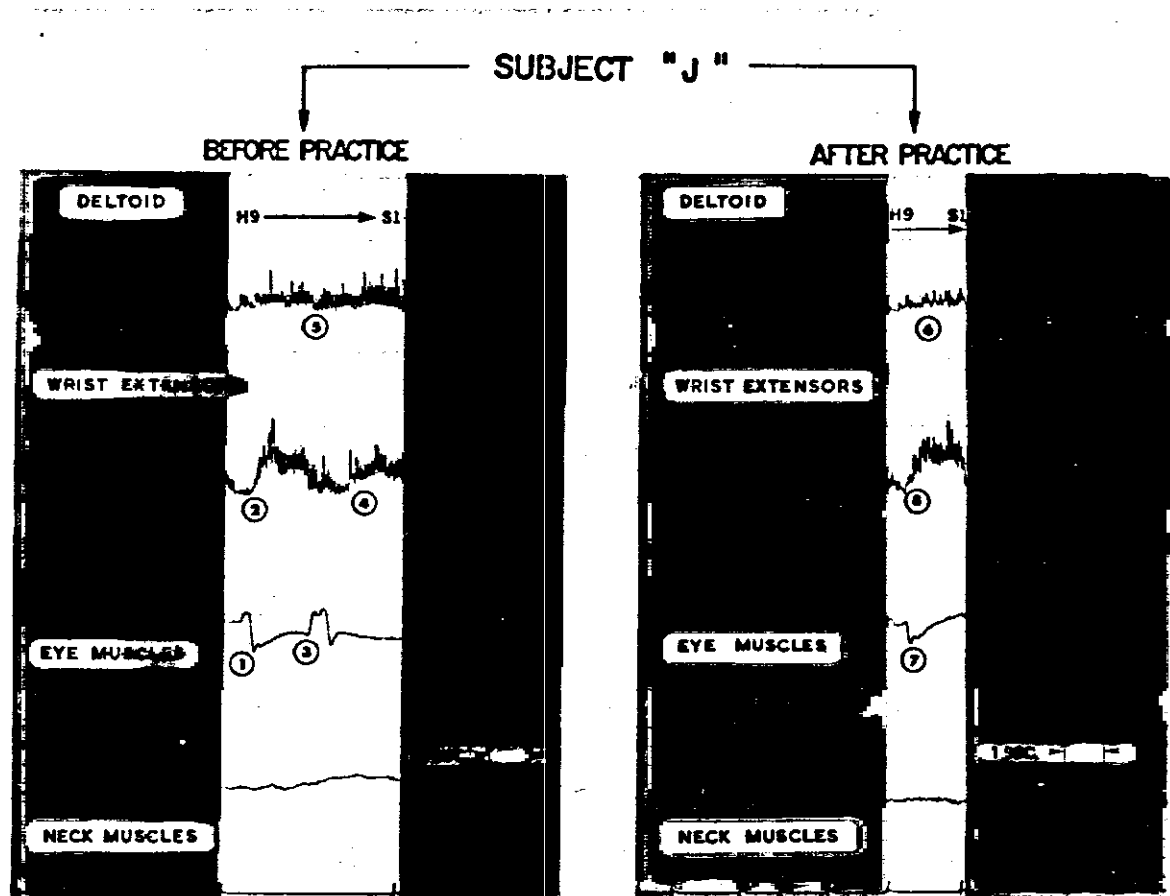
LOW WORK TOLERANCE

DISPLACEMENT - D - 47° 20"



Tichauer, E. R., Gage, H., Harrison, L. B.: The use of Biomechanical Profiles in Objective Work Measurement. J. Ind. Eng. IV: 20-27, 1972.

Figure 32-61 (A & B). Biomechanical profiles can be used to distinguish between individuals who are likely to have low or high work tolerance. Two workers performed a number of forward reaches. The firing rate in the deltoid (A) muscle, particularly at low velocity, is commonly far higher for individuals of low work tolerance, left, while the wrist extensors' myograms (B) of such workers are continuous and unstructured. Both of these factors are likely to be indicative of relatively high effort accompanied by poor efficiency of performance — the worker manipulates for fine positioning before arriving at the target. Neck muscles' activity (C) show that the low tolerance worker does too much of the scanning with the head. The lack or presence of purposeful anticipatory eye scanning (D) is also a good predictor of sustained performance ability.¹⁶



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Figure 32-62. The state and quality of worker's training can be measured by electromyographic kinesiology, and the work habits which need retraining can be pinpointed. Before practice (left), the subject moves her eyes to search (1), then moves her wrist (2), looks again (3), finally does useful work with her wrist as she positions a second time (4). During the entire motion (which goes from the horizontal to a side target point), the deltoid (5) is under constant tension since the elbows are kept high as the shoulder is moved. The total motion consumes 4.7 seconds. The practiced performance (right) resulted from proper training. The subject carried out instructions such as: "keep the elbows down." Deltoid activity is minimal (6); eye movement (7) is purposeful and efficient — Subject "J" looks first, scanning the entire visual field; the wrist (8) is then moved to the located target. The trained subject needs less than half the reach time.¹⁵

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Important Notice: The American Industrial Hygiene Association (Technical Committee on Ergonomics) publishes from time to time "Ergonomics Guides" each one concerned with a specialized aspect of the field (e.g., *Ergonomics Guide to Manual Lifting*); all these should be considered indispensable references for daily practice.

GLOSSARY

Angle of Abduction Angle between the longitudinal axis of a limb and a sagittal plane (q.v.).

Antagonist A muscle opposing the action of another muscle. An active antagonist is essential for control and stability of action by a prime mover (q.v.); e.g., the biceps and pronator teres are antagonists in pronation and supination.

Anthropometry The measurement of man's body dimensions, generally performed with calipers which measure the distance between specific anatomical reference points. For more details, see Dreyfuss: "The Measurement of Man," Whitney Library of Design.

Axis of Rotation The true line about which angular motion takes place at any instant. Not necessarily identical with anatomical axis of symmetry of a limb nor necessarily fixed. Thus, forearm rotates about an axis which extends obliquely from lateral side of elbow to a point between the little finger and ring finger. The elbow joint has a fixed axis maintained by circular joint surfaces, but the knee has a moving axis at its cam-shaped surfaces articulate. Axis of rotation of tools should be aligned with true limb axis of rotation. Systems of predetermined motion times often specify such axes incorrectly.

Axis of Thrust Line along which thrust can be transmitted safely. In the forearm, it coincides with the longitudinal axis of the radius. Tools should be designed to align with this axis. Ulnar or radial deviation which produces misalignment causes bending stress acting on the wrist.

Biceps Muscle The large muscle in the front of the upper arm.

Bicipital Tuberosity A protuberance on the medial surface of the radius to which the biceps attaches.

Biomechanics The study of the human body as a system operating under two sets of laws: the laws of Newtonian mechanics and the biological laws of life.

Brachialis Muscle Short, strong muscle originating at lower end of the humerus (q.v.) and inserting into ulna (q.v.). Operates at mechanical advantage, powerful flexor of forearm, employed when lifting.

Camber Generally refers to a tilt or curve. In seating design, the camber, or slope of the chair with respect to the horizontal is optimally 8° from front to back.

Capitulum of Humerus A smooth hemispherical protuberance at the distal end of the humerus articulating with the head of the radius. Irritation caused by pressure between the capitulum and head of the radius is called tennis elbow.

Carpal Tunnel A passage in the wrist through which important blood vessels and nerves pass to the hand from the forearm. Ulnar or radial deviation cause misalignment of the carpal tunnel and irrigation of structures passing through it.

Carpal Tunnel Syndrome A common affliction of assembly workers caused by compression of the median nerve in the carpal tunnel. Often associated with tingling, pain or numbness in the thumb and first three fingers. Reduces manipulative skills, particularly if thumb is involved, and frequently reduces work output.

Deltoid Muscle The muscle of the shoulder responsible for extending the arm sideways, and for swinging the arm at the shoulder. Overuse of the deltoid muscle may cause fatigue, pain in the shoulder and unwarranted fear of heart disease.

Distal Away from the central axis of the body.

Distal Phalanx Colloquially known as the "knuckle," the long bone of the finger or toe away from the central axis of the body (distal). Frequently used as an anatomical reference point in work analysis.

Dynamometer Apparatus for measuring force or work output external to a subject. Often used to compare external output with associated physiological phenomena (electromyography, spirometry, etc.) to assess physiological work efficiency.

Epicondylitis Inflammation or infection in the general area of an epicondyle; e.g., tennis elbow.

Ergonomics A multidisciplinary activity dealing with the interactions between man and his total working environment plus such traditional environmental elements as atmosphere, heat, light and sound as well as all tools and equipment of the workplace.

Extensor Muscles A muscle which, when active, increases the angle between limb segments; e.g., the muscles which straighten the knee or elbow, open the hand or straighten the back.

Extensor Tendon Connecting structure between an extensor muscle and the bone into which it inserts. Examples are the hard, longitudinal tendons found on the back of the hand when the fingers are fully extended.

External Mechanical Environment The man-made physical environment; e.g., equipment, tools, machine controls, clothing. Antonym: internal (bio)mechanical environment, q.v.

Flexor Muscles A muscle which, when contracting, decreases the angle between limb segments. The principal flexor of the elbow is the brachialis muscle. Flexors of the fingers and the wrist are the large muscles of the forearm originating at the elbow. Cf., extensor muscle.

Foot-Pounds of Torque A measurement of the physiological stress exerted upon any joint during the performance of a task. The product of the force exerted and the distance from the point of application to the point of stress. Physiologically, torque which does not produce motion nonetheless causes work stress

whose severity depends on the duration and magnitude of the torque. In lifting an object or holding it elevated, torque is exerted and applied to the lumbar vertebrae.

Humerus The bone of the upper arm which starts at the shoulder joint and ends at the elbow. Muscles which move the upper arm, forearm and hand are attached to this bone.

Iliac Crest The upper rounded border of the hip bone. No muscles cross the iliac crest and it lies immediately below the skin. It is an important anatomical reference point because it can be felt through the skin. Seat backrests should clear the iliac crest.

Inertial Moment Related to biomechanics, that moment of force-time caused by sudden accelerations or decelerations. Whiplash of the neck is caused by an inertial moment. In an industrial setting, side-stepping causes application of a lateral inertial moment on the lumbosacral joint, which may cause trauma, pain, and in any case will lower performance efficiency. The inertial moment is one of the seven elements of a lifting task.

Internal Biomechanical Environment The muscles, bones and tissues of the body, all of which are subject to the same Newtonian force as external objects in their interaction with other bodies and natural forces. When designing for the body, one must consider the forces that the internal mechanical environment must withstand.

Ischemia Lack of blood flow. Loss of sufficient replacements to maintain normal metabolism in the cells. Caused by blockage in the circulatory system or failure of the cardiac system. Blockage may be by internal biological agents such as arterial wall deposits or by external environmental agents such as poorly designed tools or workplaces which press against arteries and occlude them. Depending on the degree of ischemia, numbness, fatigue and tingling may be evidenced in the limbs. At the workplace, loss of precision in manipulation may lead to reduced efficiency, poor quality and possibility of accidents.

Ischial Tuberosity A rounded projection on the Ischium. It is a point of attachment for several muscles involved in moving the femur and the knee. It can be affected by improper design of chairs and by situations involving trauma to the pelvic region. When seated, pressure is borne at the site of the ischial tuberosities. Chair design should provide support to the pressure projection of the ischial tuberosity through the skin of the buttocks.

Isometric Work Referring to a state of muscular contraction without movement. Although no work in the "physics" sense is done, physiologic work (energy utilization and heat production) occurs. In isometric exercise, muscles are tightened against immovable objects. In work measurement, isometric mus-

cular contractions must be considered as a major factor of task severity.

Kinesiology The study of human movement in terms of functional anatomy.

Kinetic Chain A combination of body segments connected by joints which, operating together, provide a wide range of motion for the distal element. A single joint only allows rotation, but kinetic chains, by combining joints enable translatory motion to result from the rotary motions of the limb segments. Familiarity with the separate rotary motions and their limitations is necessary for comprehension of the characteristics of the resultant motion. By combining joints whose axes are not parallel, the kinetic chain enables a person to reach every point within his span of reach.

Man-Equipment Interface Areas of physical or perceptual contact between man and equipment. The design characteristic of the man-equipment interface determine the transfer of information and motor skill. Poorly designed interfaces may lead to localized trauma (e.g., calluses) or fatigue.

Latissimus Dorsi A large flat muscle of the back which originates from the spine of the lower back and inserts into the humerus at the armpit. It adducts the upper arm, and when the elbow is abducted, it rotates the arm medially. It is actively used in operating equipment such as the drill press where a downward pull by the arm is required.

Lumbar Spine Lowest section of the spinal column or vertebral column immediately above the sacrum. Located in the small of the back and consisting of five large lumbar vertebrae, it is a highly stressed area in work situations and in supporting the body structure.

Lumbosacral Joint The joint between the fifth lumbar vertebrae and the sacrum. Often the site of spinal trauma because of large moments imposed by lifting tasks.

Mechanotactic Stress Stress caused by contact with a mechanical environment.

Mechanotaxis Contact with a mechanical environment consisting of forces (pressure, moment), vibration, etc. One of the ecological stress vectors. Improper design of the mechanotactic interface may lead to instantaneous trauma, cumulative pathogenesis, or death.

Median Nerve A major nerve controlling the flexor muscles of the wrist and hand. Tool handles and other objects to be grasped should make good contact with the sensory feedback area of this nerve located in the palmar surface of the thumb, index, middle, and part of ring finger.

Mid-Sagittal Plane A reference plane formed by bisecting the human anatomy so as to have a right and left aspect. Human motor function can be described in terms of movement relative to the mid-sagittal plane.

Moment Magnitude of the force times distance of application.

Moment Concept The concept based on theoretical and experimental bases that lifting stress depends on the bending moment exerted at susceptible points of the vertebral column rather than depending on weight alone.

Musculo-Skeletal System The combined system of muscles and bones which comprise the internal biomechanical environment.

Olecranon Fossa A depression in the back of the lower end of the humerus in which the ulna bone rests when the arm is straight.

Palmar Arch Blood vessel in the palm of the hand from which the arteries supplying blood to the fingers are branched. Pressure against the palmar arch by poorly designed tool handles may cause ischemia of the fingers and loss of tactile sensation and precision of movement.

Popliteal Clearance Distance between the front of the seating surface and the popliteal crease. This should be about 5" in good seat design to prevent pressure on the popliteal artery.

Popliteal Crease (or Line) The crease in the back of the leg in the hollow of the knee when lower leg is flexed. Important anatomical landmark.

Popliteal Height of Chair The height of the highest part of the seating surface above the floor.

Popliteal Height of Individual The height from the crease in the hollow of the knee to the floor is called the "popliteal height" of the individual concerned.

Pronation Rotation of the forearm in a direction to face the palm downward when the forearm is horizontal or backward when the body is in anatomical position. An important element of industrial demanded motions inventory, it is performed by muscles whose efficiency is a function of arm position.

Proximal Describing that part of a limb which is closest to the point of attachment. The elbow is proximal to the wrist which is proximal to the fingers.

Radial Deviation Flexion of the hand which deflects its longitudinal axis toward the radius. It causes the head of the radius to press against the capitulum of the humerus, and may lead to irritation of the elbow ("tennis elbow"). Tool design should minimize radial deviation. Strength of grasp is diminished in radial deviation.

Radius The long bone of the forearm in line with the thumb. It is the active element in the forearm during pronation and supination. It also provides the forearm connection of the wrist joint.

Raynaud's Syndrome Constriction of the blood vessels of the hand from cold temperature,

emotion, or unknown causes. Afflicts women predominantly and affects both hands simultaneously. Hands become cold, blue and numb and lose fine prehensile ability. On recovery, hands become red accompanied by burning sensation. Easily confused with one-sided numbness and tingling caused by poor tool design and resulting pressure.

Sagittal Plane A plane from back to front vertically dividing the body into right and left portions. Important in anthropometric definitions. Mid-sagittal plane is a sagittal plane symmetrically dividing the body.

Sensory Feedback Use of external signals perceived by sense organs (e.g., eye, ear) to indicate quality or level of performance of an event triggered by voluntary action. On the basis of sensory feedback information, decisions may be made; e.g., permitting or not permitting an event to run its course; enhancing or decreasing activity levels.

Sensory End Organs Receptor organs of the sensory nerves located in the skin. Each end organ can sense only a specific type of stimulus. Primary stimuli are heat, cold, or pressure, each requiring different end organs. Knowledge of end organ distribution is of importance to the safety engineer. For example, there are few heat receptors on the outer surface of the forearm, so that the skin may be severely burned before heat is sensed.

Sternomastoid Muscles A pair of muscles connecting the breastbone and lower skull behind the ears, which provide support for the head. When operating together, the right and left sternomastoids pull the head forward and downward, and when operating singly, each turns the head to the opposite side. They oppose the semispinalis muscles and stabilize the head. In the workplace, the worker's head position should be nearly vertical to minimize activity of the semispinalis and sternomastoid muscles. The sternomastoid is also functionally important in head scanning.

Supination Rotation of the forearm about its own longitudinal axis. Supination tends to turn the palm upward when the forearm is horizontal and forward when the arm is in anatomical position. Supination is an important element of available motions inventory for industrial application, particularly where tools such as screwdrivers are used. Efficiency in supination depends on arm position. Workplace design should provide for elbow flexion at 90 degrees.

Tendons Fibrous end sections of muscles. It attaches to bone at the area of application of tensile force. When its cross-section is small, stresses in the tendon are high, particularly because the total force of many muscle fibers is applied at the single terminal tendon. The site of many industrial diseases caused by trauma, biomechanically improper movements,

or failure of lubrication, the tendon must be protected in tool and workplace design.

Tennis Elbow Sometimes called epicondylitis. An inflammatory reaction of tissues in the lateral elbow region. In an industrial environment it may follow effort requiring supination against resistance (as in screwdriving) or violent extension of the wrist with hand pronated. Can frequently be avoided by assuring that the axis of rotation of a tool or machine control coincides with the orthoaxis of rotation of the forearm.

Tenosynovitis A disease of the wrist. Inflammation of the tendon sheaths of the wrist often associated with continual ulnar deviation during rotational movements (e.g., screwdriving) or by other overwork or trauma. In industry, extensor sheath inflammation is more frequent. Work tolerance is reduced because of pain during wrist and finger movement.

Trauma An injury or wound, generally caused by a physical agent. Cuts, bruises and abrasions are obvious examples of trauma, but trauma may be present even though it is not visible; e.g., strained muscle. The causes of trauma must be anticipated in workplace design or tool design. Protective devices and special clothing (work shoes, gloves) are used to avoid trauma.

Triceps The large muscle at the back of the upper arm that extends the forearm when contracted.

Trigger Finger Also known as snapping finger. A condition of partial obstruction in flexion or extension of a finger. Once past the point of obstruction, movement is eased. Caused by thickening of a tendon or localized reduction of the tendon sheath. In the workplace, flexing against strong antagonists and flexing of the distal phalanx without middle phalanx movement is suspected. Tool handles should be designed for trigger operation by the thumb.

Ulna One of the two bones of the forearm. It forms the hinge joint at the elbow and does not rotate about its longitudinal axis. It terminates at the wrist on the same side as the little finger. Task design should not impose thrust loads through the ulna.

Ulnar Deviation A position of the hand in which the wrist is bent toward the little finger. Ulnar deviation is a poor working position for the hand and causes nerve and tendon damage. It reduces the useful range of pronation and supination by approximately 50%, and work performed in ulnar deviation proceeds at low efficiency. Handtool design should avoid ulnar deviation.

Viscerotaxis One of the ecologic stress vectors. A form of chemotaxis concerned with the internal contact of chemical agents within the body. Chemical exposure via the gastrointestinal tract, the pulmonary system, and the urogenital systems are examples of viscerotaxis.

Work Strain The natural physiological response reaction of the body to the application of work stress. The locus of the reaction may often be remote from the point of application of work stress. Work strain is not necessarily traumatic but may appear as trauma when excessive, either directly or cumulatively, and must be considered by the industrial engineer in equipment and task design. Thus, increase of heart rate is non-traumatic work strain resulting from physical exertion, but tenosynovitis is patho-

logical work strain resulting from undue work stress on the wrists.

Work Stress Biomechanically, any external force acting on the body during the performance of a task. It always produces work strain. Application of work stress to the human body is the inevitable consequence of performance of any task, and is therefore only synonymous with "stressful work conditions" when excessive. Work stress analysis is an integral part of task design.

THE INFLUENCE OF INDUSTRIAL CONTAMINANTS ON THE RESPIRATORY SYSTEM

George W. Wright, M.D.

INTRODUCTION

Those persons responsible for evaluation and control of the industrial environment for the purpose of preventing respiratory injury should have (1) knowledge of the anatomy of the respiratory system, (2) an understanding of the factors governing entry, deposition, removal and retention of gases and particles presented to the system and (3) some knowledge of the way in which tissues of the respiratory system react to gases and particles.

The type and severity of tissue response is related to the dose and the nature of the specific agent present. Air, which looks dirty or has an offensive odor may, in fact, pose no threat whatsoever to the tissues of the respiratory system. In contrast, some gases essentially odorless or at least not offensive, and some particles even when present in numbers too small to make the air appear dirty, can cause severe and serious tissue injury. Information about these matters provides an essential motivation to the industrial hygienist and his co-workers and gives them a more balanced approach to their activities. Lack of such knowledge converts a responsibility which should be most interesting and rewarding into a series of rather dull activities.

The progenitors of man evolved in an environment which probably contained a higher concentration of particles and noxious gases than exists now. One could anticipate therefore, that man might retain some ability to overcome such hazards or his genetic precursors would not have survived during that distant period. The fact is, man does possess anatomical and physiological mechanisms which protect the tissues from injury by many airborne agents. The multiple branchings and tortuous course of the narrow passageways through which air is conducted on its way to the deeper portions of the lungs favor the deposition of particles upon the more resilient surface of the proximal conducting tubes, rather than the fragile, more distal gas exchanging surface. The entire surface of the air-containing parts of the lung is covered by a thin layer of fluid which, not only serves as a protective layer, but also as a carrier or vehicle upon which particles are transported from the lung to the pharynx via the mucociliary escalator. This mechanism, plus that of the phagocytic system, is extraordinarily efficient in removing particles or storing them within cells, the macrophages, which are capable of tolerating many kinds of particles without injury. The surface cells of the lung replicate at a high rate and when they are injured, they are rapidly re-

placed by normal cells. Recovery from tissue injury via these regenerative forces is often surprisingly complete. These various mechanisms of upper airway deposition, surface protection, particle transport and cell regeneration make it possible for man to tolerate surprisingly high concentrations of airborne particles and noxious gases. Nevertheless, the system can be overwhelmed with subsequent persistent injury depending upon the concentration and the kind of gases and airborne particles to which it is exposed. This chapter is aimed at setting forth the principles governing the reactions of the respiratory system to the environment. It is not a compendium of occupational respiratory diseases, nor is it in any sense a textbook of pulmonary anatomy and physiology.

PERTINENT FEATURES OF THE ANATOMY AND PHYSIOLOGY OF THE RESPIRATORY SYSTEM

The human lung is much like a fish's gill, developed in the course of our evolution in a position inside rather than outside the body. It is a gas-exchanging mechanism comprised of a large membrane, on one side of which blood flows and on the other side of which there is a gas phase. A high gradient for oxygen and CO₂ exchange is maintained by the flow of venous blood over one side, and by the pumping of air into and out of the lungs, thus maintaining an optimum concentration of oxygen and CO₂ in the gas phase overlying the other side of the membrane. The gas-exchanging surface is comprised of blood capillaries overlaid by a very thin single cell layer having an effective surface of approximately seventy square meters. Blood is brought to this membrane via pulmonary arteries and conducted away from it via the pulmonary veins. A second system of tubes, the bronchial system, conducts air to and from the gas phase contained in the alveoli, the thin walls of which contain the capillaries. The heart pumps blood through the system, and the muscles of respiration move the chest bellows, and thus pump the respired air to and from the gas phase in the alveoli. One of the marvels of animal construction is that this highly complex and effective system is housed in a relatively small space and is protected from mechanical injury by being contained within the chest cavity. In this discussion we will be concerned chiefly with the air-conducting system and the terminal air spaces or alveoli, the walls of which constitute the membrane separating the gas from the blood phase.

The air-conducting system begins with the

nose, mouth and pharynx. The mouth and oral-pharynx are a globular, open chamber. The nasal and naso-pharyngeal chambers, in contrast, contain ridges or projections, the turbinates. The passages through the nose are semi-separate, narrow and tortuous and this causes the airstreams traversing this system to be turbulent and to change direction frequently, and to be so narrow that the center of the moving airstream is close to the wall of the passages. This arrangement favors deposition of the particles and makes for a more effective gas absorbing surface in this region than exists in the mouth and oral pharynx.

A single tube or airway, the trachea, emerges from the pharynx. This tube divides into the right and left bronchus, each of which further divides into branches entering each lobe of the two lungs. The bronchial system undergoes twenty-three branchings, each of slightly smaller diameter than its parent. The walls of the bronchial tubes become progressively thinner and at the seventeenth branching, small out pouchings or chambers — the alveoli — begin to appear. Subsequent branchings have walls composed essentially of alveoli. Progressing from the trachea toward the ultimate end structures, all divisions devoid of alveoli are called bronchi or bronchioles. When a few alveoli appear in the wall of the conducting system, the tube is designated as a respiratory bronchiole and, when many are present, the tube is an alveolar duct. The ultimate structure at the very end is a wider chamber, the atrium, and from this room only alveoli project.

Air conduction or mass movement of air traverses all bronchi and bronchioles, but at the alveolar duct, or some more distal point, mass movement of air ceases. Further movement of gas molecules into the alveoli, or from the center of the alveoli to the surface of the alveolar membrane, is by diffusion. The anatomical point at which the transition from mass movement of air to pure diffusion occurs is uncertain and probably varies with depth of breath. The location of this interface where mass movement of air ceases and diffusion becomes the only mechanism for more distal movement of particles is of some importance. Particles larger than 0.5 microns do not diffuse, but move through the airways by being entrained in mass movement of air. Hence, particles larger than 0.5 microns penetrate the lung only where mass movement of air occurs and the majority that are deposited fall on the walls of the conducting tubes. Based upon position, some undoubtedly fall by gravity effect into the alveolar openings and thus onto the alveolar surface. A relatively small proportion of the total particles larger than 0.5 microns in diameter entering the lung actually reach the alveolar surface.

The surface of the nasal passage is approximately 160 cm² and in most places the air flows through channels approximately one millimeter in diameter. These dimensions, plus the fact that the air stream changes its direction several times and is turbulent at various points during its passage through the nasal structures, makes the nasal passageway effective as a filter for airborne particles

and also as a gas absorber, particularly for those gases such as sulphur dioxide which have a rather high solubility in the fluids covering the inner surface of the nose. In adults, the trachea is approximately twenty millimeters, the third or fourth branching of the bronchi five millimeters, and the sixteenth branching 0.5 millimeters in diameter. Further branchings arrive at a tube approximately 0.4 millimeters in diameter. The conducting tubes become slightly wider during each inspiration and narrower during expiration. The frequent change of direction of the branching air tubes and their small diameter greatly favors the deposition of particles from the air passing through them. Thus, those airways proximal to any point in the conducting system act as a filter protecting those passages located more distal to that point.

The nasal passages and the air conducting tubes are lined by a mucous membrane having most important characteristics. The surface of the membrane is covered by mucous, a liquid which arises in part from cells making up the surface of the membrane, and in part from secreting glandular structures located beneath the surface of the membrane, but connected to that surface by a tubular structure. The mucous forms a sheet overlying the tissue surface and would rather rapidly fill the lumen of the conducting system if it were not for the fact that a mechanism exists for propelling the mucous from the deeper parts of the lung towards the pharynx, where it either can be swallowed or expectorated. The majority of the cells making up the surface of the mucous membrane lining the nasal passages and conducting tubes bear a multitude of cilia on their luminal surface, located just underneath the mucous blanket. The cilia beat rhythmically in a fashion which propels the overlying mucous sheet in the direction of the mouth and thus constantly removes the secretions. The mucous blanket serves two obvious purposes. First of all, it acts as a protective layer on top of the delicate cells which line the respiratory conducting system. Equally important, the blanket provides a vehicle for removal of particles which are continuously deposited upon it from the overlying air mass. Thus the mucociliary escalator system becomes a very potent mechanism whereby the lung undergoes continuous self-cleansing. The mucociliary apparatus extends from the pharynx down through the fifteenth or sixteenth generation of branching. The surface of subsequent branchings, including that of the alveoli, is lined by a thin liquid film, which according to recent studies, is constantly being replaced but at a far slower rate than that of mucous secretion. This thin lining probably is removed by a push from the film-forming cells combined with a pull by its attachments to the mucociliary sheet. In essence, there is a continuous cleansing phenomenon provided by removal of a film of varying thickness and composition, extending all the way from the alveolar surfaces up to the pharynx.

A second cleansing mechanism is provided by phagocytic cells, the macrophages, which are found primarily in the alveolated parts of the lung. The origin of the macrophages is not certain, but the

evidence suggests there are always some present, and these can be enormously and rapidly augmented by local cell division and, via the blood stream, by cells of a similar nature formed in other parts of the body. Macrophages are large enough to engulf particles measuring as much as fifteen microns in their largest aspect. These cells also form clusters around even larger particles and produce giant multinucleated cells. The macrophage individually or in clusters, may live for a long period of time with their engulfed particles, provided the nature of the particle is not such as to cause the death of the macrophage. Some macrophages, since they are mobile, find their way out onto the mucociliary escalator and are excreted together with their engulfed particles by that cleansing mechanism.

A third mechanism of lung cleansing is provided by the lymphatic system. There is a liquid filled space between the capillary blood vessels and the surface of the alveoli, into which particles can penetrate or perhaps be carried by phagocytic cells. This liquid filled space is in direct continuity with the lymphatic tubular system which provides for the flow of a liquid, the lymph, in a direction paralleling the bronchi and directed towards progressively larger tubes. Ultimately the lymph is discharged into the venous system, but enroute it passes through aggregates of lymphoid tissue cells, including the large aggregates or lymph nodes at the lung root. Some of the particles that penetrate into this tissue space just below the alveolar surface ultimately appear in and are held by these collections of lymphoid cells. Other particles appear to traverse the lymph nodes and ultimately are discharged into the venous system. The exact mechanism of this transport of particles and their storage is unknown. A substantial proportion of the particles suspended in the inhaled air remain airborne and leave the lung during exhalation. Those particles which are deposited on the surface of the conducting and more distant portions of the airway are removed by the mucociliary escalator, engulfed by macrophages, pass into the lymphatics, become retained in the lymph nodes or enter the blood stream and some portion of the total remain free in the tissues of the lung.

It is worth noting that particles deposited on the distal portions of the mucociliary escalator can traverse the distance from the fourteenth or fifteenth generation of bronchi up to the pharynx within as little as thirty minutes. Cleansing of this portion of the air-conducting tubes therefore is quite rapid. Those particles deposited in a more distal area move much more slowly; it may take days or weeks in order to be cleared or sequestered. Some particles, either naked or engulfed by macrophages, simply remain indefinitely on the surface or in the interstitial tissues between the alveoli.

Bands of smooth muscle encircle the conducting system throughout its entire length. The utility of this muscle tissue is unclear but because of its presence, the lumen of various portions of the conducting system can be markedly narrowed

when this muscle contracts. The mucous producing cells can respond quite rapidly to stimuli of various kinds with an augmentation of flow of mucous. Under the influence of some kinds of stimulation, the mucous membrane becomes engorged with blood retained in the capillaries and by an excess production of interstitial tissue fluid. These various mechanisms lead to some degree of narrowing of the airway and consequent elevation of resistance to airflow through the conducting system. These phenomena likewise can be reversed quite rapidly, either by removing the stimulus or by applying appropriate drugs. The muscular system is under the control of nerve impulses and the same appears to be true, to some degree at least, of the mucous secreting glands and possibly even of the ciliary action.

The surface cells, blood vessels, lymphatics and conducting tubes, especially those that are thin walled, are supported by an interlacing network comprised of strands of collagen, reticulin and elastic tissue, termed the connective tissue. This tissue also has its substrate of cellular components, chiefly fibroblasts. The replication rate of this tissue is slower than that of the surface cells or blood vessels, but can proceed in an orderly fashion. If injured, however, the replacing tissue may lose its properly organized structure, and instead form masses of fibrosis or scar tissue. The precise mechanism whereby this occurs is uncertain. As will be discussed later, some kinds of particles evoke a rather marked fibrosis and persistent cellular reaction, while other particles are quite inert and produce little or no such reaction. This brief account of the anatomy and physiology of the conducting system and alveolar structures should be of help in understanding the manner in which the respiratory system reacts to inhaled gases and particles.

Behavior of Gases Which Enter the Respiratory System

Gases are made up of particles of molecular size which move both by mass transfer, as in the flow of gas along a tube, and also by diffusion under the influence of the gravitational forces between molecules. If one breathes back and forth into a bag containing a foreign gas of low solubility, the mass movement of air and diffusion forces will lead to an even distribution of gases through the lung-bag system within three or four minutes of quiet breathing, and within a matter of a few seconds if one takes rapid deep breaths. If the foreign gas has a high index of solubility in the fluids lining the conducting system and the gas is of relatively low concentration, the major portion of the inhaled gas may be absorbed in the upper airways, especially in the nose, and the concentration of the gas reaching the depth of the lung will be lower than at the point of entry. This is particularly true during breathing through the nose. For this reason, gases such as SO_2 will predominantly affect the nose and upper airways, whereas gases of low solubility, such as nitrogen dioxide, will affect the airways rather evenly throughout their entire length. Some gases, as for example nitrogen and carbon monoxide,

appear to be totally inert insofar as their influence on the cellular structure of the respiratory system is concerned. Other gases such as phosgene, nitrogen dioxide, sulphur dioxide, and ozone may have a profound effect on the tissues dependent upon the concentration presented to the cells making up the tissues at the point of contact.

Behavior of Particles Which Enter the Respiratory System

If, by suitably gentle technique, one digests the lungs of fifty- to sixty-year-old individuals, including those who may have worked in the dusty trades, one will obtain a residue which can be assumed to have come from exogenous sources via the airborne route over the years. These tiny particles have a most interesting size range. Many will be found to be so small as to be visible only by electron microscope magnification, while others, generally those larger than 0.5 microns in diameter, can be visualized by appropriate illumination and 450x magnification. Of this entire population of particles retained over a period of many years, approximately half will be smaller than 0.5 microns in diameter. Of those that are larger, almost all will be between 0.5 and 5.0 microns in diameter. Fewer than 0.2 of a percent of the total will be larger than 5 microns in diameter, and less than 0.002 percent will be larger than 10 microns in diameter. If one defines a fiber as a particle having an aspect ratio such that the length is three or more times its diameter, one will observe fibers for the most part to be less than fifty microns in length, although some may be as much as two hundred microns long. Even so, the diameters of these fibers will be distributed as indicated above. If, in contrast, one samples the ambient air to which the general public or those who work in the dusty trades are exposed, one finds particles of these dimensions, but in addition, many of much larger diameter and length. It is incumbent upon us, therefore, to reach an understanding of why it is that the long term retention of particles is limited to the sizes just described, in spite of the fact that millions of particles of greater diameter become airborne and, therefore, have the potential for entry into the respiratory system. The explanation for this arises from our knowledge of the behavior of particles suspended in air (aerosols) and the anatomical and physiologic peculiarities of the lung as described in the preceding paragraphs.

For the immediately ensuing paragraphs we will consider particles to be of a non-fiber character. Particles can vary markedly as to shape and, dependent on composition, as to density; both of these factors play a role in the behavior of particles in air suspension. For our purposes we will consider all particles as being spheres of unit density with the understanding that there could be some variation between particles as to speed of settling, depending on their shape and density. For this part of the discussion we will also think of particles as being far larger than those of molecular size. In this respect the major point would be that those particles larger than 0.5 microns will exhibit essentially zero diffusion activity, and even

those down to 0.1 will have minimal such reaction. Those of electron microscope size down to .01 microns and lower will respond to molecular bombardment, and thus exhibit a considerable diffusion activity.

Several physical forces are conducive to the removal of particles from an airborne suspension and their deposition upon surfaces of the respiratory system. Particles suspended in a moving air stream possess inertial forces tending to maintain the direction of motion of the particle. When the air column changes its direction, as at a branching point of the conducting system, or in the tortuous passages of the nose, the entrained particle will tend to continue in its previous direction and be precipitated upon the surface. This effect is directly proportional to the size of the particle, the speed of the air stream, and thus of the particle, and inversely proportional to the radius of the tube. Gravitational forces also remove particles from the air stream and precipitate them on the surface of the respiratory system.

The terminal settling velocity of a particle is directly related to its density, the gravitational constant and to the square of the particle diameter. It is inversely related to air viscosity. Since the gravitational constant and air viscosity are the same at all times, the terminal velocity is in fact predominantly related to particle density and diameter. The degree to which deposition on the basis of gravity will occur is thus related to these two factors, plus the distance through which the particle must fall and the time permitted for the event to occur.

Particle deposition by diffusion is limited essentially to those particles having a diameter smaller than 0.5 microns and, in fact, smaller than 0.1 micron. The smaller the particle the more rapidly diffusion movement can occur. The electron microscope size particles are relatively uninfluenced by any deposition force other than that of diffusion, and the fact that such large numbers of electron microscope sized particles are found in the lung residue indicates that diffusion can play a major role in the deposition of this size particle. Electrostatic and thermal forces have been thought possibly to play a role in deposition of particles in the lungs, but this is still uncertain.

On the basis of known behavior of particles in air suspension and the anatomical arrangement of the conducting tubes, it was predicted that particles larger than ten microns in diameter would be removed completely in the passage of the air stream through the nose and upper airways and that particles between five and ten microns in diameter would be deposited primarily in the upper airways on the mucociliary escalator. Only those particles in the range of one to two microns would be likely to penetrate into the deeper portions of the lung where some deposition in the alveoli might occur by gravity. Particle deposition would, on the basis of these calculations, be least for those particles having a diameter of 0.5 microns. Deposition of particles smaller than this might be increased by diffusion, particularly in

the most distal portions of the air system.

Numerous actual experimental determinations have confirmed this general distribution of location of deposition. For nasal breathing it has been shown that particles larger than ten microns in diameter are almost completely removed and few, if any, reach the conducting tubes of the lungs per se. Some smaller particles also are deposited in the nose, but the majority of these pass through and then are deposited, dependent primarily upon their diameters, along the upper or lower airways. It can be seen from these studies that particles greater than three microns in diameter will have very little opportunity to penetrate deeply and be deposited in the most distal portions of the conducting tubes, where the cleansing action and mucociliary apparatus would be less effective. Since almost 100% of the particles larger than three microns in diameter would fall on the mucociliary escalator and be removed, there is a reasonable explanation for the fact that so few particles of larger size are found in the lung residue after a lifetime of exposure to aerosols of ambient air which undoubtedly contained particles of larger size.

A fiber, defined as a particle the length of which is three or more times its diameter, represents a special case in terms of deposition. As is true of other particles, the settling velocity of a fiber is dependent primarily upon its diameter. One can think of a fiber as being a string of non-fibrous particles insofar as the settling velocity is concerned. In a moving air stream, fibers tend rather strongly to align their length parallel to the direction of air flow. Those fibers that are straight and rigid will therefore present an end-on aspect essentially that of their diameter. Fibers that are curved, curled, or bent in a U shape will have an end-on aspect equal to the width of the curl or curvature. Insofar as interception is concerned there thus will be a much greater chance for deposition of the non-straight fibers, a factor of considerable importance in the narrow airways and in the boundaries of air flow close to the surface. It has been demonstrated that curly fibers penetrate to the deeper portions of the lung much less readily than do straight fibers of equivalent diameter. Length becomes important also to the degree that the fibers are distributed in a random way in the moving air stream. Thus a fiber one hundred microns long oriented at right angles to the direction of flow will have a much greater change of impacting on the surface than will those oriented parallel to the direction of flow. While one does observe an occasional fiber two hundred microns long in the lung dust residues, by far the majority are shorter than fifty microns in length.

Factors Governing the Reaction of the Lung to Gases and Particles

The recognition of whether or not a lung reaction in response to a stimulus has occurred is to a high degree dependent upon the tools and criteria used for such recognition. This is a matter of great importance and often ignored when determining the significance of a specific reaction with respect to whether or not the cellular changes

have led to impairment in terms of function, life expectancy, and employability. Cell death and replacement by replication characterizes the organism from conception to death. Physical factors and external agents, such as bacteria and viruses, constantly influence the orderly progression of cell death and replacement during the state that we call good health. From time to time these external agents may exert an influence of sufficient magnitude to interfere with function or life expectancy, and these episodes are thought of as representing disease.

When one examines the body of a healthy person, utilizing the light microscope one can always find some areas of inflammation and scarring and mild disorder of cell replication which is termed metaplasia. As one examines tissues with the electron microscope, one can recognize alterations of cell structure under circumstances which the light microscope will not recognize. During life one is usually limited to the use of less refined tools in order to recognize the presence of abnormalities, and in general our concept of disease is based upon these tools. Such tools are coarse to the degree that the quantitative aspects of abnormality must reach a certain extent before they will disclose the presence of injury. There is thus a quantitative aspect as well as a qualitative aspect in our concept of disease. There is a further factor involved in deciding whether or not an injury is meaningful and thus deserves the appellation of disease. This has to do with whether or not the impairment is of sufficient magnitude to interfere with life and normal pursuits which make up one's life style. For example, some scars representing the end stage of injury are found in the lungs of every adult. Nevertheless, when these scars are minor in extent they do not in any way interfere with function or shorten the life expectancy of the person. In the light of these statements, it is imperative that one realize there is no sharp line of demarcation between being healthy or ill, normal or diseased, injured or uninjured. We can speak in rather broad terms of the way in which gases and particles may or may not injure the lung, but one must bear in mind that the quantitative aspects are probably more important under most circumstances than are the qualitative ones.

The above comments are germane to a balanced understanding of the factors that govern the import of tissue reaction to external agents. Three characteristics determine whether or not tissue injury will occur and be of an extent great enough to impair function, or shorten life. These factors are (1) the nature of the agent, (2) the quantity or dose of the agent brought to bear in action upon the tissues, and (3) the reactivity of the tissues, oftentimes referred to as the host-factor.

Particles and gases vary as to their inherent physical and chemical nature, and this influences whether or not injury occurs. There are some gases as for example nitrogen, and particles such as carbon and most silicates, which under almost all circumstances are essentially inert in terms of evoking tissue reaction. Such particles, when retained in the lung, are engulfed in macrophages

and ultimately come to reside in the tissue, or in lymph nodes where the reaction is either non-existent, or at most a mild foreign body inflammatory process. Under unusual circumstances of exceedingly high concentration, as for example nitrogen under several atmospheres of pressure, or carbon particles in extra-ordinarily excessive amounts, a cell reaction of greater significance may occur. In contrast, there are some gases such as phosgene and particles such as free crystalline silica, which, because of their inherent quality, are biologically quite active and when present in high enough concentrations can evoke a biological reaction of important magnitude. Bacteria are a special case because these particles, when deposited in the lung, may either be destroyed by macrophages or may grow in large enough numbers to produce disease. In ordinary life pursuits most particles and many gases are inert or relatively inert in the concentrations commonly met with.

On the basis of much evidence, it is generally held that there is a dose or quantity of potentially biologically active particles that will be tolerated without overt evidence of tissue reaction. In terms of an important reaction, this is certainly the case. In terms of recognition of a cellular reaction such as macrophage accumulation in the lung, or subtle changes recognized only by electron microscope or biochemical disturbance of cell structure or function, there is some question as to whether or not this is true. It must also be recognized that the cell reaction to the agent may be an appropriate one and considered a normal reaction rather than an abnormal one. For example, premature death of a cell and its replacement by a normal cell can be thought of as a normal body mechanism for tolerating exogenous agents. In the same sense, the phagocytic action of macrophages with storage of inert particles therein is a normal body function and can scarcely be considered an injury. For our purposes, all injury of a meaningful sort is dose related. This appears to be the case, at least in the minds of most students of the problem, even with respect to carcinogenesis.

The host factor plays an important role, but unless the dose can be accurately measured it is very difficult to quantitate the host reactivity. There are striking examples of true allergic hypersensitivity causing a person to react violently to doses of allergen readily tolerated by the non-allergic. There is also a considerable variation from individual to individual in terms of their immune responses and cellular responses, which is not on an allergic basis. This ordinarily is referred to as hyperreactivity and it accounts for the fact that more serious tissue injury may develop in one individual than in another even though the dose administered to both individuals is the same. This is an important phenomenon because it requires us either to set safe levels for specific agents in terms of the effect on those who are most reactive, or it requires us to find some means of excluding from contact with such agents, those people who are hyper-reactors.

Taking into consideration these three major factors it is no wonder that there is considerable

personal variation in terms of whether or not disease occurs in response to deposition of particles or exposure to gases, and that there should be some confusion in the minds of the uninformed with respect to the fact that some gases and particles can exist in high concentrations without ensuing disease.

VARIOUS WAYS IN WHICH THE RESPIRATORY SYSTEM CAN REACT TO AIRBORNE PARTICLES AND NOXIOUS GASES

All parts of the respiratory system can be injured with consequent impairment of function as a result of the inhalation of certain kinds of gases and particles. Among the manifestations of such injury or stimulation are (1) changes of resistance to airflow through the conducting tubes, (2) hypersecretion of mucous, (3) paralysis of the mucociliary escalator, (4) mobilization of macrophages in the tissues and air spaces of the lung, (5) cell injury with consequent acute inflammatory processes or pulmonary edema, (6) chronic inflammation of a granulomatous nature, (7) the development of pulmonary fibrosis or scar tissue, and (8) cell transformation or carcinogenesis. As indicated at the outset of this chapter, it would not be appropriate to discuss all these in detail, but some comments with respect to each of these will be useful.

Changes of Resistance to Airflow

An increase of resistance to airflow, either of an acute and reversible nature or of a chronic and persistent nature, may develop as a result of inhalation of certain noxious gases and particles. It has been shown that deposition of finely divided particles or the inhalation of certain gases such as SO_2 or hydrochloric acid mist will appreciably increase the resistance to airflow and that this is readily reversible following removal of the stimulus or by the use of appropriate drugs.

The site of the stimulation is both in the nose and along the course of the tracheo-bronchial tree. It is presumably caused by contraction of the circular smooth muscle plus some engorgement of the mucosa with consequent anatomical narrowing of the lumen of the conducting system. It is probable that all kinds of finely divided particles may do this to some degree. The dose required for this reaction is usually quite large except in those persons truly allergic. If a specific allergen is deposited in the nose or upper airways, the sensitized person will respond with rapid and oftentimes very severe bronchial narrowing. In this instance the dose may be extremely small. It is also of interest that in this circumstance the particle size can be quite large. Most pollens are greater than ten microns in diameter. These are readily deposited in high concentration in the nose and upper airways where they trigger the acute response. The ability to cleanse these areas by the mucociliary escalator removes the pollens and terminates the episode. Perhaps the most exquisite example of this in an industrial setting is the severe asthmatic response of those who have been sensitized to toluene-2, 4-diisocyanate (TDI).

Hypersecretion of Mucous

Many gases and most particles are irritating to the mucosa of the nose and conducting system of the lungs. When the dose is sufficiently large and the stimulus strong enough, there is an outpouring of mucous from the appropriate cells, leading to cough and an increase of sputum. Acute short term exposures produce a reaction that is fully reversible and in all probability this should be considered a normal phenomenon and not a disease manifestation.

There is some evidence, especially among heavy cigarette smokers, that a persistent stimulation by irritant gases and particles will produce persistent hypersecretion and enlargement of the mucous secreting glandular system. This is to some degree reversible on removal of the stimulus, but in some individuals there appears to be a persistent hypertrophy and hypersecretion even after the stimulus is removed. The excess secretion leads to chronic productive cough and this condition is termed chronic bronchitis. The accumulation of secretions in the lumen of the air tubes and the thickening of the mucosa consequent to hypertrophy of the glandular system causes a reduction in the lumen of the air tubes and therefore an increase of resistance to airflow. Such individuals not only have chronic cough and excess sputum production, but also evidences of chronic obstructive airway impairment. There is controversy as to whether this occurs as a result of industrial exposure to gases and particles, but it is generally agreed that industrial environments characterized by high levels of irritant gas or particles aggravate chronic bronchitis.

Paralysis of Mucociliary Escalator

There is evidence in experimental animals that gases such as SO₂ and NO₂ paralyze, at least temporarily, the cilia and thus interfere with the effective removal of mucous secretions. There is some evidence that in response to certain doses there may be a stimulation of the cilia. Recovery from this kind of paralysis appears to be rapid and there is no evidence to indicate that persistent or permanent paralysis of cilia occurs under ordinary life circumstances. The combination of daily excess mucous production and impairment of ciliary action, however, leads to an excessive accumulation of mucous in the conducting tubes. This in turn leads to an increase in resistance to airflow and to inadequate cleansing of the lung with the result that colonization of bacteria can occur with greater ease. As a result, acute bronchitis or pneumonia may ensue. Prolongation of the "residence time" of some biological agents also may occur and be an important influence in causing tissue injury.

Mobilization of Macrophages

Though essentially all of the particles larger than ten microns, and a large proportion of those two to five microns, lodge on the mucociliary escalator and thus are removed, a substantial proportion of those under five microns, and particularly those that are under two microns in diameter, will penetrate far enough out into the lung to be deposited beyond the mucociliary escalator and in

the alveolous bearing portion of the lung. Under normal circumstances there are relatively few macrophages in this portion of the lung at any one time. These are present in part for the purpose of sequestering, removing or digesting foreign material taken into the lungs from the general environment. When greater numbers than usual of particles are deposited, there is an augmentation of the macrophage population and in some circumstances the numbers can become very large. This macrophage response is a normal function and cannot, in itself, be considered to constitute a disease.

Macrophages engulf the particles either as single cells or functioning as clusters of cells and retain the particles for the lifetime of the macrophage. The exact life of the macrophage is unknown, but it is measured in weeks and probably in months. Presumably when the macrophage dies and the particles are released, they are rephagocytized by another macrophage.

When inert particles are injected intratracheally into the lungs, there is an initial massive outpouring of macrophages in the regions where the particles are distributed. Over an ensuing period of weeks and months the number of macrophages becomes less and the number of free particles in the lung tissue becomes smaller. One can at this later time observe numerous macrophages filled with particles lying on the surface of the alveoli or in the interstitial tissues and large numbers of particles may be seen in the regional lymph nodes. Fibers shorter than ten to fifteen microns also are phagocytized. Segments of longer fibers may be incorporated in one or more macrophages or entirely surrounded by a cluster of macrophages. At any one time, particles, including fibers, may be seen entirely outside of macrophages even years after they have been introduced into the lung. It is not known whether they have never been phagocytized or are at that moment between periods of residence within a macrophage.

Macrophage reaction is clearly a very important one for removal and sequestration of particles. It is tempting to speculate that the macrophage surrounds the particles and either coats the particle or, by surrounding it with its own protein, breaks the direct contact between the surface of the particle and other cells in the tissues and therefore renders the particle innocuous. There are some circumstances, as for example, free crystalline silica, where those particles small enough to be phagocytized by the macrophage actually kill the macrophage within a matter of a few days. The released particles are rephagocytized and again kill the macrophage. The importance of this phenomena will be discussed under the paragraph on pulmonary fibrosis.

Cell Injury with Acute Inflammation or Pulmonary Edema

Acute cell injury is limited essentially to reaction to noxious gases rather than to particles. Exception to this would be a consideration of bacteria as particles. Gases such as phosgene and nitrogen dioxide and to a lesser degree sulphur dioxide or sulphurous acid mist will, dependent

upon the concentration, produce anything from a mild irritation manifested by hypersecretion of mucous to a severe reaction characterized by death of the cells lining the airways and most distal portions of the lung. In the latter circumstances the lining cells of the conducting tubes are destroyed with the exception of the most basal layer of cells. From this basal layer there is the potential for a reconstitution of the normal cell system lining the conducting tubes. In the alveolar bearing areas, cell injury may lead to destruction of the alveolar surface cells and also of the capillary cell wall with a resultant pouring out of blood plasma or whole blood leading to hemorrhagic pulmonary edema. Depending upon the severity of the reaction, there can be a very rapid outpouring of liquid with death virtually due to drowning in the accumulation of fluid in the deep portions of the lung. With lower concentrations of these gases, the death of the cells making up the alveolar wall is slower and there is a delayed pulmonary edema occurring four to six hours after the exposure. This can be just as fatal as the more acute and sudden reaction. When there is a still lower intensity of exposure, the walls of the alveoli may maintain their physical integrity and gradually be reconstituted in a normal fashion. It is of interest that when particles are inhaled, their distribution within the lung is localized or patchy in nature. The same is true for the inhalation of gases, if the period of inhalation is rather brief, as for example, only a few minutes rather than hours. For this reason not all parts of the lung are involved equally in the severe reaction, and a patchy distribution of pulmonary edema is the rule. If the individual survives the acute reaction, the subsequent course is one of recovery with little or no residual injury. This kind of chemical pneumonia in its earliest stage is a hemorrhagic edema, but in the later stage there is an outpouring of leukocytes and sometimes actual bacterial infection supervenes followed by lobar or bronchial pneumonia. In some unusual circumstances, as for example, exposure to the salts of beryllium, there may be a more gradual or sub-acute development of the chemical pneumonia. Experiments have shown an astonishing ability of animals to recover from this kind of acute cell injury with reconstitution of lung tissue that has in all facets the appearance of normal lung tissue.

Chronic Inflammation of a Granulomatous Nature

This is sometimes termed "chronic interstitial lung disease" and it occurs in individuals exposed to some salts of beryllium, farmers exposed to moldy hay and in certain other occupations such as the handling of bagasse and removal of bark from trees. The exact nature of this disease from an etiologic point of view is uncertain, but it would appear to be predominantly a hypersensitivity reaction with the development of a chronic inflammatory disease in the distal parts of the lung. The nature of the injury is such as to lead to more or less persistent changes which can fluctuate in severity and be reversed to some degree by steroids. Occasionally the injury is such as to lead to the

development of pulmonary fibrosis. In some circumstances the exciting agent is thought to be a thermomycete. In all of these cases there appears to be a rather high degree of individual susceptibility. Depending on the extent of the disease, clinical manifestations can either be absent or severe.

Pulmonary Fibrosis

A classical example of pulmonary fibrosis secondary to the inhalation of particles is the reaction to the inhalation of substantial amounts of free crystalline silica. The hypothesis for pathogenesis of this disease, silicosis, having the strongest scientific support is as follows. The particles of free silica, when deposited beyond the mucociliary escalator and picked up by the macrophages, appear to kill the macrophage and in the process release a material capable of stimulating the connective tissue of the lung to produce fibrous scars. This clearly is a dose-related disease.

There are two kinds of scar production, probably based on two separate mechanisms. The particles of silica appear to be collected in focal areas in the lungs inside the macrophages and, at the death of the macrophage, they release the fibrogenic agent which leads to the development of a nodular kind of dense connective tissue characterized by a proliferation of fibrous tissue elements and the laying down of a central area of collagen. These focal points of fibrosis, scattered through the lung, characterize what is termed simple discreet nodular silicosis. In many individuals this is the only reaction that occurs.

In some such individuals, however, a second reaction characterized by the development of a massive irregular scar sometimes reaching five or more cm. in diameter develops. The nodular character is lost and the predominant feature is the large mass of scar tissue. Around the periphery the reaction is more cellular in nature. In contrast to the simple discreet nodular reaction, which appears to be self-limited after removal from exposure to dust, the massive scars tend to continue to enlarge and hence the term "progressive" massive fibrosis. It is postulated that the discreet nodular lesion is the reaction to a fibrogenic material released locally and hence its discreet focal character. In contrast the progressive massive fibrotic lesion is thought to be caused by coalescence of the simple nodular lesions plus the laying down of large amounts of gamma globulin. In other words, the progressive massive fibrosis is in part an immunological reaction and hence its progressive nature. There is not full agreement with this hypothesis. It is of considerable interest that the coal miner, whose nodular lesion is very different from that of the silicotic nodule in that far less scar tissue develops in the "coal worker nodule," nevertheless may go on to develop the large scars of progressive massive fibrosis. The same can apparently occur following unusually heavy exposure to iron oxide or to pure carbon black. It would appear that progressive massive fibrosis is an immunological reaction and thus is a manifestation of hyper-reactivity or an unusual host factor.

In contrast to the nodular lesion produced by the focal collection of free crystalline silica and the reaction to silica in the lung, the reaction to asbestos fiber is of a quite different nature. In this case, the very short fibers, less than five microns long, are phagocytized by the macrophage and appear to reside in the macrophage without harming it. Longer fibers which cannot be totally enclosed within the macrophage and remain naked in the lung tissue or on the surface of the alveolus lead to a cellular reaction which is of a granulomatous nature. If the reaction becomes mature enough, actual fibrous tissue is laid down in a non-nodular manner creating a pattern distinctly different from that of silicosis. Progressive massive fibrosis does not appear to develop as a result of exposure to asbestos, but the question of whether or not the granulomatous and fibrotic reaction to the asbestos fiber is progressive even after removal from exposure is unsettled. The reaction to asbestos fiber is not as focal and is much more generalized than is the reaction to free crystalline silica. In all of these examples where extensive scar tissue forms, lung substance is lost and a restrictive type of pulmonary function impairment occurs. Because of the focal nature, with normal intervening lung tissue, the silicotic reaction is accompanied by less impairment of blood gas exchange than occurs in the more generalized kind of tissue reaction characterizing the response to inhalation of asbestos fibers.

Carcinogenesis

There are numerous cell types in the lungs, most of which undergo division or replication within the lung in order to replace the senile and dying cells or, under intermittent stress, to augment certain cell types such as the macrophage. The epithelial or lining cells of the airways and alveoli are estimated to replace themselves completely every few weeks. It is probable that this rate of replication is accelerated under the stimulus of surface cell injury or irritation. Normally, cell division proceeds in an orderly fashion with the continuous development of identical, normally formed and constituted cells. In response to the influence of irritation and other factors, the cells may gradually change their character and organization and undergo metaplasia. If the alteration is of a particular kind, the cells lose their customary organization and orderly replication and undergo malignant transformation. The frequency with which this happens is unknown, but in some individuals the cancerous cells survive, become established and propagate to produce clinical malignant tumors. It is known that some kinds of inhaled particles foster the development of metaplasia and cancer. For example, the frequency of lung cancer is excessively high in workers exposed to particles of chromium, nickel, asbestos, uranium and other agents. Cigarette smoke, a complex of irritating gases, including nitrogen dioxide, when combined with small particles and hydrocarbons, has carcinogenic action. While single agents have been shown to be carcinogenic in experimental animals, a much higher yield of tumors is obtained if agents are combined. For example, if the

surface cells of the bronchi are caused to replicate in an accelerated manner by SO₂ or trauma, benzo (a) pyrene becomes a potent carcinogen, even though it is a weak one when used alone. It would appear that cells are more vulnerable to malignant transformation when they are replicating at a high rate. The concept of co-carcinogen action and multi-factorial influences in carcinogenesis seems to be well established. That there is a host factor as well is very likely.

RESIDENCE TIME AND COMBINED EXPOSURE

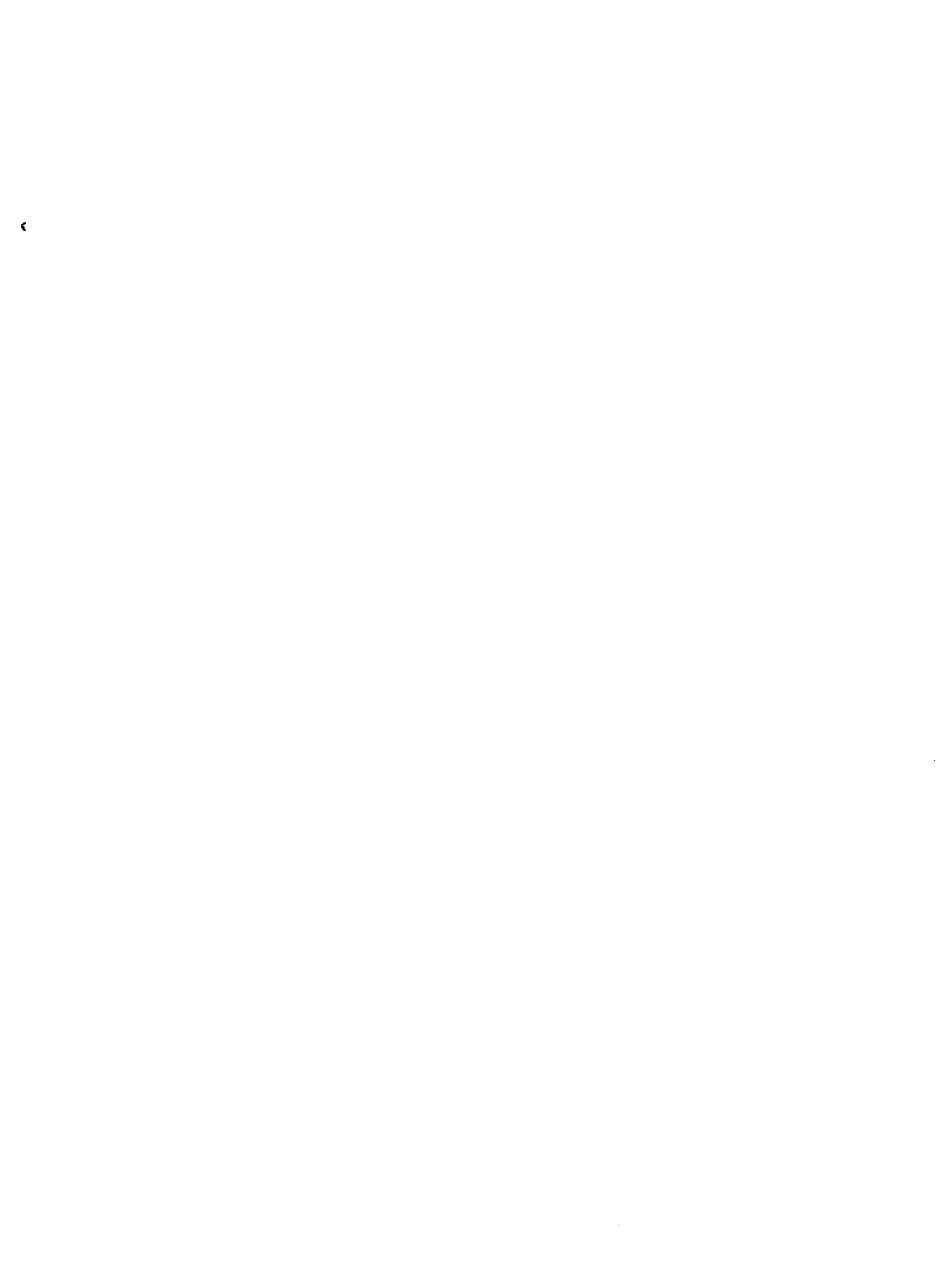
Two other concepts with respect to the action of particles deposited on the surface of the lung need to be pointed out in order to establish a better understanding of the possible biological effects of dust and gases. While the deposition of particles on the surface of the proximal conducting airways protects the more distal air tubes and favors particle removal by the mucociliary apparatus, there is an appreciable "residence time" of such particles. During that period of minutes to hours, the biological effects leading to chronic bronchitis, metaplasia and lung cancer could be initiated. If co-existing gases paralyze the cilia and reduce their effectiveness, the residence time would be prolonged.

A second potentiating effect might occur by reason of the fact that particles, which might ordinarily be inert, can become carriers by having biologically active agents adsorbed upon their surface. This might concentrate the active agent and prolong the effect when the coated particle is deposited in the lung.

These two factors might play a role not only in carcinogenesis but also in the other biological effects discussed in this chapter. The importance of taking into account multiple co-existing exposures is becoming more and more apparent and reveals a heretofore inadequately appreciated responsibility of the industrial hygienist.

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OCCUPATIONAL DERMATOSES: THEIR RECOGNITION, CONTROL AND PREVENTION

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INTRODUCTION

Occupational diseases of the skin comprise a broad assortment of skin changes caused by an infinite number of substances or conditions encountered in the work environment. Because of the varied clinical displays, they are appropriately termed "occupational dermatoses," but other titles as industrial dermatitis, occupational eczema, occupational contact dermatitis, and professional eczema are also used. More specifically related to cause are such descriptive titles as cement eczema, chrome dermatitis, chrome holes, fiberglas dermatitis, oil acne, rubber itch, and tar cancer, among others.

These disorders have plagued mankind since antiquity, but little was written about them until 1700 when Ramazzini published his classical text entitled, "De Morbis Artificum," (A Treatise of the Diseases of Tradesmen). Contained within this book are descriptions of occupational skin diseases which remain remarkably accurate today. In 1755, Percival Pott described cancer of the scrotum among chimney sweeps. This was probably the first report dealing with an occupationally induced cancer. Throughout the 18th and 19th century, interest in occupational diseases of the skin was prominent in England, France, Italy and Germany. As industrialization spread to other countries, more people were employed and occupational diseases, including those affecting the skin, occurred in greater numbers. With the advent of World War I, industry expanded enormously in the United States and with it there developed a strong interest in diseases of occupation which has led to better understanding of the work hazards, the diseases they produce, and what could be done to control them.

That occupational skin disease is an important sector in dermatology is without question. However, these disorders are equally important in the field of occupational medicine, industrial hygiene, occupational health nursing and to the insurance companies. This is readily understood because dermatoses are by far the most common of the occupational diseases, numbering no less than one-half to three-fourths of all industrial illnesses reported. They are no less important to the working population, who number between 73 and 80 million. About one-third of this number, 23 million, work in big industry. The remaining 40 to 50 million work in small plants (500 employees or less). Anyone who works is a potential candidate for an occupational skin disease. If he works in a large industrial plant, the chance of developing a skin

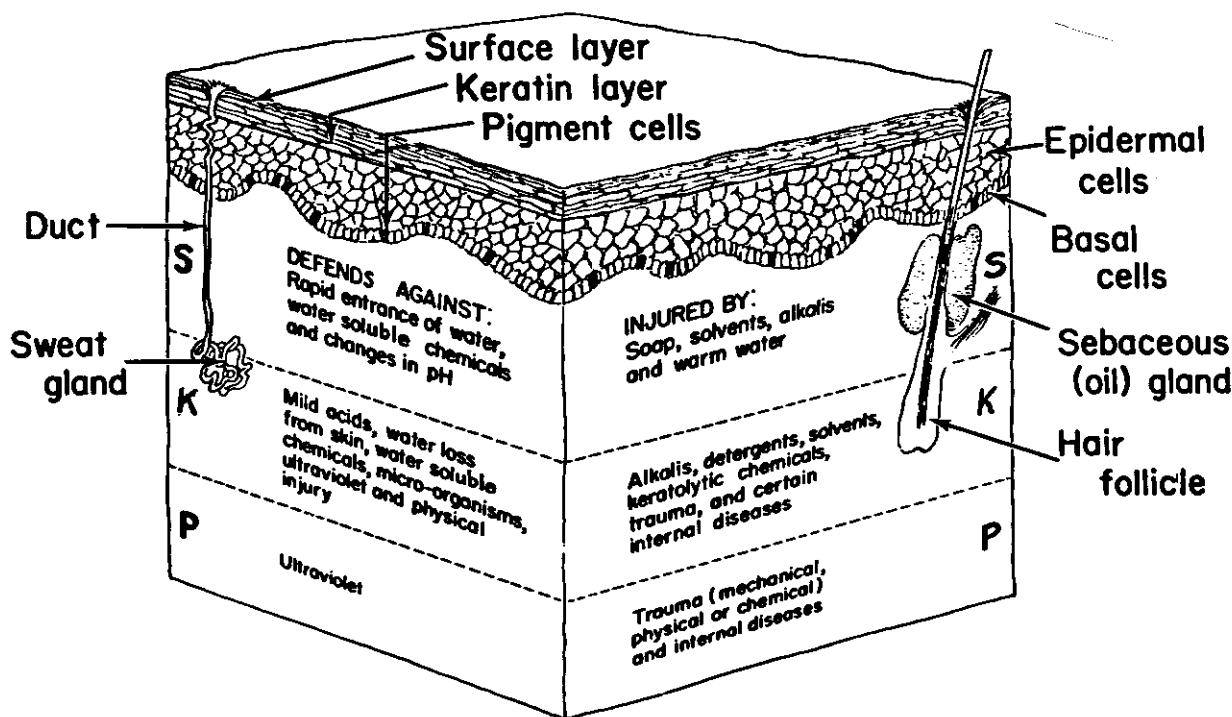
ailment is less because the medical, nursing and hygienic services are keyed to prevent occupational diseases. Conversely, work in a small plant often is attended by greater risk to health because protective measures generally are poor in quality, if present at all. In any event, it has been estimated that 1% of the working population suffers from occupational skin disease during the course of the year. Thus, with our present employment level, we can expect the occurrence of between 730 and 800 thousand cases. The resulting economic impact of this disease frequency is unknown, but it is estimated that the amount of money required to compensate for lost time and medical care associated with occupational dermatoses each year is in excess of 150 million dollars. Further, there is no way of calculating the dollars lost because of occupational diseases which result in job changes, loss of efficiency and production, or the rehiring and retraining of help.

DEFENSE MECHANISMS OF THE SKIN

The skin is the largest organ of the body. It has approximately 20 square feet of surface area for potential contact with foreign substances in nature and in the industrial environment. It is a multi-functioning organ whose anatomical and physiologic properties subserve protection by regulating body heat, receiving sensations, secreting sweat, manufacturing pigment, and replenishing its own cellular elements. Each of these functions is important in the maintenance of a healthy skin and any deviation from normal can alter the health of the skin and sometimes that of the entire body.

The structure or anatomical design of the skin is protective because of its thickness, resiliency, and the capacity of certain of its layers to inhibit the entrance of water and water-soluble chemicals. Its thickness and elasticity protect the underlying muscles, nerves and blood vessels. Additionally, the thickness and color of the skin afford protection against the effects of sunlight and other sources of physical energy.

Structurally, skin is composed of two layers — the epidermis and the dermis. Epidermis has two essential levels — an outermost stratified layer of horn cells called the "stratum corneum" and the inner living cells from which the horn cells arise. Stratum corneum cells are shed, yet replenished continually because the inner living epidermal layer keeps reproducing cells which eventually become stratum corneum cells. In short, the epidermis has its own self-support system. The stratum corneum layer is essential for protection,



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Figure 34-1. Diagram of the Skin's Protective Layers.

being thickest on the palms and soles. Chemically, it is a complex protein structure which is relatively resistant to mild acids, to water and water-soluble chemicals; but vulnerable to alkaline agents, strong detergents, desiccant chemicals, and solvents (Figure 34-1).

In the lowermost region of the epidermal layer are the basal cells from which all of the epidermal cells arise. Nestled within the basal cell layer are melanocytes or pigment-producing cells which furnish protection against ultraviolet radiation. This comes about through a complex enzyme reaction leading to the production of pigment or melanin granules which are engulfed by the epithelial cells which, in turn, migrate to the upper level of the skin and eventually are shed. Melanin serves as a protective screen against sunlight because the granules absorb photons of light. This mechanism occurs naturally throughout the lifetime of an individual. Sunlight and certain chemicals stimulate pigment formation and, at times, its activity can be inhibited.

Dermis is thicker than epidermis and is composed of elastic and collagen tissue which provide the skin with its resiliency. Invested also in the dermis are sweat glands and ducts which deliver sweat to the surface of the skin; hair follicles in which hairs are encased; sebaceous or oil glands which excrete their products through the hair follicle openings on the skin; blood vessels; and nerves.

Body temperature is regulated by the excretion of sweat, circulation of the blood, and the

central nervous system. Blood is maintained at a relatively constant temperature even though the body can be exposed to wide ranges of temperature variations. Sweat facilitates greatly the cooling of the overheated skin surface by evaporation. At the same time, dilation of the blood vessels within the skin also permits heat loss. Conversely, when the body is exposed to severe cold, blood vessels will contract to conserve heat. Nerve endings and fibers present in the skin participate in the receptor and conduction system which allows the individual to differentiate between heat, cold, pain and sense perception. This latter quality allows one to discriminate between dryness or wetness, thickness or thinness, roughness or smoothness, hardness or softness.

Secretory elements within the skin are the sweat glands and the sebaceous glands. Perspiration or sweat contains products from the body's metabolic function, but 99% of sweat is water. Excessive or inadequate sweating can be harmful not only to the skin, but to the general health. Sebaceous or oil glands are situated in the dermis and connect to hair follicles which exit on the surface of the skin. They manufacture an oily substance called "sebum," whose precise physiologic function is not well-understood. Present in normal amounts, it appears to offer some surface protection to the skin. Over-function of these glands is associated with acne.

Coating the outer surface of the keratin layer is a waxy type of mixture composed of sebum, breakdown products of keratin, and sweat. It is

believed that the emulsion-like mixture impedes somewhat the entrance of water and water-soluble chemicals, but its actual protective quality is minimal. It does assist in maintaining the surface pH of the skin, which is normally in the range of 4.5 to 6. Its protective capability is minimized because it is easily removed by soaps, solvents and alkalis. None the less, it is continually replenished under normal conditions and does constitute an extra layer of protection which must be removed before keratin cells can be attacked.

Absorption of materials through the skin occurs when the continuity of the skin is disrupted by an abrasion or a laceration or a puncture. Absorption of fat-soluble chemicals, fats and oils can occur via the hair follicle which contains the hair bulb and a portion of the hair shaft. Some substances as organophosphates are absorbed directly through the intact skin; further, skin permits the ready exchange of gases, except for carbon monoxide. Sweat ducts offer little, if any, avenue for penetration. From the above it is evident that the skin has its own built-in defense mechanism. However, many direct and indirect causes of occupational skin disease can alter this normal defense pattern.

CAUSES OF OCCUPATIONAL DERMATITIS

Indirect or predisposing factors which lead to the development of an occupational dermatosis are generally associated with race, age, sex, texture of the skin, perspiration, season of the year, lack of cleanliness and allergy.

An outstanding example of how racial characteristics predispose to the development of an occupational dermatosis is seen in the marked reaction of the red-head or blond, blue-eyed, light complexioned individual to sunlight. The converse is seen in the resistance to sunlight or ultraviolet displayed by dark or melanotic skin. This racial difference is true in the case of sunlight and in the handling of certain chemicals as tar and pitch which react with sunlight, but dark skin is not universally resistant to the industrial environment.

It has been noted that young workers develop occupational dermatoses more readily than the older workers. This is not a predisposition associated with any peculiar structure of their skin, rather it is the direct result of their frequent disregard for exercising caution in handling injurious materials at work.

Women are just as prone as men to develop occupational skin diseases. In manufacturing plants they work at many of the same jobs and come into contact with chemicals — organic and inorganic, solvents, machine oils, plastics, etc. Women have a natural tendency to be more fastidious in their cleansing habits at work; but, as a group, they also experience additional exposure to cleansers, detergents, waxes and other agents in the household.

Workers with naturally dry skin are less able to tolerate the action of solvents and detergents. Those with oily skins can resist solvents more readily, however, they also are predisposed to

developing acne-like lesions induced by cutting oils. Insoluble oils collect within the hair follicle openings and irritate that area sufficiently to cause an inflammation of the hair follicle. Permitted to continue, oil acne will result.

Although sweating is a normal physiologic action, in excess it is often detrimental. Increased perspiration in the armpits and in the groins may cause a breakdown of the skin surface which allows chemicals and bacteria to be more active at those sites. Excessive perspiration also can cause prickly heat, particularly among workmen exposed to high degrees of temperature.

Occupational dermatitis is generally more common during warm weather. When the work area is hot, workmen become lax in the use of protective clothing and, thereby, overexpose themselves to hazardous substances. Warm weather also means greater exposure to sunlight, poisonous plants and insects, the effects of which may or may not be related to the job.

Keeping the skin free of harmful agents encountered at work is readily accomplished by frequent washing and the proper use of protective devices. However, workmen with poor cleansing habits are prone to develop an occupational skin disease. These same individuals tend to wear soiled work clothing for prolonged periods of time. This practice enhances the amount of contact between the skin and chemical contaminants in the soiled clothing.

It is a natural tendency on the part of many people to believe that all dermatitis is based on allergy. Among the working population, allergy accounts for about 20% or less of all the occupational dermatoses seen. Certain individuals known as "atopics" are born with a predisposition for the development of allergic diseases such as hay fever, asthma, hives and eczema. However, these people are no more disposed to allergic contact dermatitis in industry than are nonallergic workmen. Certain industrial or environmental substances are well-known allergens, but these materials can cause a contact allergy in anyone. When one develops an occupational contact allergy it does not mean that he has to quit work. By using good protective measures, he can generally continue at his job. However, there are certain people who develop such a high level of allergic reaction that they must seek other types of work.

Direct Causes

In order of their importance and frequency, the direct causes of occupational dermatitis can be classified as chemical, mechanical, physical and biological.

Chemical

Organic and inorganic chemicals are the major dermatoses hazards present in the work environment. They constitute a never-ending list because each year the chemical spectrum gains additional agents capable of injuring the skin. Chemicals act as primary irritants or allergic sensitizers or photosensitizers. A primary irritant is a substance which, if permitted to contact the skin in sufficient concentration for a sufficient length of time, will produce a demonstrable effect upon the skin at the site of contact. In short, a primary irritant

will affect the skin of anyone. Some irritants are strong or absolute in their action; for example, chromic acid, nitric acid, sodium hydroxide or chloride of lime can produce their effect within moments after contact, or at least within a few hours following initiation of contact. Other substances act as relative or marginal irritants and require several contacts before any of their effects are seen; for example, prolonged exposure to soap and water or to soluble cutting fluids or mild solvents as acetone.

About 80% of all occupational dermatoses are caused by primary irritants. Most inorganic and organic acids act as primary irritants. Certain inorganic alkalis as ammonium hydroxide, calcium chloride, sodium carbonate, sodium hydroxide are skin irritants. Organic alkalis, particularly the amines, also are active irritants. Metallic salts, notably the arsenicals, chromates, mercurials, nickel sulphate and zinc chloride, produce severe irritant effects on skin. Organic solvents represent a large number of substances, such as the chlorinated hydrocarbons, petroleum base compounds, the ketones, the alcohols, terpenes, among others, which irritate skin because of their solvent qualities.

Primary irritants damage skin because they have an innate chemical capacity to do so. Many primary irritants are water-soluble and, thereby, actively able to react with certain tissue within the skin. Even the water-insoluble compounds which comprise many of the solvents react with the lipid elements within skin. We do not know the precise mechanism of primary irritation on the skin, but some useful generalizations serve as indices to explain the activity of groups of materials in the irritant category.

Keratin Solvents

All of the alkalis, organic and inorganic, injure the keratin layer when concentration and exposure time is adequate. These agents soften the keratin cells and succeed in removing many of them. At the same time, they bring about considerable water loss from this layer resulting in dry, cracked skin which prepares the way for secondary infection and also, at times, for the introduction of allergic sensitization.

Fat and Oil Solvents

Just as organic solvents dissolve oily and greasy industrial soils, they remove the surface lipids and disturb the keratin layer of cells so that they can no longer maintain their water-holding capacity. Workmen exposed each day to the action of the organic solvents develop exceedingly dry and cracked skin.

Protein Precipitants

Several of the heavy metal salts precipitate protein and denature it. Best known for this action are the salts of arsenic, chromium, mercury and zinc.

Reducers

Salicylic acid, oxalic acid, urea, as well as other substances, in sufficient concentrations, can actually reduce the keratin layer so that the latter is no longer protective and an occupational dermatosis results.

Keratin Stimulants

Several chemicals stimulate the skin so that it undertakes peculiar growth patterns which may lead to tumor or perhaps cancer formation. Certain petroleum products, a number of the coal tar based materials, arsenic, and some of the chlorinated hydrocarbons can stimulate the epidermal cells to produce these effects.

Primary irritant chemicals are commonly encountered in industry; they account for about 80% of all of the occupational dermatoses seen; they attack the skin in various ways; strong irritants can injure the skin in a matter of moments or hours; weak or marginal irritants may require several days. Because a workman must come into contact with a primary irritant does not mean that he will necessarily develop an occupational dermatitis. Exposure to irritant materials can be controlled when proper precautions are taken.

Sensitizers

Chemicals which cause allergic contact dermatitis are far fewer in number than are the primary irritant substances. Best known among the allergenic agents are such plant toxins as poison ivy, poison oak, and poison sumac. Other well-known cutaneous sensitizers are the alkaline dichromates, epoxy resin systems, hexamethylene tetramine, phenolformaldehyde resins, among others. A sensitizer does not cause visible change on the skin following first contact; but after several contacts, which may require days or sometimes months, it causes specific changes in the skin so that further contact on the same or other parts of the body will induce a dermatitis. Allergic contact dermatitis is rarely seen amongst workers before the fifth or seventh day after exposure is initiated, whereas primary irritant dermatitis can occur within a few hours or a few days. Only in a few instances, as for example, when exposed to poison ivy or epoxy resin systems or phenol-formaldehyde plastics, do large numbers of workers become allergically sensitive.

Photosensitivity

There are two forms of photosensitivity dermatitis — phototoxic and photoallergic. Excess exposure to sunlight or artificial ultraviolet can injure the skin through a phototoxic effect. Many workmen are exposed to various forms of natural and artificial light, for example, farmers, policemen, road builders, telephone and electric linemen and sailors. Additional to exposures from natural and artificial light sources are numerous chemicals, plants and drugs which react with selected wavelengths of natural and artificial light to cause phototoxic or photoallergic dermatitis. The best-known industrial chemicals with this capacity are derivatives of coal tar, as anthracene, phenanthrene, and creosote; and certain dyes — acridine, eosin and rose bengal. Further, a host of topically applied and ingested drugs can interact with specific wavelengths of light to produce these effects. Examples of these are certain chlorinated compounds (present in soaps for antibacterial purposes), tranquilizers of the phenothiazine type and drugs related to sulfonamid and some antibiotics.

Mechanical Causes

Anyone who works experiences some type of a mechanical trauma involving friction or pressure. Friction may result in an abrasion or, more commonly, a callus, produced by repetitive types of hand motions or through using a certain type of tool. Those who work with pneumatic tools may experience untoward effects of the hands and forearms, depending on the type of tool being used. High frequency tools can produce what is called "painful white fingers," a disorder accompanied by spasmodic pain in the fingers of the hand operating the tool. Heavier pneumatic instruments, like hammers, riveters and chisels, can cause painful tendinous or muscle or bone injury to the hands and forearms.

Physical Causes

Heat, cold, sunlight, artificial ultraviolet and ionizing radiation are capable of injuring the skin. Jobs involving exposure to high temperature induce excessive sweating and prickly heat. High levels of heat may also cause systemic symptoms and signs as heat cramps, heat exhaustion and even heat stroke. Burns of the skin can result from electric shock, sources of ionizing radiation, molten metals and glass, and solvents or detergents being used at elevated temperatures.

Low temperatures may induce frostbite and permanent damage to blood vessels. The ears, nose, fingers and feet are common sites for this type of cold injury. Electric and telephone linemen, highway maintenance workers, farmers, fishermen, policemen, postmen, among other outdoor employees, may experience this type of skin injury.

Many people who work outdoors are exposed to sunlight and increasing numbers come into casual or prolonged contact with artificial ultraviolet sources as molten metals and glass, welding operations and the plasma torch. A newer light source is found in operations using the laser apparatus. Since these monochromatic beams can injure skin and other biologic tissue, appropriate protective devices should attend their use.

Numerous ionizing radiation sources are being used in industry. Alpha radiation, though not injurious to skin, is dangerous if inhaled or ingested. Beta radiation can injure skin and the body in general if inhaled or ingested. Gamma radiation and x-rays are well-known skin and systemic hazards when sufficient exposure occurs. X-ray diffraction instruments pose a potential source of skin injury to those employed in the operation of these devices.

Biologic Causes

Bacteria, viruses, fungi and parasites attack the skin and sometimes produce systemic disease of occupational origin. Animal breeders, agricultural workers, bakers, culinary employees, florists, horticulturists, laboratory technicians and tannery workers are among the ones who may develop an occupational dermatosis or a systemic disease caused by one of the biologic agents. Where these substances are known to be connected with the work, all necessary precautions for preventing

disease must be exercised. A common type of skin infection seen among workmen is caused by staphylococci invading the site of a previous wound.

Clinical Types of Occupational Dermatoses

Several clinical variations of occupational skin disease are known to occur; however, the lesions produced on the skin rarely are characteristic of a specific chemical. Nevertheless, certain types of skin changes do suggest contact with certain classes of agents, for example: (a) Acute contact dermatitis is generally caused by a primary irritant or a sensitizing chemical, a poisonous plant or a photosensitizing agent. (b) Acne-like skin diseases usually mean contact with petroleum oils and greases, tar or pitch or certain chlorinated hydrocarbons which induce chloracne, for example, chlorinated diphenyls and triphenyls, chlorinated diphenyl oxide, among others. (c) Pigment changes in which there is a loss or gain in pigmentation. Several complex phenolic compounds present in germicidal agents have caused loss of skin pigment. Some examples are tertiary butyl phenol, tertiary amyl phenol, tertiary butyl catechol. Conversely, petroleum oils, asphalt, pitch, photoreactive chemicals and sunlight produce gains in pigment formation. (d) New growths. Sunlight, x-ray, tar, arsenic trioxide, impure paraffins and certain shale oil fractions are known to cause skin tumors, which may become cancerous. (e) Ulcers. Arsenic trioxide, chromic acid, sodium chromate, potassium dichromate, lime, thermal burns and forceful injury can cause ulceration of the skin.

These five examples of occupational skin changes (dermatoses) are presented in a decreasing order of frequency. To recognize them and understand their causation requires a familiarity with diseases of the skin and the environmental factors which influence their development. It involves understanding the nature of the lesion, the site of the eruption, the course of the disease and the correct interpretation of any clinical tests found necessary to aid in the diagnosis. Occupational skin problems are best managed by physicians familiar with them.

PREVENTION OF OCCUPATIONAL SKIN DISEASE

Dermatoses caused by substances or conditions present in the work environment are largely preventable, but only through the conjoint effort of management, supervision and the workman. That such can be accomplished is best demonstrated in large industrial plants, while the converse is demonstrated in hundreds of small work establishments where little, if any, interest is shown in preventive measures. Two major approaches to the control of occupational diseases, in general, or dermatoses, in particular, are: (a) environmental control measures and (b) personal hygiene methods.

Engineering Controls

The best time to introduce engineering controls is when a plant is being designed. At that

time, control measures can be integrated more readily into the operations than after the plant has been built. Ideally, operations would be conducted in entirely closed systems, but not all industrial processes lend themselves to this approach. When closed systems are used, raw materials can be brought to the manufacturing site in sealed cars or containers and their contents emptied into storage tanks or bins, and later cycled through retorts or other reaction apparatus, meanwhile preventing contact with the material being processed. If this type of control system is unattainable, it is generally possible to install local systems which collect the irritant dusts, vapors, fumes and mists. In any event, it is recognized that elaborate ventilation systems are costly and most plants cannot afford this method of control. Smaller plants may have many devices intended for control purposes, but experience shows generally that small plants depend more upon personal hygiene practices than on environmental control measures.

Personal Hygiene

If a workman is to minimize contact with harmful agents, he must have access to facilities for washing his hands and be furnished other means of keeping clean at work. It is up to the plant to provide adequate washing facilities and good cleansing materials. Washbasins must be well designed, conveniently located and kept clean, otherwise they will be used infrequently, if at all. The farther a workman must walk to cleanse his skin, the less likelihood there is of his doing so. Inconveniently located washbasins invite such undesirable practices as washing with solvents, mineral oils or industrial detergents, none of which were intended for skin cleansing. For workmen to keep their skin reasonably free of injurious agents, they must use washing facilities at least three times a day — during work, before lunch, after lunch and before leaving the plant. Working with toxic chemicals and radioactive substances requires the daily use of showers.

Many industrial hand cleansers are available as plain soap powders, abrasive soap powders, abrasive soap cakes, plain soap cakes, liquids, cream soaps and waterless hand cleaners. Workmen generally like powdered soaps because they gain a sense of having removed soils because of the frictional element. Most powdered cleansers with abrasives will remove tenacious soils, but waterless cleaners have become very popular because they remove greases, grimes, tars, paint and some plastics with relative ease. However, care must be exercised in selecting waterless cleaners because many of them contain excess alkalis and solvents, which cause excessive drying of the skin and sometimes contact dermatitis.

Management should have more than a passing interest in providing good washing facilities and good cleansing products. All too frequently, the cleansing agents are purchased by people having no familiarity with their quality. The practice usually results in procuring industrial hand cleansers which are cheapest in price.

Disposable hand towels are desirable because

they can be discarded after use. They are an excellent replacement for the old fashioned machinist waste.

Protective Clothing

It is not necessary that all workmen wear protective clothing, but for those jobs in which its use is required, good quality clothing should be obtained. Manufacturers now provide a large selection of protective garments of rubber, plastic films, leather, cotton or synthetic fibers designed for specific purposes. For example, we now have access to different clothings which protect against acids, alkalis, extreme exposures of heat, cold, moisture, oils and the like. When such garments must be worn, management should purchase and control the use of the protective gear. They should see to it that the clothing is serviced and laundered often enough to keep it protective. When workmen are required to purchase their own protective clothing, they generally buy the cheaper materials with little thought being given to the purpose for which it is intended. Further, if work clothes are laundered at home, it can cause contamination of family wearing apparel with chemicals, fiberglass or other dusts.

Protective clothings include hair covers as caps and nets, coveralls, smocks, aprons, sleeves, gloves and shoes. Protective sleeves and gloves are helpful devices, but care must be exercised in their use. Unless they are made of tear-away fabric or film, a sleeve or glove may cause serious injury to an arm or a hand. Cotton or leather gloves are useful for protecting the hands against friction and dusts. Synthetic rubber gloves are used for protection against acids and alkalis. Neoprene dipped cotton gloves will protect against most liquid irritants. Some workmen do not like to wear rubber gloves because the rubber causes the hands to perspire excessively. Gloves with built-in liners are probably less efficient and comfortable than plain plastic or rubber gloves which can be worn over replaceable cotton liners. Each workman requiring this type of protective gear can have three or four pairs of washable cotton liners which can be changed when his hands become saturated with perspiration. Major manufacturers of protective clothings have descriptive catalogs which provide useful information in selecting the best protective apparel for certain exposures.

Barrier Creams

Generally speaking, a barrier of protective cream is the least effective way of protecting skin. Nevertheless, there are instances when a protective cream may be the best method available for preventing contact with harmful agents, for example, if the face cannot be covered by a shield or gloves cannot be worn. There is no all-purpose protective cream. Several manufacturers compound a variety of products, each designed for a certain type of protective purpose. Thus, there are barrier creams for protecting against dry substances and those which protect against wet materials. Using a barrier cream to protect against a solvent is not as effective as using an impervi-

ous glove; however, there are compounds which offer some protection against solvents, providing the creams are used with sufficient frequency. To use a protective cream correctly, it must be applied on clean skin at the beginning of the work shift, removed and reapplied at the break, removed at lunch, reapplied after lunch, again in the afternoon and, of course, removed at the close of the work shift. When barrier creams are used, they should be selected because of a particular need by workmen who cannot wear other types of equipment. They should not become the substitute for protective clothing.

In summary, management is responsible for furnishing the facilities and products required to keep the work-place safe. Similarly, the workman has certain responsibilities in a prevention program. He must wear protective clothing if it is required; he must wash with frequency if he is working with irritant or toxic chemicals. If he develops an occupational dermatitis in spite of his attempts to prevent its occurrence, he should report immediately to the plant dispensary or to his physician for prompt diagnosis and medical treatment.

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PRINCIPLES FOR CONTROLLING THE OCCUPATIONAL ENVIRONMENT

Jack E. Peterson, Ph.D.

INTRODUCTION

Hazards and potential hazards in the occupational environment can be purely mechanical in nature, or they can take the form of materials which are capable of causing fire or explosion, or of producing injury by inhalation, skin or eye contact, or by ingestion. Physical forms of energy such as noise, non-ionizing and ionizing radiation, and heat are also potential hazards. Most basic to the control of any hazard is the concept that it can be controlled. Once the hazard is defined properly and the need for and the degree of necessary control is determined, then the only requirements are imagination, trained personnel and money to put the control methods to work.

The basic principles for controlling the occupational environment consist of substitution, isolation and ventilation. Not all basic control principles are applicable to every form of hazard, but all occupational hazards can be controlled by the use of at least one of these principles. Ingenuity, experience and a complete understanding of the circumstances surrounding the control problem are required in choosing methods which will not only provide adequate control, but which will consider installation, operating and maintenance costs and personal factors such as employee acceptance, comfort and convenience. Furthermore, hazards, costs and benefits can change with time so that hazard control systems need continuous review and updating. The aim, then, must be not only to devise efficient hazard control methods, but to evaluate the effectiveness of those methods at regular intervals.

SUBSTITUTION

Usually, when one thinks of controlling a hazard he thinks automatically of adding something to do the controlling. For example, an engineer is more likely to think of controlling a vapor hazard by ventilation than by substituting a less hazardous material for the one which is causing the problem. Yet, substitution of less hazardous materials or process equipment, or even of a less hazardous process, may be the least expensive as well as the most positive method of controlling an occupational hazard.

Unfortunately, substitution is not a technique easily taught. No one can sit down with a slide rule, pencil and paper and decide how to best use substitution to eliminate an occupational hazard. Instead, the principle of substitution is demonstrated best with examples so that by analogy the

student may apply what he has learned to his particular problem.

Process

One of the main hazards to our atmospheric environment results from the use of gasoline-powered internal combustion engines in nearly all of our automobiles.¹ Control of this source of air pollution is being attempted in many ways, from the passage of laws to the modification of gasoline to the substitution of a less hazardous process. Substitute processes range from diesel engines to electric motors, and even include the greatly increased use of mass transit systems. That there is no agreement on the best "less hazardous process" (or in fact, that process substitution is necessary) indicates that more study is needed and problem solutions may be political as well as scientific.

Choosing a substitute process is not always difficult. For instance, dipping an object into a container of paint almost always creates much less of an inhalation problem than does the process of spraying that object. Cutting is usually less noisy than breaking or snapping; mechanical stirring causes less material to become airborne than does sparging; generating electric power from nuclear energy causes less air pollution than does the use of fossil fuel, but hydroelectric power is less polluting than either; and distillation usually causes fewer problems than does crystallization.

After considering many examples of process substitution, one principle appears to stand out: the more closely a process approaches being continuous (as opposed to intermittent), the less hazardous that process is likely to be. This principle is a fairly general one and applies to energy hazards such as noise, as well as to the more familiar material hazards. This principle is not always useful, but its application should be considered whenever hazard control by process substitution is attempted.

Equipment

Where the process itself does not need to be changed to reduce hazards, the needed control often can be achieved by substituting either equipment or materials handled, or both. Substituting equipment is nearly always less expensive than substituting processes and often can be done "on the job." On the other hand, finding a substitute material may be easy or may require extensive research and/or process changes. For these reasons, equipment is substituted more often than either processes or materials.

Equipment substitution is often the "obvious" solution to an apparent hazard. An example might be the substitution of safety cans for bottles to store or contain flammable solvents, or the substitution of safety glass for regular window glass in the sash of a "fume" hood. Examples such as these can be multiplied indefinitely because they are obvious on inspection.

One of the main requirements for efficient equipment substitution is the awareness of alternatives. Persons concerned with hazard reduction must familiarize themselves with all kinds of "safety" equipment as well as with the processes and process equipment in their jurisdiction. For example, sideshield safety glasses are unlikely to be substituted for regular spectacles unless someone knows the need for, as well as the existence of, the side-shield glasses. Unless someone knows that neoprene gloves are being ruined by contact with chlorinated hydrocarbons, and also knows that polyvinyl alcohol gloves are available and impervious to this kind of attack, a substitution is unlikely.

Realistic suggestions for process equipment substitution are often based on a background in both engineering and industrial hygiene, but even without an extensive background, a fresh look at an old process or problem can pay large dividends. The man who gets out and around within a plant, a company, a city or a nation is likely to observe new solutions to problems and thus is likely to be able to apply them elsewhere. Good equipment substitution is based on common sense, ingenuity, keeping up with the state of the art, and the experience of working with people, processes, and the equipment used by both.

Material

After equipment substitution, material substitution is the technique most often used to reduce or to eliminate hazards in the occupational environment. Examples abound. The substitution (forced by a tax law in 1912) of red for white phosphorus in matches drastically reduced both an industrial and a "general" hazard. Substitution of perchloroethylene for petroleum naphtha in the dry cleaning industry essentially eliminated a serious fire hazard. Using tritium-activated phosphors instead of radium-based paint for watch and instrument dials has reduced the hazards associated with the manufacture of the dials, and in addition has reduced by a small amount the background radiation experienced by the general public. Removing beryllium phosphors from fluorescent lamps not only eliminated a hazard to the general public, but also eliminated a more serious hazard to the men manufacturing such lamps.

Many years ago the principal cold cleaning solvent was petroleum naphtha. Because of its fire hazard, a substitute material was sought. Carbon tetrachloride appeared to be ideal because of its low flammability, good solvent power, and low price. Experience and a great deal of research, however, showed that a serious fire hazard had been traded for a perhaps even more serious vapor inhalation hazard. Today, carbon tetrachloride is

being supplanted by several other chlorinated hydrocarbons, notably 1, 1, 1-trichloroethane, trichloroethylene, perchloroethylene and methylene chloride. Each of these substitutes is far less toxic and far less hazardous to handle than is carbon tetrachloride, although each has its own hazards. In addition, the fluorinated hydrocarbons are being used more and more despite their expense, mainly because their inhalation and fire hazards are so low.

The principle of material substitution carries with it the same type of reward and the same potential hazards as other kinds of substitution. Substitution of a different material can reduce or eliminate hazard, but one hazard can be substituted for another inadvertently. A careful watch must be kept for unforeseen hazards that may crop up when any kind of substitution is used. An excellent source of information about the toxic properties and hazards of materials and their substitutes is the Hygienic Guide series published by the American Industrial Hygiene Association.

ISOLATION

Isolation is the term applied when a barrier is interposed between a hazard and those who might be affected by that hazard. The barrier may be physical, or distance or time may provide the isolation considered necessary.

Stored Material

Stored material rarely poses an overt hazard, and therefore, whether it is raw material or finished product, those concerned are likely to take it for granted and to assume that it poses no threat. This assumption can be dangerous.

When flammable liquids are stored in large tanks above ground, common practice is to group the tanks on a "tank farm" but to isolate each tank from the others by means of a dike made of earth or concrete. If a major spill does occur, the (possibly flaming) liquid is restrained by the dike from coming close enough to other storage tanks to affect them. For more positive protection, tanks are buried to interpose an even more formidable barrier between their contents and the general environment. A further example is to restrict the volume of material stored in a single container. This exemplifies the use of isolation to reduce a hazard by imposing many small barriers rather than one large one between the contents and the environment.

Where the principal hazard of a liquid arises from inhalation rather than from fire, the imposition of a physical barrier becomes much more difficult than simply building a dike. When the quantities are relatively small (up to a few tens of gallons, perhaps) the best storage technique uses both isolation and ventilation. An example of this practice is the more and more common use of ventilated storage cabinets in laboratories.² Such cabinets are usually made of fire resistant material and air is drawn through them constantly by means of a fan which discharges out-of-doors. This type of arrangement interposes both a physical and a ventilation barrier between the contents of storage vessels and the laboratory environment and in ad-

dition, may free much valuable hood space for other than storage use.

Solids usually are stored either in original containers (bags, cans, or drums), bins, or simply in piles which may even be out-of-doors. Except in unusual cases, solids rarely pose problems in storage which compare in magnitude with those of liquids and gases. Outside storage piles can be unsightly and can be the source of air pollution problems; in such cases a physical barrier is the usual answer. The barrier may be as simple as a tarpaulin or as complex as a storage building with several kinds of materials handling equipment.

Equipment

Most equipment used in processing operations is designed to be safe if it is used properly. On the other hand, there are times and cases where this is far from true. Equipment that is operated under very high pressure, for instance, may well pose a severe hazard even when operated correctly. In such cases, the proper action to take is to isolate the equipment from the occupational environment. Usually physical barriers are used and the barriers may be very formidable ones, indeed. Extensive use may be made of armor plate as well as reinforced concrete, mild steel, and even wood. Viewing the work area may be done by remote controlled television cameras, simple mirrors or periscopes.

Equipment isolation may be the easiest method of preventing hazardous physical contact, for instance with hot surfaces. Insulating a hot water line may not be economical from a strictly monetary standpoint, but may be necessary simply because that line is not sufficiently isolated from people by distance.

Inhalation hazards can often be reduced markedly by equipment isolation. One example is that of isolating pumps. Nearly all pumps used in industry can leak and will do so, at least occasionally. Proper planning should take this fact into consideration, perhaps by arranging vessels and piping so that pumps handling hazardous materials can all be located in one area. That area, then, can be isolated physically from the remainder of the process equipment. If, then, the pump room (and/or each pump) is ventilated properly, minor leaks will be of no consequence, and major ones will be repairable without a serious inhalation hazard to the mechanic.

Process

Process isolation is usually thought to be the most expensive of the isolation methods of hazard control, and thus is probably the least used. Nevertheless, with today's space-shot-perfected techniques, some extremely complex processes and equipment have been shown susceptible to remote control, and in principle there is probably no process which cannot be operated remotely if the expense of remote operation is justified.

Process isolation techniques were given great impetus when men sought ways in which to handle radioisotopes safely. They found that the hazard from external radiation sources could be attenuated with shielding and distance, but both of these techniques required the development of very

sophisticated methods of remote operation. Master-slave manipulators were designed to allow direct "handling" of equipment from very remote locations and this, in turn, accelerated the development of different viewing methods, complex electronic systems, and the theory and philosophy of remote operation.

The modern petroleum processing plant is an example of the use of remote processing. Many of the newer plants are based almost completely on centralized control with automatic sampling and analysis, remote readout of various sensors, on-line computer processing of the data, and perhaps actual computer control of process equipment. These techniques were not developed with hazard control uppermost in mind; instead, economy of operation was the spur, but safety was a by-product.

Computer-controlled processing also appears to be gaining acceptance in the chemical industry. For the most part, this change has been in response to economic pressures because, despite their high initial costs, computer-controlled continuous processing plants can be operated with much less expense than that associated with manual operation, and at the same time produce a superior product. Such plants enjoy the advantages of remote operation and also those of continuous processing with attendant relatively low volumes of materials actually being handled. This combination can result in a very low hazard potential.

Process isolation, however, by its very nature can pose some rather extreme hazards. That is, when human intervention is required, the potential hazard may rise abruptly from near zero to near certainty. In such cases, full use must be made of techniques of isolating the man from his environment.

Workmen

Isolating workmen from their occupational environment has been used since antiquity, and will continue to be necessary in the foreseeable future. The first blacksmith to don an apron of hide was using this principle just as certainly as is the present day radioisotope handler with his plastic airsupplied sealed suit and its connecting "tunnel."³ Pliny, the Elder, wrote about the use of pig's bladders by miners to reduce the amount of dust inhaled⁴ and today advertising men extol the virtues of masks made of polyurethane foam to accomplish the same thing.

Using personal protective equipment of any sort exemplifies the principle of isolating man from his occupational environment. Protective equipment for workers should usually be designed for emergency or temporary use, but this does not always hold true. Experts in the safety field stress the continual use of some sort of eye protection if only because loss of vision is such an extreme penalty to pay for a moment's inattention. Hard hats and safety shoes with steel toecaps are other examples of protective equipment designed to be cheap insurance against severe loss. Some kinds of personal protective equipment are so ubiquitous as to be almost a badge of the trade. The butcher's

apron, the chef's tall hat, the welder's helmet, the first baseman's glove, the logger's boots and the fullback's shoulder pads are all devices designed to help isolate man from his occupational environment.

Today it is possible to isolate anyone from practically any environment for nearly any length of time. We can send men through the vacuum of space to the moon, for instance, or send them to the depths of the sea, completely protected from rather extreme environments. Nevertheless, even though essentially complete protection is possible, it is rarely used.

Completely isolating a man from his occupational environment is difficult and expensive; therefore, when worker isolation is necessary, it is usually partial rather than complete. Even partial isolation can result in discomfort (consider wearing a gas mask all day, for instance), and in such cases other techniques of controlling the environment should be considered seriously. Face shields, ear plugs, rubber gloves and the like should always be available if their use is warranted, but the aim of the engineers and planners should be to make their continual use unnecessary. Furthermore, all emergency protective equipment should be inspected periodically and tested if necessary to assure that it will perform its intended function in use.

Testing of protective equipment and planning for its proper use (see Chapter 36) are both very complex fields. By its nature, most equipment of this type is designed for use at times when all of the hazards are not delineated readily — where, in fact, the real hazards may never be known. For instance, canister-type gas masks have been regarded as suitable for respiratory protection in emergencies provided that the air still contains enough oxygen to sustain life. Chemical reactors, tanks, sewers and buildings on fire don't always provide enough oxygen to sustain life, and therefore, injuries do occur from asphyxiation. Furthermore, the canister on the mask may not be designed to protect against the air contaminant(s) actually present and again people are injured despite their gas masks. While the traditional gas mask still has uses, in many cases it should be replaced by one of the supplied-air type which can be worn in an oxygen-deficient atmosphere which contains unknown concentrations of unknown gases, vapors and particulates. This type of mask will do a good job in such atmospheres provided that it fits,⁶ that the reservoir contains sufficient air for the necessary time, and that the regulator is functioning properly.

Gas masks are not the only pieces of protective equipment that actually may not protect in the emergency where they are used, but they exemplify the idea that obtaining equipment for protection is no guarantee that the equipment will be effective. Judicious testing of equipment designed to isolate man from his occupational environment is a necessity.

VENTILATION

Ventilation (see Chapters 39 and 42) can be

used to insure thermal comfort as well as to keep dangerous vapors from the breathing zone of a worker. It can be misused in an attempt to blow away radiant heat or used improperly to control the dust hazard from a grinder. Ventilation equipment is found everywhere, much of it designed, engineered, and used improperly, even though a similar expenditure of time, effort and money could well have resulted in adequate or better-than-adequate control of the occupational environment.⁶

From the point of view of the engineer, ventilation systems can be either local or general in nature, and they can attempt control mainly by exhausting or supplying air properly. These designations cannot, of course, be absolute because, for instance, local supply for one area is general supply for any other part of that room or building. Nevertheless, the intention of the planner will control this discussion.

Local Exhaust and Supply

Localized ventilation systems nearly always attempt to control a hazard by directing air movement. The velocity of the moving air may also be a consideration, but except in high velocity-low volume systems, it is used only to assure that the direction of movement is the correct one.

There are two main principles governing the correct use of local exhaust ventilation to control airborne hazards. The first is to enclose the process or equipment physically as much as possible. The second is to withdraw air from the physical enclosure (hood) at a rate sufficient to assure that the direction of air movement at all openings is always into the enclosure. All other considerations are secondary. If these principles are followed, no airborne material will escape from the enclosure so long as the enclosure is intact and the ventilation system is operating properly.

There are times where no enclosure is possible and where control of airborne hazards must be accomplished simply by the direction and velocity of air movement. These cases are not exceptions to the basic principle because, at the point where control must be assured, if the direction of air movement is always into the hood there will be control of materials suspended in that air. Similarly, if an air-tight enclosure were to be used, then no air need be moved to assure control of a vapor or an aerosol, but the principles have not been violated.

Three of the problems associated with local exhaust systems stand out. First, and most obvious, is that of poor design. All too many ventilation systems appear to have been laid out by someone who has no knowledge of how to handle air properly. These systems abound in abrupt expansions and contractions, in right-angle entries, in the overuse of blast gates to attenuate problems, and so on. Since the advent of the ACGIH Ventilation Manual,⁷ poor exhaust or supply system design has had no excuse because good technique is so easily available.

The second problem is that of inadequate exhaust. It is exemplified by the exhaust system which has been added to from time to time, until nothing associated with the system works at all

well. The solution is simply to make sure that all systems, old as well as new, are well engineered.

The third problem of local exhaust systems is that of inadequate supply. People who are willing to install extra hoods at the drop of a hat (probably adding them to an already overloaded exhaust system) almost uniformly seem to feel that adequate supply air is a luxury or frill which they can do without. This tendency is accentuated by the widespread knowledge of a "rule of the thumb" which states that so long as the number of air changes per hour in the building is less "X" there is no need for a separate supply system. (The value of "X" varies from thumb to thumb, but is likely to be from 2 to 4.) This rule assumes that the building isn't "tight" and that infiltration of air will equal or exceed that exhausted.

Almost all buildings "leak" a little, and some leak a lot of air. Nevertheless, another principle of controlling the occupational environment by local exhaust is "always supply at least as much air as will be exhausted." A mechanical air supply system can and will do many things that infiltration cannot. A mechanical system can supply air that is filtered (and thus clean), tempered (warmed or cooled as necessary) and in the proper location to eliminate drafts and to avoid excessive disturbance of air at the faces of local exhaust hoods. None of these benefits can be gained by counting on infiltration for supply.

Local supply in itself is used occasionally to effect control or to assist in control of local exhaust. A combination of supply and exhaust, for instance, is sometimes used as a "push-pull" system to control vapors from large open tanks,⁸ the supply air being used to "push" vapors into the exhaust system. If properly engineered, such systems can work well and can effect control by the movement of much less air than would be necessary if only exhaust were used.

The main use of local supply systems is not, however, to control hazardous vapors but, instead, to reduce heat stress problems. For this application, air is usually supplied on an individual basis and each man is allowed to control the direction and/or the velocity of air impinging on his work station. The air used is not cooled, but is supplied at high velocities (up to 500 fpm); it cools by sweat evaporation and by convection, if its temperature is below the man's skin temperature (as is usually the case).

General Exhaust and Supply

General exhaust and supply systems attempt to control the occupational environment by dilution. This principle can be used for many types of problems, ranging from hazardous vapors to locker room odors to problems of dust, humidity and temperature. A principle of general ventilation is that it be used to control problems that inherently are widespread. That is, it makes sense to use general exhaust and supply ventilation to control the temperature and humidity of all the air in an office building, but it does not make sense to try to control the fume generated by one welder with an exhaust fan located in the opposite wall. General ventilation is almost always unsuccessful

when used to control "point" sources of airborne contaminants, and in addition, is very wasteful of air when used for such purposes.

Even local systems must have air to exhaust, and usually that air is supplied by a general system — one that is not associated with any particular hood or exhaust port. Some dilution of air contaminants will take place because of the general supply system, but its main purpose is simply to provide air to be thrown away by the exhaust system.

Air moving equipment can be expensive, and air filtering and tempering equipment can be even more so. Therefore, some engineers attempt to save money by recirculating some exhaust air back into the supply system. While this practice is standard in office buildings, it is rarely applicable in factories and shops because the air handled by the exhaust system cannot usually be cleaned adequately. Once-through systems, therefore, are standard except where the contaminant in the exhausted air is an easily handled particulate with a low inhalation toxicity. Sawdust, for example, is usually low in toxicity (although some woods are sensitizers), and the particles may be large enough to be removed easily from an air stream. In such a case, recirculation of some part of the exhaust air could be considered.

Inadvertent recirculation of exhausted air is a growing occupational health problem. When exhaust stacks and supply inlets are not separated adequately, part of the exhaust air will be captured by the inlet and recirculated to the building. This problem is prevalent in buildings designed by architects who are more concerned with the appearance of a roofline than they are with the health of those who will work in the building.⁹ The problem also occurs between buildings, especially when roof elevation differences are not great, and elsewhere when little or no attention has been paid to the possibility of recirculation.

Recent work has shown that the best way to prevent recirculation is to discharge exhaust air in such a manner that all of it will escape from the "cavity" which forms as a result of wind moving over and around buildings.^{10, 11} The intake can then be located at any convenient place, usually close to the roof, with assurance that recirculation will be negligible. Unfortunately, the prediction of cavity height above a roof is not yet an exact science, but enough is known so that intelligent decisions can be made. The recirculation problem must be considered whenever highly toxic, highly hazardous, or highly odorous materials are discharged by an exhaust system, whether or not a mechanical supply system is present.

EDUCATION

The first and most basic principle of almost any discipline is that knowledge is needed in order to apply that discipline to practical problems. Some knowledge comes with experience, but experience can be a poor teacher. More or less formal education can supplement experience and can direct it into the most productive channels. Nearly all people with line responsibility in indus-

try, and many with staff responsibility, can become involved with controlling the occupational environment. All of these people can profit from education in this area.

Management

Few managers become involved directly in the practical aspects of hazard control, yet very little hazard control is done without management backing. Managers exist mainly to motivate people (or to allow people to motivate themselves), but even expert motivators cannot channel activity into areas of which they are ignorant. Education of management should deal much more with the "why" of hazard control than with the how, when, where or whom.

There has been very little effort to formalize the education of managers in most industries; usually they are taught about hazards in meetings, conferences and personal chats by men who work for them. Informal education is better than no education at all, but the present best hope is the recent proliferation of short courses prepared and presented for representatives of high echelon management. A short course is the easy way to obtain quite a lot of valuable information with a small expenditure of time. This approach has been used successfully in the field of hazard control and much more use of it should be made in the future.

Short courses for managers should identify hazards in broad areas; details should be reserved for examples. The courses should concentrate particularly on the costs and benefits of controlling the environment, but should not completely neglect humanitarian aspects. Legal requirements which must be met should also be a part of the course content, but where a "carrot" exists, its use will almost always produce better results than will a club. Particularly for managers, the carrots (rewards) should be searched out, found and emphasized.

Engineers

At least a portion of the work of every industrial hygienist can be traced to equipment and/or process design failure. In many "failure" cases the person who designed the equipment or process simply was not aware of the potential consequences of the failure, or that such a failure was possible. Examples range from the purchase of equipment noisy enough to be hazardous, to the use of carbon tetrachloride or benzene as solvents, to the specification of gasoline-powered lift trucks for an enclosed warehouse, to the omission of a necessary fire door. In general, these failures arise from ignorance rather than from malice or from a "devil-may-care" attitude. Furthermore, the decision which resulted in a failure probably was made by someone quite far removed from the consequences of the decision — a planner, perhaps, or an engineering designer.

Educating engineers in regard to environmental hazards has, in the past, taken place mainly on the job by association with more experienced people. In recent years a few short courses have been given to supplement on-the-job training, but all too often any remedy applied is both too little and too late.

The logical place for engineers to be exposed to the knowledge that the environment abounds with hazards is when they are students at the undergraduate level. What is necessary then is not a program designed to turn these people into industrial hygienists or safety engineers, but instead, a course or courses which tend to open their eyes to the consequences of decisions they may make in their professional capacity. Undergraduate engineers (and most graduate engineers, for that matter) simply are not aware that it is perfectly possible to write noise specifications for much equipment; that carbon tetrachloride and benzene have excellent, much less hazardous, substitutes; that LPG fueled lift trucks generate much less carbon monoxide than do gasoline-powered lift trucks, that electric lift trucks are available and entirely suitable for most lift truck tasks; or when and where to install fire doors. The hazard gamut is so large that the typical short course can only scratch the surface, and a semester-long exposure stands a much better chance of getting the idea across.

Several colleges and universities already offer one or more courses surveying the fields of industrial hygiene for undergraduates especially in engineering curricula. With such courses as the foundation, short courses later in professional life should be able to keep engineers reasonably well up to date on environmental hazard control provided, of course, that they regularly read the literature related to the field.

Supervisors

In most circumstances, the further a supervisor is from actual control of a process, the more he deals with men and the less he deals with things. Supervisors usually work only through other people and consequently, they become aware of most environmental hazards from other people, or through their actions. In the case of an obvious hazard within his jurisdiction, a supervisor either can deal with the hazard with his own resources or he can solicit aid from others. Generally, which action to take is rather obvious, but some of the hazards posed by the occupational environment are subtle rather than obvious, and most supervisors are not equipped to deal with the subtle variety at all.

Education of supervisors usually should be process and process equipment oriented. The aim of the education should be to teach them about the subtle hazards that may be found in the environment of their employees and when and under what circumstances to request aid in solving the problems those hazards pose. Supervisors who are knowledgeable and well informed about hazardous processes, operations and materials are often able to control hazards early enough so that outside aid is not necessary except for periodic checks or reviews.

Workmen

Traditionally, little effort has been made to teach workmen about either the equipment or the materials that they handle. In the past few decades, safety engineers have shown over and over again that there are direct benefits to be gained

from teaching workmen about the physical hazards in their environment and how to avoid those hazards. More recently, industrial hygiene engineers have begun, usually in periodic safety meetings, to teach workmen about the hazards of materials and energies and, perhaps not surprisingly, have found similar benefits.

Hazards associated with the occupational environment impinge first on the men who work directly with materials, process equipment and processes. As these men are the first affected, they may well be the first to recognize adverse effects, and if so, if they are knowledgeable about the effects of the materials and energies they work with, they may be able to pinpoint problems before those problems become severe.

The main arguments against educating workers about the real and potential hazards of the materials and energies to which they are exposed have been that such knowledge would create apprehension, cause malingering, and give the unions another club to hold over the head of management. Where worker education has been used, however, groundless fears have evaporated, attendance has improved, and unions have been more cooperative, especially in matters concerning the health and safety of workmen.

An aware workman can often anticipate and circumvent hazards before they become serious to him, his fellow workers, or to the physical facilities. Furthermore, once the source of a hazard has been found, workmen, rather than supervisors or engineers, quite often have the best ideas of how to eliminate the problem with the least effort and expense. And finally, aware workmen often can be used to assist in industrial hygiene surveys,¹² thereby freeing the industrial hygiene engineer for perhaps more productive tasks.

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PERSONAL PROTECTIVE DEVICES*Harry F. Schulte***GENERAL PHILOSOPHY**

It is one of the fundamentals of industrial hygiene that personal protective devices are "last resort" types of controls, to be used only where engineering controls cannot be used or made adequate. It should be noted that this fundamental is stated unequivocally in the standards adopted under the Occupational Safety and Health Act.¹ There are many jobs in industry which are short-term or which must be conducted where exhaust ventilation or other control measures cannot be employed on short notice. Protective devices are also extremely important as a second line of defense against inadvertent or unexpected conditions. Thus, when a man dons a respirator or a face shield before opening a container of toxic material he does not expect to need this equipment, but he is prepared and protected if the toxic material escapes its confinement.

Personal protective devices appear to be very simple to provide and use in contrast to such equipment as exhaust ventilation or sound absorbing barriers. It is the purpose of this chapter to show that this is not necessarily true, and to provide the reader with essential information on the selection and correct manner of use of personal protective devices. In making a selection of equipment to be used the employer is advised to consider the wishes of the workers who must use the equipment, since worker acceptance is the key factor in a successful protective equipment program. For this reason the comfort factor should be given considerable weight at the expense of costs but not of protection. Full discussion of the use of the devices with the employees, training in their use and instructions for care and maintenance are very important. For example, handing a man a respirator and telling him to use it is not only an ineffective technique, but it can be very dangerous.

PROTECTION AGAINST INHALATION HAZARDS**Where Used**

There will always be a temptation to resort to respirators as a cheap substitute for a ventilation system. If this is done it is clear that management has not carefully considered the alternatives since reliance on, and effective use of, respirators is definitely not cheap. A careful study may be required to determine that no other effective control measures can be used. Respirators are designed to protect only against certain specific types of substances and in certain concentration ranges, depending on the type of equipment used. Many other factors should be considered carefully in

making the decision that other engineering controls are not practical. Nevertheless, there are many places where respirators can and should be used with full knowledge of their limitations and requirements.

Approval Systems and Schedules

The U. S. Bureau of Mines gave its first approvals of oxygen breathing apparatus in 1918 and gradually extended this activity to include all types of respirators. Each approved respirator and each approved filter, canister or cartridge bears an approval stamp or mark. Approvals are issued according to a series of "schedules" which describe the tests to be performed on each type of respirator and the standards it must meet to receive approval. Lists of approved devices are issued periodically by the Bureau and supplements are added to include newly approved devices. The last complete list of approved devices was issued by the Bureau of Mines as Information Circular No. 8436 and included devices approved up to December 31, 1968.² Supplements were issued in January 1970 and February 1971.

The approval schedules themselves are subject to occasional reviews and new schedules are developed to meet the needs for protection against new hazards or to reflect the development of new kinds of devices. Where respirators are used regularly, these schedules should be consulted since they set forth the precise information to be obtained in the test procedures as well as the limitations of the tests. Prior to 1971 the U. S. Department of Agriculture performed tests and issued approvals on respirators to be used in working with pesticides. This function has now been taken over by the Bureau of Mines. With the passage of the Occupational Safety and Health Act and the subsequent formation of the National Institute for Occupational Safety and Health (NIOSH), the approval system has been in the process of change. In 1972 NIOSH took over the approval function from the Bureau of Mines for aboveground uses. Considerable research is now underway to expand the scope of the approval tests and to develop more satisfactory procedures to meet the changing and expanding needs.

Particle-Removing Air Purifying Respirators

Applications and functions. These devices are designed to protect the wearer against inhalation of material dispersed in air as distinct particles — as a dust or fume in the case of solid particles or as a mist or fog in the case of liquid droplets. They consist, principally, of a facepiece with some type mechanical filter. The material to be protected

against may be a nuisance dust such as sawdust, a pneumoconiosis-producing dust such as silica or coal dust, a toxic dust like lead oxide, a metal fume like cadmium, a highly toxic dust like beryllium oxide or a radioactive dust such as plutonium. These examples range in their degree of protection required from relatively minor to extremely high. Respirators to meet this range of requirements differ chiefly, *but not solely*, in the efficiencies of their filters.

Limitations. The user of any air purifying respirator must be certain that the atmosphere contains adequate oxygen and that the only harmful materials present are those which can be removed by the respirator to be worn. There are many ways in which air can leak around the filter, seriously reducing the protective capability of the respirator. Failure of the filter to seat properly in its holder, leaking valves and imperfect sealing of the respirator to the wearer's face are all significant. Some of these factors can be controlled by proper design but all require good and frequent inspection and maintenance.

Facepieces. There are two basic types of facepieces used on air purifying respirators — half masks and full face masks. The half masks do not cover the eyes and hence offer no eye protection nor do they interfere as much with vision as do the full face masks. The half mask must contact a rather complex facial surface and the possibility of leaking is greater than in the case of the full face mask. Obviously, faces vary considerably in their dimensions from one individual to another and since a given respirator is usually made in only one size, a successful fit for the respirator cannot be made on all persons. Recently some manufacturers have begun making some respirators in several sizes. Where this choice is not available, it is essential that the employer stock several different models of respirators, usually from several different manufacturers. A fitting program, to be discussed later, is required to provide adequately fitted respirators.

A serious problem with full face respirators is obtaining an adequate seal for the worker who must use corrective glasses. Where the temples of conventional eyeglasses emerge from the facepiece, there is a serious place of leakage. Some masks provide methods of mounting a special set of corrective lenses inside the respirator facepiece. Half masks are usually held on the face by means of a single set or a double set of elastic bands. The double sets of straps are practically a necessity in assuring a reasonable face fit and each set should fasten to separate suspension points on the respirator. Full face masks, being much heavier, are supported by a head harness which should have at least five adjustable straps.

Most respirator facepieces contain valves to direct the flow of air from outside, through the filter, into the nose and then back outside. Valveless respirators are being used, but are not approved for use with hazardous materials. The most important valve is the exhalation valve which opens during expiration allowing expired air to pass directly outside the mask. It closes during

inhalation and must close positively and quickly to prevent toxic material being drawn into the facepiece.

The inhalation valve is located close to the point where the filter attaches to the facepiece. It opens during inhalation to allow air to be drawn in through the filter and closes during exhalation to prevent the passage of moisture-laden expired air through the filter. Some approved respirators do not have inhalation valves. Obviously, all valves should offer minimal resistance to air flow, but low resistance is particularly important in the exhalation valve. Resistance to exhalation is much less tolerable than is resistance to inhalation.

Filters. Filtration by fibrous filters is the method universally used in respirators for removing particles from the air. The filter material may be a loosely or tightly packed mass of fibers of cotton, wool, synthetic fibers, glass or mineral fibers, or it may be a paper made of these materials. The filter efficiency is influenced by the particle size, shape and density of the aerosol and by a number of other factors determined by the filter and the respirator.

The diameter of the fibers used in the filter is important since higher collection efficiencies are obtained with finer fibers. The tightness with which the fibers are compressed is another factor leading to higher efficiency. As a filter is used in a dusty atmosphere its efficiency usually increases with time since the layer of collected dust becomes an additional filter. It should be noted that all of these factors leading to increased filter efficiency also lead to increased resistance to breathing. This limits the extent to which these factors can be used to obtain higher particle removal efficiency. The only way to compensate for high filter resistance is by providing large filter surface areas. Thus, many filters are folded in various ingenious ways to achieve large surface areas in small spaces. Filters may be incased in "cans" or holders to protect the folded filter.

There are approval schedules for respirators for protection against (1) pneumoconiosis-producing and nuisance dusts, (2) toxic dusts (not significantly more toxic than lead), (3) metal fumes (not significantly more toxic than lead), (4) chromic acid mist, (5) dusts significantly more toxic than lead and (6) various combinations of these. A summary of some of the requirements for approval are given in Table 1 taken from the AIHA-ACGIH Respirator Manual.³

Special Purpose Respirators. Because of recognition of the necessity of maintenance and regular servicing and cleaning of respirators, there has been increased interest in the possibility of single-use respirators. These could be discarded when breathing resistance became excessive or the respirator became dirty or damaged. Some simple respirators of this type have been used in the past — a surgeon's mask is an example — but they have never been approved because of their low efficiencies and lack of exhalation valves. Recently several manufacturers have begun making single-use masks, and one has been approved under a new

TABLE 36-1
U.S. BUREAU OF MINES APPROVAL SCHEDULES AND TESTS
TEST CONDITIONS AND PERFORMANCE REQUIREMENTS
FOR DISPERSOID RESPIRATORS

Dispersoids Covered by Respirator for Protection against	Test Dispersoid	Concentration of Dispersoid, mg/m ³	Duration of test, hr	Maximum Allowable Leakage, mg	Maximum Final Resistance to Air Flow, mm of H ₂ O
Pneumoconiosis-producing and nuisance dusts	Silica dust; geometric mean not more than 0.6 μ; σ _g = 1.9	50 ± 10	1.5	3.0	50
Toxic dusts (not significantly more toxic than lead)	Litharge, ~75%; free metallic lead, ~25%; geometric mean not more than 0.6 μ; σ _g = 1.9	15 ± 5	1.5	0.43 (Pb)	50
Metal fumes (not significantly more toxic than lead)	Freshly generated lead fume	15 ± 5	5.2	1.50 (Pb)	50
Chromic acid mist	Electrolytically generated chromic acid mist	15 ± 5	5.2	1.0	50
Pneumoconiosis-producing and nuisance mists	Mist formed by atomizing a silica dust-water suspension	10 ± 5	5.2	5.0	50
Various combinations of above types of dispersoids	Respirator must meet requirements for each type.*				

*For example, the protection against dusts not significantly more toxic than lead, the respirator must meet the requirements for the first two items in this table, that is, for pneumoconiosis-producing and nuisance dusts and for toxic dusts not significantly more toxic than lead.

From RESPIRATORY PROTECTIVE DEVICES MANUAL published by American Industrial Hygiene Association and American Conference of Governmental Industrial Hygienists, 1966.

Bureau of Mines approval schedule recently adopted for such masks. Replacement (and disposal) costs must be balanced against cleaning and maintenance costs.

Nuisance dust masks, including some not carrying Bureau of Mines approvals, may still have some use in industry. These may be useful in woodworking shops, on workers operating machines on dusty roads and farms, and for workers sensitive to pollens in certain seasons. Their costs are likely to be lower than those for approved masks and the reasons for their lack of approval should be given careful consideration. Thus a mask may fail to meet approval standards because of high breathing resistance, and this is likely to make it unacceptable for long wearing by workers. On the other hand, a mask may be a simple device for which no approval schedule exists, and it may be adequate, highly acceptable and useful to the librarian required to clean dust from stacks of books. Such masks must be kept strictly separate from masks used for genuine protection against hazardous materials.

A new type of respirator which is being employed where high efficiency must be combined

with low breathing resistance is the powered filter respirator. In this device a battery-powered pump forces air through the filter, and by way of a hose, into the facepiece. The rechargeable battery, pump and filter are carried in a compact unit worn on the belt or other harness. For heavy work requiring large air volumes and low resistance to breathing in atmospheres containing highly toxic materials, this powered filter device is proving both useful and popular. Workmen cleaning coke ovens and uranium miners are among those who are using this respirator.

Gas and Vapor-Removing Air Purifying Respirators

Applications. These respirators are designed to protect the wearer against the inhalation of materials in the air that are present in the form of gases or vapors. Respirators for protection against such materials are equipped with a container or canister filled with a sorbent which absorbs, adsorbs or reacts with the hazardous gas in the atmosphere. Some sorbents are highly specific for a particular compound and so the respirator containing only this sorbent gives no protection against any other material. Other sorbents take

out whole classes of compounds such as acid gases or organic vapors.

Limitations. Like the particulate removing respirator, the gas removing device is useless unless adequate oxygen is present. Unless the device is specifically equipped with a filter in addition to the sorbent, it will not offer adequate protection against any hazardous particulate substances. Leakage around canisters can also occur as around filters but this is less likely. Leakage around the facepiece is also possible but, since these respirators usually offer less resistance to breathing than filter types do, there is a slightly smaller chance of this type of leakage. Once a sorbent canister is opened and used, the sorbent may absorb moisture or other deleterious materials from the air and deteriorate even without further usage.

For respirators designed for use under highly dangerous conditions some canisters are equipped with devices which change color when sorbent depletion approaches. For respirators designed for use under less hazardous conditions the odor of the gas penetrating the canister is the only warning. For these reasons simple gas removing respirators are most frequently designed for a single usage in dealing with a specific situation.

Facepieces. Essentially the same information relating to facepieces on particulate removing respirators applies also to gas and vapor removing respirators. Because many gases and vapors are also irritating or damaging to the eyes, full face respirators are much more frequently required than half masks. Half mask respirators usually carry relatively small sorbent canisters which can be used only for short periods in relatively low concentrations of gas. Even with the full facepiece and its head harness, the sorbent canister for heavy duty usage may be too heavy to be supported on the facepiece. It may be worn on a chest harness or strapped to the belt. The canister is then connected by a hose to the facepiece.

Sorbents. As previously noted, some sorbents may be used only in dealing with specific chemical compounds or with classes of compounds. Thus manufacturers have specific sorbents for ammonia or chlorine. Many canisters contain combinations of materials to assure absorption of a specific compound. It is important to note whether protection against the substance required is claimed on the canister of the device to be used. Obviously, it is not always possible to include the complete list of all such compounds on each canister, and the canister may effectively remove some materials not listed. A list of sorbents for a large number of materials is given in the Respirator Manual.⁴ The Bureau of Mines makes approval tests on only a limited number of common industrial toxic chemicals.

Since there is usually little warning of impending canister failure, the instructions of the manufacturer must be carefully followed regarding the length of time the device can be worn and the circumstances of its use. The effectiveness of a canister depends on the presence of a reactive chemical and canisters usually deteriorate with time. Here again, the manufacturer's instructions re-

garding shelf life should be followed and outdated canisters should be discarded.

Types. Gas masks are full facepiece units with large canisters. The names of the substances against which the mask gives protection are written on the canister and, in addition, the canisters are given specific colors for identification purposes.⁶

Chemical cartridge respirators are half mask respirators with small cartridges and are used for protection against the inhalation of atmospheres that are not immediately dangerous to life. Those used for protection against organic vapors are limited to use in concentrations not exceeding 0.1% by volume of such vapors; they are not satisfactory for all organic compounds. Mouthpiece respirators are small, compact devices for self-rescue in short term emergency situations (Figure 36-1). Instead of a facepiece this device fits in the mouth with a clip to put on the nose to force breathing through the mouth and the respirator.

Various combinations of filter and vapor removing respirators are available. A widely used device of this type is the universal gas mask which contains a filter plus sorbents for organic vapors, acid gases, ammonia and for the oxidation of carbon monoxide. This mask is used where the nature of the contaminants cannot be completely identified or where it is known that the atmosphere



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Figure 36-1. Mouthpiece Respirator — Self Rescue Device.

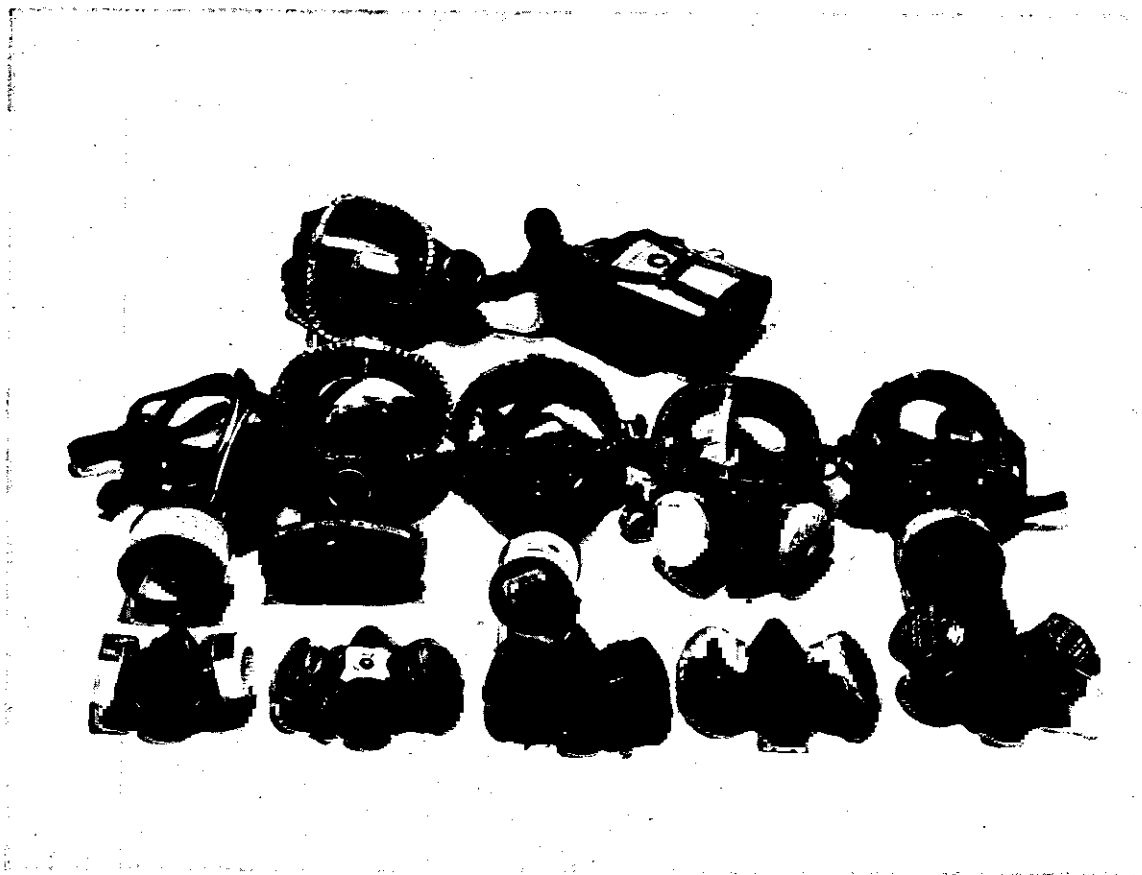
contains several of the above materials. It is the best respirator for protection against oxides of nitrogen in moderate concentrations. It must be remembered that it offers no protection when there is little or no oxygen present. Some manufacturers use the same basic facepiece for a variety of applications and various filters and canisters can be used on the same unit. Figure 36-2 illustrates air purifying respirators.

Atmosphere Supplying Respirators

Applications. When a lack of oxygen is known, or suspected or when a very high degree of protection is required the only suitable device is the atmosphere supplying respirator. This consists of a source of air or oxygen which is fed through a hose to a mask or a helmet. Intermediate mixing and regulating equipment may be required. Supplied air devices offer essentially no resistance to breathing, and the atmosphere supplied may be cool and more acceptable than that from other types of respirators.

Facepieces. A variety of facepieces are used with atmosphere supplying respirators. Half masks and full face masks are similar to those previously described although the valves are somewhat different. In addition to these, helmets may be used which cover the entire head and a cover may extend down to the waist as in the abrasive blasting hood. Another type of facepiece is the air supplied face shield. In this, the air is supplied by a hose to a perforated or slotted tube at the top of the face shield and the jets of air are directed downward past the eyes, nose and mouth. It is difficult to adjust this device to avoid entraining contaminated air and blowing it into the breathing zone. There are other combinations of atmosphere supplying equipment with hoods, blouses and complete clothing

Hose types. There are several varieties of the hose types including the hose mask with blower, hose mask without blower and the air-line respirator. The hose mask with blower can be used in any



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Figure 36-2. Air Purifying Respirators.
Front Row — Half Masks
Second Row — Full Face Masks
Rear — Universal Gas Mask.

atmosphere provided that enough respirable air is supplied to the wearer by means of the blower. The blower must be hand operated and the blower operator serves as an observer capable of rescuing the wearer in case of accident. The hose mask without blower is used under conditions not immediately dangerous to life and from which the wearer can escape without the aid of the respirator.

The air-line respirator (see Figure 36-3) consists of a source of compressed air to which the facepiece is connected by means of a small diameter hose. In the line is a pressure reduction valve and some type of flow regulating device. This equipment is used for protection in atmospheres that are not immediately dangerous to life or health or from which the wearer can escape without the aid of the respirator.

There are two basic types or modes of operation of air-line respirators — continuous flow and demand. In the first, the air is fed to the facepiece continuously and a positive pressure is maintained inside the mask at all times and any leakage will be outward. Considerably more air is used than is consumed in breathing. In the demand type a valve which regulates the flow of air opens only when a slight negative pressure is produced inside the mask as a result of inhalation. Thus, only air used in breathing is drawn from the source. Since a negative pressure is produced inside the face-



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Figure 36-3. Airline Respirator.

piece it must fit tightly to the face or contaminated air will be drawn in. Usually the demand type has a by-pass valve so the wearer can switch to continuous flow if he desires. A newer variation is the pressure-demand type of flow regulation. In this, a small positive pressure is always maintained in the facepiece even on inhalation. The demand valve opens to supply air when the positive pressure decreases to a certain level as a result of inhalation. Thus leakage is always outward if a poor fit of facepiece to face is obtained. *Self-contained breathing apparatus.* In this apparatus the wearer carries his own supply of air or oxygen and so he is able to move about without attaching hoses which limit his travel distance and maneuverability. Since the wearer is limited to the supply of air which he can carry, several methods are used to conserve this supply. Demand and pressure-demand valves may be used in the same manner as in the air-line respirator. A bypass for continuous flow is also provided, but can be used only for very short periods or the supply will be quickly exhausted. Either air or oxygen may be used in this type of apparatus.

Another type of device uses recirculation to conserve the oxygen supply. In this unit the exhaled air is not expelled but passes through an absorber which removes carbon dioxide and then enters a breathing bag. Here it mixes with fresh oxygen from the gas cylinder and then passes back to the facepiece for rebreathing. Oxygen only enters the breathing bag when the pressure in the bag drops below a fixed value. Since the oxygen content of exhaled air is still about two-thirds of that of inhaled air, it is only necessary to make up this difference from the tank and thus the recirculating type can be used for much longer periods for the same quantity of oxygen carried. Both demand and recirculating equipment are marked for use only for a specified period of time ranging from thirty minutes to three hours.

A third type of self-contained breathing apparatus uses a chemical source of oxygen which is liberated when carbon dioxide and moisture are absorbed from the exhaled air. A breathing bag is provided to mix the incoming oxygen with the purified exhaled air. This apparatus can be used for thirty minutes only and includes a timer to warn of the approaching limit (see Figure 36-4) Once the canister is opened it cannot be resealed for further use even if it has been used for only a few minutes. Like all chemical cartridges it has a limited shelf life even if unopened. *Combination types.* One variety of air-line respirator utilizes a small cylinder of compressed air worn on the user as an emergency device. If anything happens to the regular air supply the wearer simply disconnects his air line, automatically switching to the small cylinder supply and unhurriedly leaves the hazardous area. In place of a compressed gas supply, a filter or a sorbent canister may also be used for emergency conditions. Even with these devices air-line respirators are not approved for use in atmospheres immediately dangerous to life.

Sources of air or oxygen. The hose mask simply



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Figure 36-4. Self-Contained Breathing Apparatus.

uses air drawn from a source outside the contaminated atmosphere. The air-line respirator may use a compressed gas cylinder of air or oxygen or a compressor which picks up outside air. If the compressor is driven by a gasoline or diesel engine extreme care must be taken to see that the engine exhausts away from the pump intake and no exhaust gases enter the breathing air system. Water-lubricated compressors, or those not requiring internal lubrication, are the best sources of compressed air for these devices since heating may cause breakdown of lubricating oil forming carbon monoxide. Oil-lubricated compressors, if used, should be equipped with thermal overload switches to turn them off if overheating occurs. In any case, the compressor should be followed by a trap and filter to remove dirt, oil and water from the air line. If a regular building supply is to be used for an air-line respirator the system must be checked repeatedly to be certain that it does not contain even small concentrations of carbon monoxide.⁶

A new alternative source of oxygen for the self-contained breathing apparatus is liquid air or liquid oxygen. Several devices using this oxygen source have been approved by the Bureau of Mines. Air from this source is cooler and may have a "fresher" odor than compressed air.

Maintenance. All types of respirators require

maintenance and cleaning. The highly complex atmosphere supplying devices must be inspected for signs of wear and deterioration and to make certain that all of the parts are functioning properly. Other types of respirators are simpler but still require regular inspection. Rubber parts deteriorate with time and exposure to ozone and other gases. Hence, hoses, facepieces and valves must be inspected regularly and parts or whole respirators replaced when necessary. All respirators should be brought in for cleaning occasionally and emergency devices cleaned after every use when cylinders of gas or canisters are replaced. Emergency devices and self-contained breathing apparatus should be inspected monthly since they are usually to be used under very hazardous conditions.

When respirators are used routinely they should be brought in regularly to be dismantled, washed and dried, inspected and parts replaced as necessary, new filters or canisters put in and the whole reassembled and stored in a clean place.

Special Topics

Worker Acceptance Factors. Good equipment is ineffective if the equipment is not accepted and used by the workers. Hence, factors leading to such acceptance must be carefully considered by management. All respirators are uncomfortable and irksome to wear but consideration of the comfort factor in respirator selection can do much to gain worker acceptance in using respirators when they are needed. Low breathing resistance is important, and while the Bureau of Mines specifies maximum values of permissible resistance, there are still differences among approved respirators. If face fit can be obtained only by very tight strap tension, the respirator cannot be worn long and its use will be avoided. A particularly important point is management's interest in the program. If every effort is made to provide conditions where respirators are not necessary then they will be better accepted when they are necessary. Regular cleaning and maintenance is evidence of management's interest. An educational program in respirator use is essential.

Training. Respirators are complex devices and cannot simply be handed to the worker with the assumption that they will be used properly. When the worker is told to use a respirator he should see the various devices available to him and have their method of operation explained including all essential parts. He should then try on the device and test the fit of the facepiece. This may be done by covering the exhalation valve, if possible, and then exhaling sharply or by closing the intake ports and inhaling. Most manufacturers include instructions for leak testing with the respirators and these directions should be followed. The worker should be taught to inspect the respirator before each use. The subject of training is discussed at considerable length in the Respirator Manual⁷ and is an extremely important topic. Where considerable numbers of respirators are worn, it is advisable to designate a specific individual to be responsible for fitting and training.

Heat problems. All respiratory equipment is very

uncomfortable and fatiguing to use under hot conditions. Supplied air equipment such as air-line respirators may be most satisfactory under such conditions and complete supplied air suits may be necessary. A small compact vortex cooler is available which can be worn on the belt or harness to supply cool air.

Communications. Some voice communication is possible while wearing a respirator but sounds are muffled and attempts to talk loudly may loosen the face fit. With most full face masks it is possible to replace the exhalation valve with a combination valve and speaking diaphragm which permits much better voice transmission. When good communication over considerable distance is necessary, it is possible to equip the full facepiece with a battery operated microphone transmitter which transmits to an outside speaker or to receivers or earphones worn by others.

Codes and sources of information. As noted, the Bureau of Mines issues approvals for all types of respiratory protective devices and the approval schedules which can be obtained from the Bureau contain full information on how the respirators are tested and the standards they must meet. The Bureau has also issued a list of dust respirators approved for use in coal mines.⁸ The American National Standards Institute has issued its American National Standard Z88.2-1969 entitled *Practices for Respiratory Protection* which contains much useful information.⁹ The most complete publication in this field is the *Respiratory Protective Devices Manual* published by the American Industrial Hygiene Association and the American Conference of Governmental Industrial Hygienists. The National Safety Council has recently published a series of articles on respiratory protection in *National Safety News*.¹⁰

A Respirator Program for Industry

The important elements of the successful plant respirator program have been discussed in previous sections of this chapter. Here they will be summarized to provide a means for checking to be certain that all factors are covered in a particular situation.

Determination of need. This will require knowledge of the hazards anticipated in carrying out a particular job. An estimate will be required of the possible concentrations of toxic material that could be produced; whether existing engineering controls, such as ventilation, can adequately meet the needs; the anticipated duration of the required protection and any limitations imposed by the job. The latter includes the intensity of the physical activity required and whether or not the worker must be able to move about without encumbering hoses. Obviously, the determination of the need for respiratory protection is a technical decision and can best be made by an industrial hygienist.

Selection of equipment. Much of the same information required in establishing the need for respiratory protection is required here also. In addition, one must have a knowledge of the types of devices available for the particular circumstances encountered. Since it is impossible to expect each plant to have on hand every type of device manufactured, equipment kept on hand must be pur-

chased in advance on a basis of surveys and studies of anticipated needs. Here, there is a requirement for close cooperation between the person in charge of the respirator program and the plant's purchasing and stores department. Preliminary education of appropriate persons in this department may be necessary since their tendency will be to stock items on a basis of price without regard to important distinctions between different pieces of equipment.

Training. This is very important and requires continuous study and updating of knowledge by the person giving the training. The latter should be the person responsible for selection of respirators to be carried in stores, or at least he should be in very close touch with this aspect, since his direct contact with workers using protective devices makes him aware of their needs.

Supervision and enforcement. The support and encouragement of supervisors, such as foremen, are essential to the program. The foremen, particularly, should be asked to participate in fitting and training even though they may have little occasion to use respiratory protective devices. This provides an opportunity to demonstrate the importance of the activity and gains their support for the program. Without this support many workers will not use the equipment correctly nor care for it adequately.

Inspection. Industrial hygienists and safety engineers in the plant must include regular inspection of the condition of respirators as one of their routine duties. It is particularly important that emergency devices such as those mounted on walls or in cabinets be checked regularly. The most important inspections, particularly of smaller devices, are those given by the worker himself. His training must include information on the importance of this and how to do it adequately.

Maintenance. In most plants there should be a central cleaning station where respirators are brought in regularly for cleaning and replacement of worn or damaged parts. In very small plants this may be done by the worker himself with the aid of the safety engineer, industrial hygienist or plant nurse.

Storage. New respirators should be stored in their original container in a clean, cool dry place before being issued. Cleaned respirators if not immediately reissued should be placed in a dust-tight container, such as a plastic bag. The worker also should be instructed to store his respirator properly after it is issued to him. A respirator crammed into a tool kit can be permanently distorted in shape so that it cannot fit. Dust accumulated on the interior of the mask is readily breathed in and wearing such a mask may be a cause of more exposure than failing to wear it.

Management interest. Top management should give some evidence of support of the program. This may be done, in part, through the plant paper or magazine or through shop bulletins or other means of indicating interest or concern. It is the responsibility of the person in charge of the program to keep management informed about the program if he is to obtain their interest and support.

PROTECTION AGAINST NOISE

The previous section of this chapter has dealt at considerable length with the subject of respiratory protection. Much of this is also applicable to devices used to protect against noise and other hazards. With hearing protective devices, both ear plugs and ear muffs, there is a need for experimentation in trying different types of devices to meet specific needs. Since the noise hazard is not as acute as the respiratory hazard more experimentation is justified. Both plugs and muffs attempt to prevent the penetration of sound through the outer ear to the inner ear; however, some sound also reaches the inner ear by conduction through bone and tissue. Thus, any protective device is limited in the degree of protection which can be achieved. In sound fields in excess of 120 decibels no protective device will give adequate protection for continuous exposure.

When ear protectors are first used by a worker, he experiences a sensation that his own voice is very loud since outside noises are reduced. As a result, he tends to speak softer making it more difficult to communicate with others especially if they are wearing protectors also. Noises signaling dangers around the worker may be muffled and their warnings not heeded.

Ear Plugs or Insert Devices

Ear plugs are small conical or cylindrical devices made to fit into and seal the ear canal against the entrance of sound. The more closely the plug approximates the shape of the ear canal the more positively it will seal. Plugs are usually made of a soft pliable material like soft rubber or plastic so they can be inserted into the ear canal with positive force without being uncomfortable. Many models have soft flanges which can seal the canal even if contact with the body of the device is incomplete. Attempts have been made to improve the usefulness and acceptability of ear plugs by introducing models with "valves" or perforations which were to allow passage of sound of certain frequencies or to block loud but not soft sounds. None of these has been successful and the plain plug remains the best. Since fitting to the ear canal is important some manufacturers make plugs for individual ears by making casts or impressions of the ears and then moulding and curing a plastic material in the shape of the impression. While such devices would appear to have a great advantage in effectiveness and comfort, this is not always the case.

Malleable wax material is available which can be moulded into the ear and discarded after use. Wadded cotton has often been used, but actually is comparatively ineffective. Cotton impregnated with wax or vaseline is much more effective. A very fine glass wool material has been introduced in recent years, often called Swedish Wool after its country of origin. This material can be rolled into plugs and gives almost as good protection, if properly used, as a good commercial plug. Dispensers for this material can be installed and the material is more acceptable to many workers than regular ear plugs.

The degree of sound attenuation provided by

ear plugs varies in different frequency bands or octaves. For good, well-fitted plugs this varies from 25 decibels in the low frequency or low pitched sounds to 40 decibels at frequencies over 1000 Hertz. Fitting of the plugs is very important in achieving good results. Most plugs come in several sizes and the correct size must be chosen to fit the individual's ear canal. Frequently different sizes are needed for the two ears. Fitting by the Medical Department is a good way of achieving this part of the program's purpose. The physician can examine the ear canal carefully for size and at the same time detect any ear infections or canal irregularities which may rule out the use of ear plugs. Some persons simply cannot wear ear plugs.

Ear Muffs

Ear muffs are much like communications type earphones in appearance although the ear cup is usually deeper. They are equipped with a headband which may go over the head or around the back of the neck. The latter type permits the wearing of a hat but usually offers slightly less hearing protection. They may also be mounted on a helmet or hard hat. The degree of attenuation obtained varies with the sound frequency and may range from 20 decibels at low frequency to 45 decibels at high frequency. There is a standard method of measuring attenuation by muffs, but it is complex and requires special equipment. Most users will have to rely on the attenuation data supplied by the manufacturer.

To attain good protection the muff should seal over the ear and the seal may be made of foam rubber or liquid-filled or grease-filled cushions. The latter two are somewhat more effective and comfortable. Large cup volumes and small cup openings lead to greater attenuation.

Proper fitting is important with muffs, but is not quite so individual a matter as with plugs. The worker should be offered a choice of several models to achieve the best fit and to gain his acceptance of the device. Where communication is necessary in a high noise level environment, ear muffs can be equipped with earphones and battery operated radios. The microphone can be muffled and mounted directly in front of the mouth.

Plugs or Muffs?

Good ear plugs may give slightly higher attenuation in the very low frequency range while muffs give better attenuation in the middle ranges. Above 1000 Hertz there is little from which to choose on a basis of the degree of protection afforded. Plugs are more acceptable to some workers while muffs are preferred by others. Where exposure to noise is intermittent, muffs are somewhat more easily removed and replaced when needed. Plugs are easier to carry than muffs, but for the same reason are more easily lost. They are also less expensive. Muffs are more comfortable for use in cold weather. Both plugs and muffs deteriorate with time and should be inspected frequently.

Evaluation

If ear protection is required, there should also be a medical program which includes audiometric

testing of exposed workers. Results of such testing will determine whether continued exposure is advisable even if protective devices are used. Obviously, every attempt should be made to control the noise by engineering methods and eliminate the need for personal protective devices. One author puts the case as follows — “When the only possible control method is ear protection, it is important — rather it is essential — that the ear protection program be continually monitored by knowledgeable and enthusiastic people who are dedicated to the task of protecting the hearing of noise-exposed employees.”¹¹

PROTECTION OF SKIN AND BODY

This section deals with the subject of what is usually called protective clothing and includes protection of the various parts of the whole body either completely or partially as may be required. The term, protective clothing, is a correct one although much protective clothing offers no more direct bodily shielding than would be offered by ordinary street dress. Since street clothing might be ruined or rendered unsuitable for street use if worn in the shop, the shop clothing provided is “protective” of one’s ordinary clothing. Chemicals, dirt, heat and cold are the chief hazards against which protective clothing are used. Certain rather specialized occupations require unusual types of protection including firemen, aircraft crews, missile fuel handlers, astronauts and divers. In general, this section is not directed to these specialized vocations but much of what we have learned about protective clothing comes from experience in providing protection for workers in such unusual environments.

There is a wide variety of materials available today to meet the requirements of many types of conditions. Fabrics such as cotton, glass fibers, Orlon, Nylon, Dynel and even Teflon are available for jackets and coveralls. These can be made impervious by coating with various plastics, rubber or Neoprene. Plastics are also available in sheet form and can be made into clothing with glued or heat-sealed seams. Respiratory protective devices often are worn with protective clothing and, in many cases, become an integral part of such clothing (see Figure 36-5).

While some protective clothing is supplied and cleaned by the worker it is more commonly done by the employer, especially if the wearing of such clothing is a requirement of the job. In many cases, work clothing cannot and should not be taken home since such clothing could become a hazard to persons handling it there. This is particularly true of workers handling radioactive materials, pesticides, beryllium and other highly toxic materials. If the employer is responsible for cleaning the clothing he, too, must decide whether to send it to a commercial laundry or to set up his own cleaning facility. For clothing contaminated with ordinary dirt, soil, grease and perspiration, a commercial laundry may be an acceptable method of handling the problem. In many cases, one or more plant laundries will have to be provided depending on the variety of exposures encountered.



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Figure 36-5. An Air Ventilated Blouse with Integral Respirator.

There is also the problem of maintenance and of replacement. Garments must be inspected before or after cleaning and worn garments discarded. Those not meeting standards of cleanliness required may have to be recycled. For radioactive materials, this may mean monitoring of each garment with a special instrument. Where the exposure is to certain chemicals, it may mean periodic tests on occasional selected garments after cleaning.

Training in the use of protective clothing is important, especially with complex gear. Even with simple laboratory coats and coveralls, workers should be given some instructions in how to care for such garments and how and when to turn them in for cleaning and replacement. For complex garments, especially those including respiratory protective equipment, regular training and refresher courses should be given. Here again, some *one* person should be in charge of selection, storage, maintenance and training in the use of such equipment. An important element in this

training is that dealing with the methods of putting on and taking off this clothing. Special standardized techniques may be necessary where clothing has or could have become heavily contaminated. If care is not exercised, contaminating materials can be brought into contact with the worker's skin or transferred to his street clothing. Separate lockers for work clothing and street clothing are necessary when hazardous materials are handled. These lockers may be on opposite sides of the shower room.

Protection Against Contamination

Situations included in this category are those where there is no immediate danger to the skin from contact with the contaminating material, but where it is undesirable to have the worker expose himself in his street clothing. This includes the mechanic or machinist exposed to dirt and grease, the operator handling toxic dusts, the laboratory employee handling various chemicals that could damage his clothing and the person working with radioactive materials or bacteriological agents. The emphasis in all of these cases is on limiting the spread of the contamination. When the worker leaves his job, he should not transfer the hazardous or undesirable material to clean parts of the plant or to places outside the plant. Clothing for these applications is often called anti-contamination or anti-C clothing. It should be noted that also within this category of jobs are those where extreme cleanliness is required for the protection of the product being made. In that case, the aim is to prevent the spread of contamination from street clothing or the worker to the product. The same requirements and procedures also prevail here.

Garments worn in these situations are principally of cotton or synthetic fibers and usually are not impervious to liquids or dusts. The mechanic and the chemical plant operator usually wear coveralls. If the material is difficult to remove he may also wear gloves and some type of cap. Footwear may consist of a pair of shoes which are left in the plant. In working with more dangerous material like toxic dusts or radioactive materials more strict regulations are necessary. Here a complete change of clothing including socks and underwear is needed and showering is essential. For heavily contaminated work special attention must be given to sealing all openings in the clothing. For dirty jobs which are not done routinely, openings may be sealed with masking tape and two suits of coveralls may be worn. If possible, the clothing should be designed to minimize the number of openings, decorative buttons and folds as these items collect contamination and make it difficult to remove.

Many workers wear full coverage clothing all day in doing their routine jobs. They may also wear surgeon's gloves or similar types to give the required sensitivity in handling objects, but these are not satisfactory if the work subjects the gloves to abrasion. Head covering in this case is usually a simple cloth cap although a hard hat may also be required on certain jobs. In addition to shoes worn only in the plant, special shoe covers may

also be required. These may be of heavy cloth, plastic coated cloth, plastic or rubber. These are particularly important to the worker who must move from one department or operation to another. By changing shoe covers he prevents the spread of the particular type of hazardous material in one department to another where a different material may be handled.

Rooms where workers remove heavily contaminated clothing must be well ventilated since removing contaminated clothing can cause suspension of the contaminant in the air where it becomes hazardous to everyone in the room. For the same reason, chutes and bins where contaminated clothing is deposited should have exhaust ventilation. For limiting contamination, consideration should be given to the possibility of using disposable clothing made of paper or plastic, particularly on very dirty jobs. Cleaning costs should be balanced against the costs of replacement and disposal. In making this evaluation careful consideration should be given to the disposal cost as this is often neglected.

Protection Against Corrosive Chemicals

Included in this category are situations where the contaminant can have an immediately damaging effect on the skin. These include exposures to strong acids and acid gases, alkalis, some organic chemicals and strong oxidizing agents. Also included are those requiring protection against very heavy contamination where ordinary anti-C clothing would permit skin contamination to levels where complete removal would be difficult. Clothing in this category is usually impervious to liquids, gases and vapors and may be made of fabrics impregnated with rubber or plastic. Rubber "frog suits" have been used for work in heavy concentrations of dangerous radioactive materials. The worker may be required to shower with the suit on and then shower to clean himself after carefully removing the suit using standardized procedures. Respiratory protective equipment is almost always required in conjunction with this clothing. It may be worn under the clothing or it may be an integral part of the clothing. An air line may be attached directly to the clothing for ventilation or it may go directly to a respirator. The head cover is usually part of the clothing in the form of a hood. Gloves must be impervious and may also be an integral part of the clothing.

Wearing impervious clothing imposes serious limitations on the amount of time the worker can wear the clothing and the strenuousness of his activity. Unless the clothing is ventilated with an air line, perspiration will rapidly accumulate inside the clothing and the body temperature may increase except in cold environments. These conditions impose a serious stress on the worker. Air-ventilated clothing is much more comfortable and permits wearing the clothing a longer period of time although it may limit the movements of the worker. Air-ventilated clothing must be studied and evaluated carefully because improper design can result in only parts of the clothing being ventilated. The air line must discharge through several openings to supply the various parts of

the suit. Where workers must work in impervious clothing for long periods close medical surveillance is required.

Protection Against Skin Penetration

Certain materials will pass through the intact skin and produce systemic toxic effects without necessarily doing any damage to the skin or causing pain. Situations involving these materials include exposure to hydrogen cyanide, missile or rocket propellant and the radioactive form of hydrogen known as tritium, either in elemental form or as water vapor. The clothing requirements for these exposures are practically the same as those discussed in the previous category. They are grouped separately because the effects produced can be very serious and there is little or no warning of failure of the protection. Thus, there is more need for frequent inspection and testing of the clothing worn in this type of exposure situation. Respiratory protection is always required.

Protection Against Heat and Cold

For mild exposure to heat the clothing should be light and well ventilated. At higher temperatures most clothing restricts the body's ability to remove body heat by evaporation of perspiration and forced ventilation of the clothing is necessary for prolonged work at elevated temperatures. Obviously, the design of clothing for protection against heat and cold emphasizes thermal insulation and the principles on which such design is based are well known. If there is a great deal of radiant heat, as around a furnace or flames, aluminized plastic, cloth or asbestos may be used to provide a reflective surface.

Air supplied clothing is particularly useful since the supplied air may be heated or cooled to maintain thermal equilibrium. Air for breathing may also be heated or cooled and very cold air may be tempered if taken in through a hose wrapped around the worker's body under the insulating clothing. For work at very low temperatures, particular attention must be paid to protection of the fingers, toes, ears and nose since they are the parts most difficult to keep at an adequate temperature and frostbite may result from exposure. Thick gloves which are necessary greatly limit manual dexterity and electrically heated gloves may be required under some conditions.

There are special pieces of protective gear used to protect parts of the body against heat, flame and sparks. The welder's leather apron and his face mask are examples. Foundry workers wear leather leggings to protect their legs against spilled molten metal. They also wear special foundrymen's shoes called Congress shoes which can be pulled off quickly if hot metal is spilled into the shoes.

There are many other devices used for the protection of the individual worker against falls, falling objects, flying particles, burns and injuries, such as safety hats, shoes, gloves, goggles, etc. They are not covered in this chapter since they are considered to be strictly "safety" items. See Chapter 47 for a general discussion of these items.

EMERGENCIES

By its very nature, personal protective equipment is important in dealing with emergencies. Mine explosions and cave-ins, industrial fires, natural disasters and gas leaks all present occasions when men must receive protection against severe and unusual conditions while saving life and property. Engineering controls such as ventilation are completely inadequate and usually inapplicable in such situations; therefore complete reliance must be placed on protective clothing and respiratory protective devices. Some of the same devices used in the daily plant activities may be applicable but in most cases it will be necessary to use more specialized devices such as self-contained breathing apparatus or fire-resistant clothing.

Equipment for dealing with emergency situations must be stored where it is readily available and yet not be placed where it can be damaged by the accident causing the emergency. This requires careful analysis to anticipate the possible emergencies and accidents which can arise. An important characteristic of emergency protective devices is that they are *stored* which means that they are actually used very rarely. Since much equipment suffers deterioration even during storage, it is necessary to set a regular schedule of inspection and testing of each device.

Most such devices are fairly complex and require trained persons for their use. An untrained person attempting to rescue an injured man in a building filled with toxic vapors is very likely to become a casualty himself. Men must be trained in how to function in an emergency and in the use of all emergency equipment. Retraining exercises must be given at regular intervals since instructions are easily forgotten, equipment is changed, and personnel may be transferred. The essential beginning of any emergency planning is a thorough analysis of the possibilities of accidents. This analysis, in itself, may lead to the correction of unsafe conditions.

STANDARDS AND INFORMATION

The approval schedules of the Bureau of Mines for respiratory protective equipment are standards in a sense as has already been noted. The American National Standards Institute has prepared consensus standards on many items of protective equipment and these are listed in the bibliography of the chapter. There are needs for additional standards for some equipment and for the revision and updating of many existing standards. The process of producing standards is a lengthy one, and changes and improvements in the various devices are being introduced continuously. There must be a willingness to experiment and test new and nonstandard devices under non-hazardous conditions in order to secure improvements in protection and acceptability.

In addition to the written standards there are various guidebooks to the selection, use and maintenance of personal protective devices prepared by organizations concerned with health and safety. These are listed at the end of the chapter and the appropriate guide should be consulted by anyone

responsible for supervising the use of these devices. Such guides have been prepared by the National Safety Council, the American Conference of Governmental Industrial Hygienists, the American Industrial Hygiene Association, the International Atomic Energy Agency and others. Most manufacturers of protective equipment furnish information on the degree of protection which can be achieved by their devices and on their proper use, care and maintenance.

References

1. *Occupational Safety and Health Administration Standards, Personal Protective Equipment*, Federal Register, 36:10590 (No. 106, May 29, 1971).
2. SCHUTZ, R. H. and E. J. KLOOS. *Respiratory Protective Devices Approved by the Bureau of Mines as of Dec. 31, 1968*, Information Circular #8436, Bureau of Mines, Pittsburgh, Pa.
3. *Respiratory Protective Devices Manual*, AIHA-ACGIH, p. 91, 1963.
4. *Ibid.*, pp. 56-58.
5. *American Standard Safety Code for Identification of Gas Mask Canisters*, K13.1-1961, American National Standards Institute, 1430 Broadway, New York, 10018.
6. VENABLE, F. S. and E. D. POLICK. "Your Compressed Air: Fit to Breathe?," National Safety News, 89:28-32, 1964.
7. *Respiratory Protective Devices Manual*, AIHA-ACGIH, Chapter 13.
8. SCHUTZ, R. H. *Approved Dust Respirators for Coal Mines*, Information Circular #8509, Bureau of Mines, Pittsburgh, Pa.
9. *American National Standard Practices for Respiratory Protection*, Z88.2-1968, American National Standards Institute, 1430 Broadway, New York, 10018.
10. "Series on Respiratory Protection," National Safety News, April-December 1971.
11. BONNEY, T. B. *Industrial Hygiene Highlights*, p.

208, Industrial Hygiene Foundation, Pittsburgh, Pa., 1968.

Preferred Reading

American Industrial Hygiene Association Journal
Health Physics
National Safety News
Industrial Hygiene Highlights
Annals of Occupational Hygiene (British)
Staub (German)

Additional Reading

Additional Standards from the American National Standards Institute:

American National Standard for Occupational and Educational Eye and Face Protection, Z87.1-1968.

American National Standard Safety Requirement for Industrial Head Protection, Z89.1-1969.

American National Standard for Men's Safety-Toe Footwear, Z41.1-1967.

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PLUMB, E. E., E. L. MENDENHALL and M. C. ROBBINS. "Evaluation of Protective Clothing and Equipment for Operations in Oxygen-Rich or Deficient Atmospheres Approaching -100°F," *Am. Ind. Hyg. Assoc. J.* 27:29, 1966.

CROLEY, J. J. "Protective Clothing — Responsibilities of the Industrial Hygienist," *Am. Ind. Hyg. Assoc. J.* 27:140, 1966.

CONTROL OF NOISE EXPOSURE*Vaughn H. Hill***DEFINITION OF PROBLEM****Measure Noise Level**

From an engineering control standpoint, the first step in a hearing conservation program is to measure the noise levels in all working areas. Areas in which the noise level does not exceed 90 dBA* need not be considered further since noise reduction is not required.

Determine Exposure Time

In areas where the noise level does exceed 90 dBA, a study should be made to determine the actual worker exposure time. Then using this exposure time and the measured noise level, one can determine whether or not the government standards are exceeded. Details regarding the use of government criteria are given in Chapter 25. It may be desirable to use a dosimeter to determine the actual daily noise exposure for comparison with government criteria. Dosimeters are discussed in Chapter 25.

Evaluate Extent of Hazard

If the combination of noise level and exposure time indicate that government criteria are exceeded, an evaluation should be made to determine the most economical solution to the problem. Considerations for making such an evaluation are: (1) reduction of noise level, (2) reduction of exposure time, (3) segregation of worker from noise, (4) substitution of more quiet machine or process or (5) provision of worker with personal protection such as ear muffs or plugs. Under the Occupational Safety and Health Act this latter option is available only if others fail. Usually all of the following will be involved in making the best evaluation: (1) management, (2) medical, (3) personnel, (4) manufacturing, (5) engineering and (6) maintenance. This chapter will be limited to the problem of reducing noise in working environments.

CONSIDERATION OF ALL POSSIBLE MEANS OF NOISE CONTROL

In a subject as broad as industrial noise control, it is impractical to discuss all possible solutions to all problems. Therefore, typical problems of the type occurring most commonly in industry will be discussed with the hope that the reader will acquire an understanding of the principles of noise control that will guide him in solving a much wider variety of problems.

The mode of attacking a noise problem is somewhat analogous to that of controlling any

environmental hazard. Appropriate control measures include such things as change in plant layout and design, substitution of less hazardous method, reduction of the hazard at its source, and reduction of the hazard after it has left its point of origin.

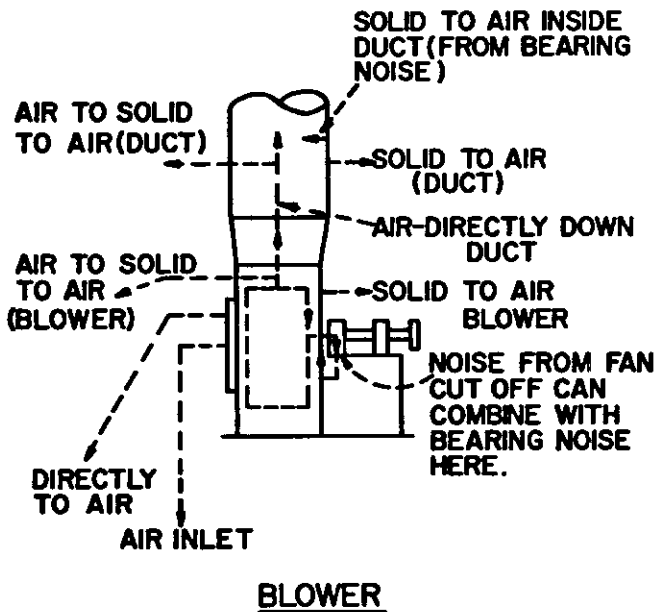
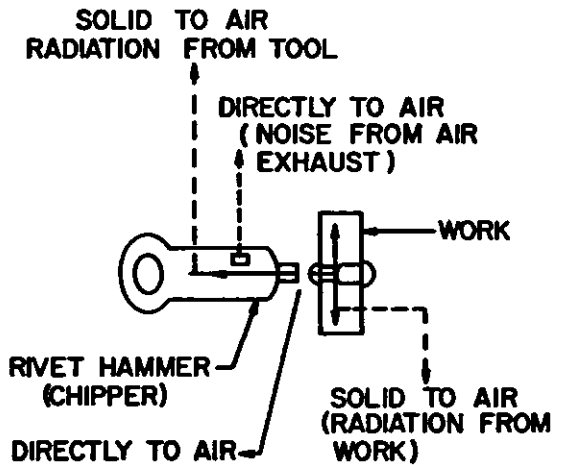
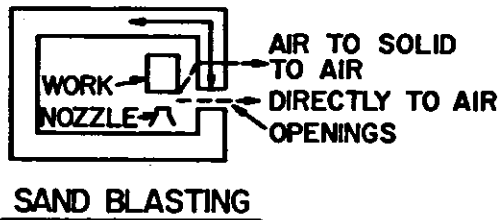
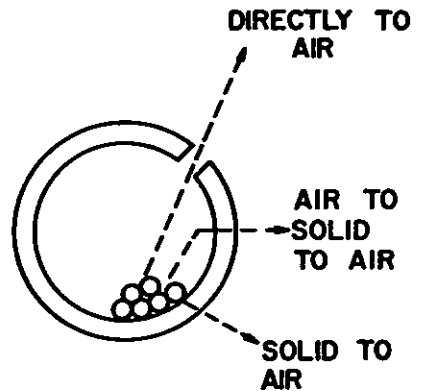
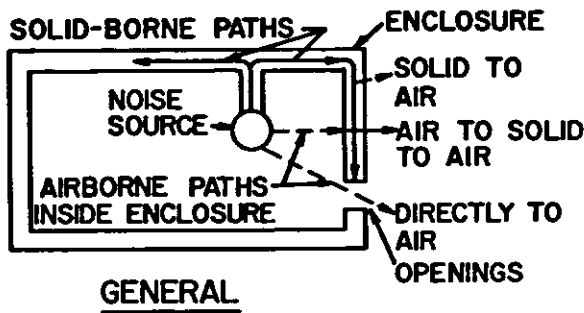
In analyzing a noise problem one must consider that sound from a source can travel by more than one path to the point at which it becomes objectionable. Therefore, noise flow diagrams such as shown by Figure 37-1 are a definite aid to accurate analysis of a given problem. For instance, this shows that sound sources inside enclosures can have (a) direct radiation of sound through openings in the enclosure, (b) sound radiation from the enclosure due to solid borne vibration from the source and (c) indirect radiation from the enclosure, that is, airborne from the source to the inside of the enclosure and subsequent reradiation from the outside of the enclosure. The problem is to determine which paths carry the most sound energy and then select appropriate methods of obtaining the desired reductions along those paths.

It has proved helpful to follow a planned method of analysis so that no possible control measure is overlooked. The following outline can be used in making such an analysis:

Noise Control Analysis Outline

- I. Plant Planning
- II. Substitution
 - A. Use quieter equipment
 - B. Use quieter process
 - C. Use quieter material
- III. Modification of the Noise Source
 - A. Reduce driving force on vibrating surface
 1. Maintain dynamic balance
 2. Minimize rotational speed
 3. Increase duration of work cycle
 4. Decouple the driving force
 - B. Reduce response of vibrating surface
 1. Add damping
 2. Improve bracing
 3. Increase stiffness
 4. Increase mass
 5. Shift resonant frequencies
 - C. Reduce area of vibrating surface
 1. Reduce overall dimensions
 2. Perforate surface
 - D. Use directionality of source
 - E. Reduce velocity of fluid flow
 - F. Reduce turbulence

*Note: This figure may be changed by regulation or law. Check for the current standard requirement.



Tyzzar, F. G.: Reducing industrial noise. Amer. Ind. Hyg. Assoc. J. 14:264-95, 1953.

Figure 37-1. Noise Flow Diagrams.

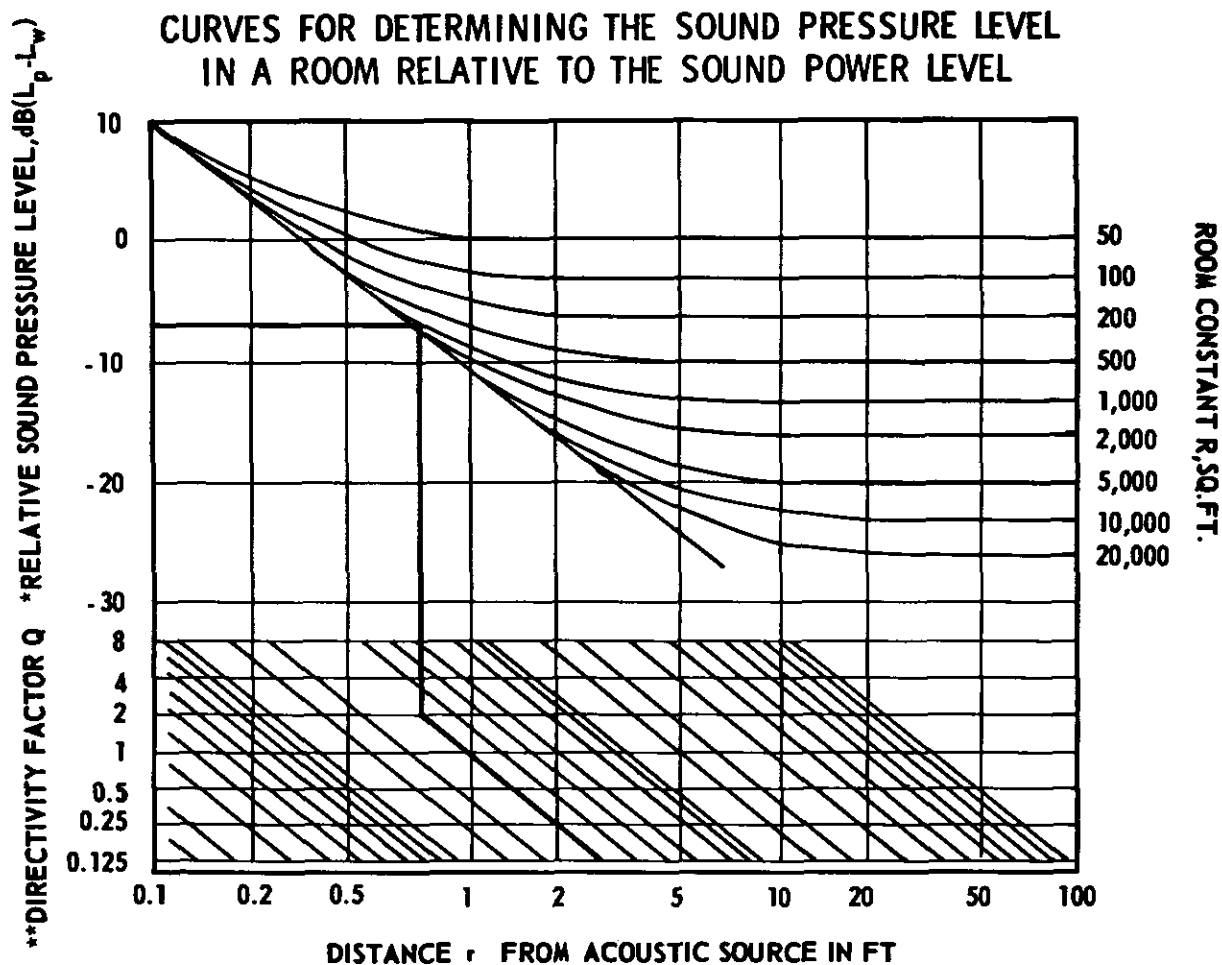


Figure 37-2. Curves for Determining the Sound Pressure Level in a Room Relative to the Sound Power Level.

IV. Modification of the Sound Wave

- A. Confine the sound wave
- B. Absorb the sound wave
 1. Absorb sound within the room
 2. Absorb sound along its transmission path.

Examples of many of these possible control measures will be illustrated in this chapter.

Plant Planning

Noise specifications. An immediate step essential to those concerned with noise control is to stop buying new noise problems. Minimum essential designs for processes and equipment must involve light, high speed machines, high pressures, high flow velocities, light building structures and minimum floor space. All of these can lead to noise problems if limits are not specified. Noise specifications are a *must* for new equipment. To properly use noise specifications one must understand Figure 37-2. This graph shows the relationship between sound power level (L_w) and sound pressure level (L_p) and their relationship to distance

from the source (r), directivity factor (Q) and room constant (R).

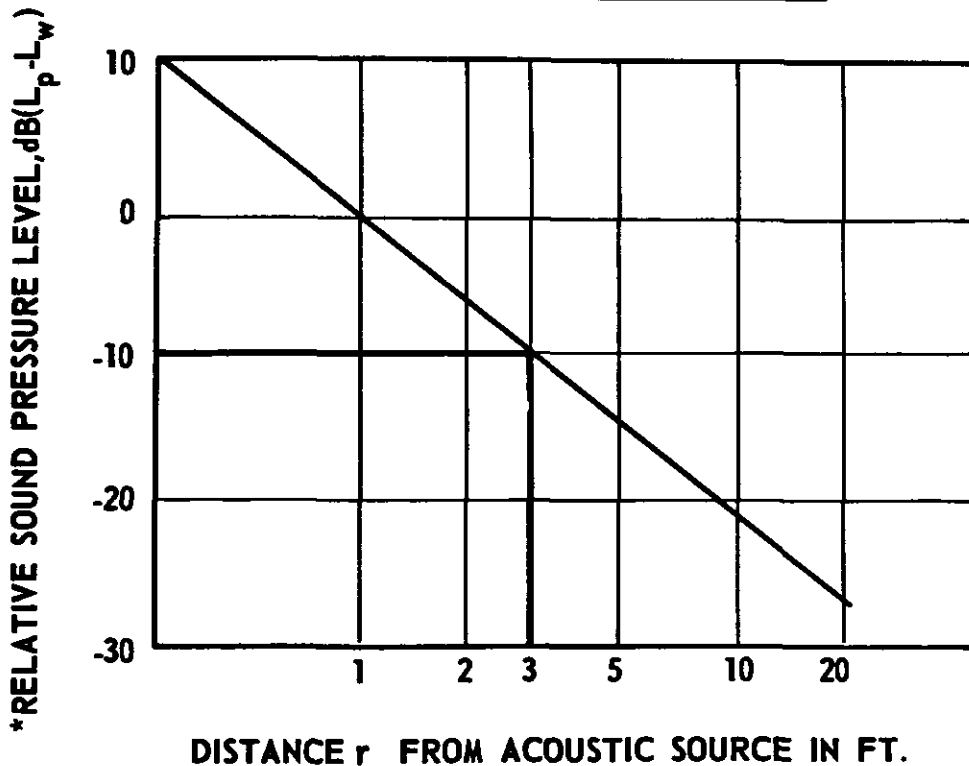
L_w is total energy of the sound source and is independent of the distance or environment. It is calculated, not measured. See Chapter 23 ("Physics of Sound") for further discussion.

L_p is sound energy flow per unit area at some distance (r) from the source. It varies with distance from the source, directivity and room constant. Therefore, these environmental conditions must be specified when expressing noise in terms of sound pressure level.

Free field radiation. When a sound source is in a free field (where there are no reflections) it will diminish with the square of the distance from the source. The relation between L_w and L_p in this case is shown by Figure 37-3. L_p can be measured with a sound level meter or analyzer.

Room constant (R). R is a measure of the ability of a room to absorb sound. It can be calculated as follows:

FREE FIELD NOISE RADIATION POINT SOURCE - NONDIRECTIONAL



$$L_w = L_p + 20 \text{ Log}_{10} r + 0.5 - T$$

Figure 37-3. Free Field Noise Radiation Point Source — Nondirectional.

$$R = \frac{\bar{\alpha} S_t}{1 - \bar{\alpha}} \text{ sq. ft.}$$

where S_t = total area of room bounding surfaces in sq. ft.

$\bar{\alpha}$ = average sound absorption coefficient of room bounding surfaces

$$= \frac{S_1 \alpha_1 + S_2 \alpha_2 + \dots + S_n \alpha_n}{S_1 + S_2 + \dots + S_n}$$

where S_1, S_2, \dots = area of each absorbing surface in sq. ft.

$\alpha_1, \alpha_2, \dots$ = corresponding coefficients of absorption

R can be estimated from Figure 37-4 as an alternative to the calculation.

Directivity factor (Q). Q is a measure of the degree to which sound is concentrated in a certain direction rather than radiated evenly in a full spherical pattern. Directivity factors for typical radiation patterns are shown in Figure 37-5. They are actually portions of spherical radiation patterns as related to the surface area of a sphere which is $4\pi r^2$.

For spherical free field radiation, that is, where there are no reflections, the radiation pattern is illustrated at the upper left of Figure 37-5 and $Q=1$.

For hemispherical radiation, such as shown at the upper right, or in areas where the sound source is near the center of the floor in a large room the same sound source would produce twice the concentration of sound energy at a point on the surface of the hemisphere as it would on the surface of a sphere of the same radius. The surface area of the hemisphere is $4\pi r^2/2$ and $Q=2$.

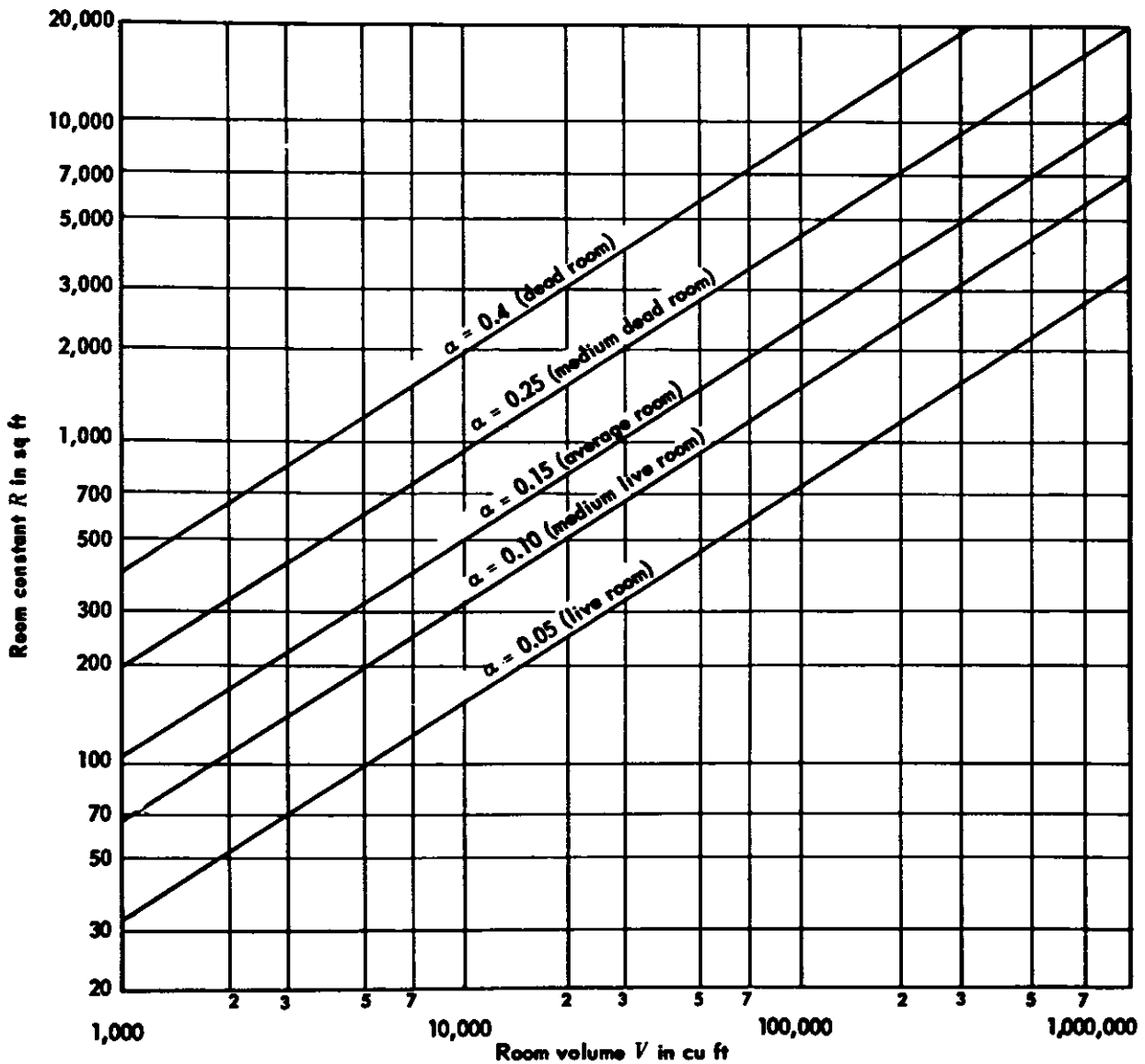
Similarly, if the sound source is near the intersection of the floor and a wall of a room such that 1/4 spherical radiation exists as shown at the lower left, the radiating area can be expressed by $4\pi r^2/4$ and $Q=4$.

Similarly, if the sound source is near the intersection of the floor and two walls of a room such that 1/8 spherical radiation exists as shown at the lower right, the radiating area can be expressed by $4\pi r^2/8$ and $Q=8$.

The source might also have a directional noise radiation pattern indicated by the vendor. If so, this would have to be taken into account in addition to the environmental radiation pattern discussed above.

This is a simplified presentation of directivity, but should be sufficient for most industrial situations.

Noise measurements made in the vendor's test laboratory can be modified to estimate the



ROOM CONSTANT FOR TYPICAL ROOMS

Beranek, L. L. (ed): Noise and Vibration Control. New York, McGraw-Hill, p. 277.

Figure 37-4. Room Constant for Typical Rooms.

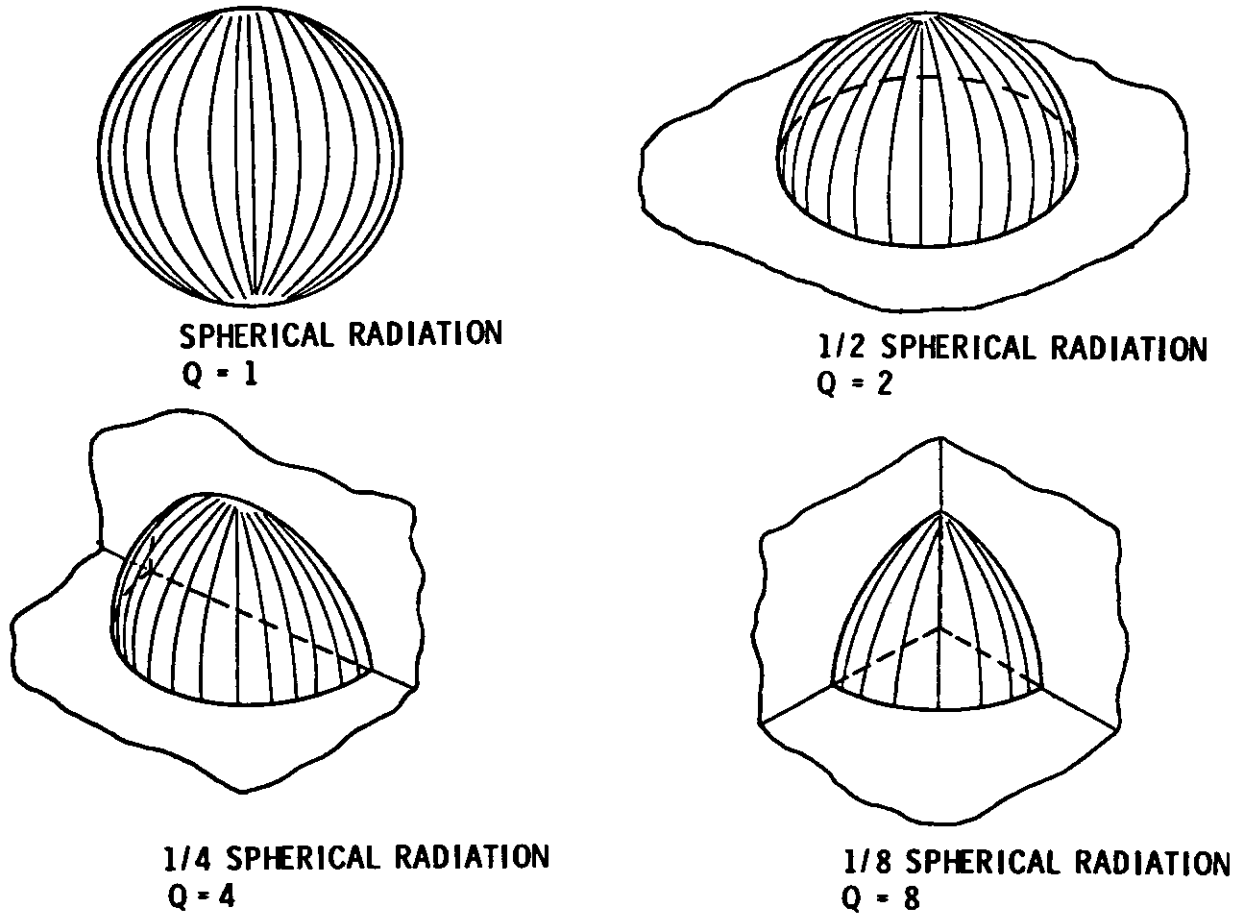
levels in the purchaser's intended environment by the use of Figure 37-2. The power level of the noise source will be the same in both locations. The sound pressure level in the purchaser's environment will be the difference between $L_p - L_w$ in the vendor's shop as compared to $L_p - L_w$ in the purchaser's environment. L_w is determined from previous calculations by working through Figure 37-2 and the measured L_p . Then L_p for the purchaser's environment can be determined by working through Figure 37-2 for the new conditions.

Substitution. Sometimes it is possible to substitute a quieter machine, process or material. It is very

likely that noise was not considered at the design stage of existing projects (plants). For new projects it will probably be less expensive to buy quiet equipment than noisy equipment that will require noise reduction treatment. Figures 37-6 through 10 illustrate some substitute possibilities.

Quieter materials. The materials used in the construction of buildings, machines, pipes, chutes and containers have a vital relation to noise control. Some materials and structures have high internal damping; others have little and ring when struck. These latter are the potential trouble makers and should be avoided where the possibility of vibrational excitation is involved. Ringing can be re-

DIRECTIVITY FACTOR (Q), SIMPLIFIED RELATIONSHIPS



duPont de Nemours & Co., Wilmington, Delaware.

Figure 37-5. Directivity Factor (Q), Simplified Relationships.

duced by damping the material or reducing the exciting impact by means of resilient bumpers. Figures 37-11 and 12 illustrate the use of quieter materials. Damping will be discussed later in this chapter.

Modification of the Noise Source

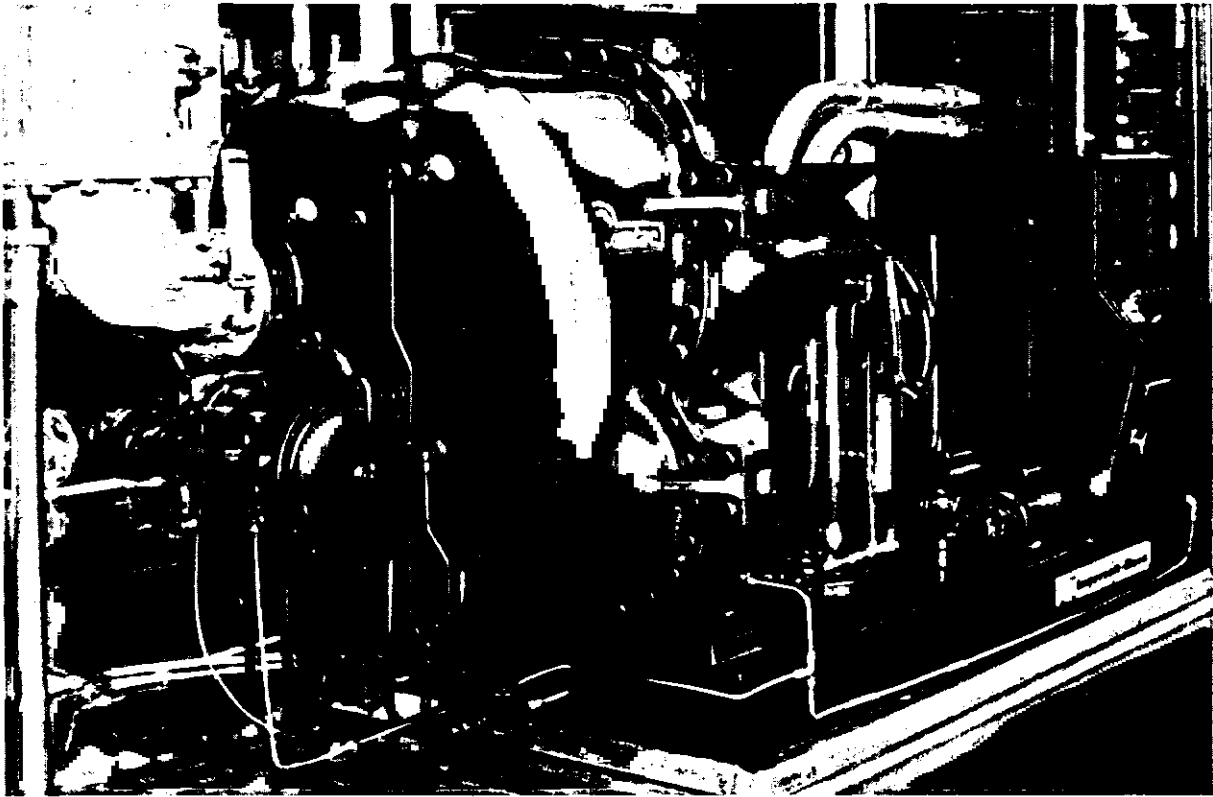
There are two basic noise sources: (1) vibrating surfaces and (2) fluid flow. In either case, usually, the nearer the source one can affect treatment, the less expensive will be that treatment because it will be minimum in size.

Direct sound away from area of interest. Many industrial sound sources are directional, that is, they radiate more sound in one direction than in others. Common examples of directional sources are intake and exhaust (vent) openings, partially enclosed sources, and large sheet metal surfaces. It is sometimes possible to utilize directionality of the source to provide noise control in a particular region of the sound field. This type of control is achieved by directing the source so that a minimum in the sound field occurs at the point or area of interest. A typical example is a vertical vent stack that directs the sound above the populated

area, or a vent stack cut off at an angle to direct the sound to one side. When the sound source is in a room it is not possible to achieve worthwhile noise reduction by source direction when the point of interest lies in the reverberant portion of the sound field. For enclosed areas containing little sound absorption the reverberant field may extend to within a few feet of the source, and direction of the source will have little effect on the sound levels throughout most of the area. Under these conditions there will be some advantage in directing the source to an area of highly absorbent material, for this effectively reduces the source strength as far as the remainder of the room is concerned. Figure 37-13 is an example where sound has been directed away from the point of interest.

Reduce vibrating surface. This type of noise source will consist of a driving force, coupled to a sound radiating surface. Control at the source may then consist of reduction of the driving force, reduction of the radiating surface response to the driving force or reduction of the radiating efficiency of the vibrating surface.

Reduce driving force. The driving (vibration ex-



Ingersoll Rand, Allentown, Pennsylvania.

Figure 37-6. QUIETER EQUIPMENT — CENTRIFUGAL COMPRESSOR: This high speed centrifugal multi stage compressor has a heavy cast case which encloses the impellers and interstage cooling system. It also encloses the noise so that operating areas around the compressor do not exceed 90 dBA provided motor and external piping noise is controlled. This compressor is a good example of a machine well designed for noise control.

citing) force is often the result of unbalance or eccentricity in a rotating piece of equipment. Such forces increase with increase in rotational speed, therefore the speed should be kept to a minimum. Figure 37-14 is an example of the effect of speed reduction. A large machine running at slower speed might be a better selection as far as noise is concerned. Certainly eccentricity and balance

should be checked to be sure they are within normal tolerance. Good alignment, lubrication, and bearing maintenance are also important in minimizing noise. Figure 37-15 shows the noise reduction achieved by improving maintenance on a blower system. Driving forces can also be caused by reciprocating members such as pistons or rams.

Impact type driving forces are produced in

Figure 37-7. QUIETER EQUIPMENT — V-BELT DRIVE.

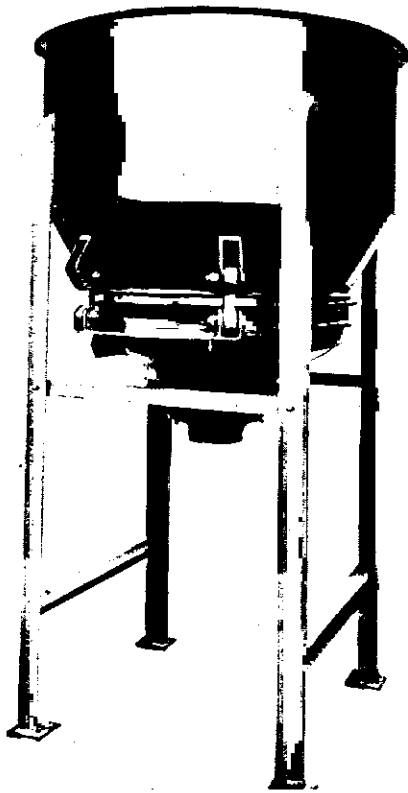
A rubber toothed type belt with flanged grooved pulleys was used to drive a pump. Noise levels were too high in the octave bands above 2400 Hz. The grooved pulleys and toothed belt were replaced with a V-belt drive. Reductions of more than 15 dB were obtained in the octave bands above 2400 Hz as shown below.

The frequency distribution of noise created by

a toothed belt drive is dependent on the tooth passage rate — the higher the speed, the higher the frequency.

If a toothed type belt must be used, the noise could have been reduced by enclosing the belt and pulleys. The enclosure should be lined with sound absorbing materials which is effective for the frequency range of interest.

Frequency — Hz — octave band	20- 75	75- 150	150- 300	300- 600	600- 1200	1200- 2400	2400- 4800	4800- 9600	9600- 19,200
Noise Reduction in dB	5	4	4	2	0	6	17	18	25



Vibra Screw Incorporated, Totowa, New Jersey.

Figure 37-8. QUIETER EQUIPMENT — VIBRATION ISOLATED HOPPER. An 8 ft. dia. hopper with electric solenoid type vibrator was creating excessive noise. A live bottom bin by Vibra Screw was installed as shown below and a noise reduction achieved as shown here. The noise reduction is due to the fact that the cone only is vibrated, there is much less vibratory power required and there is no metal to metal impacts.

Frequency—Hz— octave band—center frequency of band	63	125	250	500	1000	2000	4000	8000
Noise Reduction—dB	7	6	20	22	16	12	12	9

most metal or plastic fabricating operations such as punching, forging, riveting and shearing. Because of the short duration of most impact forces, considerable noise reduction can be achieved by modifying the system to provide a smaller force over a longer period of time. Figure 37-16 shows how this can be accomplished with a punch. Figure 37-17 illustrates this principle on a 48" shear. Here the cutting blades are segmented and skewed to give a shear type cut.

Impact type forces can also be reduced by providing resilient bumpers at the point of impact. Examples of this method include lining tumbling barrels, chutes, hoppers, stock guides, etc. Figures 37-11 and 12 illustrate this method of control.

It is a rare case where a machine causes

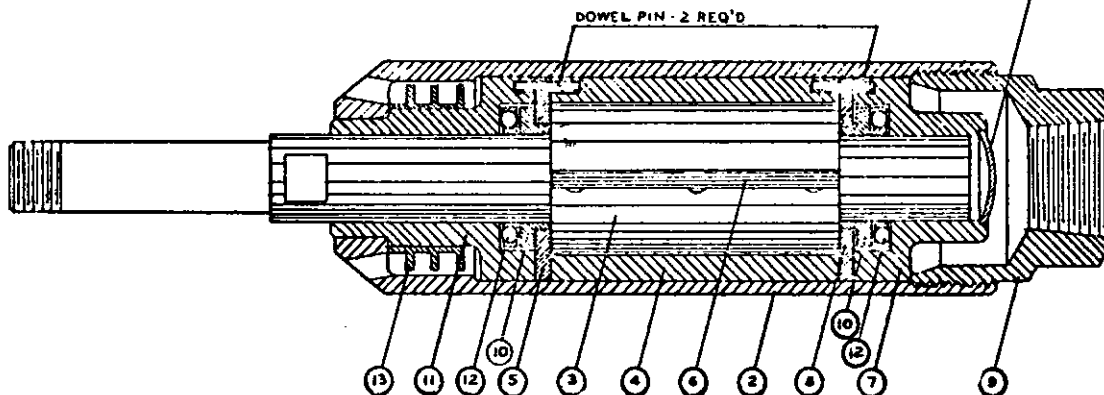
sufficient vibration of a building to cause the building to radiate noise in excess of 90 dBA. However, a common pitfall about equipment mounting should be pointed out here. It is becoming common practice to mount machines and their drives on a common base of steel weldments. This is fine for alignment and shipment, but for vibration producing machines such as cutters, pulverizers, grinders, blowers, compressors, the steel base can become a serious noise radiator. This problem can easily be overcome by constructing the steel base so that after installation it can be filled with nonshrinking concrete or sand. If it is desired to vibration-isolate the equipment, the isolators should be between the concrete filled steel base and the building floor. The heavy base is also desirable in this case so that center of gravity of the equipment will be lower, that is, nearer the level of the vibration isolation mounts. For stability's sake the level of the isolators should be as close as practical to the vertical center of gravity of the vibrating machine. Since good vibration isolators are readily available and manufacturing instructions for selection and installation are adequate for most cases, further discussion will not be given here. Vibration isolation is usually not necessary except near offices or control rooms or where process equipment dictate the need. Vibration isolation of equipment can cause the more serious problem of pipe line failure at the flexible joints in the lines required by the increased vibration of the isolated equipment.

Reduce response of vibrating surface. The response of a vibrating member to a driving force can be reduced by damping the member, improving its support, increasing its stiffness or increasing its mass. When the frequency of the driving force is equal to the natural frequency of the member being vibrated, large surface displacements are usually developed. This condition is known as resonance. Most mechanical structures have a family or series of resonances which are rather widely spaced in the low frequency range but are more closely spaced at higher frequencies. Because of the large surface displacements developed at resonance, there is usually increased noise radiation. Resonant vibration may be limited effectively by damping, decoupling or detuning by shifting the natural frequency. Optimizing a damping treatment is usually a complicated procedure best left to the experts if the cost can be justified. For many industrial problems it is satisfactory to use a simple rule of thumb approach. For the rough treatment typical of industrial environments, constrained layer damping is usually preferred. This means covering the vibrating surface with a thin sheet of damping material plus an outer covering of sheet metal. The sandwich so formed is cemented (both surfaces) and bolted together on 6" to 8" centers. The rule of thumb is that for vibrating panels having a thickness of up to 16 gauge, use an outer steel plate (restraining plate) of the same gauge as the vibrating plate. For vibrating plates of 16 gauge to 1/8" thick, use a restraining plate of 16 gauge steel. For vibrating plates of 1/8" to 1/4" thick, use a 1/8" thick re-

115000-B-2 7/16

FIGURE 37-9

An Elliott No. 1380 tube cleaner (2-7/8" dia.) created excessive noise. A new design, Elliott No. 115,000 was substituted. The new design had a built in muffler for the air discharge of the turbine drive as shown by the drawing. Noise reduction DISC PLUG-1 REQ'D achieved is shown in the table.



14	CA PLUG	P-8161K	1																	
13	MUFFLER UNIT	115088	1																	
12	THRUST BEARING	112054	2																	
11	FRONT BEARING ASSEM	112050	1																	
10	THRUST WASHER	112037	2																	
9	MACHINE COUPLING	112031	1																	
8	REAR PLATE	112027	1																	
7	REAR BEARING ASSEM.	112009	1																	
6	FADDLE	112008	5																	
5	FRONT PLATE	112007	1																	
4	SHELL	112006	1																	
3	ROTOR	115005 A	1																	
2	BODY	115002-2 7/16	1																	
1	ASSEMBLY	115000-B-2 7/16																		
	PART # 4E	PART No	REQ	CNF	OUT	L	M													

BODY DIAM 2 7/16
SHAFT THRD 3/4",
HOSE CONN 3/4" NPT.

TYPE "DBT" - MUFFLED
AIR DRIVEN MOTOR
(EXTRA LONG ROTOR)

FOR

BY H CR Jd DATE 6-13-66

ELLIOTT COMPANY
SPRINGFIELD OHIO
NEWARK N J

SE-
115000-B-2 7/16

Elliott Company, Springfield, Ohio.

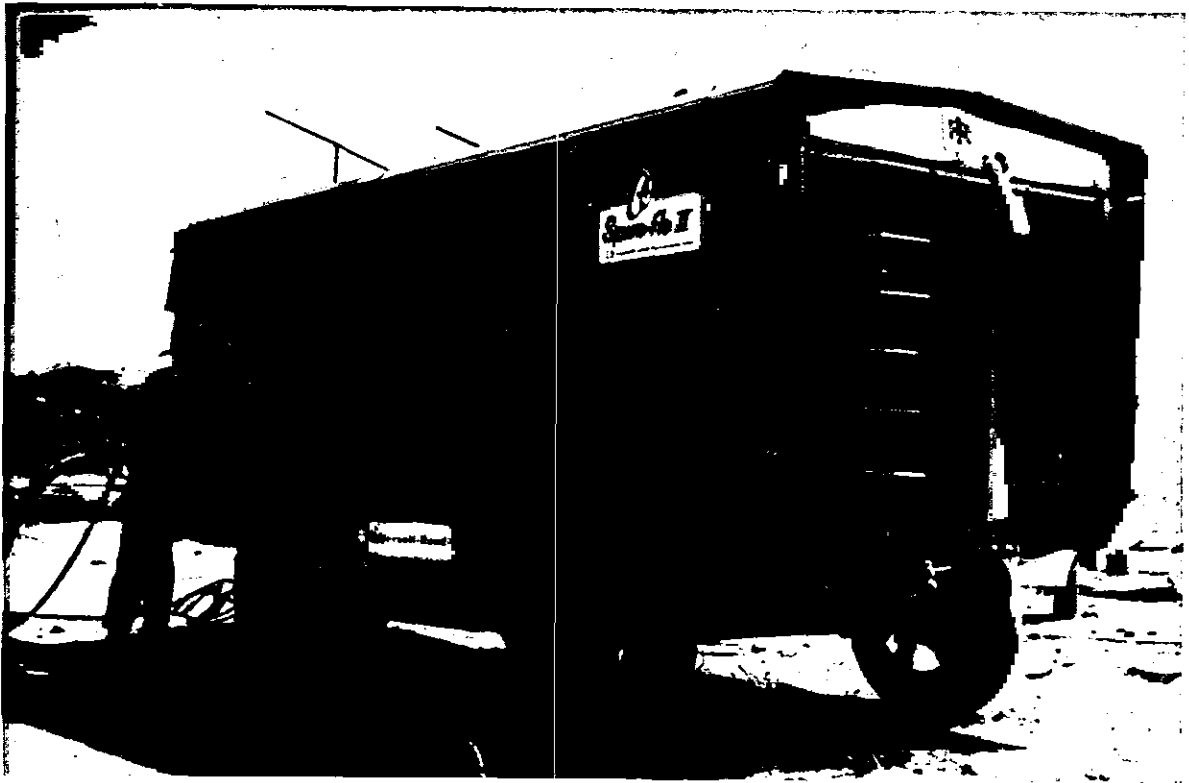
Figure 37-9. An Elliott No. 1380 tube cleaner (2-7/8" dia.) created excessive noise. A new design, Elliott No. 115,000 was substituted. The new design had a built-in muffler for the air discharge of the turbine drive as shown by the drawing. Noise reduction achieved is shown in the table.

straining plate. For vibrating plates of 1/4" thick or heavier, use a 1/4" thick restraining plate. The common damping materials are damping felt, elastomeric damping sheeting and sheet lead. All material selected should be compatible with the temperature and environmental conditions involved such as exposure to chemicals and oils. It is to be noted that the flat unsupported surfaces are the ones radiating the most noise. Corners of box-like structures, reinforcing bosses, etc., are so rigid they probably do not require damping. This simplifies the damping treatment because it eliminates many double curved surfaces which would be difficult to laminate. Manufacturers of damping materials can advise regarding the most effective use of their materials. Do not hesitate to use the heavy restraining plates suggested above. They make the panel significantly stiffer and reduce not only resonance but the driven response as well. The extra weight and stiffness might be the most important factor in reducing the noise. Figure 37-18 illustrates constrained layer damping and

damping by means of filling structure with sand. Figure 37-19 illustrates noise control by increased mass and stiffness.

Reduce efficiency of noise radiating surface. The sound energy generated by vibrating surfaces depends not only upon the velocity of surface motion but also upon the area of the radiating surface. Because the displacement of most surfaces is limited by the constrained edges, the surface velocity will decrease with frequency, and the area must increase if constant sound output is to be maintained. Therefore, the effective radiation of low frequency sound is usually limited to large surfaces. Conversely, any surface of more than several square inches can effectively radiate sound at frequencies above 1000 Hz. In general, any regularly shaped area with one dimension greater than one-fourth wavelength can effectively radiate sound at the frequency corresponding to that wavelength in air.

Surfaces radiating low frequency sounds can sometimes be made less efficient radiators by di-



Ingersoll Rand, Allentown, Pennsylvania.

Figure 37-10. QUIETER EQUIPMENT — PORTABLE AIR COMPRESSOR: The Ingersoll Rand portable air compressor shown above was designed with noise control as a specification. All functional components of this diesel — engine powered machine including engine, compressor, mufflers, fuel tanks, receiver separator tank and frame are completely enclosed in an aluminum, glass fiber, sheet steel sandwich-panel material. Improved cooling by increased air flow through mufflers was required for this enclosed machine. The noise reduction achieved by this design is shown below.

Frequency — Hz — octave band center frequency of band	63	125	250	500	1000	2000	4000	8000
Noise reduction in dB	8	13	24	17	10	10	10	14

viding them into smaller segments or otherwise reducing the total area. The use of perforated or expanded metal can often result in less efficient sound radiation from sheet metal guards and cover pieces.

Turbulent fluid flow. A very common industrial noise source is high velocity fluid flow. The strange thing about it is that usually the velocity required by the industrial process is not high enough to

create a serious noise problem. For example, where compressed air is used to clean or wipe a product, such as blowing water from a freshly extruded plastic, the noise source is the sonic velocity of the gas passing through the pressure reducing valve. The noise source is not the air velocity which wipes the water from the plastic. This problem (and many more similar ones) can be solved by placing a muffler just downstream from the

Figure 37-11. QUIETER EQUIPMENT — RESILIENT LINING FOR TUMBLING BARREL.

The tumbling of steel balls against the steel shell of a ball mill can produce excessive noise. By lining the steel with resilient material this noise

will be reduced by a considerable amount. One such mill lined with rubber produced the noise reduction shown below.

Frequency — Hz — octave band — center frequency of band	63	125	250	500	1000	2000	4000	8000
Noise reduction — in dB	3	4	6	7	11	12	15	19

RESILIENT HAMMER HEAD

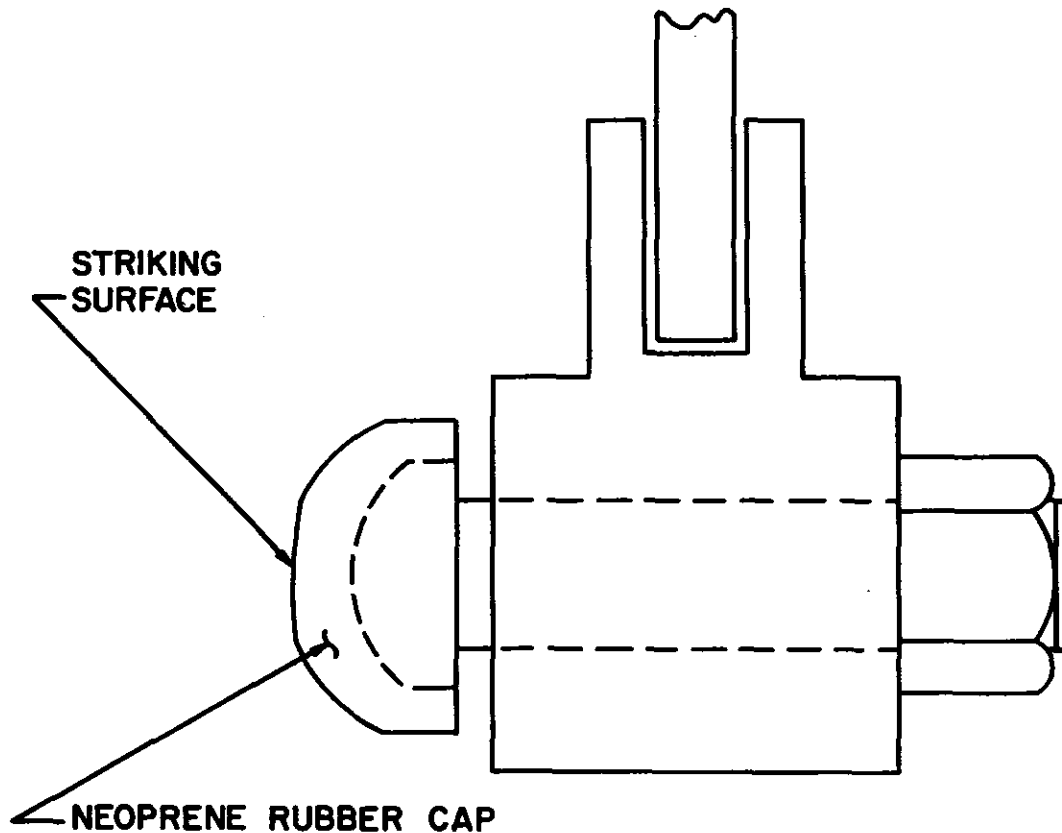


Figure 37-12. QUIETER MATERIAL — RESILIENT HAMMER HEADS: Rotary dryers commonly use hammers (Knockers) on the outside of the dryer shell to prevent product buildup on the inside. The metal to metal impact noise produced is usually objectionable. This noise can be reduced by providing resilient heads for the hammers. By providing sufficient striking area between hammer and shell, the resilient facing material can usually be made to transmit the desired vibration to the dryer shell without causing the objectionable metal to metal impact noise. In one case, the overall noise level was reduced 28 dB. Common materials used for the face of hammers are Adiprene®, neoprene, nylon, Fabreeca and rawhide.

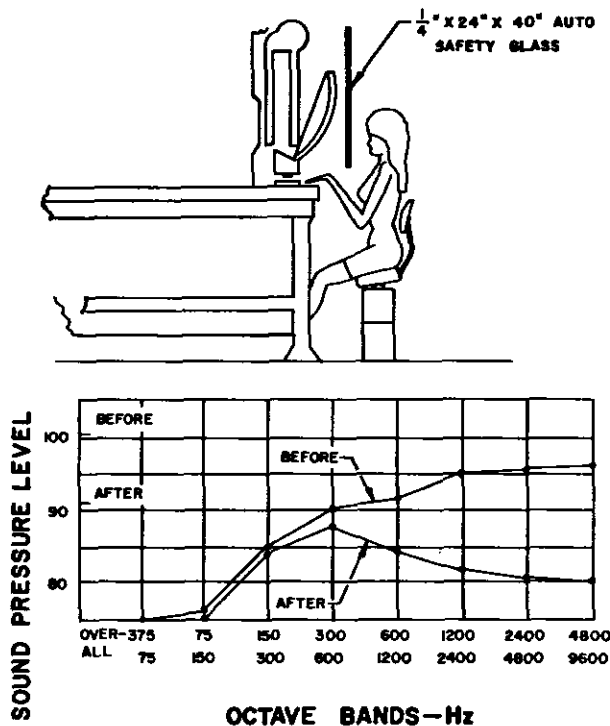
NOTE: Lempco Automotive, Inc., supply nylon hammer heads and Garland Mfg. Co. supply rawhide hammer heads.

valve as shown by Figure 37-20. The muffler is to remove noise from the sonic velocity in the valve. Then with the nozzle downstream from the muffler designed for minimum velocity to do the job, there should be no noise problem. Velocities as high as 10,000 ft. per minute can be used without excessive noise, and even this velocity may not be needed for many processes. The rule is, for low noise don't use velocities higher than necessary. In particular, don't use sonic velocities. Beware of gas pressure reducing valves.

Where the ratio of upstream to downstream absolute pressures is 1.9 or greater, sonic velocity and excessive noise is produced — unless the reduction is controlled through the use of a special valve which avoids sonic velocity. A valve which

accomplishes this achieves a gradual pressure drop and expanding volume such that sonic velocities are not reached. The valve consists of a stack of plates as shown by Figure 37-21 and each plate has small gas passages as shown by Figure 37-22. The high pressure gas enters from below as the stem rises. When the stem passes by the ID of a plate, the gas flows through the tortuous path to the plate O.D. where it is at the low pressure level. As the valve stem rises, more plates (and passages) are exposed and more volume of gas passes. This is called the "Drag Valve." It can be designed for any desired noise level and gas flow.

For existing pressure reducing valves or for applications where quiet valves cannot be used due to dirty gas or lack of economic justification,



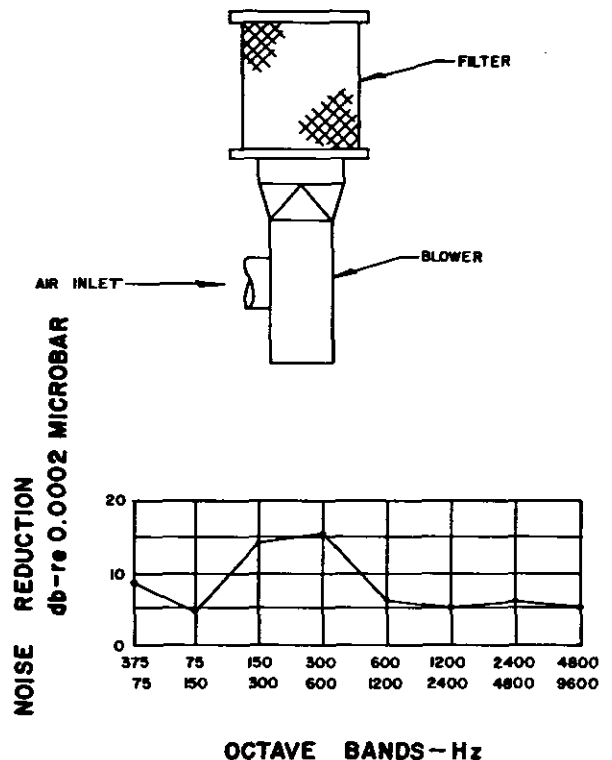
AIHA Noise Committee: Industrial Noise Manual, 2nd Edition. Detroit, American Industrial Hygiene Association, 1966.

Figure 37-13. NOISE SHIELD — DIRECT SOUND AWAY FROM POINT OF INTEREST. The use of shields between a noise source and an employee is usually quite effective when both the source and the employee are close to the shield and when the noise is predominantly high frequency. An example is shown on the punch press which uses compressed air jets to blow foreign particles from the die. The installation of 1/4" thick safety glass shield gave the reduction shown in the graph.

other means of noise control are available. If commercial mufflers can be used, the noise can be controlled as shown by Figure 37-23. If mufflers cannot be used, external pipe covering can be applied as shown by Figure 37-24. This last treatment is not as economical as it might appear since sound can travel long distances down pipes with little attenuation and the pipe covering might be quite expensive. In addition, the sound might produce excessive vibration in downstream equipment and cause failure of such things as heat exchangers and packed columns or cause excessive noise radiation from suction bottles, etc.

To select mufflers for the usual type pressure reducing valves one must estimate the noise level just downstream from the valve. Unpublished work by K. U. Ingard provides a convenient method for doing this.

Figure 37-25 shows that by relating the absolute pressure drop ratio and the gas flow in lbs.

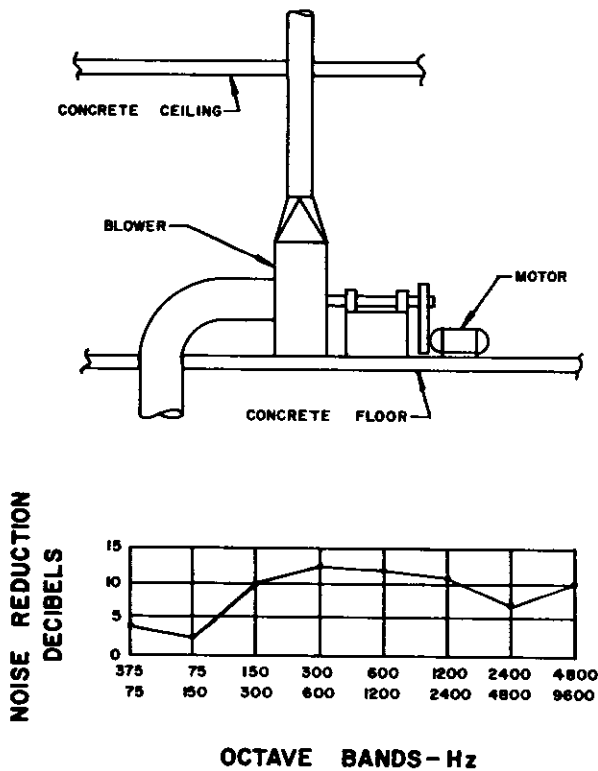


AIHA Noise Committee: Industrial Noise Manual, 2nd Edition. Detroit, American Industrial Hygiene Association, 1966.

Figure 37-14. MINIMIZE ROTATIONAL SPEED. The blower for a vapor collection system produced excessive noise while moving 3600 cfm at 2.8" static pressure. It ran at 3450 rpm and had a 12.5" diameter material wheel. It discharged into a cylindrical filter consisting of 1.5" thick glass fiber compressed to 0.75". A quieter fan was selected and the noise reduction achieved is shown on the graph. The new blower ran at 900 rpm and had a 32.265" diameter air wheel. A material wheel was not required since only air and oil vapor were being handled.

per minute, the overall sound power can be determined. Then by means of Figure 37-26 the octave band power levels can be determined. In Figure 37-26 the zero line corresponds to the overall power level as determined from Figure 37-25. The frequency scale used in Figure 37-26 is normalized to the frequency $f_1 = 0.2 c/d$ where c is the speed of sound in the gas and d the equivalent valve diameter. The frequency f represents the center frequency of the corresponding octave band. To illustrate the use of Figure 37-25 and 26, consider the following example:

- Effective port area of valve = 1 sq. in.
- Mass flowrate = 50 lb. per minute
- Gas = air at 190°F
- Upstream pressure = 100 psig
- Downstream = 48 psig



AIHA Noise Committee: Industrial Noise Manual, 2nd Edition. Detroit, American Industrial Hygiene Association, 1966.

Figure 37-15. REDUCE DRIVING FORCE — IMPROVED MAINTENANCE (BLOWER). An exhauster running at 705 rpm, 6" static pressure, and 13,800 cfm was badly out of balance and the bearings needed replacing. As a result the blower produced excessive noise. After balancing and installing new bearings the noise was reduced as shown by the graph.

Determine the octave band power levels generated at the valve discharge and the octave band sound pressure levels in the 3" line just downstream from the valve.

From Figure 37-25 at 50 lb. per minute and a pressure ratio of 2.1 the overall power level (L_w) would be 127 dB. The equivalent valve port diameter for an effective area of 1 sq. in. is —

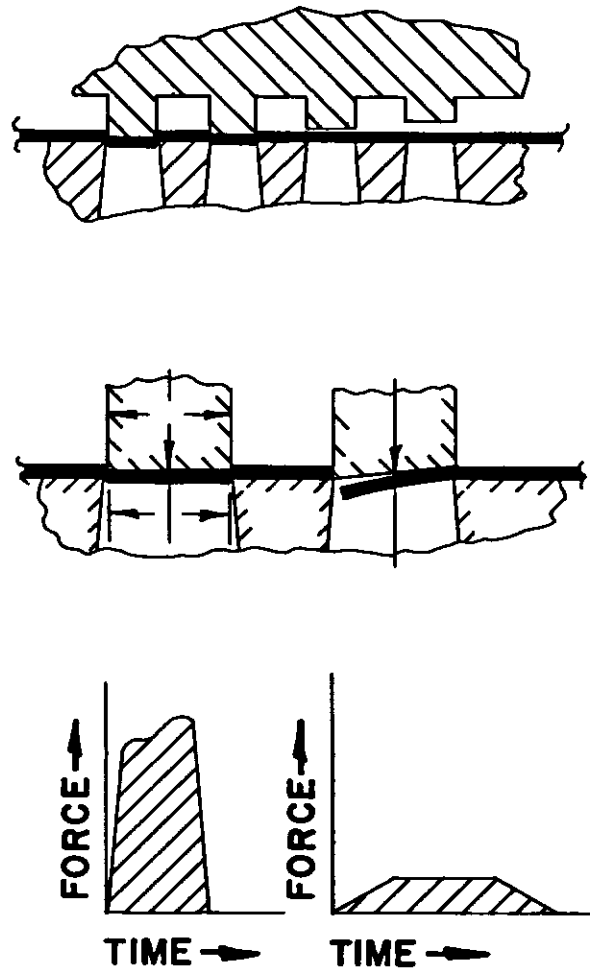
$$A = \pi \left[\frac{d}{2} \right]^2$$

$$\text{when } A = 1 \quad d^2 = \frac{4}{\pi} \quad d = \sqrt{\frac{4}{\pi}} = 1.13''$$

From Keenan & Kaye Gas Tables,¹ $C = 1248$ ft. per sec. for air at 190°F. Then:

$$f_1 = \frac{.2C}{d} = \frac{.2 \times 1248}{1.13} = \frac{.2 \times 1248 \times 12}{1.13} = 2650 \text{ Hz}$$

Checking the frequency ranges of the octave bands, we find that 2650 falls in the 6th octave band which has a frequency range of 1400 to 2800 Hz and a center frequency of 2000 Hz. Now referring to Figure 37-26 for $f/f_1 = 1$



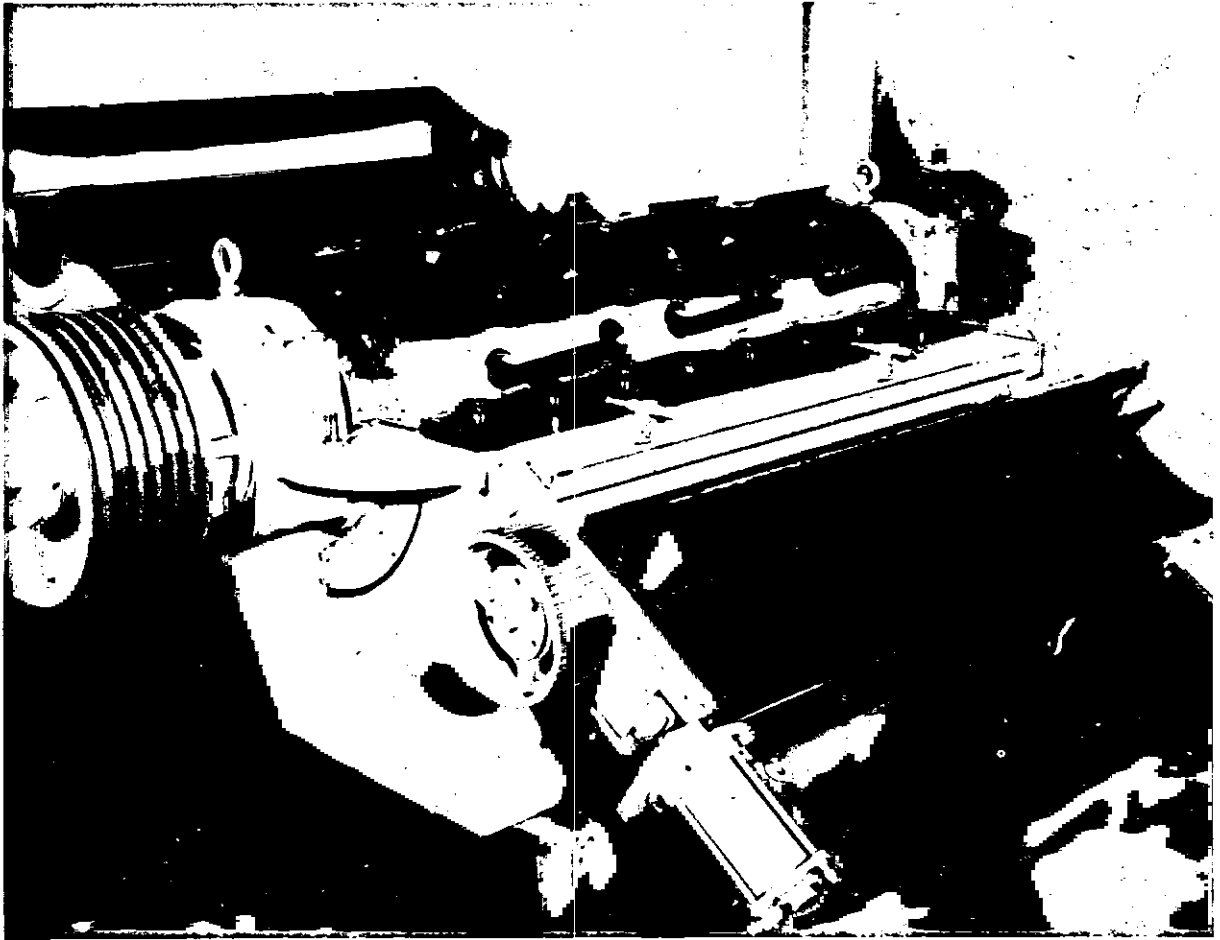
AIHA Noise Committee: Industrial Noise Manual, 2nd Edition. Detroit, American Industrial Hygiene Association, 1966.

Figure 37-16. REDUCE DRIVING FORCE — SEGMENTED PUNCH AND SHEAR CUT. Illustration of Stepped Punches for Punching Several Holes at One Stroke of the Press. Schematic illustration of blanking operation, showing the effect of shear angle on the punch. The force-time diagram for each condition is shown.

and a pressure ratio of 2.1, the octave band L_w for the 6th octave band would be 127-7 or 120 dB. To obtain L_w for the other octave bands, consider them relabeled as follows:

- For the 7th octave band $f/f_1 = 2$
- For the 8th octave band $f/f_1 = 4$
- For the 5th octave band $f/f_1 = 1/2$
- For the 4th octave band $f/f_1 = 1/4$ etc.

The next step is to determine from Figure 37-26 the number of dB to be subtracted from the overall L_w to obtain the octave band power levels. This would result in the values shown in column 5 of Table 37-1. Subtracting column 5 from column 4 gives the octave band power levels shown



duPont de Nemours & Co., Wilmington, Delaware.

Figure 37-17. Reduce Driving Force — 48" Film Cutter with Skewed, Segmented Blades.

Figure 37-18. REDUCE RESPONSE OF VIBRATING SURFACE BY DAMPING (EXTRUDER GEAR CASE).

duPont de Nemours & Co., Wilmington, Delaware.

The casing of a 2000 HP extruder gear was radiating excessive noise. The gear cover was $\frac{3}{8}$ " steel. The base was 1" steel with 1" thick 9" deep ribs. Measurements with an accelerometer showed that the $\frac{3}{8}$ " steel and the 1" steel were vibrating at approximately the same intensity. This indicated that all surfaces should be damped.

The $\frac{3}{8}$ " steel was damped with $\frac{1}{4}$ " damping felt No. 11 N (by Anchor Packing Co.) plus an outer covering of $\frac{1}{4}$ " steel. The sandwich ($\frac{3}{8}$ "

steel + $\frac{1}{4}$ " felt + $\frac{1}{4}$ " steel) was bolted together on 8" centers.

The irregularity of the 1" steel of the base made constrained layer damping (as used on the cover) impractical. Instead, $\frac{1}{4}$ " steel plate was welded to the 9" deep ribs and the voids filled with sand. The photographs below show the gear before and after treatment. The table below shows the noise reduction achieved after treatment of only one of three units in the room.

Frequency — Hz — octave band — center frequency of band	63	125	250	500	1000	2000	4000	8000
Noise reduction — in dB	X	X	X	4	17	26	24	18

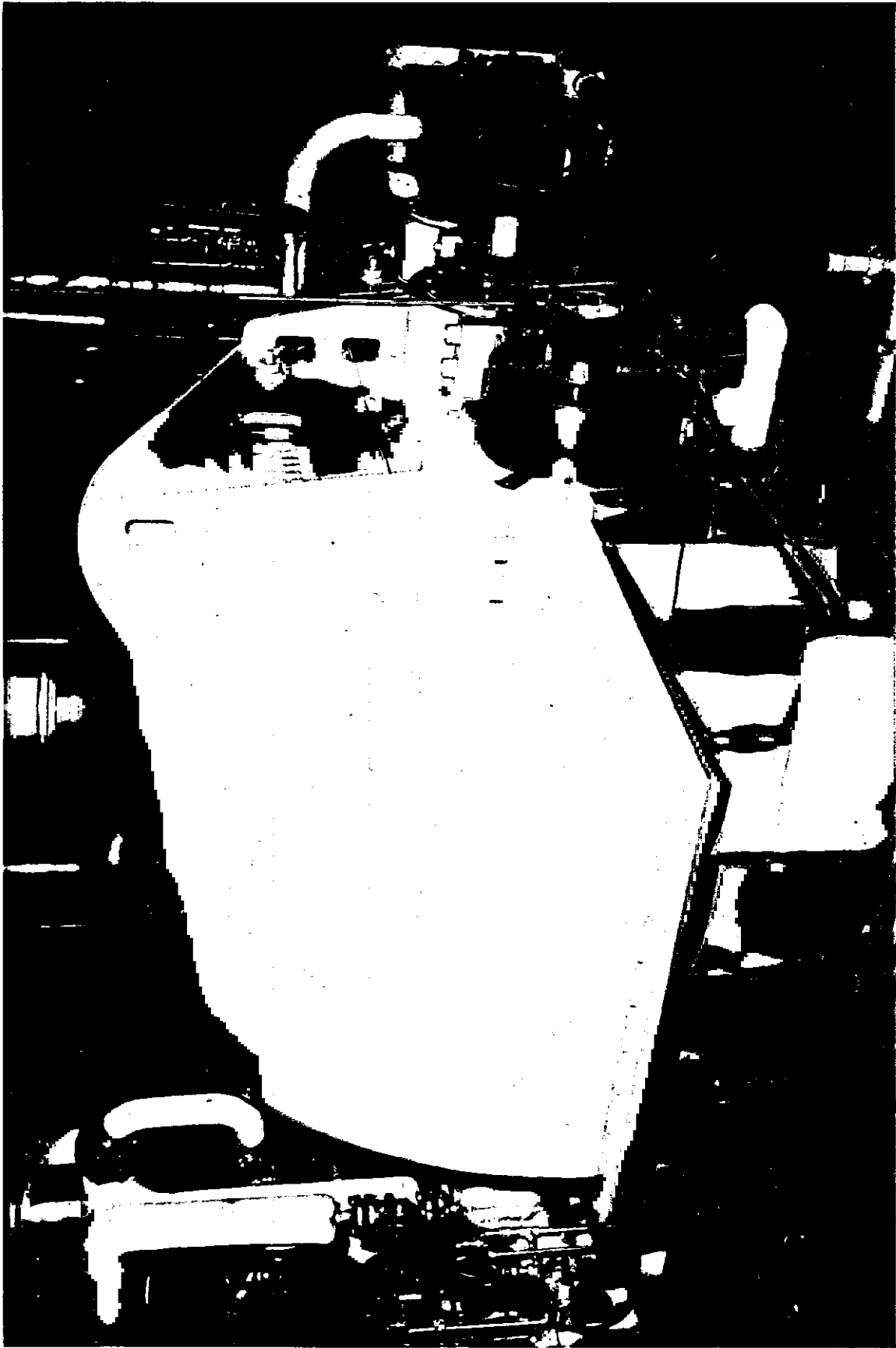


Figure 37-18. (BEFORE)

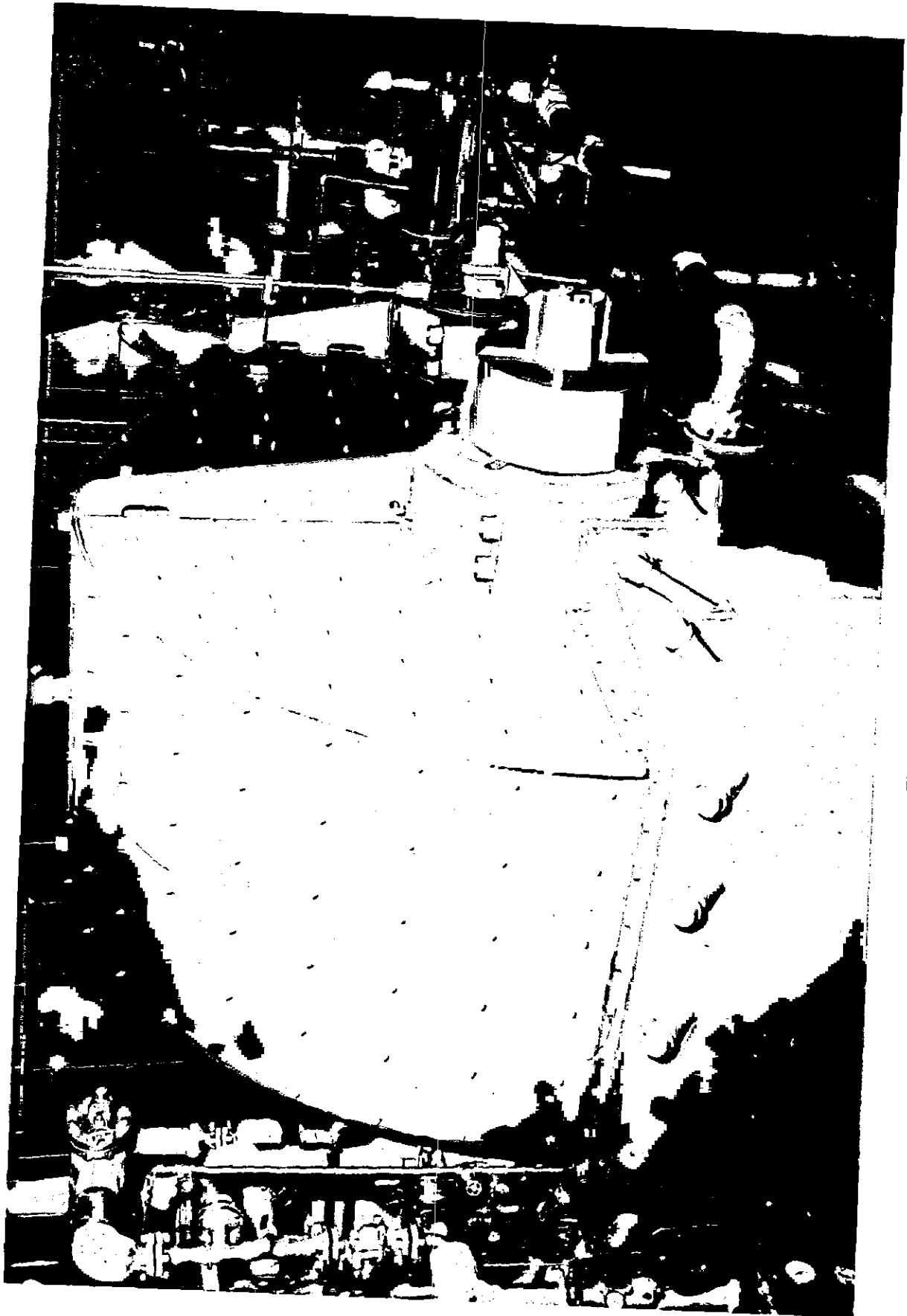
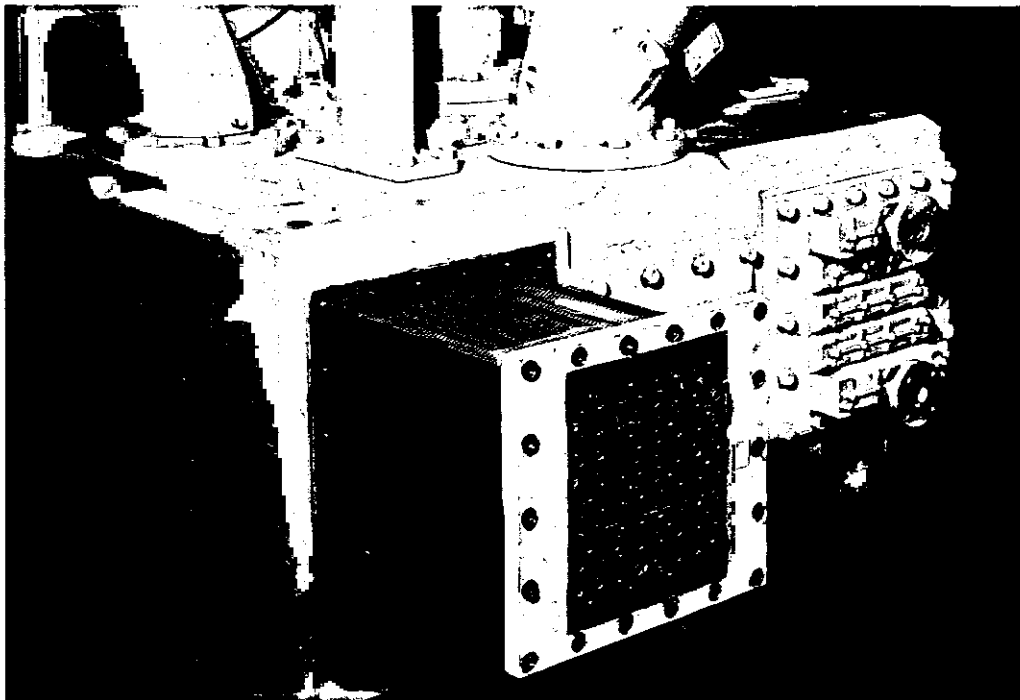
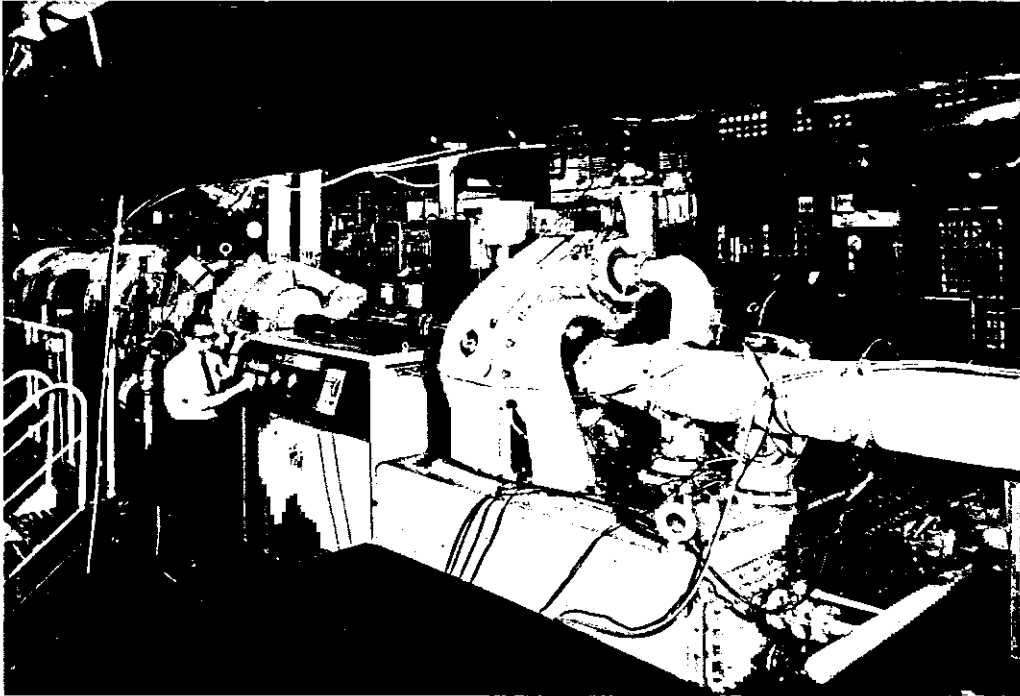
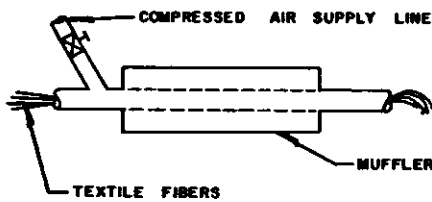


Figure 37-18. (AFTER)



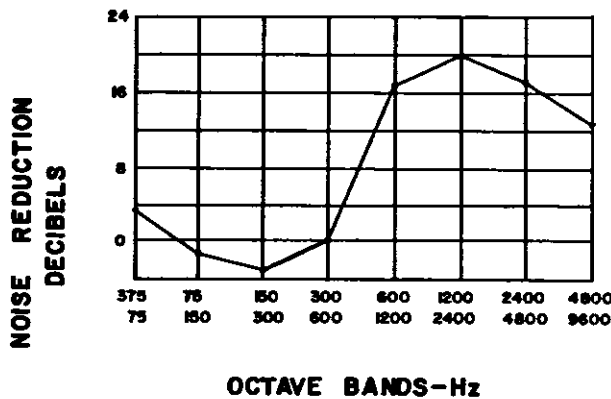
Studebaker — Worthington Inc., New York, New York.

Figure 37-19. REDUCE RESPONSE OF VIBRATING SURFACE BY INCREASED STIFFNESS AND MASS (CENTRIFUGAL COMPRESSOR). These two photographs show a Worthington multi stage high speed centrifugal compressor which had noise control in mind during the design stage. Note the heavy cast construction of this machine. To meet the environmental criteria of 90 dBA, the only parts that require acoustical covering are the gear case cover and the steel interstage piping couplings. Here is another case where extra weight in the machine indicates economical noise control without the inconvenience of enclosure.



AIHA Noise Committee: Industrial Noise Manual, 2nd Edition. Detroit, American Industrial Hygiene Association, 1966.

Figure 37-20. ABSORB THE SOUND WAVE — ALONG ITS TRANSMISSION PATH. An air ejector is used to strip waste textile fibers from perns. The curve shows the noise reduction achieved 3 feet from the ejector by means of the dissipative muffler. The air supply line is 1/2", the pressure 100 psi, and a 1" dissipative muffler was used. Notice that the noise levels in the 75 to 150 and 150 to 300 cps octave bands were increased slightly, which is characteristic of this type of muffler. The noise of this problem is due to the pressure reduction at the valve and not the velocity of air exhausting from the pipe. This is apparent since the pipe size is the same at the inlet and discharge of the muffler.



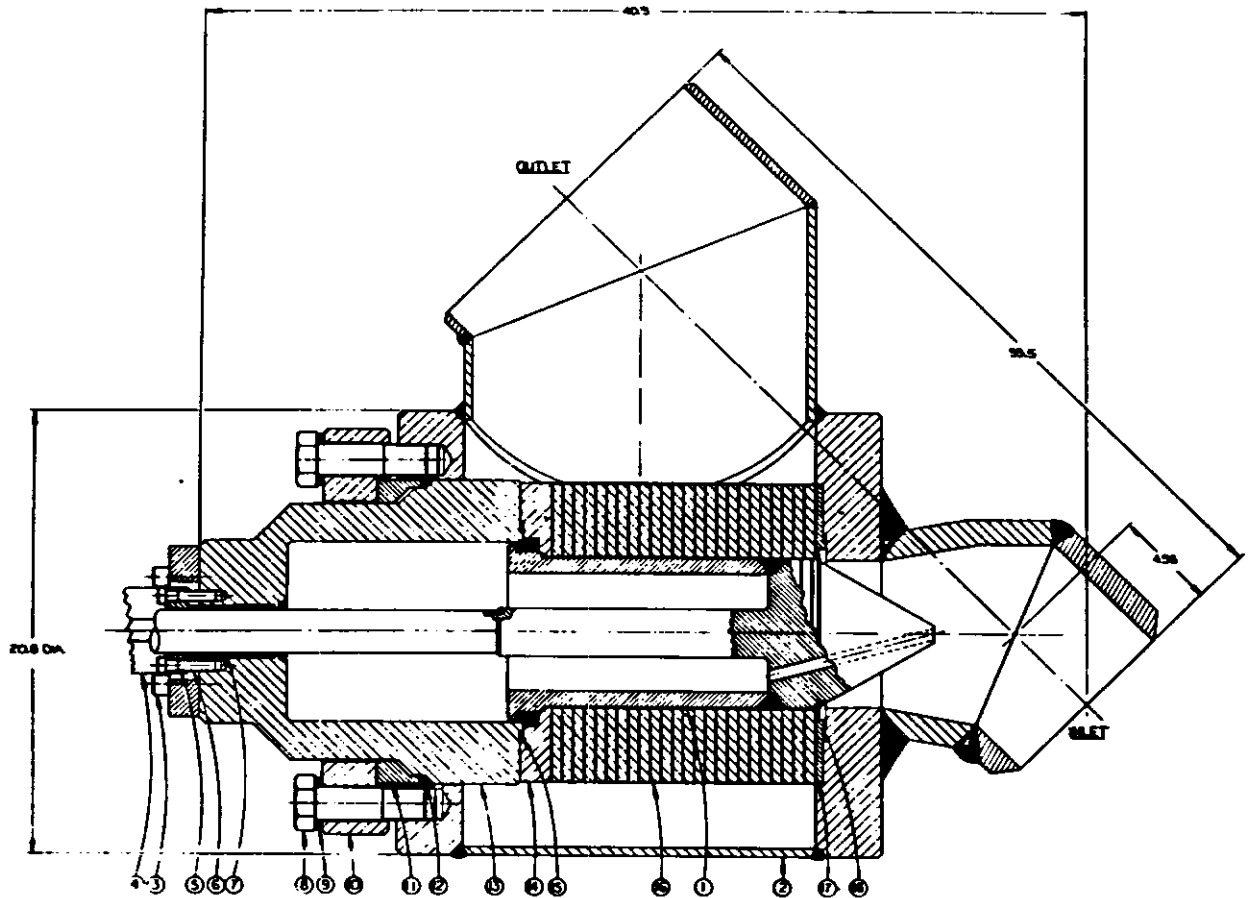
in column 6. The next step is to determine the sound pressure level (L_p) in the 3" pipe just downstream from the valve. This can be determined by the following formula.

$$L_p = L_w - 10 \log_{10} D$$

where D = area of the pipe in sq. ft.

For a 3" pipe $L_p = L_w - 10 \log 0.0491 = L_w + 13 \text{ dB}$

This means that the octave band levels of Column



Control Components, Los Alamitos, California.

Figure 37-21. Reduce Velocity of Fluid Flow and Use Quieter Equipment — Quiet Pressure Reducing Valve.

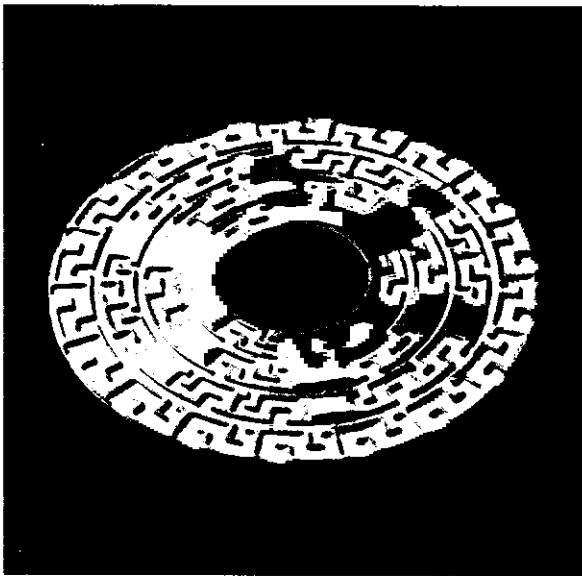


Figure 37-22. REDUCE VELOCITY OF FLUID FLOW AND USE QUIETER EQUIPMENT — QUIET PRESSURE REDUCING VALVE. The "Drag Valve" shown in the drawing at left and described on page 14 is a pressure reducing valve which can provide the desired pressure drop but at the same time limit the maximum velocity thru the valve to minimize the vibration and erosion and limit the noise reduction to most any desired level. The photograph at left shows a typical plate which illustrates the tortuous path the gas must take in passing from the inside (high pressure) to the outside (low pressure). For one design where 300 PSIG air was being vented to atmosphere, the noise reduction shown below was achieved as compared to venting through the more common orifice type valve.

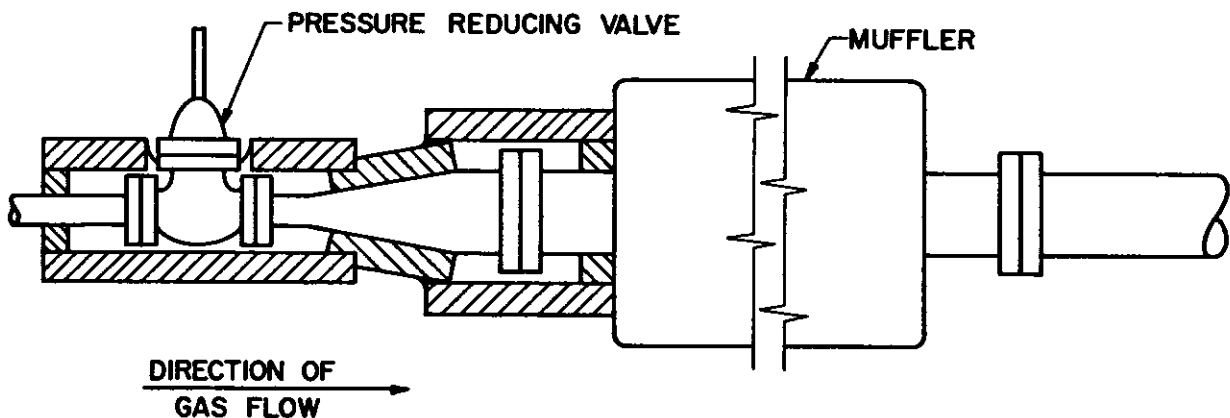
Frequency— Hz—octave band— center fre- quency of band	63	125	250	500	1000	2000	4000	8000	16000	31500
Noise reduc- tion—in dB	24	19	28	17	18	25	34	34	29	25

6 would have to be increased by 13 dB to obtain the octave band sound pressure levels that would have to be contained by the pipe walls or pipe walls plus covering, or would be the basis for selecting a muffler to reduce noise transmission down the pipe.

Streamline the flow. Once the velocity of a gas stream has been reduced to a minimum, additional reduction might be achieved by streamlining any obstructions in its path. The higher the velocity the more important it is to streamline the flow path.

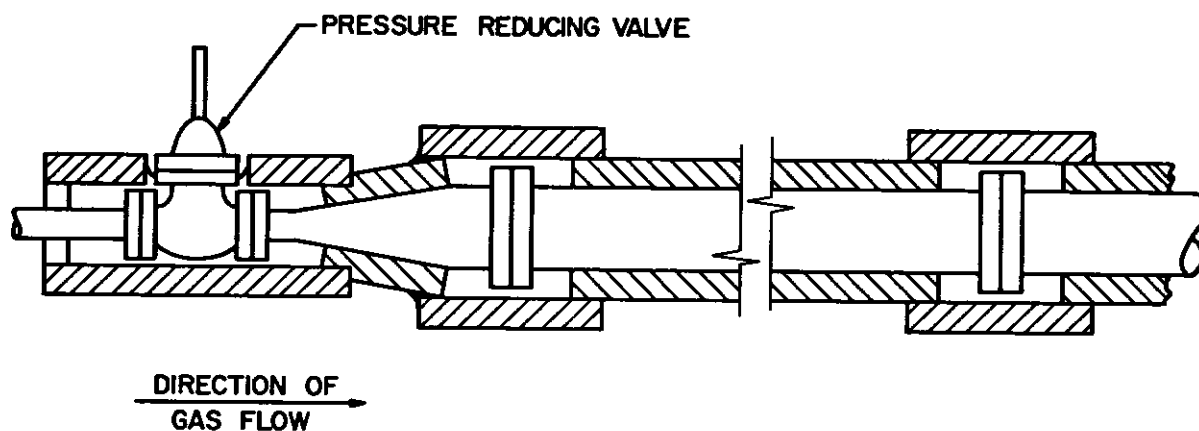
Modification of Sound Wave

Enclosures or partial enclosures. When enclosing a sound source with an unlined enclosure, the noise level inside the enclosure will build up to a considerably higher level than that measured without the enclosure. To avoid a lengthy calculation of this reverberant buildup, one can line the enclosure. If this is done so that the average sound absorption coefficient inside the enclosure is at least 0.70, the reverberant buildup will be insignificant. This allows one to select materials for the enclosure which have a transmission loss (TL) equal



duPont de Nemours & Co., Wilmington, Delaware.

Figure 37-23. CONFINE THE SOUND WAVE — MUFFLE AND ACCOUSTICAL LAGGING: Cover valve and piping between valve and muffler with 2" fiberglas (3 to 4 lb/cu ft plus an outer covering of Coustifab 488C). For unusually high pressure drops and flows, 16-gage steel weather covering might be required.



duPont de Nemours & Co., Wilmington, Delaware.

Figure 37-24. CONFINE THE SOUND WAVE — ACOUSTICAL LAGGING ONLY: Cover valve and downstream piping as described on Figure 23. This method might require the covering of a considerable amount of piping (100 ft or more). In this case, one must be careful not to excite equipment located downstream from the valve. Exceptions of such equipment would be thin-walled heat exchangers, separators, and spray towers.

to the difference between the noise level without the enclosure and the desired noise level with the enclosure. It is good practice to add 5 dB to this difference as a factor of safety. Table 37-2 lists the TL of the more common building materials. This method assumes that the enclosure of the noise source is complete and well sealed. If the enclosure is not complete and well sealed refer to Figure 37-27 for estimating the effect on TL of the leaks or openings. Figure 37-28 shows some common seals and fasteners used for acoustical enclosures. If openings are needed for ventilation or feeding materials into or out from the enclosure, mufflers should be installed at these openings to maintain the desired TL of the rest of the enclosure. If the desired TL is not very great, partial enclosures, that is, enclosures with fairly large openings might be sufficient. The effectiveness of a partial enclosure can be determined by calculating the percent open area as compared to a complete enclosure, and then referring to Figure 37-27.

Absorb sound wave. In general, sound absorbing materials are soft and porous. They are porous so that the sound wave can enter the material but the material must have a high enough flow resistance to reduce the amplitude of the sound wave. If the material is too dense (has too high a flow resistance) the sound will be reflected. If the material is not dense enough (flow resistance too low) the sound wave will pass through unchanged. Materials are rated in their ability to absorb sound by their sound absorption coefficient (α). This is the percent of incident sound which is absorbed in striking it. Table 37-3 lists the sound absorbing coefficients of various materials. The Acoustical Materials Association periodically publishes such data for materials manufactured by their members.

It is important to note that α varies with frequency. Figure 37-29 illustrated this for 6 lb./ft.³ Fiber glass. Notice that below 1000 Hz, α drops off markedly for ½" thick material. At 1" thickness this drop in α occurs below 500 Hz. For 3" material the drop in α occurs when the frequency is less than 250 Hz. The point is, when using α in a noise control problem it is important to use α at the frequency of interest.

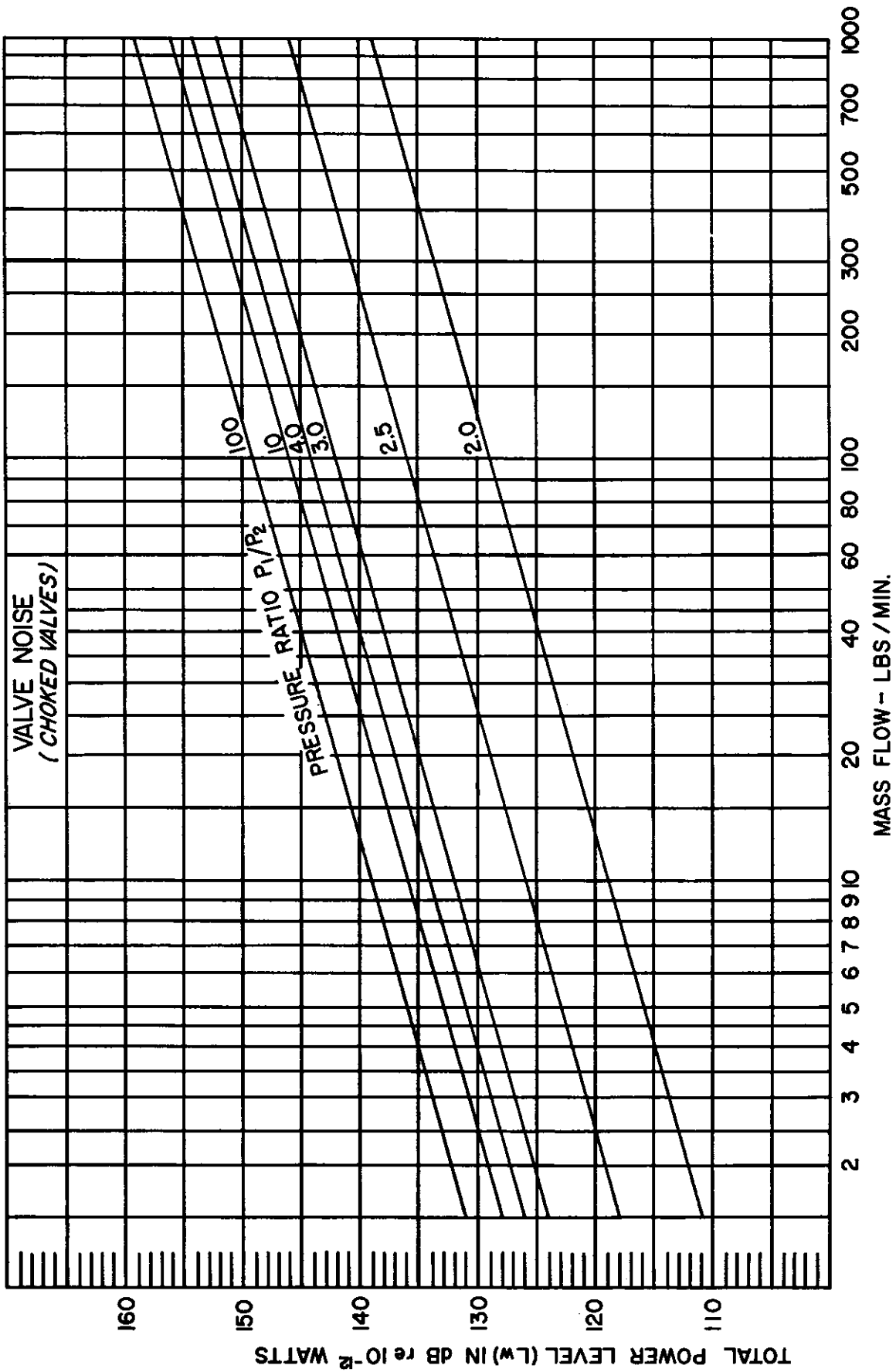
Room Absorption

Noise control by absorption in room bounding surfaces is very limited in effectiveness and relatively expensive due to the large surface areas which must be treated. Seven to 10 dB is probably the maximum reduction that can be expected, and in most cases 5 dB would be the best one could accomplish. Room absorption can only reduce the reverberant buildup in a room and therefore is not very effective for the worker if he must be close to the noise source. Room absorption is most effective where (a) the room has little or no sound absorbing material in it before treatment, (b) the room has multiple noise sources (4 or more), each producing about an equal amount of noise, and (c) the noise of any one machine alone does not exceed the criteria. If these conditions exist and room absorption appears to be the most attractive means of noise control, the reduction can be estimated as follows:

$$\text{Noise Reduction in dB} = 10 \log_{10} \frac{A_2}{A_1}$$

where A_1 = total number of absorption units (sabins) in the room before treatment

A_2 = total number of absorption units (sabins) in the room after treatment.

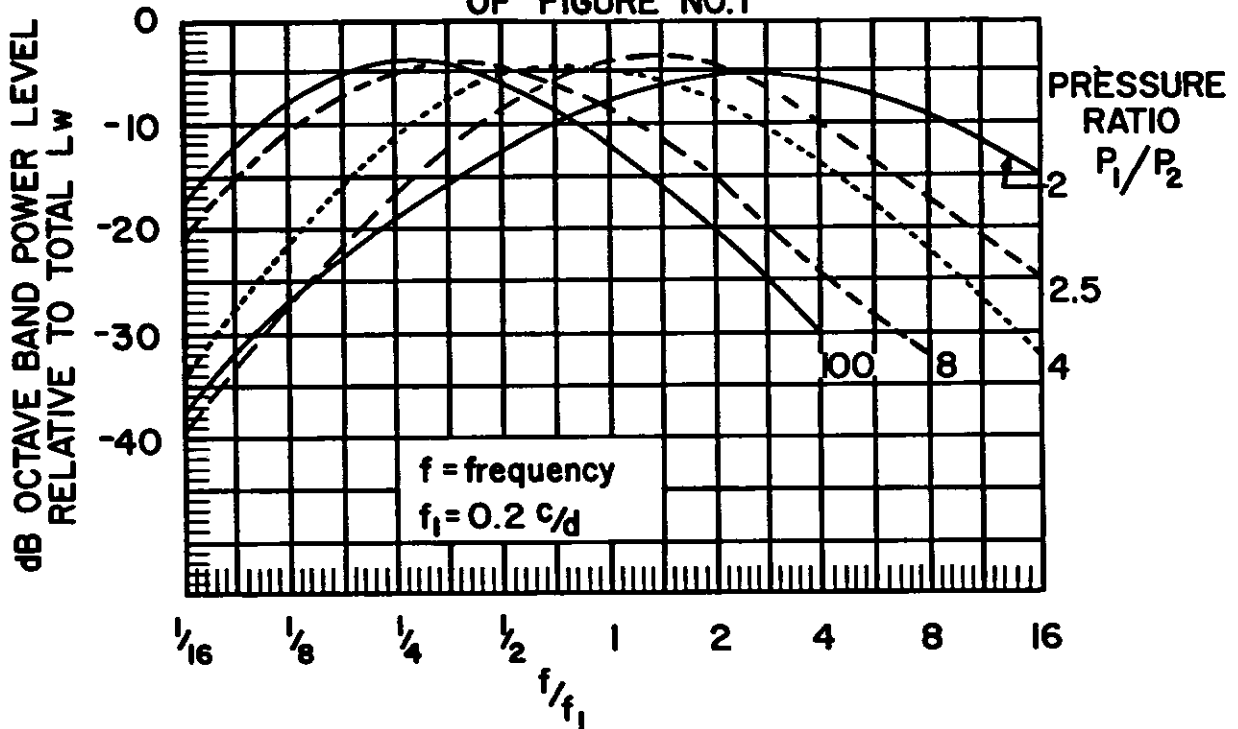


Ingersoll Rand, Allentown, Pennsylvania.

Figure 37-25. Valve Noise (Choked Values).

VALVE NOISE OCTAVE BAND POWER LEVEL

ZERO dB CORRESPONDS TO THE TOTAL LW
OF FIGURE NO.1



Ingersoll Rand, Allentown, Pennsylvania.

Figure 37-26. Valve Noise (Octave Band Power Level).

A sabin is a measure of the sound absorption of a surface and is the equivalent of one sq. ft. of a perfect absorptive surface.

This formula is presented in monograph form in Figure 37-30. The total number of absorption units mentioned above is the sum of all the room surface areas multiplied by their respective absorption coefficients. Absorption due to other materials and people should also be included in the calculation.

Absorption along Transmission Path

The most common example of noise absorption along the transmission path is the commercial muffler. Figure 37-31 illustrates the three most common types. The most common one shown by the upper sketch is the straight through lined duct type. It is very effective provided the lining is effective for the frequency of the sound involved, the length is adequate and the ID does not exceed 6". The performance of such a muffler can be estimated as follows:

$$\text{Noise Reduction in dB per foot of length} = 12.6 \frac{P^{1.4}}{A}$$

where α = absorption coefficient of the lining material at the frequency of interest
 P = perimeter of the duct in inches
 A = cross sectional area of the duct in sq. inches

To simplify the use of this formula, Table 37-4 shows the value of $12.6\alpha^{1.4}$ for various absorption coefficients. If the ID must be greater than 6" or if the noise reduction required makes it necessary to use a longer muffler than desirable, then the configuration shown by the center sketch of Figure 37-31 can be used. Here the absorptive center portion makes it possible to have relatively narrow flow passages through the mufflers. This provides good performance even where muffler length must be minimized.

Where mufflers having absorption linings cannot be used, the combination resonant, reactive, and dispersive type mufflers shown by the bottom sketch of Figure 37-31 can sometimes be used. The performance of these mufflers is strongly dependent on gas flow through them, and prediction of performance in a given application is very difficult. It is recommended that this type mufflers be bought on a performance guarantee.

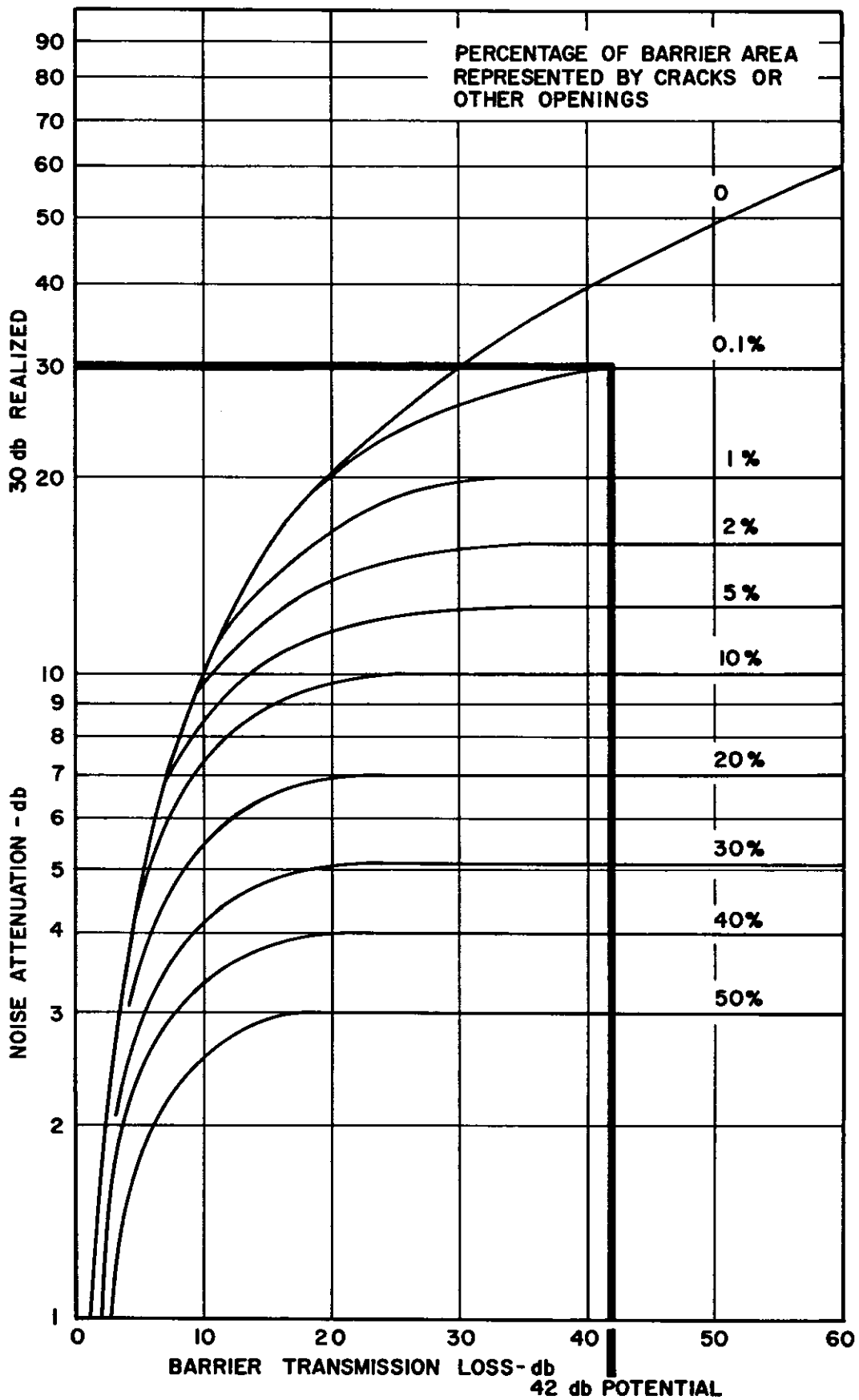
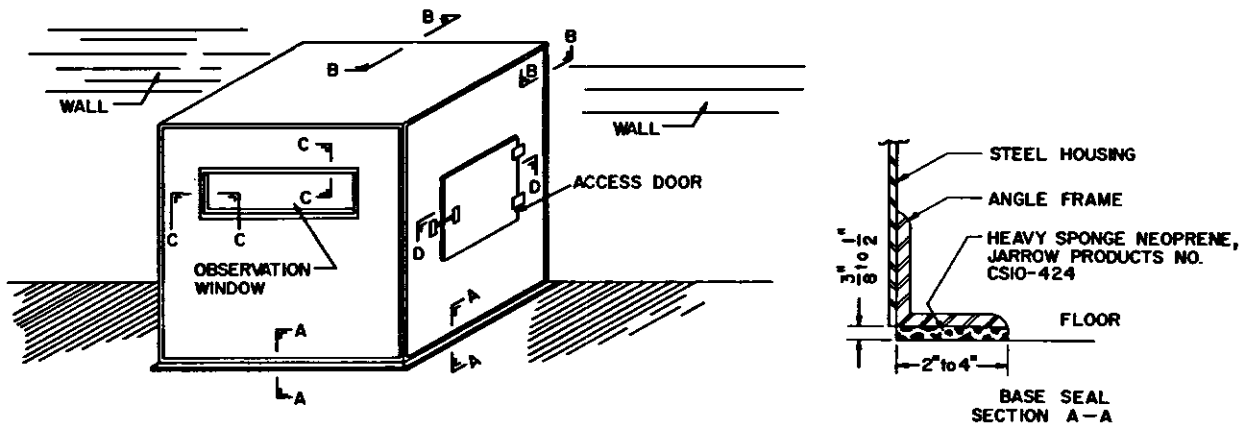
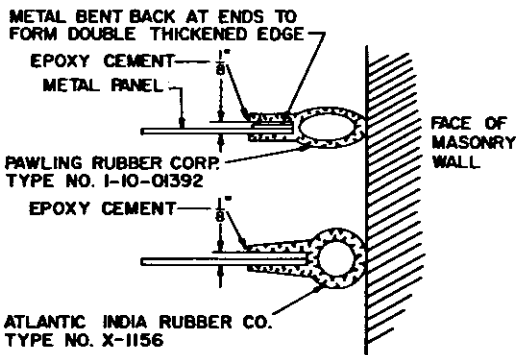


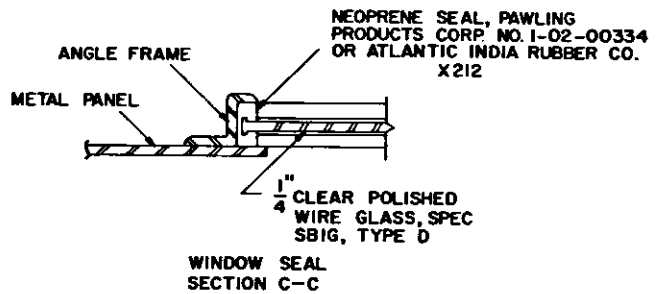
Figure 37-27. Effect of Leaks.



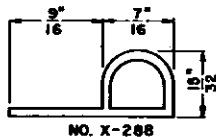
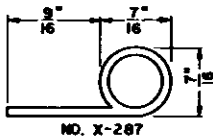
TYPICAL ENCLOSURE



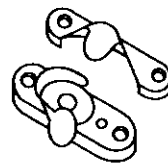
MOUNTING SEALS
SECTION B-B



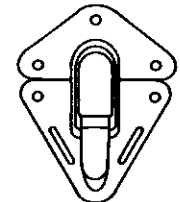
WINDOW SEAL
SECTION C-C



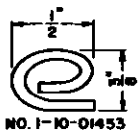
ATLANTIC INDIA RUBBER CO.



SASH LOCK
TYPE NO. 1487
HAGER HINGE CO.



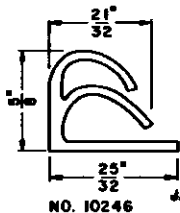
DRAW ACTION TYPE
SESSIONS NO. 491110



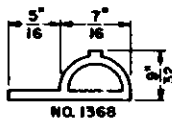
NO. I-10-01453
PAWLING RUBBER CORP.



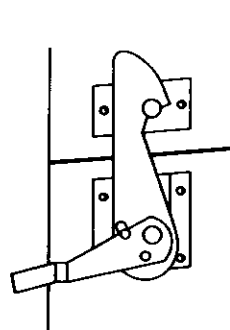
NO. I-10-02697



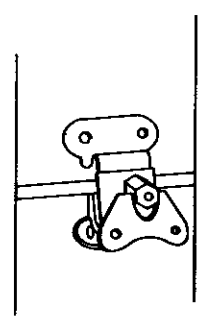
NO. 10246
JARROW PRODUCTS, INC.



NO. 1368



HOOK LOCK TYPE

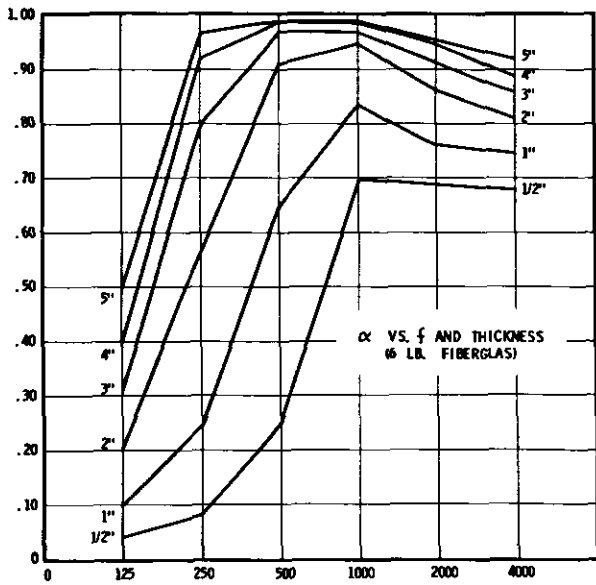


LINK LOCK TYPE

SIMMONS FASTENER CORP.

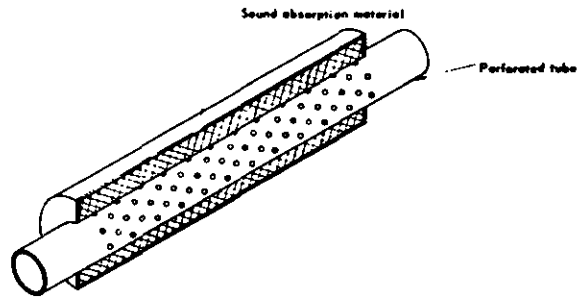
duPont de Nemours & Co., Wilmington, Delaware.

Figure 37-28. TYPICAL ACCESS DOOR SEALS AND FASTENERS. Note: An enclosure built to house a noise source must have all cracks and openings tightly sealed in order to reduce leakage of noise. The enclosure below illustrates applicable principles of sealing and fastening base, wall, door, and observation window. It should not be considered a complete enclosure design because of possible need for ventilation, accoustical lining, etc.

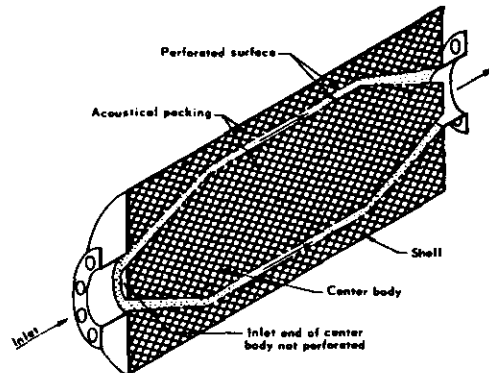


Owens-Corning Fiberglas, Toledo, Ohio.

Figure 37-29. Effect of Material Thickness and Frequency on Absorption.



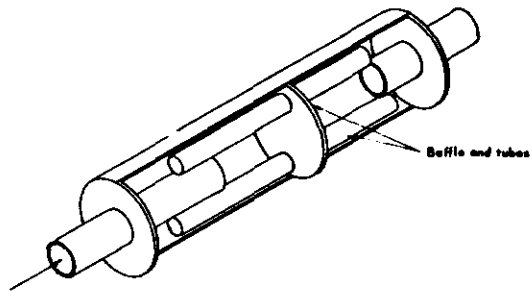
DISSIPATIVE MUFFLER - STRAIGHT-THROUGH TYPE



DISSIPATIVE MUFFLER - CENTERED-BODY TYPE

duPont de Nemours & Co., Wilmington, Delaware.

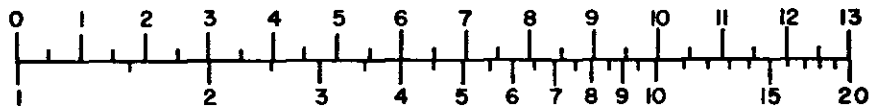
Figure 37-31. Mufflers.



NONDISSIPATIVE MUFFLER

MONOGRAPH FOR DETERMINING EFFECT OF ROOM ABSORPTION

DECIBEL REDUCTION



ABSORPTION RATIO a_2/a_1

AIHA Noise Committee: Industrial Noise Manual, 2nd Edition. Detroit, American Industrial Hygiene Association, 1966.

Figure 37-30. Monograph for Determining Effect of Room Absorption.

TABLE 37-1
OCTAVE BAND SOUND PRESSURE LEVEL DETERMINATION

Octave Band Number	f/f_1	P_1/P_2	Overall L_w	Relation of Overall to Octave Band L_w	Octave Band L_w	L_p in 3" pipe
8	4	2.1	127 dB	-6	121	134
7	2	"	"	-5	122	135
6	1	"	"	-7	120	113
5	$\frac{1}{2}$	"	"	-11	116	129
4	$\frac{1}{4}$	"	"	-19	108	121
3	$\frac{1}{8}$	"	"	-27	100	113
2	$\frac{1}{16}$	"	"	-37	90	103

TABLE 37-2
Sound Transmission Loss of General Building Materials and Structures

Item	Material or Structure	Thick- ness Inches	Wt. lb/ sq ft	Sound Transmission Loss (dB)											
				125	175	250	350	500	700	1000	2000	4000			
A Doors															
1	Heavy wooden door—special hardware—rubber gasket at top, sides and bottom	2½	12.5	30	30	30	29	24	25	26	37	36			
2	Steel clad door—well sealed at door casing and threshold			42	47	51	48	48	45	46	48	45			
3	Flush—hollow core—well sealed at door casing and threshold			14	21	27	24	25	25	26	29	31			
4	Solid oak—with cracks as ordinarily hung	1¾		12		15		20		22	16				
5	Wood door (30"×84") special soundproof constr.—well sealed at door casing and threshold.	3	7	31	27	32	30	33	31	29	37	41			
B Glass															
1		½	1½	27	29	30	31	33	34	34	34	42			
2		¼	3	27	29	31	32	33	34	34	34	42			
3		½	6	17	20	22	23	24	27	29	34	24			
4		1	12	27	31	32	33	35	36	32	37	44			
C Walls—Homogeneous															
1	Steel sheet—fluted—18 gage stiffened at edges by 2×4 wood strips—joints sealed		4.4	30	20	20	21	22	17	30	29	31			
2	Asbestos board—corrugated stiffened horizontally by 2×8 in. wood beam—joints sealed		7.0	33	29	31	34	33	33	33	42	39			
3	Sheet steel—30 ga	.012	½	3	6		11		16		21	26			
4	Sheet steel—16 ga	.0598	2½	13	18		23		28		33	38			

TABLE 37-2 (Cont'd.)
Sound Transmission Loss of General Building Materials and Structures

Item	Material or Structure	Thick- ness Inches	Wt. lb/ sq ft	125	175	250	350	500	700	1000	2000	4000
5	Sheet steel — 10 ga	.1345	5.625	18	23		28		33		38	43
6	Sheet steel	¼	10	23	28	38	33	41	38	46	43	48
7	Sheet steel	⅜	15	26	31	39	36	42	41	47	41	51
8	Sheet steel	½	20	28	33		38		43		48	53
9	Sheet Aluminum — 16 ga	.051	.734	5	8		13		18		23	28
10	Sheet Aluminum — 10 ga	.102	1.47	8	14		19		24		29	34
11	Plywood	¼	.73		20		19		24		27	22
12	Plywood	½	1.5	8	14		19		24		29	34
13	Plywood	¾	2.25	12	17		22		27		32	37
14	Sheet Lead	⅛	3.9			32		33		32	32	32
15	Sheet Lead	¼	8.2			31		27		37	44	33
16	Glass fiber board — 6 lb/cu ft	1	½	5	5	5	5	5	4	4	4	3
17	Laminated Glass Fiber (FRP)	¾				26		31		38	37	38
D	Walls — Nonhomogeneous											
1	Gypsum wallboard—two ½" sheets cemented together — joints wood battened	1	4.5	24	25	29	32	31	33	32	30	34
2	Gypsum wallboard—four ½" sheets cemented together — fastened together with sheet metal screws — dovetail-type joints paper taped	2	8.9	28	35	32	37	34	36	40	38	49
3	¼" plywood glued to both sides of 1×3 studs 16 in. O.C.	3	2.5	16	16	18	20	26	27	28	37	33
4	Same as 3 above but ½" gypsum wallboard nailed to each face	4	6.6	26	34	33	40	39	44	46	50	50
5	¼" Dense fiberboard on both sides of 2×4 wood studs 16 in. O.C. — Fiberboard joints at studs	4½	3.8	16	19	22	32	28	33	38	50	52
6	Soft type fiberboard (¾") on both sides of 2×4 wood studs 16 in. O.C. — Fiberboard joints at studs	5	4.3	21	18	21	27	31	32	38	49	53
7	½" gypsum wallboard on both sides of 2×4 wood studs 16 in O.C.	4½	5.9	20	22	27	35	37	39	43	48	43
8	Two ⅜" gypsum wallboard sheets glued together and applied to each side of 2×4 wood studs 16 in. O.C.	5	8.2	27	24	31	35	40	42	46	53	48
9	2" glass fiber (3 lb/cu ft) + lead — vinyl composite (0.87 lb/sq ft)						4		4		13	26 31

TABLE 37-2 (Cont'd.)
Sound Transmission Loss of General Building Materials and Structures

Item	Material or Structure	Thick- ness Inches	Wt. lb/ sq ft										
				125	175	250	350	500	700	1000	2000	4000	
10	3/8" steel + 2.375 in. polyurethane foam (2 lb/cu ft) + 1/16 steel					38		52		55	64	77	
11	Same as 10 above but 2 1/2" glass fiber (3 lb/cu ft) instead of foam					37		51		56	65	76	
12	1/4" steel + 1" polyurethane foam (2 lb/cu ft) + 0.055 in. lead vinyl composite (1.0 lb/lb/sq ft)					38		45		57	56	67	
E	Masonry												
1	Reinforced concrete	4	53	37	33	36	44	45	50	52	60	67	
2	Brick — common	12	121	45	49	44	52	53	54	59	60	61	
3	Glass Brick—3 3/4 x 4 7/8 x 8	3 3/4		30	36	35	39	40	45	49	49	43	

TABLE 37-2
Sound Transmission Loss of General Building Materials and Structures

Item	Material or Structure	Weight Lbs/Ft ²	Loss in Decibels at Indicated Frequencies, H _z									
			128	192	256	384	512	768	1024	2048	4096	
E	Masonry											
4	Concrete block — 4" hollow, no surface treatment		27	29	32	35	37	42	45	46	48	
5	Concrete block — 4" hollow, one coat resin-emulsion paint		30	33	34	36	41	45	50	55	53	
6	Concrete block — 4" hollow, one coat cement base paint		37	40	43	45	46	49	54	56	55	
7	Concrete block — 6" hollow, no surface treatment		28	34	36	41	45	48	51	52	47	
8	Concrete block — 8" hollow, no surface treatment		18	24	28	34	37	39	40	42	40	
9	Concrete block — 8" hollow, one coat cement base paint		30	36	40	44	46	48	51	50	41	
10	Concrete block — 8" hollow, filled with vermiculite insulators		20	29	33	36	38	38	40	45	47	
11	Concrete block — 4" hollow, no surface treatment		21	26	28	31	35	38	41	44	43	
12	Concrete block — 4" hollow, one coat resin-emulsion paint		26	30	32	34	37	42	43	46	44	
13	Concrete block — 4" hollow, two coats resin-emulsion paint		24	31	33	35	38	42	44	47	44	
14	Concrete block — 4" hollow, one coat cement base paint		23	30	35	38	42	43	44	48	43	
15	Concrete block — 4" hollow, two coats cement-base paint		34	38	40	42	45	47	49	51	46	
16	Concrete block — 6" hollow, no surface treatment		22	27	32	36	40	43	46	45	43	

TABLE 37-2 (Continued)
Sound Transmission Loss of General Building Materials and Structures

Item	Material or Structure	Weight Lbs/Ft ²	Loss in Decibels at Indicated Frequencies, H _z								
			128	192	256	284	512	768	1024	2048	4096
17	Concrete block — 4" hollow, no surface treatment		30	36	39	41	43	44	47	54	50
18	Concrete block — 4" hollow, one coat cement base paint on face		30	36	39	41	43	44	47	54	49
19	Concrete block — 6" hollow, no surface treatment	Dense Aggregate	37	46	50	50	50	53	56	56	46
20	Concrete block — 6" hollow, one coat resin-emulsion paint each face		37	50	54	52	53	55	57	56	46
21	Concrete block — 8" hollow, no surface treatment		40	47	53	54	54	56	58	58	50
22	Concrete block — 8" hollow, two coats resin-emulsion paint each										

TABLE 37-3
Sound Absorption Coefficients of Materials

The absorption coefficient (α) of a surface which is exposed to a sound field is the ratio of the sound energy absorbed by the surface to the sound energy incident upon the surface. For instance, if 55% of the incident sound energy is absorbed when it strikes the surface of a material, the α of that material would be 0.55. Since the α of a material varies according to many factors, such as

frequency of the noise, density, type of mounting, surface condition, etc., be sure to use the α for the exact conditions to be used and from performance data listings such as shown below. For a more comprehensive list of the absorption coefficients of acoustical materials, refer to the bulletin published yearly by the Acoustical Materials Association, 335 East 45th St., New York, N. Y. 10017.

Materials	Frequency	Coefficients					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Brick — glazed		0.01	0.01	0.01	0.01	0.02	0.02
Sand — dry — 4" thick		.15	.35	.40	.50	.55	.80
Sand — dry — 12" thick		.20	.30	.40	.50	.60	.75
Sand — wet — 14 lb water per cu ft 4" thick		.05	.05	.05	.05	.05	.15
Water		.01	.01	.01	.01	.02	.02
Glass Fiber — mounted with impervious backing — 3 lb/cu ft, 1" thick		.14	.55	.67	.97	.90	.85
Glass Fiber — mounted with impervious backing — 3 lb/cu ft, 2" thick		.39	.78	.94	.96	.85	.84
Glass Fiber — mounted with impervious backing — 3 lb/cu ft, 3" thick		.43	.91	.99	.98	.95	.93
Steel (Estimated)		.02	.02	.02	.02	.02	.02
Brick, unglazed		.03	.03	.03	.01	.05	.07
Brick, unglazed, painted		.01	.01	.02	.02	.02	.03
Carpet, heavy, on concrete		.02	.06	.14	.37	.60	.65
Same, on 40 oz hairfelt or foam rubber (carpet has porous backing)		.08	.24	.57	.69	.71	.73
Same, with impermeable latex backing on 10 oz hairfelt or foam rubber		.08	.27	.39	.34	.48	.63
Concrete Block, coarse		.36	.44	.31	.29	.39	.25
Concrete Block, painted		.10	.05	.06	.07	.09	.08
Concrete, poured		.01	.01	.02	.02	.02	.03

TABLE 37-3 (Continued)
Sound Absorption Coefficients of Materials
Coefficients

Materials	Frequency	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Fabrics							
Light velour, 10 oz per sq yd, hung straight, in contact with wall		.03	.04	.11	.17	.24	.35
Medium velour, 14 oz per sq yd, draped to half area		.07	.31	.49	.75	.70	.60
Heavy velour, 18 oz per sq yd, draped to half area		.14	.35	.55	.72	.70	.65
Floors							
Concrete or terrazzo		.01	.01	.015	.02	.02	.02
Linoleum, asphalt, rubber or cork tile on concrete		.02	.03	.03	.03	.03	.02
Wood		.15	.11	.10	.07	.06	.07
Wood parquet in asphalt on concrete		.04	.04	.07	.06	.06	.07
Glass							
Large panes of heavy plate glass		.18	.06	.04	.03	.02	.02
Ordinary window glass		.35	.25	.18	.12	.07	.04
Gypsum Board, ½" nailed to 2 × 4's 16" o.c.		.29	.10	.05	.04	.07	.09
Marble		.01	.01	.01	.01	.02	.02
Openings							
Stage, depending on furnishings				.25 — .75			
Deep balcony, upholstered seats				.50 — 1.00			
Grills, ventilating				.15 — .50			
To outside				1.00			
Plaster, gypsum or lime, smooth finish on tile or brick		.013	.015	.02	.03	.04	.05
Plaster, gypsum or lime, rough finish on lath		.14	.10	.06	.05	.04	.03
Same, with smooth finish		.14	.10	.06	.04	.04	.03
Plywood Paneling, ¾" thick		.28	.22	.17	.09	.10	.11
Water Surface, as in a swimming pool		.008	.008	.013	.015	.020	.025

ABSORPTION OF SEATS AND AUDIENCE

Values given are in Sabins per square foot of seating area or per unit

Materials	Frequency	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Audience, seated in upholstered seats, per sq ft of floor area		.60	.74	.88	.96	.93	.85
Unoccupied cloth-covered upholstered seats, per sq ft of floor area		.49	.66	.80	.88	.82	.79
Unoccupied leather-covered upholstered seats, per sq ft of floor area		.44	.54	.60	.62	.58	.79
Chairs, metal or wood seats, each, unoccupied		.15	.19	.22	.39	.38	.39

TABLE 37-4
SOUND ABSORPTION COEFFICIENT
VS. $12.6\alpha^{1.4}$

Sound Absorption Coefficient	$12.6\alpha^{1.4}$
0.50	4.78
0.55	5.46
0.60	6.16
0.65	6.89
0.70	7.65
0.75	8.43
0.80	9.16
0.85	10.02
0.90	10.87

Preferred Reading — Books

1. BERANEK, L. L. — *Noise and Vibration Control*, McGraw-Hill Book Co., New York, 1971.
2. HARRIS, C. M. — *Handbook of Noise Control*, McGraw-Hill Book Co., New York, 1957.
3. HARRIS, C. M. and CREDE, C. E. — *Shock and Vibration Handbook*, Volume 2, McGraw-Hill Book Co., New York, 1961.

Preferred Reading — Periodicals

Sound and Vibration — Published monthly by Acoustical Publications, Inc., 2710 E. Oviatt Road, Bay Village, Ohio 44140.

Journal of Sound and Vibration — Published bi-monthly by Academic Press, Inc. (London) Limited.

CONTROL OF EXPOSURES TO HEAT AND COLD

Harwood S. Belding, Ph.D.

HEAT

Introduction

At this point we expect the student to have acquired an understanding of the several elements which act to determine the stress of hot environments (Chapter 31) and of the physiological effects of heat exposures on the body (Chapter 30). The task in this section is to identify methods of control of occupational exposures to heat. These methods must be adapted to the nature of the heat stress and, if chosen properly, can be expected to ameliorate resulting physiologic strains.

Control of heat hazards has been discussed in several publications. Engineers may wish to consult more comprehensive publications issued by the American Industrial Hygiene Association¹ and the American Society of Heating, Refrigerating and Air Conditioning Engineers.² These offer some details not provided here, in particular on thermal control of large factory spaces by ventilation. Engineering aspects of ventilation are also given in Chapter 39. Earlier, Hertig³ and Hertig and Belding⁴ discussed methods of heat control. Wason⁵ provided a comprehensive treatment of many aspects of the subject.

The ultimate goal of heat control engineering may be to create a climate of work in which true thermal comfort prevails. However, this seldom is achievable when large furnaces or sources of steam or water are present in the work area. In compromising with his ideal of providing comfort, the engineer may rationalize his shortcomings with the knowledge that man evolved as a tropical animal; he is well-endowed with physiologic mechanisms to cope with substantial levels of heat stress, particularly if he is acclimatized. It has even been suggested that some exercise of these natural mechanisms among well individuals may, as in the case with physical exercise, have beneficial effects (Chapter 30). This type of justification of hot working conditions is less warranted when jobs demand use of mental or perceptual facilities or of precise motor skills. In such cases thermal discomfort can distract attention; also, heat tolerance of physically inactive workers is less in some respects than for those whose duties require physical activity.

Analysis of the Problem and Options for Control

Before initiating control measures the engineer will wish to partition the components of the heat stress to which the worker is exposed, or in planning a new operation, is expected to be exposed. This information may be used not only as a basis for rational selection of the means of control, but also may be used, together with similar data ob-

tained following adoption of control measures, to demonstrate the effectiveness of corrective actions that have been taken. It is evident that the heat stress for the individual worker depends on:

- (1) the bodily heat production, (M), of the tasks which he performs
- (2) the number and duration of exposures
- (3) the heat exchanges as affected by the thermal environment of each task; namely exchanges by radiation (R), convection (C) and evaporation (E), as affected by air temperature (T_a), temperature of solid surround (T_w), air speed (v), and water vapor pressure of the skin (P_{ws}) and the air (P_{wa})
- (4) thermal conditions of the rest area
- (5) the clothing that is worn.

Items 1 and 2 represent elements of behavioral control; 3 and 4, environmental control; and 5 may be regarded as a combination of both.

The approach toward control may involve modification of one or more of these determinants of the heat stress. The challenge is to select specific methods for attack which will be both feasible and effective. Serious errors can result from resorting to some single pet engineering solution. Consider the consequences of ducting outside air to the task site. This air usually is blown at the worker at a temperature as warm as the upper reaches of the shed where the ducts have been installed. This will enhance cooling by evaporation of sweat, but if the air is warmer than the skin (35°C , 95°F), it will increase the convective heat load. Consideration of the trade off between needed heat loss and increased heat gain is essential. And, provided that the plant air is reasonably clean, the same goal might be achieved less expensively with portable fans. However, in such a situation the real mistake may be the failure to recognize that the heat problem derives from radiant load from a furnace and this is not decreased by air movement. This mistake has been made less frequently in recent years, but elaborate ducting across the ceilings of older plants exists as evidence of inappropriate action to control radiant heat loads.

Let us examine means and effectiveness of the five listed modifiers of the heat stress.

(1) *Decreasing the physical work of the task.* Metabolic heat can comprise a large fraction of the total heat load. However, the amount by which this factor may be reduced by control is quite limited. This is because an average sized man who is simply standing quietly while pushing buttons will produce heat at a rate of 100 kcal/hr

whereas one who is manually transferring fairly heavy materials at a steady pace will seldom have a metabolic rate higher than 300 kcal/hr and usually not more than 250 kcal/hr.⁶ Obviously, control measures, such as partial mechanization, can only reduce the (M) component of these steady types of work by 100 to 200 kcal/hr; nevertheless mechanization can also help by making it possible for the worker to be more isolated from the heat source, perhaps in an air conditioned booth.

Tasks such as shovelling which involve metabolic heat production at rates as high as 500 to 600 kcal/hr require that rest be taken one-half to two-thirds of the time simply because of the physical demands of the labor. Thus, the hourly contribution of (M) to heat load will seldom exceed 300 kcal/hr. It is obvious that mechanization of such work can increase worker productivity by making possible a decrease in the time needed for rest.

(2) *Modifying the number and duration of exposures.* When the task in a hot environment involves work that is a regularly scheduled part of the job, the combined experience of workers and management will have resulted in an arrangement which makes the work tolerable most of the time for most of the workers. For example, the relief schedule for a task which involves manual transfer of hot materials may involve two workers only because of the heat, and depending on the duress, these workers may alternate at five-minute or up to hourly intervals which have been determined empirically. Under such conditions overall strain for the individual will be less if the cycles are short.⁷ Where there is a standardized quota of hot work for each man, it is sometimes lumped at the beginning of the shift. This arrangement may be preferred by workers in cooler weather; however, there is evidence that the strain of such an arrangement may become excessive on hot days. The total strain, evidenced by fewer heart beats, will be less if the work is spread out.

The stress of hot jobs is dependent on vagaries of weather. A hot spell or an unusual rise in humidity may create overly stressful conditions for a few hours or days in the summer. Nonessential tasks should be postponed during such emergency periods, in accordance with a prearranged plan. Also, assignment of an extra helper can importantly reduce heat exposure of members of a working team. However, there is danger in this practice when unskilled or unacclimatized workers are utilized in this role.

Many of the critically hot exposures to heat faced in industry are incurred irregularly, as in furnace repair or emergencies, where levels of heat stress and physical effort are high and largely unpredictable, and values for the components of the stress are not readily assessable. Usually such exposures will force progressive rise in body temperature. Ideally such physiologic responses as body temperature and heart rate would be monitored and used as criteria for limiting such exposures on an *ad hoc* basis. Practically, however, the tolerance limits must be based on ex-

perience of the worker as well as of his supervisor. Fortunately, for most workers most of the time individual perception of fatigue, faintness or breathlessness may be relied upon for bringing exposures to a safe ending. The highly motivated individual, particularly the novice who desires acceptance, is at greater risk. In the same spirit, foremen should respect the opinion of an employee when he reports that he does not feel up to work in the heat at a particular time. Non-job personal factors such as low grade infection, a sleepless night or diarrhea (dehydration affects sweating) which would not affect performance on most jobs, may adversely affect heat tolerance.

Perhaps the best advice that can be offered for control of irregular exposures is (a) that formal training and indoctrination of effects of heat be provided supervisors and workers; and (b) that this include advice to the effect that each exposure should be terminated before physical distress is severe. There is abundant evidence that the physiological strain of a single exposure which raises internal body temperature to 39°C (102.2°F) is such as to contra-indicate further exposures during the same day; it may take hours for complete recovery. More work can be achieved during several shorter exposures and with less overall strain.

(3) *Modifying the thermal environment.* The environmental engineer will usually identify important sources of heat stress in a qualitative sense, without resorting to elaborate measurements. Thus, his experience will suggest that when air is static and the clothes of the workers become wet with sweat it will help to provide a fan.

Nevertheless, there are advantages in quantitative analysis of the heat stress (and where possible determination of physiological strains) on workers. The effects of various approaches to control can then be predicted and improvements in thermal conditions at the workplace can be documented for higher levels of management based on measurements made before and after action has been taken.

We cite concrete examples to illustrate how the quantitative analytic approach may be used.

CASE 1. First is a case which is encountered frequently under ordinary conditions of hot weather. Let us assume a laundry where the humidity is high ($P_{wa} = 25$ mm Hg) despite the operation of a small exhaust fan on the wall. There is no high level heat source so T_w is about the same as T_a .

In the simplest situation we take T_a and T_w equal to the temperature of the skin, which, under heat stress, may be assumed to be 35°C (95°F). This means heat exchange by R and C is zero.* Let us examine the case on the basis that exposure is continuous and the average physical work is moderate ($M = 200$ kcal/hr). The heat load to be dissipated, E_{req} , is then,

$$\begin{aligned} M + R + C &= E_{req} \\ 200 + 0 + 0 &= 200 \end{aligned}$$

*In this case $R + C$ is changed by about 17 kcal/hr for each °C of deviation of T_w and T_a from T_{sk} .

The workers wear only shorts or shorts and halter. The air speed is low, 20 m (65 ft.) per minute. Analysis in accordance with Chapter 31 for the seminude condition yields indication of maximum cooling by evaporation of sweat, E_{max} .

$E_{max} = 2.0 v^{0.6} (42 - P_{wa})$, where 42 mm Hg is P_{ws} of completely wetted skin at 35°C; or

$E_{max} = 2 \times 6.0 (42 - 25) = 200$ kcal/hr (approx.)

Nominally, a worker under these conditions would be just able to maintain bodily heat balance if he kept his skin completely wet. To do this he would have to sweat extravagantly, which means some dripping. It is easy to see why the workers wear as little clothing as possible. Wearing a long-sleeved work shirt and trousers would reduce E_{max} by about 40 percent, or to 120 kcal/hr. The resulting excess of heat load over E_{max} would result in rise of body temperature and it can be estimated that the ordinary limit of tolerance would be reached in about an hour.

When, as in this case, the heat load is itself moderate, the attack of the control engineer should be aimed at increasing E_{max} . In most such situations the management or the workers might find it expedient to bring in fans for spot "cooling." Note that since E_{max} is 0.6 power function of air speed, tripling of air movement across the skin would result in doubling of E_{max} . In this case an increase from 20 m/min to 60 m/min is easily achieved and it is predicted that such air speed will raise E_{max} to 400 kcal/hr. Sweat would be reduced to about 0.35 liters/hr and would be evaporated easily; the skin would no longer be dripping wet. It is clear that this control measure has limitations. For example, if air speed were already 60 m/min tripling would produce a wind which might disrupt operations.

A more effective permanent approach would be to replace the small exhaust fan with exhaust hoods opening over the principal source of moisture. This would work well in a dry climate, but in a humid one the make-up air from outside might have such a high P_{wa} as nearly to cancel the value of hoods. It is obvious that in Case I the use of mechanical air conditioning would prove expensive.

CASE II. This is selected to show how the wearing of clothing can be advantageous and the presence of high air speed a liability under very hot, dry conditions. Assume $T_a = 45^\circ\text{C}$ (113°F), $T_w = 55^\circ\text{C}$ (131°F), $v = 100$ m (300 ft.) per minute and P_{wa} , 10 mm. We use the same M as in Case I. Long-sleeved shirt and trousers are worn.*

*The formulae used are explained in Chapter 31 and summarized here.

NUDE	kcal/hr	CLOTHED
$11(T_w - 35)$	R	$6.6(T_w - 35)$
$1.0 v^{0.6} (T_a - 35)$	C	$0.6 v^{0.6} (T_a - 35)$
$2.0 v^{0.6} (42 - P_{wa})$	E_{max}	$1.2 v^{0.6} (42 - P_{wa})$

T_w is approximated from temperature readings of a six-inch blackened globe, T_g , using $T_w = T_g + 0.24 v^{0.5} (T_g - T_a)$; v is in m/min; "35" is assumed T_{skin} ; "42" is P_{ws} of completely wet skin at T_{skin} of 35°C.

$$M + R + C = E_{req}$$

$$200 + 130 + 95 = 425 \quad E_{max} = 610 \text{ kcal/hr}$$

Suppose the worker wore only shorts under these circumstances. R, C and E_{max} would be increased:

$$M + R + C = E_{req}$$

$$200 + 220 + 160 = 580 \quad E_{max} = 1010 \text{ kcal/hr}$$

The total heat load is increased about 155 kcal/hr. The specific cost of baring the skin would be about 0.26 liter per hour, raising the total requirement of sweating to 1.0 liter per hour, as compared with 0.71 liter per hour when wearing shirt and trousers.

Thus under conditions where T_w and T_a are above 35°C and P_{wa} is low, the wearing of clothing reduces heat stress and strain. In examining the above model it will be apparent that there is an optimum amount of clothing in such situations. This is the amount which reduces E_{max} to a value only slightly in excess of E_{req} . The long-sleeved shirt and trousers happen to be just about right for this purpose under the given conditions.

With low P_{wa} as in a semi-arid area, a more satisfactory solution probably might be reached through installation of an evaporative cooler. In Case II, inside temperature was usually 5°C hotter than outside, due to process heat and insulation on the roof of the shed. Assuming outside T_a usually does not exceed 40°C (104°F) and P_{wa} is about 10 mm Hg, outside air drawn through a water spray washer in large volume theoretically could be reduced to prevailing out-of-door wet bulb temperature, namely 22°C (72°F), though in practice probably only 80 percent efficiency could be achieved. Most of the wash water could be recycled. P_{wa} of the conditioned air would be raised from 10 to 20 mm Hg. The temperature of the work space might actually be reduced by this means to 30°C. If so, the components of heat load for clothed workers would be reduced by 35 percent from $E_{req} = 425$ to $E_{req} = 280$; E_{max} would still permit free evaporation of sweat.

$$M + R + C = E_{req}$$

$$200 + 130 - 50 = 280 \quad E_{max} = 420 \text{ kcal/hr}$$

CASE III. This case is chosen to illustrate the dramatic reduction in heat load achievable by provision of appropriate shielding when radiation from a furnace is substantial. Practical examples of the reduction in radiant heat load achievable by these means are provided by Lienhard, McClintock and Hughes,⁸ by Haines and Hatch,⁹ and by others.^{5, 10} This case is chosen from the first of these references, because the situation is real, and physiological and environmental data are available. The task is that of skimming dross from molten bars of aluminum. The worker stands at the task. Manipulation of a ladle involves moderate use of shoulder and arm muscles and requires an M of about 200 kcal/hr. The environmental temperatures before the corrective action were reported as $T_g = 71.7^\circ\text{C}$ (161°F), $T_a = 47.8^\circ\text{C}$ (118°F) and $T_{wb} = 30.5^\circ\text{C}$ (87°F). Air was forced from an overhead duct at 275

m/min (900 fpm).^{*} Note that the humidity was very high (Pwa = 24 mm Hg) which is characteristic of the local climate. In terms of heat load and Emax the situation was:

$$M + R + C = E_{req} \\ 200 + 870 + 220 = 1290 \quad E_{max} = 630 \text{ kcal/hr}$$

It is obvious from the deficiency of evaporation and the enormous load that the workers, despite full clothing and a face shield, were able to perform this task only for a few minutes at a time. Heat exhaustion was not uncommon (and might partly be attributable to the difficult hot conditions prevailing in the nearby rest area).

Engineers undertook control of this heat exposure by interposing finished aluminum sheeting between the heat source and the worker. Infra-red reflecting glass at face level permitted seeing the task and space was left for access of the arms in using the ladle. As a result of these measures it was recorded that both Tg and Ta were reduced to 43°C (110°F). The same air speed was present as before and if we assume the same Pwa we obtain:

$$M + R + C = E_{req} \\ 200 + 50 + 140 = 390 \quad E_{max} = 630 \text{ kcal/hr}$$

By this action to reduce R the heat load was brought to a level that is reasonable for prolonged work, but did not completely eliminate the heat stress. The predicted requirement for sweating to maintain heat balance was reduced from the previously impossible-to-sustain level of 2.1 liters/hr to about 0.7 liter/hr. (The before and after average levels actually observed for two workers were not far from these predictions, namely 2.1 and 1.1 liters/hr. The same two subjects also showed a marked reduction in heart rate, as a result of the changes, from an average of 146 to 108 beats/min.)

The percent reduction of the radiant load can be taken as a measure of the effectiveness of the reflective shielding, and in this instance approximates 85 percent. Large errors in the estimate of R are possible at extremely high globe temperatures, but in this case it appears that the maximum relief one could expect from shielding was achieved. Haines and Hatch⁹ reported smaller reductions in R of 51 to 74 percent from interposing a sheet of aluminum at eleven different work sites in a glass factory. Others¹ have shown reduction of 90 percent or more under ideal conditions not likely to prevail on the plant floor.

Control of Radiation: Further Considerations. While in Case III we have dealt with some aspects of control of R by shielding, the two other classical approaches of industrial hygiene engineering, namely control at the source and control at the man, offer possibilities which must be considered.

Application of insulation on a furnace wall can reduce its surface temperature and thereby the

level of R. A by-product of such treatment is saving in fuel needed to maintain internal furnace temperatures. Application of a polished metallic surface to a furnace wall will also reduce R. However, a polished metallic surface will not maintain its low emissivity^{*} if it is allowed to become dirty. A layer of grease or oil one molecule thick can change the emissivity of a polished surface from 0.1 to 0.9. And the emissivity of aluminum or gold paints for infrared is not necessarily indicated by their sheen. If the particles are smaller than about one micron they emit almost like a black body. (The same is true for fabrics coated with very fine metallic particles.)

Equal or even more effective reduction of R is achievable with non-reflective barriers through which cool water is circulated.

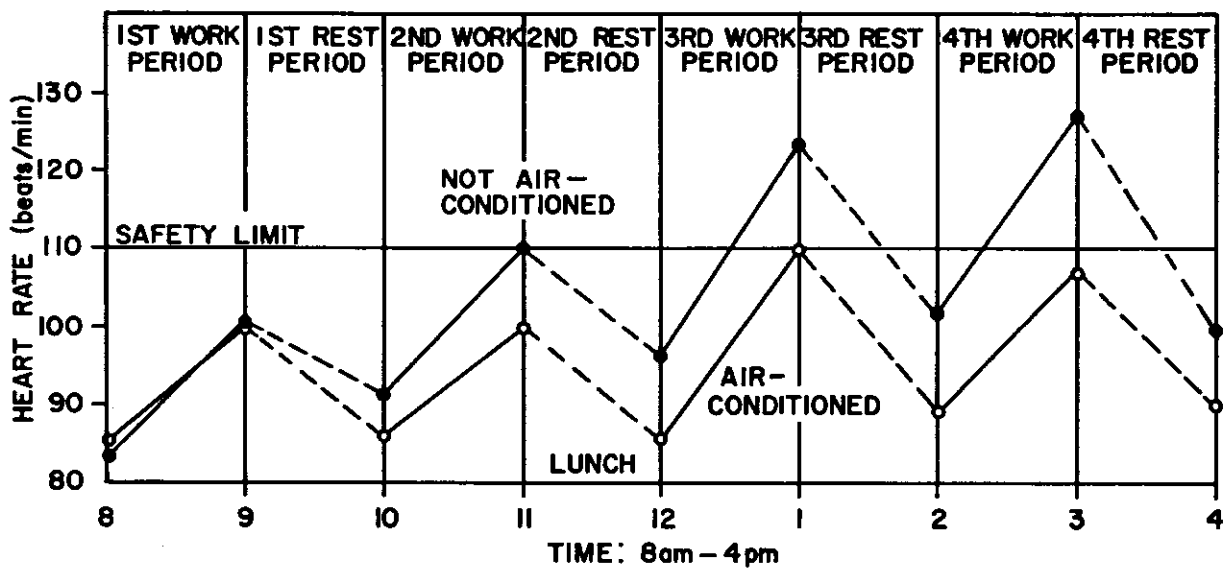
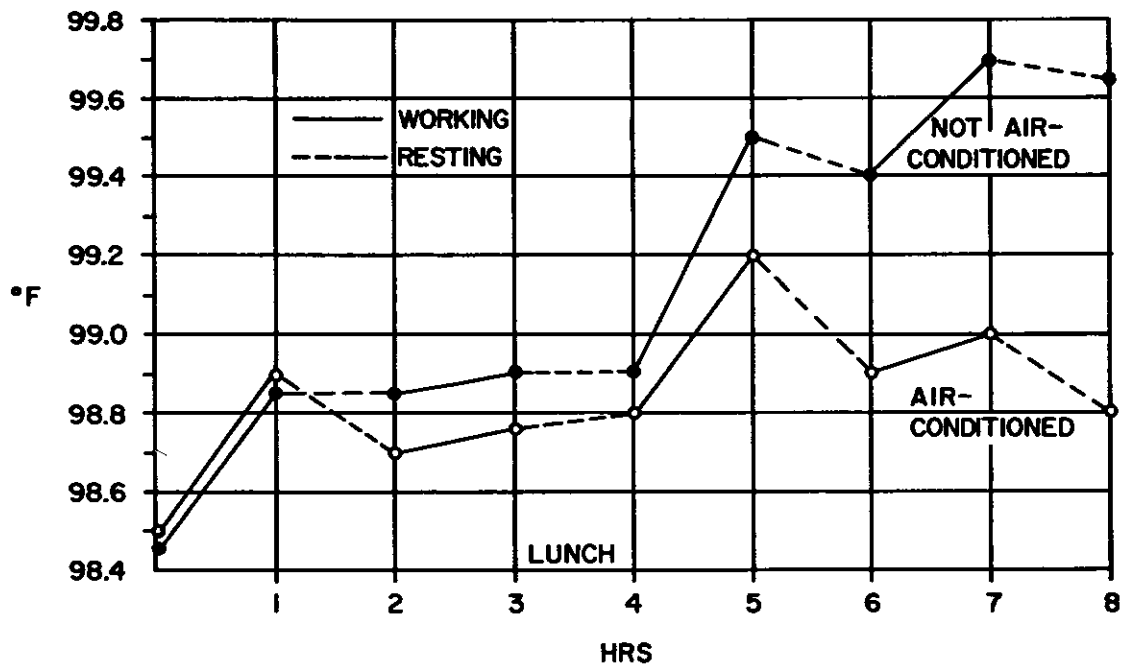
The engineer is frequently baffled in shielding by the fact that access to the heat source is required for performance of the task. We have seen various solutions to this problem. One is a curtain of metal chains which can be parted as required and which otherwise reduces emission like a fireplace screen. Another is a mechanically activated door which is opened only during ejection or manipulation of the product. And finally, remotely operated tongs may be provided, taking advantage of the fact that radiant heating from an open portal is limited to line of sight and falls off as the reciprocal of the square of the distance from the source.

(4) *Thermal conditions of the rest area.* Brouha⁷ states "It is undeniable that the possibility of rest in cool surroundings reduces considerably the total cost of work in the heat." This is demonstrated by responses of heart rate and body temperature of two groups of men doing the same job with and without access to an air conditioned space for recovery (Figure 38-1). There is no solid information on the optimum thermal conditions for such areas but we have laboratory data which support setting the temperature near 25°C (77°F). This feels chilly upon first entry from the heat, but adaptation is rapid.

The placement of these areas is of some importance. The farther they are from the workplace the more likely that they will be used infrequently or that individual work periods will be lengthened in favor of prolonged rest periods.

^{*}Emissivity is the capacity to radiate relative to a black body, which has a capacity of 1.0. Bright metal surfaces are poor emitters, having emissivities of less than 0.1. Absorptivity of materials for radiant energy is equivalent to their emissivity i.e., a black body is a perfect absorber. Reflectivity is 1.0 minus the emissivity. These characteristics are dependent on spectral wavelength, which is shorter for bodies at higher temperatures. The radiation dealt with here is in the infrared range, of longer wavelength than visible light. The emissivity and absorptivity of unpolished surfaces in this range are close to those of a black body, regardless of color. Thus light-colored oil paint will emit as a black body, as will skin, regardless of its color, and as will clothing. The near side of a polished metallic shield (1) will reflect back 90 percent of the energy which impinges from a furnace and (2) will emit from its far side only 10 percent of the energy that was absorbed. To be doubly effective in this way a shield must be exposed to air on both sides.

^{*}High speed air jets (8-inch to 12-inch diameter) are frequently used for purposes of man-cooling. These directly affect air speed over only a small portion of the body. Directed downward, the speed measured near the legs may be only 10 to 20 percent of that at the head. The head represents only 10 percent of the body surface, the legs 40 percent.



Brouha, L.: Physiology in Industry, 2nd Edition. New York, Pergamon Press, 1967.

Figure 38-1. Average Heart Rates and Body Temperatures at Beginning and End of Successive Work and Rest Periods. Group with lower levels of responses rested in an air conditioned room.

Incidentally, the same principle applies for positioning of water fountains. When they are remote from the worker, substantial dehydration is more apt to occur. The proper temperature for drinks under hot conditions is often asked. There is no scientific answer, but most men will not willingly drink fluids that are close to body temperature. They welcome chilled water and seek chilled soft drinks and ice cream when these are available in rest areas. (Actually a liter of intake at 8°C (46°F) will contribute to body cooling by extracting 30 kcal of body heat; a half pint of frozen sherbet will remove about the same amount.) Experienced workers recognize that frequent intake of small amounts of fluid is better than large draughts.

(5) *Clothing: (a) Conventional work clothing.* Heat exposures may be controlled through selective wearing of clothing, as illustrated by Cases I and II. In Case II we illustrated effects of an ordinary work shirt and trousers in reducing heat transfer by radiation, convection and evaporation by about 40 percent from the values applicable to seminude men.¹¹ Design as well as thickness can be exploited. Note that air movement under clothing, that is provided for by loose fit and generous openings, will have twice as much effect on E_{max} as it does on C (see coefficients). On the other hand, in dry environments with high air speed, tighter fit may be employed to reduce gain by C without critical reduction of E_{max} . Additional thickness may be exploited for further reduction of gain by $R+C$ and may be of particular value when alternating between extremes of heat and cold in open sheds in wintertime. In such situations long underwear may be advantageous because it acts as a "heat sponge." Thickness can also be an advantage in clothing for fire fighting.

(b) *Aluminized reflective clothing.* We have reported effects of wearing aluminum-coated clothing on heat exchanges.¹¹ Somewhat to our surprise our samples provided only about 60 percent reduction of radiant heat gain as compared with the 40 percent available from ordinary work clothing. At high humidities ($P_{wa}=20$ mm Hg and above) a full aluminized suit, consisting of long coat, full trousers, spats and hard hat, represented a greater handicap for prolonged use than ordinary work clothing. Subjects became overheated because the suit interfered with evaporation of their sweat. In a trial where only the front of the body was exposed to the high level radiant source, we found that an aluminized apron and similar reflective covering for the front of the legs provided nearly as much protection as the full suit and permitted necessary evaporation.

(c) *Thermally conditioned clothing.* Numerous ideas have been incorporated in special clothing for maintaining comfort in extreme heat (or cold). Some systems supply appropriately cool air from a mechanical refrigerator to points under a jacket or coveralls. When air from a remote source is used there are two problems. One is the gain of heat through the walls of the supply tubing. This problem has been solved in some cases

by using porous tubing which will leak an appropriate amount of supply air to keep the wall of the tubing suitably cool. The other problem is distribution of the air through the suit. With a simple, single orifice it is difficult to cool a sufficient area of skin; cooling limited to the face or trunk is usually not enough. Provision of several orifices, though better, will create bulk and restrict mobility. In fact, the restriction of movement resulting from tethering the worker to supply line will often contraindicate this type of system.

The vortex tube source of cool air has been used successfully in some situations.³ The device is carried on the belt. Air introduced tangentially at high velocity is forced into a vortex, which results in two separable streams of air, one cold which is distributed under the suit, the other hot which is discarded. Compressed air requirements to operate the vortex system are large.

Self-contained sources of conditioned air which can be back-packed have also been developed. One contains a liquid which is sealed into a finned container. After being cooled in a deep freeze the container is placed in the pack. A small battery-driven fan circulates air across the fins and into the suit. A single charging of this device may extend tolerance for relining furnace walls from several minutes to 30 or 60 minutes.

More sophisticated devices employ a closed fluid-filled system and a fairly elaborate network of small tubing for distribution.

The nuisance factor must be considered with all such devices. Men will not go to the trouble of donning them unless they recognize more than a marginal advantage. On the other hand, with such devices it has sometimes been possible to change hot tasks which required long rest pauses into continuous duty operations involving fewer workers.

Checklist

The emphasis of this section has been on rationalization of the options for control of heat exposures, based on consideration of all elements of specific situations. Often there are several options which may be capitalized upon simultaneously without conflict. In other cases trade-offs must be weighed. Table 38-1 is a checklist which may be helpful in considering options which have been discussed in the text.

COLD

Introduction

Protection of the body against excessive cooling has not received popular attention of occupational health workers to the extent of protection against heat, even though many workers are exposed to cold conditions. This is despite the fact man has much more innate ability to adapt to heat, attributable to his well-developed sweating mechanism. In cold, he can only resort to constriction of skin blood vessels or shivering. If nude, at rest, and in still air the dermal vasoconstriction will avail to provide heat balance only down to about 28°C (82°F). Man's adaptation to cold has been based on his ingenuity in pro-

TABLE 38-1
CHECKLIST FOR CONTROLLING HEAT
STRESS AND STRAIN

Item	Actions for Consideration
Components of Heat Stress	
M, body heat production of task	reduce physical demands of the work; powered assistance for heavy tasks
R, radiative load	interpose line-of-sight barrier furnace wall insulation metallic reflecting screen heat reflective clothing cover exposed parts of body
C, convective load	if air temperature above 35°C (95°F) reduce air temperature reduce air speed across skin wear clothing
E _{max} , maximum evaporative cooling by sweating	increase by decreasing humidity increasing air speed
Acute Heat Exposures	
R, C and E _{max}	air or fluid conditioned clothing; vortex tube
duration and timing	shorten duration each exposure; more frequent better than long to exhaustion
exposure limit	self-limited, based on formal indoctrination of workers and foremen on signs and symptoms of overstrain
recovery	air conditioned space nearby
Individual Fitness for Work in Heat	determine by medical evaluation, primarily of cardiovascular status careful break-in of unacclimatized workers water intake at frequent intervals non-job related fatigue or mild illness may temporarily contraindicate exposure (e.g. low grade infection, diarrhea, sleepless night)

viding himself with insulative clothing and heated shelter.

Clothing Requirements

The same heat balance equation that is used for heat exposures is applied also for cold. Equilibrium is achieved when $M + R + C = E$, but in cold weather R and C are minus quantities. E will reflect activity of the sweat glands as needed to balance the equation. When not overclothed, E is still present to the extent that body water diffuses through the skin (about 15 grams per hour with cooling value of 10 kcal per hour) and the lungs. The lung loss is also about 15 g per hour when inactive, but increases in proportion to ventilation of the lungs during activity. There are also small losses in warming cold inspired air,¹² which are neglected in this treatment. Minimum combined losses by E are commonly assumed to be about 25 percent of M when clothing requirements are being considered. Thus, 0.75 M is the heat available for loss by (R+C) when heat balance is being maintained without recourse to excessive sweating.

Over the thermal range of interest, Newton's Law of Cooling is applicable; this states that heat loss will be proportional to the thermal gradient

divided by the insulation. In this instance:

$$(R + C) = \frac{T_s - T_a}{\text{Insulation}}, \text{ where}$$

T_s and T_a are skin surface and air temperature, respectively. In the equilibrium state, and since $(R + C) = 0.75 M$, insulation requirement for a known thermal gradient may be expressed as:

$$\text{insulation required} = \frac{(T_s - T_a)}{0.75 M}$$

The unit used for describing insulation needs or insulation value with respect to clothing of man is the clo.*¹³ In this unit the insulation required is:

$$I_{\text{clo}} = \frac{5.55(T_s - T_a)}{0.75 M}$$

The value 5.55 is the coefficient which applies where T_s and T_a are in °C and M is in kcal per square meter of body surface per hour.

Application of the equation is illustrated in answering the question: How much insulation is required to maintain comfort for a man seated at rest (M = 50 kcal/m²·hr) at 21°C (70°F)? The

*The unit was selected to represent the approximate insulation value of a business suit. One clo will maintain a thermal gradient of 0.18°C over an area of one square meter when the thermal flux is one kcal/hr.

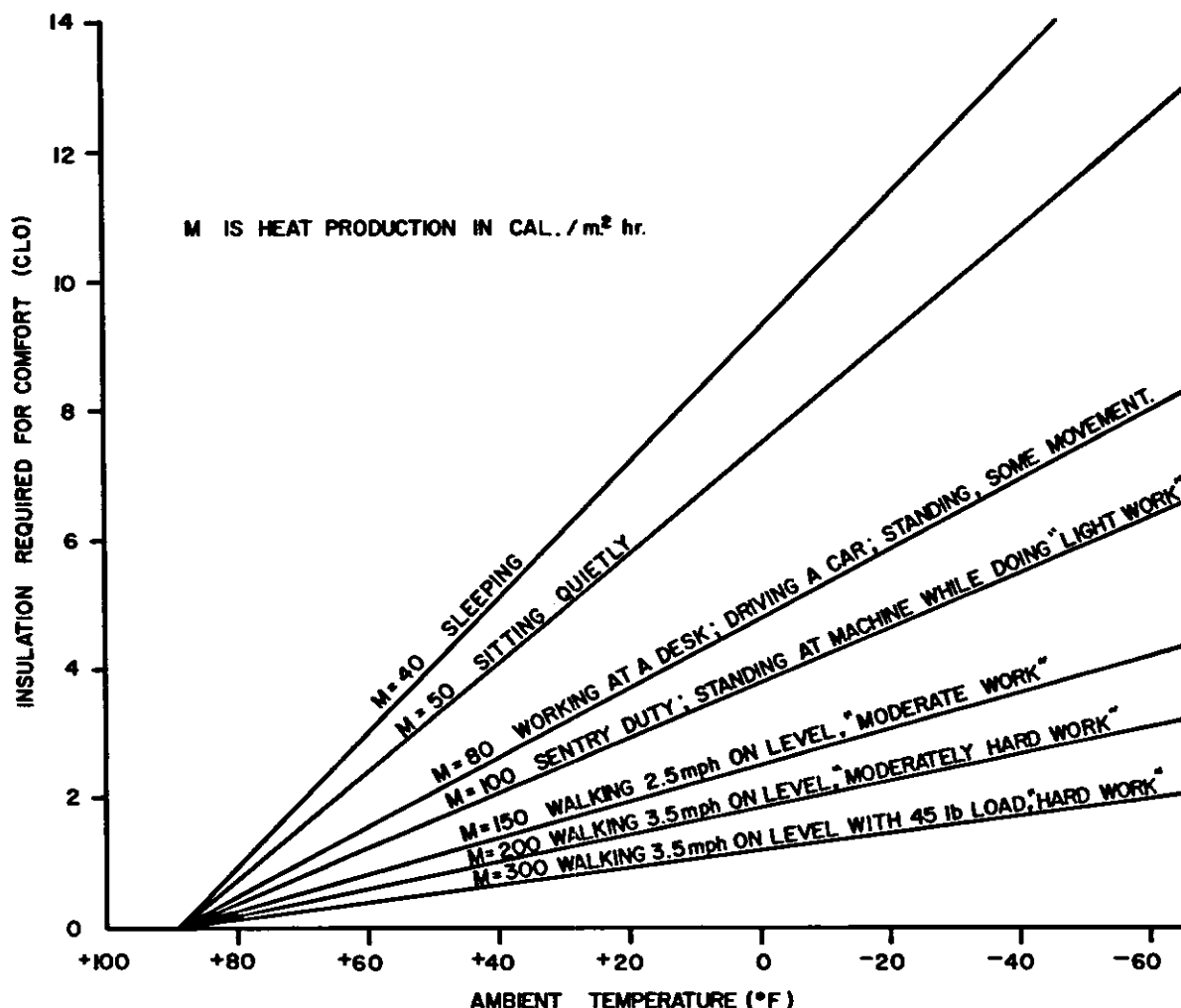
skin temperature for comfort is known to average about 33°C, so

$$I_{clo} = \frac{5.55(33 - 21)}{38} = 1.7$$

The total insulation need may be met from two sources, both of which fundamentally involve immobilization of a layer of "still air" (under practical conditions one-quarter inch of "still air" is worth about 1 clo). The first source is the film of air which always overlies the outside of the clothing, or the surface of the skin when it is bare). This insulation of air, I_a , is worth about 0.7 clo when the body is inactive and is exposed to the natural convection present in a room. I_a varies as a power function of the reciprocal of air speed: at 30 m (100 ft) per minute it is 0.5 clo, at 100 m (330 ft) per minute it is 0.3 clo. The second source of insulation must be the clothing itself, I_{cl} . Thus, the clothing needed at 21°C would be 1 clo in still air, because I_a contributes 0.7; at 100 m per minute the clothing *per se* would have to be worth 1.4 clo.

When at rest as in the example, each added clo of insulation will protect to a 6.8°C (12°F) lower temperature. This means a total requirement for thermal equilibrium of 4.8 clo while sitting at 0°C (32°F). On the other hand when working at a fairly hard M of 200 a total of only 1.2 clo should suffice for heat balance at the temperature; i.e., $5.55(33/150) = 1.2$. The requirements for various levels of work at various temperatures are shown in Figure 38.2. The disparity of requirements for work and rest gives rise to one of the biggest problems for workers who are out-of-doors for prolonged periods in cold weather. The tendency of the inexperienced is to overdress. The result is copious sweating in the body's attempt to maintain heat balance while working. The heavy clothing will not permit sufficient evaporative cooling. A substantial amount of the sweat is accumulated in the clothing and continues to evaporate during subsequent rest, thus counteracting available insulation at a time when it is most needed.

When in sunlight the net heat loss by (R + C)



Newburgh, L. H. (ed.): Physiology of Heat Regulation and the Science of Clothing. New York, Hafner, 1968 reprint of 1949 Edition.

Figure 38-2. Prediction of Total Insulation Required for Prolonged Comfort at Various Activities in the Shade as a Function of Environmental Temperature. From reference 14.

is reduced. The amount of reduction depends on the intensity of the solar energy as well as the thickness and color of the clothing. When nude the effect of sunlight may be considered the same as elevation of T_a by about 10°C (18°F). In heavy clothing the effect will be much less, probably 2 to 3°C .¹³

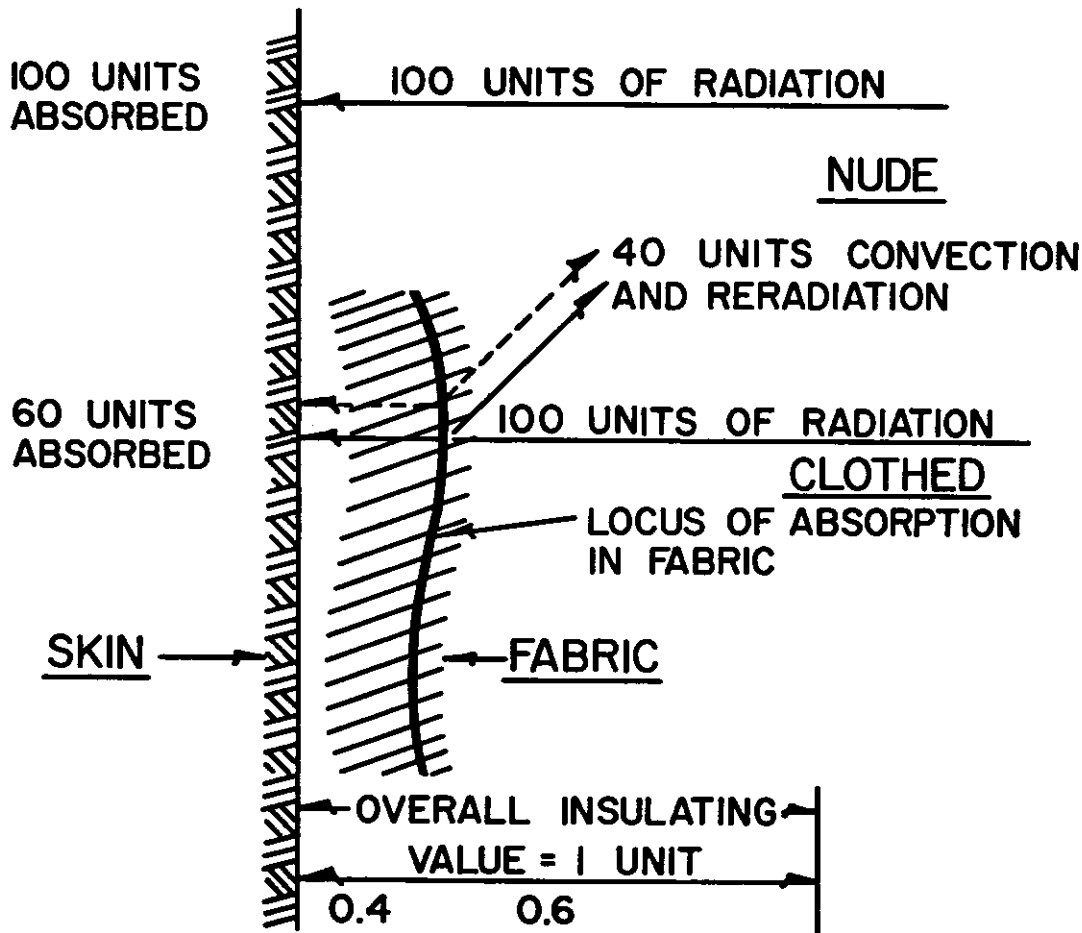
It has been estimated that when clothing insulation is less than adequate to maintain heat balance some 40 to 80 kcal/m² may be withdrawn in body cooling before undue discomfort develops.¹⁴ Thus, if exposures are time-limited there is margin for error in selection of insulation.

Materials and Design of Clothing

The thermal worth of clothing may be determined by human calorimetry. A volunteer subject wears the garment assembly while engaged in constant activity in a room of fixed thermal conditions. M is estimated from measurement of oxygen consumption; T_s and internal body temperature by thermocouples; and evaporative heat loss by change in body weight. The data can be ap-

plied to finding I_{clo} with the equation. Alternatively, an electrically heated copper manikin can be brought into thermal equilibrium, and on the basis of knowledge of the heat input and T_s and T_a , the insulation value can be calculated.

The insulating value of clothing depends on the thickness of air which it effectively immobilizes, not on specific insulation of the materials themselves. Thus an equal thickness of steel wool and eider down will provide about the same insulation. To adjust for vagaries of weather and variables of work load cold weather outfits should be multilayered. Even so, it is difficult to raise the total protection above 3 clo without markedly interfering with body movements. The outer layer and perhaps a secondary layer should be of wind resistant fabric. Lightness of garments is achieved through use of resilient, low density materials (quilted fibers, pile, loosely woven wool or synthetics). Looseness of fit and easily adjustable closures will provide help in modifying the insulation to meet variable needs for work and rest.



Hertig, B. A., Belding, H. S.: Evaluation and control of heat hazards in: Temperature: Its Measurement and Control in Science and Industry. New York, Reinhold Publishing Corp., 1963, vol. 3, pt. 3, p. 347.

Figure 38-3. Diagrammatic Cross Section through Skin and Clothing To Show Factors Affecting Efficiency of Protection against Long-Wave Radiant Energy.

In extreme cold, there is no adequate protection for hands during periods of inactivity; this is because thruflow of warm blood is reduced to almost nothing. Mittens are better than gloves because they present less surface area for heat loss. Blood flow to the feet is similarly curtailed whenever overall Iclo falls below the requirement for heat balance. The best known foot protection is provided by insulated boots sealed inside and outside by vapor barriers. The face, which has good circulation of blood, will usually be adequately protected if a forward-projecting fur ruff is available to protect against wind. Masks are not recommended for prolonged use in extreme cold because frostbite may develop unnoticed.

A principle of clothing applicable to both hot and cold weather was illustrated in this chapter by our finding that 40 percent of radiation impinging on ordinary work clothing does not reach the skin. Actually, the effect is dependent on the ratio of insulation lying outside the locus of absorption (including Ia) to the total insulation, as shown in Figure 38-3. The same principle applies to heat absorbed or emitted from other sources. For example, the effectiveness of electrically heated garments depends on proximity of the wires to the skin.

In hot or cold weather clothing the efficiency of evaporative cooling by sweat is likewise dependent on the locus of the evaporation. If directly from the skin the efficiency is 100 percent. However, if the sweat is wicked outward and evaporated at some distance from the skin the efficiency is lowered accordingly and extra sweat must be produced to achieve the same amount of body cooling.

Further details on protection against cold appear in references (12) and (13).

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PRINCIPLES OF VENTILATION*John E. Mutchler***INTRODUCTION**

Ventilation is one of the most important engineering control techniques available to the industrial hygienist for improving or maintaining the quality of the air in the occupational work environment. Broadly defined, ventilation is a method of controlling the environment with air flow. In industrial ventilation this air flow may be used for one or a combination of the following reasons:

1. Heating or cooling;
2. Removing a contaminant;
3. Diluting the concentration of a contaminant;
4. Supplying make-up air.

These basic uses of industrial ventilation can be divided into three major applications:

1. The prevention of fire and explosions;
2. The control of atmospheric contamination to healthful levels;
3. The control of heat and humidity for comfort.

All of these applications are important to the industrial hygienist, and each must be understood thoroughly in order to provide safe, healthful and comfortable working conditions. The control of heat and humidity is covered in Chapter 38. This chapter, "Principles of Ventilation," together with Chapters 40, 41 and 42, deals primarily with the control of atmospheric contamination for assuring a healthful work environment.

CLASSIFICATION OF VENTILATING SYSTEMS

The control of a potentially hazardous airborne contaminant by ventilation can be accomplished by either one or both of two methods: diluting the concentration of the contaminant before it reaches the worker's breathing zone by mixing with uncontaminated air, or capturing and removing the contaminant at or near its source or point of generation, thus preventing the release of the contaminant into the workroom. The first of these methods is termed "general ventilation" or "dilution ventilation"; the second is called "local exhaust ventilation." Dilution ventilation does not reduce or eliminate the total amount of hazardous material released into the workroom air; local exhaust ventilation prevents the release of the contaminant within the workroom. Normally, local exhaust ventilation is the preferred and more economical method for contaminant control compared with dilution ventilation.

The differences between dilution and local exhaust ventilation are not always clearly defined.

Nevertheless, the following criterion is used in classifying a ventilation system as one type or the other:¹

A ventilation system is a dilution ventilation system if the concentration of contaminant in the exhaust air stream is not significantly higher than in the general room air; it is a local exhaust system if the concentration of material in the exhaust air stream is significantly higher than that in the general room air.

General Ventilation

The term "general ventilation" suggests that a room or an entire building is flushed by supplying and exhausting large volumes of air throughout the area. Properly used, general ventilation can be very effective for the removal of large volumes of heated air or for the removal of low concentrations of non-toxic or low toxicity contaminants from minor and decentralized sources. General or dilution ventilation is achieved by either natural or mechanical means. Often the best overall result is obtained with a combination of mechanical and natural air supply with mechanical and natural exhausters.

Natural General Ventilation. The natural means by which buildings or enclosures can be ventilated include wind and thermal convection. These two effects, usually in combination, result from natural pressure differences and air density differences respectively, causing natural displacement and infiltration of air through windows, doors, walls, floors and other openings. Obviously, if it were sufficient, natural ventilation would be much cheaper than mechanical ventilation, but wind currents and thermal convection are erratic and sometimes hard to predict. Therefore, natural ventilation is unreliable as a primary control method. Erratic wind direction alone makes this aspect of natural ventilation undependable as a primary method of solution to any critical dilution ventilation problem.

When the wind is blowing, a pressure is exerted on the upwind side and a suction is exerted on the downwind side of the building. Wind forces can be accurately predicted for a flat terrain, but the determination of wind forces within a cluster of industrial buildings defies the inherent simplicity which design parameters must exhibit to be useful and applicable to ventilation engineering problems.

The amount of air that enters a building under a natural ventilation scheme depends both upon the wind and upon thermal effects occurring within the building. Warmer air inside a building rises

and leaks out of openings, cracks, and vents in the upper areas; colder air leaks into the building by the same process in the lower areas, assuming the same degree of tightness throughout.

Thermal (air density) effects are more predictable than wind forces, and these effects can be reduced by calculation to useful engineering parameters.^{2, 4} Air density differences are often significant in hot, dry, industrial areas such as foundries and steel mills. The combined effect of wind and temperature differences can be significant under certain conditions, and can be characterized quantitatively in some applications.

The design of modern industrial buildings has increased the problem of controlling man's working conditions. Older buildings often provided a significant amount of natural ventilation because they were tall and narrower in width than length. Heated air rose to the roof and was expelled at the top of the building, while replacement air entered the building at the lower perimeter. This type of design is still used in many hot industries such as foundries but obviously this arrangement cannot provide acceptable working conditions under all circumstances.

Mechanical General Ventilation. The modern large-area, low-height industrial plant and most multi-story buildings of masonry and glass construction, present entirely different ventilation problems. In these cases, natural ventilation forces are practically nil, and mechanical ventilation must be relied on almost completely. To this end, mechanical exhaust of contaminated air is required and mechanical air supply must be provided all year round to reach interior areas, provide adequate air distribution and prevent creation of negative pressures in the building.

In large open industrial buildings, general ventilation can be achieved by roof fans used with or without gravity ventilators. Where little or no heat is available to furnish natural ventilation or where roof head-room is low, roof fans should be used in place of gravity ventilators to provide a measure of general exhaust ventilation.

The best method of providing general ventilation in a closed building is to supply air through duct work and distribute it into the work areas in a manner that will provide both humidity and temperature control.

Local Exhaust Ventilation

A local exhaust system is one in which the contaminant being controlled is captured at or near the place where it is created or dispersed. In contrast to dilution or general ventilation, local ventilation places much more reliance on mechanical methods of controlling air flow. A local exhaust system usually includes the use of hoods or enclosures, ductwork leading to an exhaust fan, an air cleaning device for air pollution abatement and finally, discharge to the outside air. Local exhaust systems usually contain more mechanical components than general exhaust systems, offer more operational parameters to be controlled within acceptable ranges, and therefore require more maintenance.

The term "local exhaust" does not necessarily imply that the system is small. For example, the

hood over a basic oxygen furnace in a steel mill is a local exhaust hood even though it may exhaust a million cubic feet per minute of air. A local exhaust system is usually superior to general ventilation if the main purpose of the ventilation is contaminant control. These advantages include the following:^{2, 4}

1. If the system is properly designed, the capture and control of a contaminant can be complete. Consequently, the exposure to workmen from the sources exhausted can be prevented. With general ventilation the contaminant has been diluted when the exposure occurs, and at any given workplace this dilution may be highly variable and therefore inadequate at certain times.
2. The volume rate of required exhaust is less with local ventilation; as a result, the volume of make-up air required is less. Local ventilation saves in both capital investment and heating costs.
3. The contaminant is contained in a smaller exhausted volume of air; therefore, if air pollution control is needed, it is less costly. As a first approximation, the cost of air pollution control is proportional to the volume of air handled.
4. Many local exhaust systems can be designed to capture large settleable particles or at least confine them within the hood and thus greatly reduce the labor required for good housekeeping.
5. Auxiliary equipment in the workroom is better protected from the deleterious effects of the contaminant, such as corrosion and abrasion.
6. Local exhaust systems usually require a fan of fairly high pressure characteristics to overcome pressure losses in the system. Therefore, the performance of the fan system is not likely to be adversely affected by wind direction or velocity, or inadequate make-up air, etc. This is in contrast to general ventilation which can be greatly affected by seasonal factors.

Glossary of Terms in Industrial Ventilation

The following list of terms have a special meaning within the field of industrial ventilation:^{2, 4, 6}

Blast gate. A device for restricting airflow in a duct, usually consisting of a flat sliding plate which moves perpendicularly to the duct center line.

Capture velocity. The air velocity at a point within or in front of an exhaust hood necessary to overcome opposing air currents and particle inertia, causing the contaminated air to flow into the hood.

Coefficient of entry. The ratio of the actual rate of air flowing into an exhaust opening to the theoretical rate, calculated by assuming that the negative static pressure in the exhaust opening is completely converted to velocity pressure.

Control velocity. The air velocity required at the face of an enclosing hood to retain the contaminant within the hood.

Damper. A device for restricting the airflow in a duct, usually consisting of a flat disc mounted on a shaft which is perpendicular to the direction of airflow.

Entry loss. Loss in static pressure caused by air flowing into a duct or hood opening.

Entry loss factor. A factor derived from the coefficient of entry which, when multiplied by the velocity pressure at the hood, yields the entry loss in inches of water gauge.

Exhaust rate. The volumetric rate at which air is removed.

Grain. A unit of weight equal to 1/7000 of a pound.

Micron. A unit of length equal to 0.001 millimeter or 0.0000394 inches.

Plenum. A receiving enclosure for gases in which the static pressure at all points is relatively uniform.

Reynolds number. A dimensionless parameter computed by dividing the product of pipe diameter, average velocity and fluid density by the fluid viscosity.

Slot velocity. Linear flowrate of air through a slot.

Standard air. Dry air at 29.92 inches of mercury absolute pressure and 70°F, weighing 0.075 pound per cubic foot.

Static pressure. The pressure of a fluid exerted in all directions equal and opposite to the pressure tending to compress the fluid. In ventilation applications, static pressure is usually the difference between the absolute pressure in an exhaust system and atmospheric pressure, such that static pressure less than atmospheric pressure is termed "negative static pressure."

Still air. Air with a velocity of 25 feet per minute or less. Under practical circumstances there is always random air motion of 10 to 20 feet per minute even in rooms regarded as tightly constructed. This non-zero convection results from thermal circulation due to temperature differences, leakage in the building due to wind pressure and thermal head, and the ordinary movement of people.

Tempered air. Supply air which has been heated sufficiently to prevent cold drafts.

Total pressure. The algebraic sum of static pressure and velocity pressure.

Transition. A change in the cross-sectional shape or area of a duct or hood.

Transport (conveying) velocity. That velocity required to prevent the settling of a contaminant from an air stream, usually related to the flow of air in a duct.

Velocity pressure. The kinetic pressure due to flow, equal to that required to bring a fluid at rest to flow at a given velocity. Velocity pressure is always positive and in the direction of air flow.

FUNDAMENTALS OF VENTILATION AIR FLOW

The basic laws describing the complete motion of a fluid are complex and largely unknown. In

the simple case of laminar flow the motion of the fluid may be computed analytically. However, for turbulent flow only a partial analysis can be made using the principles of fluid mechanics. The air flow in a local exhaust system is always turbulent to some degree; that is, the Reynolds number, an index of turbulence, is greater than 4,000. Therefore, the analytical solution to motion of air in exhaust systems is largely empirical and depends on experimental data.

Conservation of Mass

A basic consideration in the principles of air flow is the continuity equation or conservation of mass. This equation states that the mass rate of flow remains constant along the path taken by a fluid. Therefore, for any two points in a fluid stream:

$$A_1 v_1 \delta_1 = A_2 v_2 \delta_2$$

where

A = cross sectional area, ft²

v = velocity, ft/min.

δ = specific weight, lb/ft³

In most applications in industrial ventilation, δ is relatively constant because the absolute pressure within a ventilation system usually varies over a very narrow range and the air remains relatively incompressible. Therefore,

$$A_1 v_1 = A_2 v_2$$

and

$$Q_1 = Q_2$$

where Q = Av, the volumetric rate of air flow, ft³/min.

Conservation of Energy

The basic energy equation of a frictionless, incompressible fluid for steady flow along a single stream line is given by Bernoulli's Theorem:

$$H + \frac{P}{\delta} + \frac{v^2}{2g} = C$$

where H = the elevation above any arbitrary datum plane, ft

P = absolute pressure, lb/ft²

δ = specific weight, lb/ft³

v = velocity, ft/sec

g = gravitational acceleration, ft/sec²

C = a constant, different for each stream-line.

Each of the three variable terms in Bernoulli's equation has the units foot-pounds per pound of fluid, or feet of fluid, frequently referred to as elevation head, pressure head and velocity head, respectively.

When Bernoulli's equation is applied to industrial exhaust systems the elevation term, H, is usually omitted since only relatively small changes in elevation are involved. Since all streamlines originate from the atmosphere, a reservoir of nearly constant energy, the constant, C, is the same for all streamlines and the restriction of the equation to a single stream line can be removed. Furthermore, since the pressure changes in nearly all exhaust systems are at most only a few percent of the absolute pressure, the assumption of incompressibility may be made with negligible error.

Velocity Pressure

Air in motion exerts a pressure called velocity pressure. Velocity pressure maintains air velocity and is analogous to kinetic energy. It exists only when air is in motion, it acts in the direction of air flow, and it is always positive in sign. In Bernoulli's equation, the term $\frac{v^2}{2g}$ represents the velocity head. The relationship between the velocity of air and velocity pressure is:

$$v = \sqrt{2gh}$$

Where v = velocity, ft/sec
 g = gravitational acceleration, ft/sec²
 h = head of air, ft

When $g = 32.17$ ft/sec² and the density of air is 0.075 pound per cubic foot, then:

$$V = 4005 \sqrt{VP} \text{ fpm}$$

where VP = velocity pressure, inches of water. Table 39-1 presents standard air velocity equivalents for velocity pressures between 0.01 and 14 inches of water.

Static Pressure

Static pressure produces initial air velocity, overcomes the resistance in a system caused by friction of the air against the duct walls, and overcomes turbulence and shock caused by a change in direction or velocity of air movement. Static pressure is analogous to potential energy and it exists even where there is no air motion. It acts equally in all directions and either tends to collapse the walls of the duct upstream from the fan or tends to expand the walls of the duct on the downstream side. Static pressure is usually negative in sign upstream from a fan and positive in sign downstream. It is measured as the difference between duct pressure and atmospheric pressure. The most common units of static pressure are inches of water.

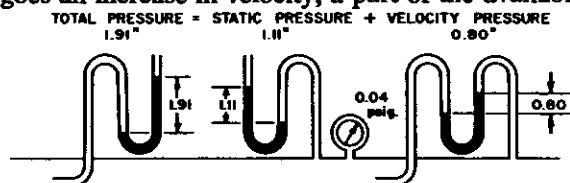
Total Pressure

The driving force for air flow is a pressure difference. Pressure is required to start and maintain flow. This pressure is called total pressure and has two components: velocity pressure and static pressure. Static pressure, velocity pressure and total pressure are all interrelated:

$$SP + VP = TP$$

Figure 39-1 shows the relationship between static, velocity and total pressure at different points in a duct system.

If gas flowing through a duct system undergoes an increase in velocity, a part of the available



American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation — A Manual of Recommended Practice, 12th Edition. Lansing Michigan, 1972.

Figure 39-1. Relationship Between Static Pressure, Velocity Pressure, Total Pressure.

static pressure is used to create the additional velocity pressure necessary to accelerate the flowing gas. Conversely, if the velocity is reduced at some point in a duct system, a portion of the kinetic energy or velocity pressure at that point is converted into potential energy or static pressure. Static and velocity pressure are, therefore, mutually convertible. However this conversion is always accompanied by a net loss of total pressure due to turbulence and shock; i.e., the conversion is always less than 100% efficient.

Friction Losses

Air in motion encounters resistance along any surface confining the flowing volume. Consequently, some of the energy of the air is given up in overcoming this friction and is transformed into heat. The rougher the surface confining the flow or the higher the flow rate, the higher the frictional losses will be.

Frictional loss in a duct varies directly as the length, inversely as the diameter, and directly as the square of the velocity of air flowing through the duct. This loss can be calculated from charts⁴ using the Fanning friction factor, which is an empirical function of Reynolds number, duct material and type of construction.

Dynamic Losses

Another type of energy loss encountered in air flow results from turbulence caused by a change in direction or velocity within a duct. The pressure drop in a duct system due to dynamic losses increases with the number of elbows or angles and the number of velocity changes within the system. The resulting pressure drop from these energy losses is expressed in units of "equivalent length." For example, an elbow of 12-inch diameter and 24-inch centerline radius is said to have an equivalent length of 17, meaning that the loss through the elbow will be the same as the loss through 17 feet of straight pipe with the same diameter operating under the same conditions (see *Industrial Ventilation*,⁴ Fig. 6-11).

Another method of defining the losses due to turbulence and friction is to express the losses in terms of velocity pressure. For example, a loss of 0.28 VP in a transition or elbow means that the incremental pressure drop is equal to 0.28 of the velocity pressure of the air stream at that point (see *Industrial Ventilation*,⁴ Figure 6-12, 6-13).

Acceleration and Hood Entrance Losses

This type of dynamic loss, h_e , is a drop in pressure caused by turbulence when air is accelerated from rest to enter a duct or opening. Turbulence losses of this type vary with the type of opening and are defined for ducts and common types of hoods in Fig. 4-8, *Industrial Ventilation*.⁴

This entry loss plus the acceleration energy required to move the air at a given velocity (one VP) comprise the hood static pressure, SP_h . SP_h is expressed algebraically as:

$$SP_h = h_e + VP.$$

SP_h can be measured directly at a short distance downstream from the hood entrance. The calculation of SP_h is the first step in the design or evaluation of a local exhaust system, discussed in Chapters 41 and 42.

TABLE 39-1
Velocity Pressures for Different Velocities —
Standard Air⁴

FROM: $V = 4005 \sqrt{VP}$

V = VELOCITY FPM
 VP = VELOCITY PRESSURE, INCHES OF WATER

VP	V	VP	V	VP	V	VP	V	VP	V	VP	V
0.01	400	0.52	2888	1.03	4064	1.54	4970	2.05	5734	3.10	7051
0.02	556	0.53	2916	1.04	4084	1.55	4986	2.06	5748	3.20	7164
0.03	694	0.54	2943	1.05	4103	1.56	5002	2.07	5762	3.30	7275
0.04	801	0.55	2970	1.06	4123	1.57	5018	2.08	5776	3.40	7385
0.05	896	0.56	2997	1.07	4142	1.58	5034	2.09	5790	3.50	7492
0.06	981	0.57	3024	1.08	4162	1.59	5050	2.10	5804	3.60	7599
0.07	1060	0.58	3050	1.09	4181	1.60	5066	2.11	5817	3.70	7704
0.08	1133	0.59	3076	1.10	4200	1.61	5082	2.12	5831	3.80	7807
0.09	1201	0.60	3102	1.11	4219	1.62	5098	2.13	5845	3.90	7909
0.10	1266	0.61	3127	1.12	4238	1.63	5114	2.14	5859	4.00	8010
0.11	1328	0.62	3153	1.13	4257	1.64	5129	2.15	5872	4.10	8109
0.12	1387	0.63	3179	1.14	4276	1.65	5144	2.16	5886	4.20	8208
0.13	1444	0.64	3204	1.15	4295	1.66	5160	2.17	5899	4.30	8305
0.14	1498	0.65	3229	1.16	4314	1.67	5175	2.18	5913	4.40	8401
0.15	1551	0.66	3254	1.17	4332	1.68	5191	2.19	5927	4.50	8496
0.16	1602	0.67	3279	1.18	4350	1.69	5206	2.20	5940	4.60	8590
0.17	1651	0.68	3303	1.19	4368	1.70	5222	2.21	5954	4.70	8683
0.18	1699	0.69	3327	1.20	4386	1.71	5237	2.22	5967	4.80	8774
0.19	1746	0.70	3351	1.21	4405	1.72	5253	2.23	5981	4.90	8865
0.20	1791	0.71	3375	1.22	4423	1.73	5268	2.24	5994	5.00	8955
0.21	1835	0.72	3398	1.23	4442	1.74	5283	2.25	6008	5.10	9044
0.22	1879	0.73	3422	1.24	4460	1.75	5298	2.26	6021	5.20	9133
0.23	1921	0.74	3445	1.25	4478	1.76	5313	2.27	6034	5.30	9220
0.24	1962	0.75	3468	1.26	4495	1.77	5328	2.28	6047	5.40	9307
0.25	2003	0.76	3491	1.27	4513	1.78	5343	2.29	6061	5.50	9392
0.26	2042	0.77	3514	1.28	4531	1.79	5359	2.30	6074	5.60	9477
0.27	2081	0.78	3537	1.29	4549	1.80	5374	2.31	6087	5.70	9562
0.28	2119	0.79	3560	1.30	4566	1.81	5388	2.32	6100	5.80	9645
0.29	2157	0.80	3582	1.31	4583	1.82	5403	2.33	6113	5.90	9728
0.30	2193	0.81	3604	1.32	4601	1.83	5418	2.34	6128	6.00	9810
0.31	2230	0.82	3625	1.33	4619	1.84	5433	2.35	6140	6.10	9891
0.32	2266	0.83	3647	1.34	4636	1.85	5447	2.36	6153	6.20	9972
0.33	2301	0.84	3669	1.35	4653	1.86	5462	2.37	6166	6.30	10052
0.34	2335	0.85	3690	1.36	4671	1.87	5477	2.38	6179	6.40	10132
0.35	2369	0.86	3709	1.37	4688	1.88	5491	2.39	6192	6.50	10210
0.36	2403	0.87	3729	1.38	4705	1.89	5506	2.40	6205	6.60	10289
0.37	2436	0.88	3748	1.39	4722	1.90	5521	2.41	6217	6.70	10366
0.38	2469	0.89	3769	1.40	4739	1.91	5535	2.42	6230	6.80	10444
0.39	2501	0.90	3800	1.41	4756	1.92	5550	2.43	6243	6.90	10520
0.40	2533	0.91	3821	1.42	4773	1.93	5564	2.44	6256	7.00	10596
0.41	2565	0.92	3842	1.43	4790	1.94	5579	2.45	6269	7.50	10968
0.42	2595	0.93	3863	1.44	4806	1.95	5593	2.46	6282	8.00	11328
0.43	2626	0.94	3884	1.45	4823	1.96	5608	2.47	6294	8.50	11676
0.44	2656	0.95	3904	1.46	4840	1.97	5623	2.48	6307	9.00	12015
0.45	2687	0.96	3924	1.47	4856	1.98	5637	2.49	6320	9.50	12344
0.46	2716	0.97	3945	1.48	4873	1.99	5651	2.50	6332	10.00	12665
0.47	2746	0.98	3965	1.49	4889	2.00	5664	2.60	6458	11.00	13283
0.48	2775	0.99	3985	1.50	4905	2.01	5678	2.70	6581	12.00	13874
0.49	2804	1.00	4005	1.51	4921	2.02	5692	2.80	6702	13.00	14440
0.50	2832	1.01	4025	1.52	4938	2.03	5706	2.90	6820	13.61	14775
0.51	2860	1.02	4045	1.53	4954	2.04	5720	3.00	6937	14.00	14986

The coefficient of entry, C_e , is a measure of how efficiently a hood entry is able to convert static pressure to velocity pressure. The coefficient of entry is defined as the ratio of rate of flow by the hood static pressure to the theoretical flow if the hood static pressure were completely converted to velocity pressure. This term is computed as follows:

$$C_e = \frac{4005A \sqrt{VP}}{4005A \sqrt{SP_h}} = \frac{\sqrt{VP}}{\sqrt{SP_h}}$$

Pressure Drop through Ductwork

The result of the friction and dynamic losses to air flowing through ductwork is a pressure drop in the system. Bernoulli's Theorem can be restated in a simplified expression of conservation of energy as follows:⁴

$$SP_1 + VP_1 = SP_2 + VP_2 + \text{losses.}$$

Static pressure plus velocity pressure at a point upstream in direction of air flow equals the static pressure plus velocity pressure at a point downstream in direction of air flow plus friction and dynamic losses.

PROPERTIES OF AIRBORNE MATERIALS

Dusts

Dusts are solid particles generated by handling, crushing, grinding, and detonation of organic and inorganic materials such as rock, metal, coal, wood, and many other materials. Dust particles do not diffuse in air in the classical sense, but the finer particles of diameters <20 microns are carried with air currents because the settling rate is so low as to be of no practical significance. Dust particles must be about 5 microns or smaller to reach the lungs; larger particles are filtered out in the nasal passages or other parts of the breathing apparatus.

Fumes

Fumes are small, solid particles created by condensation from the gaseous state, generally after volatilization or by chemical reaction such as oxidation. Fumes are usually submicronic in size.

The outstanding characteristic of most fumes is their tendency to flocculate and coalesce. Very small spherical fume particles tend to attach themselves together in long chains or clumps of particles due to Brownian diffusion and electrostatic attraction.

Mists

Mists are suspended liquid droplets generated by condensation from the gaseous to the liquid state or by breaking up a liquid into a dispersion such as by splashing, foaming and atomizing. Fogs are similar to mists but the term is usually reserved for high concentrations of very fine droplets that are more frequently airborne.

Smoke

Smoke is the aerosol mixture which results from the incomplete combustion of carbonaceous material such as coal, oil, tar and tobacco.

Vapors

Vapors are the gaseous forms of substances which are normally in the liquid or solid state and which can be changed to these states either by increasing the pressure or decreasing the temperature alone.

Gases

Gases are normally compressible, formless fluids which occupy the space of an enclosure and which can be changed to the liquid or solid state only by the effect of increased pressure and decreased temperature or both.

Effective Specific Gravity

Frequently, the location of exhaust hoods is mistakenly based on a supposition that the contaminant is "heavier than air" or "lighter than air." In most health hazard applications this criterion is of little value; hazardous dusts, fumes, vapors and gases are truly airborne, following air currents and are not subject to appreciable motion, either upward or downward, because of their own density.

APPLICATIONS OF DILUTION VENTILATION

When considering whether dilution or local exhaust is better, it should be remembered that dilution ventilation has four limiting factors:⁴

1. The quantity of contaminant generated must not be excessive or else the air volume necessary for dilution will be impractical.
2. Workers must be far enough away from contaminant evolution or else the contaminant must be in sufficiently low concentrations so that workers will not have an exposure above acceptable concentrations.
3. The toxicity of the contaminant must be low.
4. The evolution or generation of contaminants must be reasonably uniform.

On the basis of these factors, dilution ventilation is usually not recommended for fumes and dust because: (1) the high toxicities often encountered require excessively large quantities of dilution air; and (2) the velocity and rate of evolution are usually very high, resulting in locally high concentrations.

Dilution Ventilation for Comfort

Ventilation for heat relief includes certain aspects of air conditioning or treating of air to control simultaneously its temperature, humidity, cleanliness and distribution to meet the re-

quirements of the conditioned space. In most residential, office and commercial ventilation the requirements are comfort for the occupants. In many industrial situations, however, comfort conditions are impractical to maintain; and the function of ventilation and air conditioning along with other control methods is to prevent acute discomfort and adverse physiological effects.

Exhaust ventilation may be used to remove heat and humidity if a source of cooler air is available. If it is possible to enclose the heat source, such as in the case of ovens or certain furnaces, a gravity or forced air stack may be all that is necessary to prevent excessive heat from entering the workroom.

Dilution Ventilation for Preventing Fires and Explosions

One function of dilution ventilation is to reduce the concentration of vapors within an enclosure to below the lower explosive limit. However, this concept must not be applied in cases where workers are exposed to the vapor. In such instances, dilution rates for health hazard control must always be applied. The reason for this distinction is fundamental and must be thoroughly understood.

Threshold Limit Values or Acceptable Concentrations for health hazard control are typically 1-3 orders of magnitude below the lower explosive limit for a given material. A table of comparative values is shown below.^{4, 7}

Material	TLV ppm	LEL	
		%	ppm
Acetone	1000	2.55	25,500
Ethanol	1000	3.28	32,800
Isopropanol	400	2.02	20,200
Toluene	100	1.27	12,700
Xylene	100	1.00	10,000

Exposure to atmospheres controlled to concentrations "below" the lower explosive limit (or some fraction thereof) could cause narcosis, severe illness or death. Therefore it is extremely important not to confuse dilution ventilation requirements for health hazard control with fire and explosion prevention.

Dilution Ventilation for Health

In general, dilution ventilation is not as satisfactory as local exhaust ventilation for primary control of health hazards. However, there are occasional circumstances in which dilution ventilation must be used because the operation or process prohibits local exhaust. Circumstances may occasionally be found in which dilution ventilation provides an adequate amount of control more economically than a local exhaust system. However, this is the exception. One should be careful, moreover, not to base economical considerations entirely upon the initial cost of the system because dilution ventilation invariably exhausts large vol-

umes of heated air from a building. This can easily result in huge operating costs in the form of conditioned make-up air which will make the general ventilation scheme much more expensive over a period of time.

Dilution ventilation for the control of health hazards is used to best advantage in controlling the concentration of vapors from organic solvents of low toxicity. In order to successfully apply the principles of dilution to such a problem, data must be available on the rate of vapor generation or on the rate of liquid evaporation. Usually such data can be obtained from the plant if it keeps any type of adequate records on material consumption.

Rate of Air Change

The volume of a room to be ventilated and the ventilation rate are frequently related to one another by taking the ratio of the ventilation rate to the room volume to yield a "number of air changes per minute" or "number of air changes per hour." These are terms that are used quite frequently in discussions of ventilation requirements. Unfortunately, through widespread use over the years, they are more often employed incorrectly than properly.

It must be understood that ventilation requirements based on room volume alone have no validity. Calculations of the required rate of air change can only be made on the basis of a material balance for the contaminant under question. Similar calculations can be made for the rate of concentration increase or decrease; however, they require not only the air change rate but also the rate of generation of contaminant. In the design of industrial ventilation, "X number of air changes" has valid application only very rarely. The term is useful when applied to meeting rooms, offices, schools and similar spaces where the purpose of ventilation is simply the control of odor, temperature, or humidity and the only contamination of the air is from the activity of people.

Dilution ventilation requirements should always be expressed in cubic feet per minute or some other absolute unit of air flow, not in "Air Changes per Minute."

Calculating Dilution Ventilation

The concentration of a gas or vapor at any time can be expressed by a differential material balance, which, when integrated provides a rational basis for relating ventilation to the generation and removal rates of a contaminant.

Let C = concentration of gas or vapor at time t

G = rate of generation of contaminant

Q = rate of ventilation

K = design distribution constant, allowing for incomplete mixing

$Q' = Q/K$ = effective rate of ventilation, corrected for incomplete mixing

V = volume of room or enclosure

Starting with a fundamental material balance, assuming no contaminant is in the supply air,

Rate of Accumulation = Rate of Generation - Rate of Removal

$$VdC = Gdt - Q'Cdt$$

Consider the following applications:

1. Concentration Buildup

Rearranging the differential material balance,

$$\int_{C_1}^{C_2} \frac{dC}{G - Q'C} = \frac{1}{V} \int_{t_1}^{t_2} dt$$

$$\ln \left(\frac{G - Q'C_2}{G - Q'C_1} \right) = - \frac{Q'}{V} (t_2 - t_1)$$

if $C_1 = 0$ at t_1 ,

$$\ln \left(\frac{G - Q'C}{G} \right) = - \frac{Q'}{V} t$$

or,

$$\frac{G - Q'C}{G} = e^{-Q't/V}$$

Example A

$$V = 100,000 \text{ ft}^3$$

$$C_1 = 0$$

$$Q = 6000 \text{ cfm}$$

$$K = 3$$

$$Q' = 2000 \text{ cfm}$$

$$G = 1.2 \text{ cfm}$$

How long before the concentration of the contaminant reaches 200 ppm?

Solution:

$$t = - \frac{V}{Q'} \left[\ln \left(\frac{G - Q'C}{G} \right) \right] = 20.3 \text{ minutes}$$

Example B

Using the same values as in the preceding example, what will the concentration of the contaminant be after one hour?

Solution:

$$C = \frac{G - G e^{-\left(\frac{Q't}{V}\right)}}{Q'} = 419 \text{ ppm}$$

2. Rate of Purging

In the case where a volume of air is contaminated, but where further contamination or generation has ceased, the rate of decrease of concentration over a period of time is as follows:

$$VdC = -Q'Cdt$$

$$\int_{C_1}^{C_2} \frac{dC}{C} = - \frac{Q'}{V} \int_{t_1}^{t_2} dt$$

$$\ln \left(\frac{C_2}{C_1} \right) = - \frac{Q'}{V} (t_2 - t_1)$$

Example:

In the room of the examples above, assume that ventilation continues at the same rate ($Q' = 2000$ cfm), but that the contaminating process is interrupted. How much time is required to reduce the concentration from 100 to 25 ppm?

$$\ln\left(\frac{C_2}{C_1}\right) = \frac{-Q'}{V} (t_2 - t_1)$$

$$\Delta t = 69.3 \text{ minutes}$$

3. Maintaining Acceptable Concentrations at Steady State

At steady state, $dC = 0$

$$Gdt = Q'Cd t$$

$$\int_{t_1}^{t_2} Gdt = \int_{t_1}^{t_2} Q'Cd t$$

at a constant concentration C , and uniform generation rate, G ,

$$G(t_2 - t_1) = QC(t_2 - t_1)$$

$$Q' = \frac{G}{C}$$

$$Q = \frac{KG}{C}$$

Therefore, the rate of flow of uncontaminated dilution air required to reduce the atmospheric concentration of a hazardous material to an acceptable level can be easily calculated, if the generation rate can be determined. Usually the acceptable concentration is considered to be the Threshold Limit Value or Acceptable Eight-Hour Time Weighted Average Concentration. For liquid solvents the steady-state dilution ventilation requirement can be conveniently expressed as:

$$Q = \frac{(6.71)(10^6)(SG)(ER)(K)}{(MW)(TLV)}$$

Where: Q = actual ventilation rate, cfm
 SG = specific gravity of volatile liquid
 ER = evaporation rate of liquid, pints/hr
 MW = molecular weight of liquid
 K = design safety factor for incomplete mixing
 TLV = Threshold Limit Value, ppm.

Example:

Methylene chloride is lost by evaporation from a tank at the rate of 1.5 pints per hour. How much dilution air is required to maintain the concentration below the TLV?

For methylene chloride,

$$TLV = 500 \text{ ppm}$$

$$SG = 1.336$$

$$MW = 84.94$$

Assuming $K = 5$,

$$Q = \frac{(6.71)(10^6)(1.336)(1.5)(5)}{(84.94)(500)}$$

$$Q = 1583 \text{ cfm}$$

Specifying Dilution Ventilation

The foregoing discussion introduced the concept of a "design safety factor" (K) for calculating dilution ventilation requirements. This K factor is based upon several considerations:⁵

1. The efficiency of mixing and distribution of make-up air introduced into the room or space being ventilated.

2. The toxicity of the solvent. Although TLV and toxicity are not synonymous the following guidelines have been suggested for choosing the appropriate K value:

Slightly toxic material: TLV > 500 ppm

Moderately toxic material: TLV 100-500 ppm

Highly toxic material: TLV < 100 ppm

3. A judgment of any other circumstances which the industrial hygienist determines to be of importance, based upon experience and the individual problem. Included in these criteria are such considerations as:
 - a. Seasonal changes in the amount of natural ventilation.
 - b. Reduction in operation efficiency of mechanical air moving devices.
 - c. Duration of the process, operational cycle and normal location of workers relative to sources of contamination.
 - d. Location and number of points of generation of the contaminant in the work-room or area and,
 - e. Other circumstances which may affect the concentration of hazardous material in the breathing zone of the workers.

The K value selected will usually vary from 3 to 10 depending on the above considerations.

*Industrial Ventilation*⁴ (Table 2-1) lists the air volumes required to dilute the vapors of twenty-nine common organic solvents to the TLV level based upon the liquid volume solvent evaporated per unit time. These values must be multiplied by a K factor to allow for variations in uniformity of air distribution, and other considerations. Hemeon⁵ includes a table of recommended dilution rates for fifty-three organic solvents. The "Ventilation Design Concentrations" in this table are not based on threshold limit values alone, but are based also on odor. All of the concentrations in this table are lower than the threshold limits, but those substances which are especially toxic or which have a very disagreeable odor have the greatest safety factors.

It must be emphasized that Threshold Limit Values are subject to revision, and the use of tables to estimate dilution values may become obsolete if the Threshold Limit Values are lowered; therefore, such a table should be used with caution, and with reference to the *latest* TLV list.

MAKE-UP AIR

All local and general exhaust ventilation systems must have air to exhaust, and by the basic consideration of conservation of mass, that air must be supplied pound for pound by a make-up air system. The supply and distribution of make-up air is often over-looked or neglected in the design of ventilation but remains fundamental to its successful operation.

Principles for Supplying Make-Up Air

1. The fresh air intake should be located away from any contaminating sources such as exhaust stacks or furnace exhausts. It is advisable to filter the fresh air to protect

the equipment and provide maximum heat exchange efficiency.

2. The air supply system must be provided with a fan, otherwise the room or building will be under a negative pressure.
3. Make-up air sources should be located to provide cross ventilation. In this way, the air can be "used twice." First, it will provide general dilution and secondly it will provide make-up air for the exhaust systems. This does not apply for spot-cooling applications where the air will be introduced directly at the work station and may vary significantly from room temperature. The air distribution pattern must be engineered carefully to provide effective area coverage without excessive cross drafts which will interfere with the workers or the existing systems.
4. Make-up air should be introduced into the "living zone" of the plant, that is, below the 8-10 foot level. In this manner, the air is used first by the people and the best results of general or dilution ventilation are obtained. This distribution also provides closer control of the ambient working temperature.
5. Make-up air temperature is usually heated or cooled to approximately the same as desired in the room being supplied. Since the air is being used for ventilation and for replacement purposes, the usual temperature range will be 65-80°F.

Recirculation of Air from Industrial Exhaust Systems

Plant Circulation. It should be apparent that if large amounts of air are exhausted from a room or building in order to remove obnoxious dusts, gases, fumes or vapors an equivalent amount of fresh, tempered air should be supplied to the room. This supplied air must be heated in cold weather, and heating costs may be large if sizable amounts of air are handled. Therefore, attempts are sometimes made to eliminate such heating costs by appropriate cleaning of the exhausted air and subsequent recirculation of the air into the room. The acceptability of such recirculation depends on the degree of health hazard associated with the particular contaminant being exhausted as well as on other factors.

It is generally accepted as good practice not to recirculate exhaust air if the contaminants therein can have an effect on the health of the worker. The reasons are:

- a. Many types of air cleaners do not collect toxic contaminants efficiently enough to eliminate the health hazard. This is especially true for gases and vapors.
- b. Poor maintenance of the air cleaner would result in the return of highly contaminated air to the breathing zones of the workers. One of the facts of life is that air cleaners are not generally production equipment, and are too often poorly maintained or not maintained at all.

- c. Improper operation of the air cleaner through mechanical failure or through ignorance or neglect on the part of the operators can also result in the return of highly contaminated air.

In general, recirculation should be avoided unless the reasons indicating its use are truly compelling. Its use will always require an understanding of the hazardous nature of the contaminant, the knowledge of the performance of the specific air cleaner, the general ventilation scheme, and the judgment of experience.

Unplanned Recirculation. Unplanned recirculation of exhausted air can be a serious problem. This usually results from inadequately separated exhaust stacks and air inlets or insufficient discharge height, either from short stacks relative to the roof line or low "effective" stack height resulting from poorly designed weather caps on stack heads. This subject is treated in more detail in Chapter 42.

AIR MOVING DEVICES

The term "air moving device" is an inclusive one which denotes machines more commonly known as fans, blowers, exhausters, turbo compressors and ejectors. By definition, an air moving device (AMD) is a power-driven machine causing a continuous flow of air. In more practical terms, the air moving device manufacturer, to gain acceptance for his product, must earn membership to the "Air Moving and Conditioning Association" by subjecting his product to its test code for air movers. In addition, air moving devices manufacturers must furnish a prospective buyer of his product, certain data relative to the product and its applications. This subject is covered in more detail in Chapter 42.

Because fans are the most commonly used exhausters in ventilation for industrial hygiene purposes, they alone are considered in this discussion.

In the field of industrial ventilation, two major types of fans are used: axial flow types, where the air flow is parallel to the fan shaft, and centrifugal type, where air flow is perpendicular to the fan shaft. These two major fan types can be further defined by listing the various units that comprise each type. The components of an air moving device which influence its performance most are the wheel and the air inlet. This will be apparent in the list below which shows comparative components for the two major types of air moving devices.

Axial Flow Fans

1. Propeller: This is an AMD with a propeller or disc wheel within a mounting ring or plate through which the air flow is predominantly parallel to the axis of rotation. This unit is used to move large volumes of air at relatively low velocity against a low static pressure (0-½" W.G.) and low temperature. This fan is commonly used for general ventilation.

2. **Duct Fan:** This is a step up in the evolution of fans from the propeller fan, in that it constitutes a propeller mounted inside a section of duct. The improvements gained in this configuration are elevated temperature applications (to 600°F in belt-drive units), and higher static pressures (from 0-2" W.G.)
3. **Tube-Axial:** This is an axial fan without guide vanes. It is used for medium to large volumes against static pressures up to 4" W.G. and temperatures up to 600°F in belt-driven units. This fan is best suited for moving an air stream containing materials that will not collect on fan blades.
4. **Vane-Axial:** This is an axial fan with either inlet or discharge vanes or both, which impart greater efficiency in delivering medium to high volumes against static pressures up to 8" W.G. Higher pressures are attainable in some units with variable pitch impellers. Temperature applications up to 600°F are attainable in belt-driven units. This type of fan is commonly used for mine ventilation or industrial systems whose characteristics vary widely.
5. **Axial-Centrifugal:** This is an axial fan with a centrifugal wheel. The wheel is available in both backwardly inclined and airfoil design. This fan is the latest improvement in axial flow air moving devices in that it combines the high efficiency of the axial unit with the quiet operation and high static pressure level of the centrifugal fan. Although temperatures of operation are relatively low (under 200°F), static pressures up to 20" W.G. are attainable. In addition, the non-overloading feature of the backwardly inclined and airfoil design wheels is an important advantage of this fan.

Centrifugal Fans

1. **Radial Wheel:** This fan is the workhorse of the dust control industry. It is the least efficient centrifugal fan type, but is quite suitable for rough service, including material handling applications. Generally it is used to handle volumes to about 100,000 CFM at static pressures to 20" W.G., and temperatures up to 1000°F.
2. **Forward-Curved Blade:** This fan delivers high volumes at low static pressure with relatively low noise levels. However, it is not very efficient, and therefore, has lost much of its favor to other type units.
3. **Backward-Inclined Blade:** Sometimes known as "power limiting" or "non-overloading," this type wheel is used more and more for general air handling. It is an efficient fan, with high top speeds and is a good choice for handling large volumes of clean air.

4. **Airfoil Design:** This unit is the latest development in centrifugal fan wheels. The airfoil wheel was developed to reduce noise levels; however it is also backwardly inclined and has the non-overloading feature. It, too, can deliver large volumes against high static pressures.

Fan Selection

In order to select the proper fan for a given application, the following information is required:⁴

1. Air volume to be moved;
2. Fan static pressure;
3. Nature and extent of airborne particulate (a radial-bladed centrifugal fan would be needed if the air stream contains a high concentration of particulates);
4. Direct or belt-drive (belt-drive can be changed for variation in air volume handled; direct drive is inflexible, but occupies less space and requires less maintenance);
5. Noise Level — (a function of tip speed, it is usually a limiting factor in industrial applications);
6. Special considerations such as high operating temperature, corrosiveness, flammable or explosive materials, and space limitations.

The application of specific fan types in the design of exhaust systems is described in Chapter 42, after a more thorough discussion of local exhaust ventilation in Chapter 41.

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INSTRUMENTS AND TECHNIQUES USED IN EVALUATING THE PERFORMANCE OF AIR FLOW SYSTEMS

Richard D. Fulwiler, Sc. D.

INTRODUCTION

Objectives

It is the objective of this chapter to discuss the topic of evaluation of air flow systems as well as provide insight on practical approaches to system evaluation, utilizing up-to-date instrumentation and techniques. The material presented herein is directed to the student as well as the practicing industrial hygienist and will embrace instruments and techniques in evaluating both local exhaust and general ventilation systems.

This chapter will not delve deeply into the theory of air flow, but will require the reader to have a basic understanding of the general principles of ventilation such as the principles of air flow, pressure drops through ducts, and characteristics of blowing and exhausting. These subjects are discussed in some detail in Chapter 39, "Principles of Ventilation."

Bases for System Evaluation

To assure adequacy of design and performance. Independent of the type of system being evaluated, it should be constructed in accordance with a design basis be it a sophisticated engineering approach or the sketches of a sheet metal fabricator. Once a system is completely installed, various air flow measurements should be made before any aspect of the process or area to be controlled has an opportunity to affect the air flow characteristics of the system.

Sufficient input must go into the design basis to assure adequacy of system performance in the control of occupational hazards. Factors to be considered are toxic vapors, gases or dusts; nuisance materials or conditions; and explosive or flammability hazards. Assessment of the hazard in terms of environmental monitoring in conjunction with an evaluation of the air flow system immediately after start up is one sure way to test the adequacy of the design and installation.

To assure system performance is maintained. Since in many instances air flow systems are not an integral part of the process in terms of production or output, it is essential to run periodic checks on their performance. This is especially true for systems which have dampers, blast gates, etc., as well as those which may be affected by accumulations of the material they are conveying or controlling.

Maintenance of the entire air flow system from the entry to the exhaust stack cannot be overemphasized. Various air flow measurements dis-

cussed below will prove invaluable in determining the adequacy of, or the need for, maintenance.

To determine the feasibility for expanding (adding to) the system. The performance of many well designed and installed air flow systems is rendered inadequate by irrational expansion of the system. Various air flow measurements will provide input for judicious expansion while still maintaining the performance initially designed into the system. In many instances, relatively minor modifications may be indicated by such measurements.

To establish improved design parameters for new systems. The evaluation of existing systems may provide valuable input related to the specific operating conditions and characteristics of the hazards being controlled which may lead to improved design of new systems. For example, higher conveying velocities may be indicated to prevent ducts from becoming clogged, or turbulence and eddy currents at a hood entry resulting in contaminant escape, may require improved hood design.

To assure compliance with federal, state, or other regulations. Obviously, the purpose of any air flow system is either the control of hazardous chemical or thermal stresses, or providing a comfortable work environment. To assure that the former purpose is met, some regulations (laws) include air flow performance parameters which must be met. Chapter 1 includes a discussion of the 1970 Occupational Safety and Health Act. The initial package of standards embraced by this Act includes standards requiring certain minimum air flow requirements be maintained. It is not the purpose of this chapter to discuss paragraph 1910.94 Ventilation¹ in detail, but merely to cite examples requiring minimum air flow parameters.

Minimum exhaust volumes for grinding wheels (Table G-4 of reference 1).

Minimum maintained velocities in spray booths (Table G-10 of reference 1).

Control velocities for undisturbed locations for open surface tanks (Table G-14 of reference 1).

Minimum ventilation rate for lateral exhaust of open surface tanks (Table G-15 of reference 1).

EVALUATING AIR FLOW SYSTEMS

Introduction

As there are numerous reasons for evaluating systems, there are degrees to which they may need to be evaluated. Instruments and techniques are

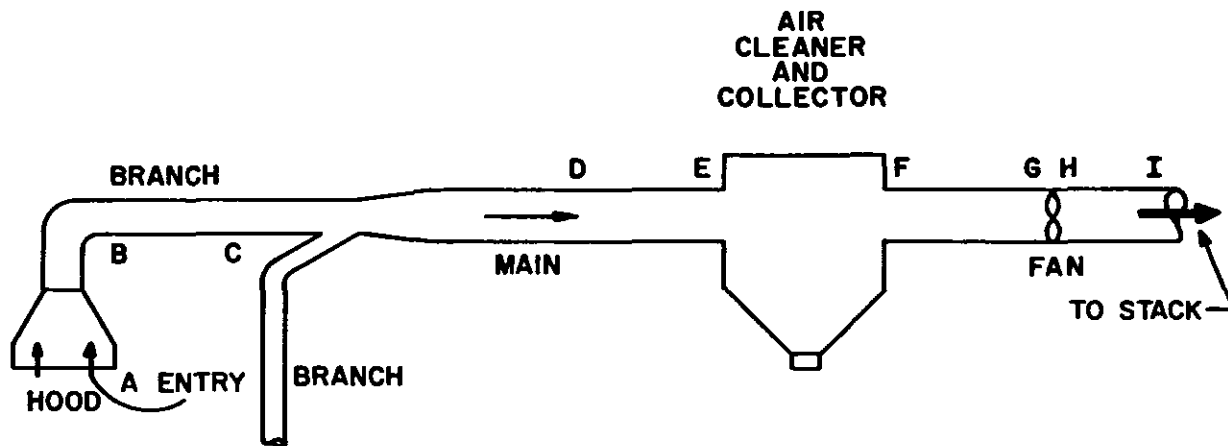
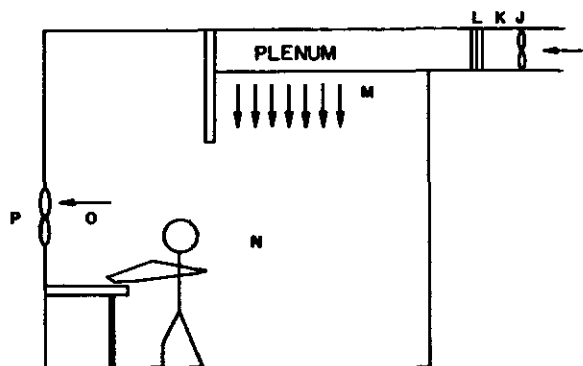


Figure 40-1. Schematic of a Local Exhaust System.

described below which may provide only a cursory evaluation of part of the system or an in-depth survey of the total system.

Figures 40-1 and 40-2 represent the two generic systems requiring air flow evaluation. Figure 40-1 is a schematic of a local exhaust system and Figure 40-2 is a schematic of a general room ventilation system² with the locations requiring evaluation identified by A, B, C, etc.

The instruments and techniques described in this chapter are in the order of increasing precision and accuracy. This order is reflected by the degree of interaction the instruments and techniques have with the system. The reader will note that visualization, the first approach discussed, barely interacts with the total system, whereas the final approach is actually titled "Measurements within the System." However, one should not lose sight of the fact that only by applying a combination of instruments and techniques can the total performance of any air flow system be evaluated.



American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation Manual, 11th Edition. Lansing, Michigan, 1970.

Figure 40-2. Schematic of a General Room Ventilation System.

Visualization — A cursory/Qualitative Estimate of Performance.

Purpose.

Visualization is an extremely important aspect of performance evaluation which heretofore has rarely been discussed in chapters or publications on air flow measurements. The primary application of visualization is as a cursory estimate of local exhaust system performance. Moreover, it provides an extremely effective technique for demonstrating the pluses of good design and the minuses of poor design to management and engineering personnel. Visualization techniques can also be used in training operating personnel in the proper use of the ventilation system.

Instruments/Materials.

"Smoke tubes" is a descriptive term applied to a glass tube containing titanium tetrachloride adsorbed on a granular medium. When the ends of the glass tube are broken and air passed through the tube, the moisture in the air reacts with the $TiCl_4$ to generate hydrochloric acid "smoke."

CAUTION: Direct inhalation of this "smoke" will be irritating to the respiratory system and should be avoided.

A squeeze bulb, rubber tubing, and the tubes can be purchased from numerous suppliers (Table 40-1) and are relatively inexpensive.

Titanium tetrachloride is a chemical reagent available through standard chemical supply companies. It is also available in single use glass ampules (Table 40-1).

CAUTION: These fumes and the liquid are corrosive to the skin, and irritating to the eyes and respiratory system.

Because of the nature of this material, glass ampules are recommended.

Smoke candles are available in a range of sizes and a few colors. They can be purchased in terms of the cubic feet of smoke produced or the duration of smoke evolution (Table 40-1). *Other sources of visualization media.* There are numerous other means of generating visual clouds

TABLE 40-1
Instruments/Purposes/Suppliers

Instruments	Purposes	Suppliers*
Smoke Tubes Titanium Tetrachloride Smoke Candles	Visualization of air flow in and around exhaust hoods. Quick indication of room pressure. Demonstrate general room air flow patterns.	E. Vernon Hill Co. Mine Safety Appliances Co. National Environmental System
Rotating Vane Anemometers	Measures air velocity.	Bendix Environmental Science Division E. Vernon Hill Co.
Vane Anemometers	Measures air velocity (some have attachments for static pressure).	Alnor Instrument Co. E. Vernon Hill Co. Bachrach Instrument Co.
Heated Thermocouple Anemometers	Measures air velocity (some are applicable for non-directional air velocity).	Hastings-Raydist Co. Alnor Instrument Co.
Heated Wire Anemometers	Measures air velocity, static pressure, temperature.	Anemostat Products
Pitot Tubes	Measures total, velocity, and static pressure.	Western Precision Co. Dwyer Instruments, Inc. Meriam Instrument Co. E. Vernon Hill Co. Ellison and Co.
Manometers	Measures total, velocity, and static pressure.	Dwyer Instruments, Inc. Meriam Instrument Co. E. Vernon Hill Co.
Aneroid Gauges (Magnehelic)	Measures total, velocity, and static pressure.	Dwyer Instruments, Inc.
Transducers	Used for remote readings and when rapid changes in pressure must be maintained.	Hastings-Raydist Co.

*This represents neither a complete list nor endorsement.

to follow air flow. A "heavier than air" cloud can be generated by simply placing dry ice in an alcohol bath. A "lighter than air" cloud can be generated by blowing air through a smoldering mixture of sawdust and oil⁸.

Techniques. Visualization media are best suited for the evaluation of air flow patterns and velocities at exhaust entries and supply outlets.

1. Smoke tubes

Smoke tubes can be carried with the industrial hygienist on any of his surveys or inspections. They can be used best as an immediate survey type tool in assessing the ability of a local exhaust system to capture contaminants. Smoke should be administered close to the hood entry initially, and gradually the smoke source moved away from the entry to observe the sphere of containment the exhaust system produces. Larger quantities of smoke can be generated inside of the hood or enclosure to estimate rate of clearance as well as to check for eddy currents, reverse air flows, and escapement. Small amounts of smoke can be used to estimate the force and direction of air from outlets as well as a qualitative check of the performance of return air outlets.

2. Titanium tetrachloride

Titanium tetrachloride is used best by swabbing it along the periphery of hoods as a check for eddy currents, reverse air flow, and lack of control. Once swabbed inside of a hood, the smoke will persist for several seconds and thus provide an opportunity for prolonged observation or photographs.

3. Smoke candles

Smoke candles can be used to estimate clearance rates and containment of large hoods such as paint spray booths, laboratory hoods, or other high volume exhaust systems. Minimal performance of the system must be determined before igniting a smoke candle to assure reasonable removal of the smoke. Smoke candles can be held by forceps and moved across hood face openings to estimate the air distribution at the face. Colored smoke can be introduced in ventilation systems downstream from the fan to check for leaks.

Limitations. There are two significant limitations. First, visualization is strictly qualitative and does not provide any information in terms of design or performance specifications. Second, the materials used may be hazardous or at the very least — a nuisance; thus their use in occupied areas should be somewhat restricted.

Air Velocity and Flow — Exhaust and Supply Openings

Relationship of velocity to rate of flow. The velocity to rate of flow relationship is expressed in Equation 1.

$$\text{Equation 1: } Q = AV$$

Where: Q = Rate of flow in cfm
 V = Average linear velocity in fpm
 A = Cross-sectional area of the duct or hood in ft²

From this equation it is possible to calculate air flow rate if the velocity (V) and cross-sectional area (A) are known.

The purpose of a local exhaust system is to capture and convey the contaminant from the source through an air cleaner to the atmosphere. Precise measurements of capture velocities as well as estimates of exhaust or supply volumes can be made at the point where the air flow system interacts with the work environment. These points are identified as "A" on Figure 40-1 and "M" and "O" on Figure 40-2.

Instruments/Techniques. In using the instruments described below, the need to take multiple measurements of a given slot, hood, or diffuser must be kept in mind. Only by making a uniform traverse of the opening being evaluated will one be able to arrive at a satisfactory average velocity to use in the calculation of air flow. The reader should review Pitot traverse techniques covered in this chapter, and in greater detail in reference 4, to develop an appreciation for multiple measurements in evaluating air flow.

TABLE 40-2.

Correction factors for rotating vane anemometers.

Opening	Correction Factor*
Pressure openings, more than 4 in. wide, up to 600 sq. in. area, with free opening 70% or more of gross area, no directional vanes.	1.03
Suction opening, more than 4 in. wide, up to 600 sq. in. area, with flange 2 in. wide, free-open area 60% or more of gross area	0.85
Volume: For suction openings, cfm = (factor) (velocity) (gross area)	
For pressure openings, cfm = (factor) (velocity) $\left(\frac{\text{gross area} + \text{net area}}{2} \right)$	

*If the opening is covered with a grille, the instrument should touch the grille face but should not be pushed in between the bars. For a free opening without a grille, the anemometer should be held in the plane of the entrance edges of the opening. The anemometer must always be held in such a manner that the air flow through the instrument is the same direction as was used for calibration (usually from the back toward the dial face).

From "Industrial Ventilation — A Manual of Recommended Practices", Committee on Industrial Ventilation,

American Conference of Governmental Industrial Hygienists, Lansing, Mich 1970.

TABLE 40-3.

Correction factors for swinging vane anemometers.

Opening	Correction Factor
Pressure	
More than 4 in. wide and up to 600 sq. in. area, free opening 70% or more of gross area, no directional vanes. Use free-open area.	0.93
Suction	
Square punched grille (use free-open area)	0.88
Bar grille (use gross area)	0.78
Strip grille (use gross area)	0.73
Free open, no grille	1.00
Volume: cfm = (factor) (area) (velocity)	

From "Operating Instructions for the Alnor Series 6000-P Velometer" Alnor Instrument Company, Chicago, Ill., 1970.

1. Rotating vane anemometers

The rotating vane anemometer is comprised of a vane or propeller on a shaft connected to gears. The air movement causes the vane to rotate. The revolutions of the vane turn the gears which register the revolutions on the dial of the instrument as linear feet. Readings are usually taken over one-minute periods, thus giving air velocity in linear feet per minute. These instruments are available in a number of sizes, however the most common vane sizes are 3, 4, and 6 inches in diameter (Table 40-1).

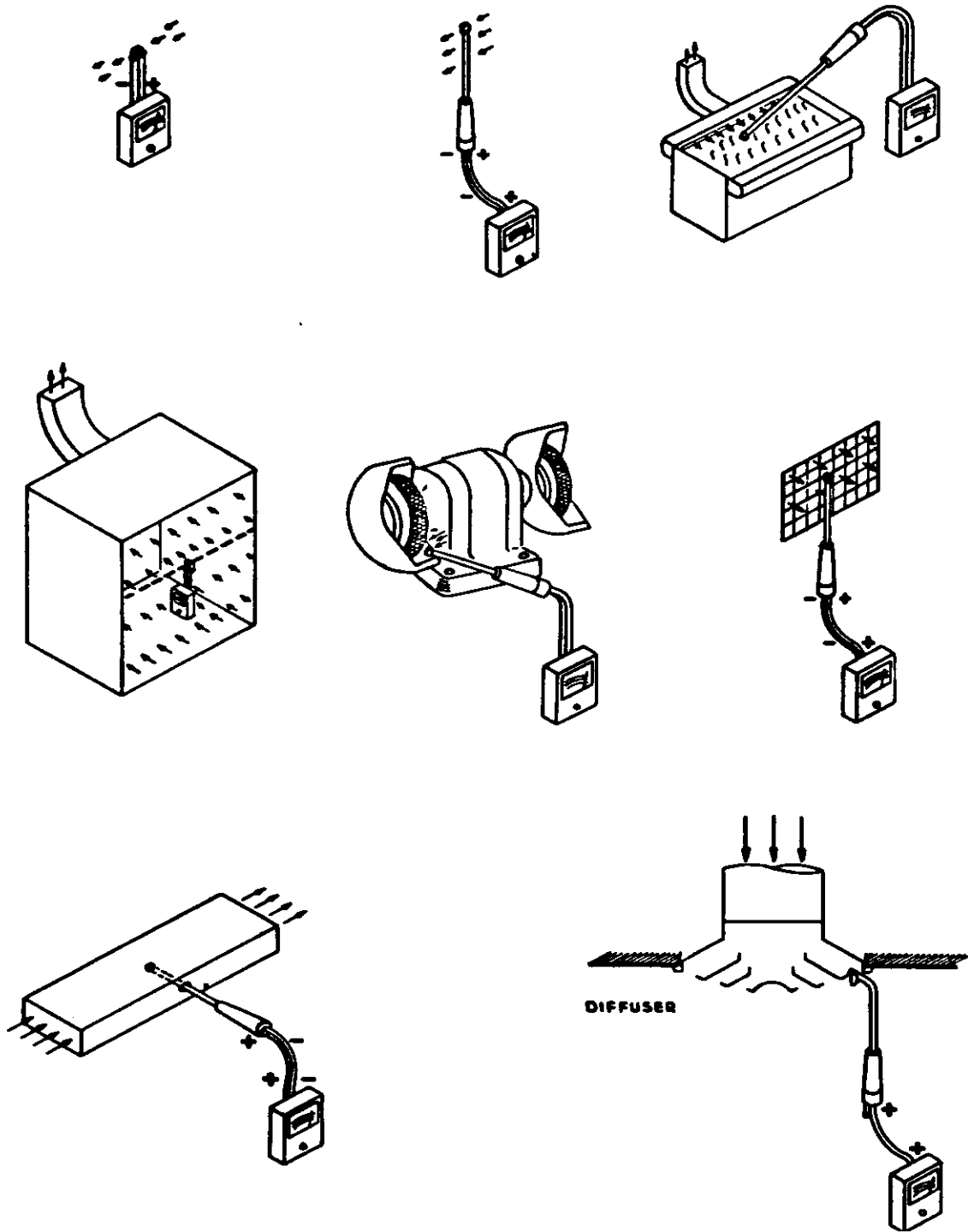
These instruments are best suited for determining air velocities and estimating air flow through large openings such as mine shafts and air supply and discharge grilles. Readings are generally obtained by traversing the opening at a uniform rate for a given period of time. Table 40-2 provides information on correction factors, techniques for taking measurements as well as the equations for calculating air flow rate.

The optimum range for these instruments is between 100 and 3000 fpm. They are best suited for use in relatively clean air and require the use of a timing device. They require frequent calibration and must be handled with care.

2. Swinging vane anemometer

The swinging vane anemometer indicates air velocity as a function of the pressure exerted by the air stream against a spring loaded swinging vane. They are quite portable and used extensively by industrial hygienists and ventilation engineers in the field (Table 40-1).

These instruments are used primarily for measuring velocities of exhaust or supply openings as shown in Figure 40-3. Fittings are available for some swinging vane devices which allow these to be used for a number of applications, such as measuring static pressures, as well as over a wide



Alnor Instrument Company, Chicago, Illinois.

Figure 40-3. Applications of a Commercially Available Swinging Vane Anemometer (Alnor Instrument Company).

range of velocities from 25 to 24,000 fpm. The optimum range of performance is 100 to 10,000 fpm.

Openings must be traversed with velocity measurements taken uniformly over the face of the grille or hood being evaluated. Care must be taken to use probes for small openings (less than 3 ft²) since the size of the device could represent a significant portion of the area. It is important to follow the operating instructions provided with the instrument, otherwise significant errors can be introduced. Correction factors for supply (pressure) and exhaust openings and information on calculating air flow are shown in Table 40-3.

When air temperatures vary more than 30°F from 70°F and/or the altitude is greater than 1000 ft. above sea level, readings should be corrected in accordance with the following equations:

$$\text{Equation 2: } V_t = V_r \sqrt{\frac{460+t}{530}}$$

Where: V_t = true velocity

V_r = velocity read from meter

t = air stream temperature

$$\text{Equation 3: } V_t = V_r \sqrt{\frac{1}{d}}$$

$$\text{Where: } d = \left(\frac{530}{460+t} \right) \left(\frac{B}{29.92} \right)$$

B = barometric pressure in inches of Hg

Caution must be exercised in using these devices in a dusty, moist, or corrosive atmosphere, since it can affect the readings as well as impair the performance of the instrument. They require periodic calibration but are a good choice for general and field applications.

3. Heated thermocouple anemometers

The operating principle of the heated thermocouple anemometer instruments is simply that air moving past a heated object removes heat. The amount of heat removed is proportional to the quantity of air passing which is a function of velocity. These instruments have one or more thermocouples as sensing elements which are heated by either alternating or direct current. A change in air flow causes a change in temperature of the thermocouples, resulting in a change in the direct current output. Another unheated thermocouple is in the direct current circuit to a meter. As a result of the changes in temperature, a change in voltage is developed which is read as air velocity.

These instruments are usually comprised of a single probe connected to an operating unit housing the circuitry, meter, batteries, etc., and are about the size of a cigar box. They are quite portable and commercially available (Table 40-1). The units incorporate balancing circuits which render errors due to radiant heat and ambient temperature fluctuations negligible. Since these instruments are direct reading and have a short response time (less than one minute), they are applicable for field as well as laboratory use. Some of the

instruments may be used in determining non-directional velocities such as general room air movement, depending upon the type of shielding around the sensors in the probe.

The limitations are related primarily to maintaining the integrity of the probe. Heavy dust loadings or corrosive materials as well as mechanical shock could damage the delicate wires in the probe. The range of air velocities is quite wide, with some instruments having advertised ranges from 10 to 10,000 fpm. A general rule of thumb is that velocities from 10 to 50 fpm may be estimated while velocities from 100 to 2000 fpm may be measured with some precision depending on the calibration of the unit. Periodic calibration is required.

These devices, as with any probe type velometer, can be used to measure entry or exit velocities of hoods, slots, grilles, etc., by placing the probe perpendicular to the direction of air flow and recording the measurements. The greater the number of measurements distributed uniformly across the opening being measured, the better the estimate of air velocity and flow rate will be.

4. Heated wire anemometers

The heated wire anemometer devices depend upon the change in resistance of a wire with a change in temperature. The degree of temperature change is proportional to the velocity of air passing the wire. Velocity is read directly on a meter which is actuated by a change in voltage from a Wheatstone bridge circuit.

Generally, the advantages and limitations are the same as those previously described for heated thermocouple anemometers.

There are some units available which can measure temperatures ranging up to 250°F and static pressures up to 10 inches of water. More precise hot wire anemometers measure velocity exclusively. Static pressure measurements will be discussed in more detail in the section titled "Measurements within the System."

5. Other thermal anemometers

a) Heated thermometer anemometer

The principle for the heated thermometer anemometer is the same as for heated thermocouple anemometers except that two thermometers are used instead of thermocouples. It is not amenable to field use because of the fragility of the thermometers and the amount of time required for the thermometers to reach equilibrium. Its primary use is that of a laboratory type device in the calibration of air samplers requiring negligible static pressure losses in the calibration train (e.g., electrostatic precipitators).

b) Kata thermometer⁷

The Kata thermometer is a special thermometer with a large bulb, containing alcohol, and a stem with marks at 95 to 100°F. It is heated above 100°F and the time required for it to cool from 100 to 95°F is a measure of the non-directional air velocity in the room. It was designed for comfort ventilation measurement, and its surface-to-volume ratio is similar to that of the human body. The useful velocity range is 25 to 500 fpm. It has the disadvantage of being fragile and

having large radiation and convection areas. A silvered bulb is necessary to minimize the effect of thermal radiation. As expected, it has a slow response time. The disadvantages are sufficient to classify this device as a poor choice for the measurement of air velocity.

MEASUREMENTS WITHIN THE SYSTEM

Precise measurements which characterize the performance of air flow systems are made within the system. Instead of measuring the velocity of air going into exhaust hoods or coming from air outlets, measurements are made *inside* the ductwork leading to the point of entry or discharge. Such locations are depicted as B, C, D, E, F, G, H and I on Figure 40-1 and J, K and L on Figure 40-2. Measurements within the system are made to determine static pressure drops associated with hood entries, ducts, across air cleaners (e.g. filters and bag houses) as well as velocity pressures. Therefore, the instruments discussed will be primarily those used to measure pressure in terms of inches of water.

Some of the anemometers previously discussed, those with relatively narrow probes and fittings, can also be used to measure air velocities within the system. Independent of the measuring device, the accuracy in determining either duct velocities or flowrate is dependent upon the location and number of measurements taken in traversing the duct. Techniques discussed under "Pitot Traverse" below can be applied to the use of most measurements requiring multiple sensing points within an air flow system.

Relationship of Velocity to Pressure Measurements

The total pressure of a system is the algebraic sum of the static pressure plus the velocity pressure. Air velocity can be computed from the velocity pressure according to equation 4.

$$\text{Equation 4: } V = 1096 \sqrt{\frac{VP}{0.075d}}$$

Where: V = velocity in fpm
 VP = velocity pressure in inches of water
 d = density factor equal to:

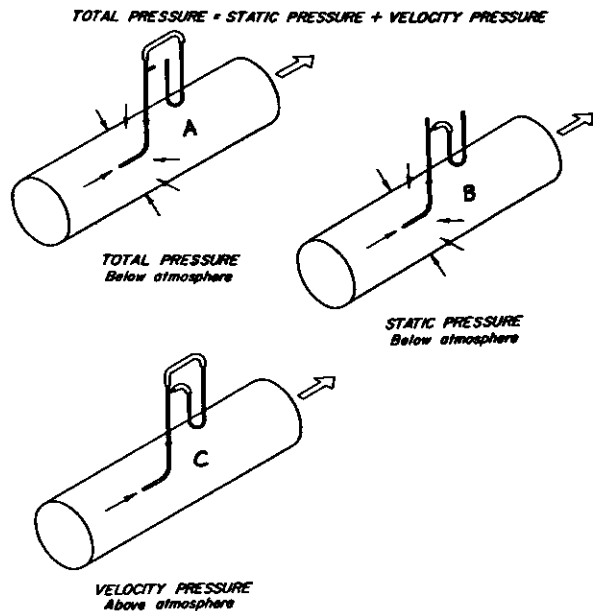
$$\frac{530}{460 + t} + \frac{B}{29.92}$$

Where: B = barometric pressure in inches of mercury
 t = air temperature in degrees F.

For air at standard conditions (70°F, 29.92" Hg), the density factor will equal unity. The equation then becomes:

$$\text{Equation 5: } V = 4005 \sqrt{VP}$$

Table 1 of Chapter 39 can be used in converting velocity pressures at standard conditions to velocities in fpm. A "rule of thumb" in making corrections for density is that they should be made when the altitude is greater than 1000 ft. above sea level, the temperature of the air in the system is $\pm 30^\circ\text{F}$ from standard, and the moisture content equal to or greater than 0.02 lb./lb. of dry air.



American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation Manual, 11th Edition. Lansing, Michigan, 1970.

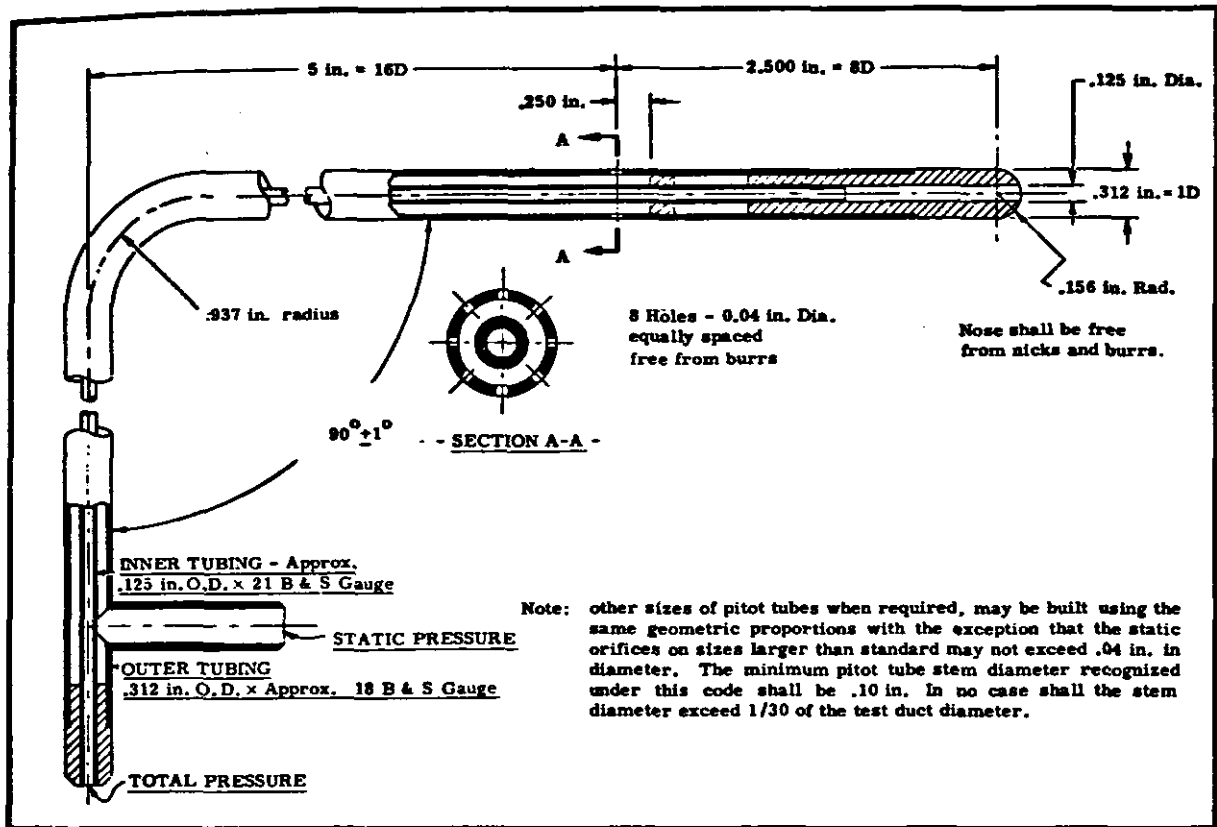
Figure 40-4. Relationship of Velocity Pressure to Static and Total Pressure for an Exhausting System.

Pitot Tube — Velocity Pressure

Equipment. The Pitot tube is the standard instrument for measuring the velocity of air in ducts. Figure 40-4 is a graphic representation showing the relationship of velocity pressure to static pressure and total pressure of an exhausting system.⁴ The Pitot tube consists of two concentric tubes. The opening of the inner tube is axial to the flow and measures total pressure (A of Figure 40-4), while the larger tube with circumferential openings measures static pressure (B of Figure 40-4). The difference between the total pressure and static pressure is the velocity pressure (C of Figure 40-4).

Pitot tubes which are built to Air Moving and Conditioning Association⁸ and ASHRAE⁹ standards are considered primary standards and require no calibration. See Figure 40-5. Standard Pitot tubes fabricated from type 304 stainless steel are recommended because of their resistance to corrosion and use over wide temperature ranges up to 1000°F. Above this temperature, water-cooled Pitot tubes are required.

Pitot tubes are used to determine the velocity pressure contours inside of ducts. These measurements are obtained by connecting the static and total pressure taps to a manometer as shown in Figure 40-6. Inclined manometers (10:1) are normally used since they increase the accuracy and precision especially for velocities below 2000 fpm. A brief table appears in reference 4 which shows that the percent error using a carefully leveled



Air Moving & Conditioning Society: Standard 210. Arlington Heights, Illinois.

Figure 40-5. The Standard Pitot Tube. Note: Other sizes of Pitot tubes, when required, may be built using the same geometric proportions with the exception that the static orifices on sizes larger than standard may not exceed .04 in. in diameter. The minimum Pitot tube stem diameter recognized under this code shall be .10 in. In no case shall the stem diameter exceed 1/30 of the test duct diameter.

10:1 inclined manometer ranges from 0.25% at 4000 fpm to 4.0% at 1000 fpm, and up to 15% at 600 fpm. Thus, Pitot tubes used in the field are generally restricted to velocities above the 600-800 fpm range. Inclined manometers which read in fpm and inches of water are commercially available (Table 40-1). Conventional ranges are 400-12,600 fpm and 600-19,200 fpm. These manometers eliminate the need to convert VP to velocity as previously discussed.

Pitot traverse. Aside from instrument error, the most significant requirement in making valid velocity or air flow measurements is the location selected for the measurements and the traverse of that location. The reason for these requirements is that air flow is not uniform in the cross section of a duct. This is especially true near such interferences as elbows, entries, etc. Therefore, for greatest accuracy, measurements should be taken at least 8.5 diameters of straight run downstream or 1.5 diameters upstream from interferences. Once the location is selected, a Pitot traverse can be conducted. Figure 40-7 shows a cutaway of both a round and rectangular duct, exemplifying the principle of measuring the VP of equal areas. Note that for round ducts it is advisable to traverse

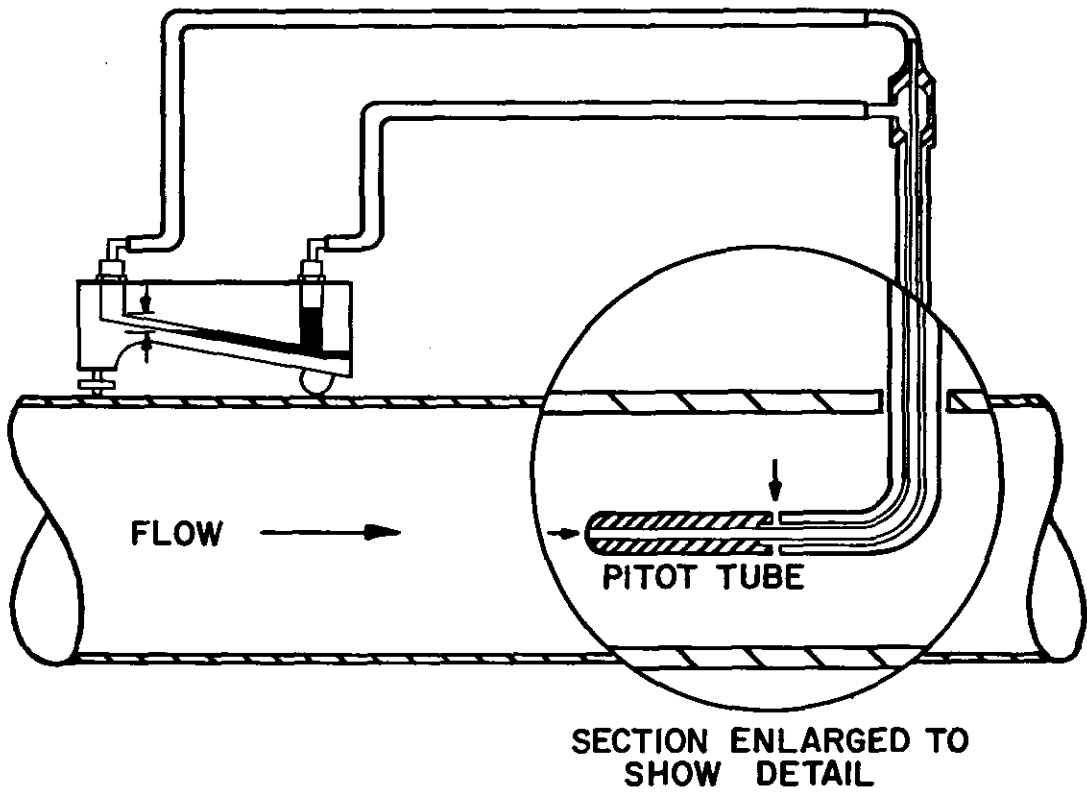
in two planes perpendicular to each other. The optimum number of measurements per plane for ducts of stated diameters is suggested below:

Duct Diameter, Inches	Number of Measurements
3-6	6
5-48	10
44 and greater	20

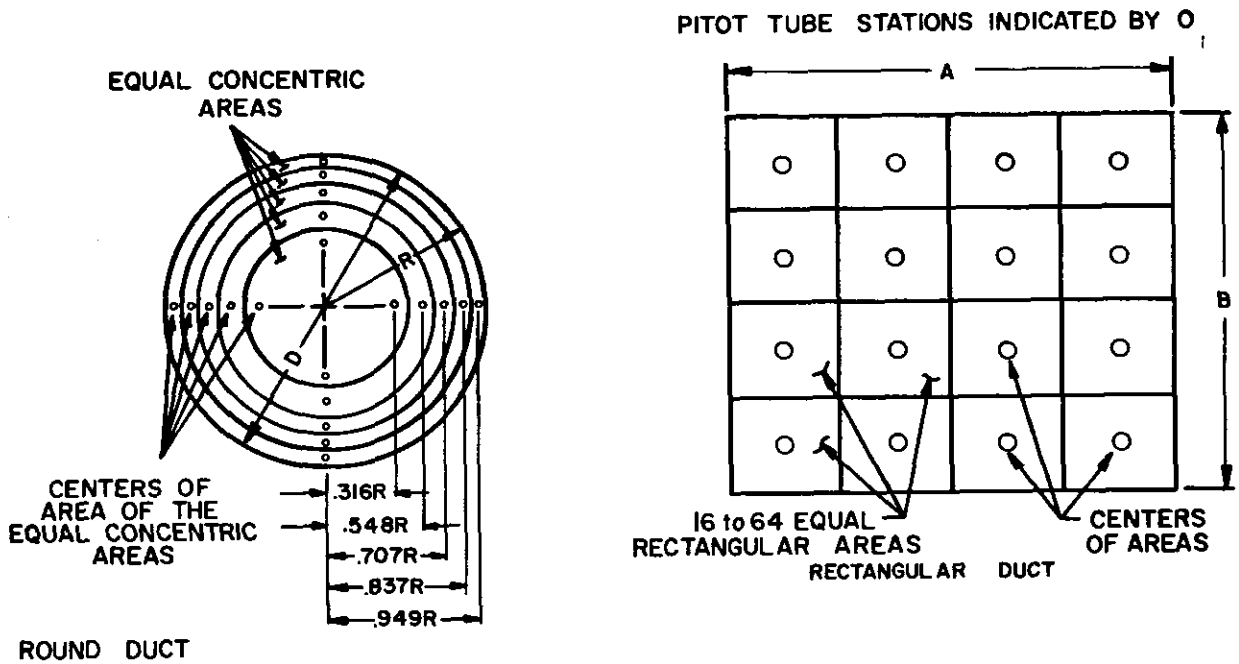
Reference 4 includes tables giving distances from the duct walls for the diameters stated above.

Like round ducts, rectangular ducts are traversed in terms of equal area segments. Rectangular ducts should be divided in a minimum of 16 to a maximum of 64 equal area rectangles with readings taken in the center of each rectangle as shown in Figure 40-7.

Once the readings as VP are taken and tabulated, the average velocity, in fpm, should be calculated. *Do not average the VP*; however the \sqrt{VP} may be averaged and converted to velocity. From the velocity in fpm (V) and the area of the duct in ft² (A), flowrate (Q) can be calculated according to Equation 1.



Dwyer Instruments, Inc.: Bulletin No. H-100. Michigan City, Indiana, p. 3.
 Figure 40-6. The Pitot Tube Connected to an Inclined Manometer.



Dwyer Instruments, Inc.: Bulletin No. H-100. Michigan City, Indiana, p. 3.
 Figure 40-7. Traverse of a Round and Rectangular Duct Area.

In cases when accuracy is not a prime consideration, a single centerline reading can be taken at least 10 diameters of straight duct downstream from the nearest interference. This VP should be adjusted by multiplying by 0.81, or the velocity should be multiplied by 0.90.

When it is not possible to find undisturbed traverse locations 8.5 to 10 diameters downstream, alternate locations should be selected on the basis of a 5:1 ratio between downstream and upstream interferences. Depending on the situation and need for accuracy, multiple points for traverse can be selected and those points within 10% agreement averaged and used to determine velocity and air flow.

Limitations. There are fewer limitations for Pitot tubes than for other air velocity measuring devices. Whereas they can be used in corrosive or variable temperature conditions, the impact and static openings can become clogged with particulate matter. Also, as with the other instruments discussed, corrections should be made if the temperature is $\pm 30^\circ\text{F}$ from standard, the altitude is greater than 1000 ft., and the moisture content is 0.02 lb./lb. or greater. They cannot be used to measure low velocities (less than 600 fpm) and require an inclined manometer which must be level and free from vibration. They are not applicable for use in small diameter ducts (less than 3 inches) or in orifice type openings.

Aneroid Gauges

The most common and best known of the aneroid gauges is the magnehelic gauge. Aneroid gauges can be used for total, static, and, in conjunction with a Pitot tube, velocity pressure measurements. They are small, extremely portable, and not as sensitive to vibration and leveling as liquid filled manometers. Since the inches of water pressure is a function of the location of an indicating needle on a dial, they are extremely easy to read. Magnehelic gauges are commercially available in ranges from 0 to 0.5" WG. (500-2800 fpm) to 0 to 150" WG. (2000-125,000 fpm) (Table 40-1).

The principal limitations are accuracy and calibration. Accuracy is usually below $\pm 2\%$ full scale. Since they are mechanical, there is a need to calibrate these devices periodically.

Manometers

Manometers range from the simple U-tube to inclined manometers already mentioned. A range of sizes and varieties of U-tube manometers are available and they may be filled with a variety of media ranging from alcohol to mercury. Readings can be converted to inches of water simply by correcting for differences in density (e.g., 1 inch of mercury is equal to 13.61 inches of water).

When extreme accuracy is not essential or in high pressure systems, U-tube manometers will suffice. However, for accuracy and in low pressure systems, inclined manometers are required.

Static Pressure Measurements

Instrumentation and taps. Instruments used in measuring static pressure include the static leg of the pitot tube as well as any pressure measuring device connected to a hole in the side of a duct.

U-tube manometers and Magnehelic gauges are quite acceptable. Whereas the exact location of the hole is not extremely critical, the type of hole is. Generally, the holes should not be located in points where there is some basis for turbulence or non-linear flow such as the heel of an elbow. Holes should be flush with the inside of the duct with no projections or burrs. Thus, holes should be drilled and not punched. The location of holes 90° apart will allow for the averaging of multiple readings to provide an improved estimate of static pressure.

Taps can range in complexity from a simple soft rubber hose held tightly against a $\frac{1}{16}$ inch hole, to soldered pet cocks for use in high pressure applications.

Applications. Static pressure measurements at strategic points in a system provide invaluable information as to the performance. These measurements are neither difficult to obtain nor do they require expensive or delicate instrumentation.

Estimation of air flow by the throat suction method* provides a fairly accurate estimation of flowrate of an exhaust opening if the coefficient of entry can be determined. Coefficient of entries for various hoods are given on Figure 2 of Chapter 42. Measurements are made between one and three diameters of straight duct from the throat of the exhaust inlet (point where the hood is connected to the branch duct). It is advisable to take multiple readings 90° apart. The flowrate in cfm can then be determined according to equation 6:

$$\text{Equation 6: } Q = 4005 C_e A \sqrt{SP_h}$$

Where: Q = Rate of flow in cfm

C_e = Ratio of actual flow to theoretical flow (Figure 2 of Chapter 42) (Entry loss in " WG)

A = Cross-sectional area of duct in ft^2

SP_h = Average static pressure reading in inches of water

Static pressure comparisons provide a means of either continuously or periodically monitoring the performance of a system. Additional information may be required, but strategically located static pressure taps can flag malfunctioning equipment, clogged ducts, dirty or broken filters, dented exhaust hoods, and changes in fan static pressure.

The permanent installation of manometers immediately downstream from exhaust hoods controlling a hazardous material or critical process is advisable, as is the placement of such devices across a filter to determine the need for shaking, cleaning, or maintenance.

Other Measuring Devices

There are a number of other devices for measuring fluid flow, but their application is restricted to either laboratory use or the calibration of air sampling devices. Some are discussed briefly below:

Orifice meter². An orifice meter is simply a restriction in a pipe between two pressure taps. There are several types of orifice meters used, but the sim-

plest and most common is the square edged orifice. If it is properly constructed, the orifice plate will be at right angles to the flow, and the surface will be carefully smoothed to remove burrs and other irregularities. Orifice meters are seldom used as permanent flow meters in ventilation systems because of their high permanent pressure loss. They are more typically used in the ventilation laboratory for calibration purposes. Permanent head loss will vary from 40 to 90 percent of the static pressure drop across the orifice as the ratio of orifice diameter to pipe diameter varies from 0.8 to 0.3. Detailed discussions of orifices and orifice equations can be found in reference 11.

Venturi meters⁷. A Venturi meter consists of a 25° contraction to a throat, and a 7° re-expansion to the original size. This differs from the orifice meter where the changes in cross section are abrupt. The advantage of the Venturi over the standard orifice is that the permanent reduction in static pressure is small, because the velocity head in the throat is largely reconverted to static pressure by the gradual enlargement. A well designed and constructed Venturi will have a permanent static pressure loss of only 0.1 to 0.2 inches of H₂O as compared to 0.4 to 0.9 for the orifice plate. Venturi meters are used in conjunction with a manometer as an in-line flow measuring device. A more detailed explanation of the Venturi is offered in reference 11.

CALIBRATION OF INSTRUMENTATION

All too often the need for calibration is not applied to devices for measuring air flow and velocity, yet as a group, with the exception of the Pitot tube, they require periodic calibration. Generally, air flow measuring instrumentation is based on electrical or mechanical systems which are sensitive to shock. In addition, use of these instruments in corrosive or dusty atmosphere affects their reliability.

A calibration wind tunnel as shown in Figure 40-8 represents the method of choice for calibrating the devices described in this section. Reference 12 is an excellent treatment of the design and use of the calibration wind tunnel. A well designed wind tunnel must have the following components¹²:

1. *A satisfactory test section.* Since this is the location of the probe or sensing element of the device being calibrated, the gas flow must be uniform, both perpendicular and axial to the plane of flow. Streamlined entries and straight runs of duct are essential to eliminate pronounced vena contracta and turbulence.
2. *A satisfactory means of precisely metering air flow.* A meter with adequate scale graduations to give readings of $\pm 1\%$ is required. A Venturi or orifice meter represent optimum choices since they require only a single reading.
3. *A means of regulating air flow.* A wide range of flows are required. A suggested range is from 50 to 10,000 fpm. Therefore, the fan must have sufficient capacity

to overcome the static pressure of the entire system at the maximum velocity required. A variable drive provides for a means of easily and precisely attaining a desired velocity.

Meters must be calibrated in a manner similar to how they are used in the field. Vane actuated devices should be set on a bracket inside a large test section with a streamlined entrance. Low velocity probe type devices may be tested through appropriate openings in the same type of tunnel. High velocity ranges of probe type devices and impact devices should be tested through appropriate openings in a circular duct at least 8.5 diameters downstream from any interference. Straighteners as shown in Figure 40-8 will reduce this requirement to 7 diameters.

NOTE: Devices must be calibrated at multiple velocities throughout their operating range.

AIR FLOW SYSTEM SURVEYS

System Start-up vs. Design Basis

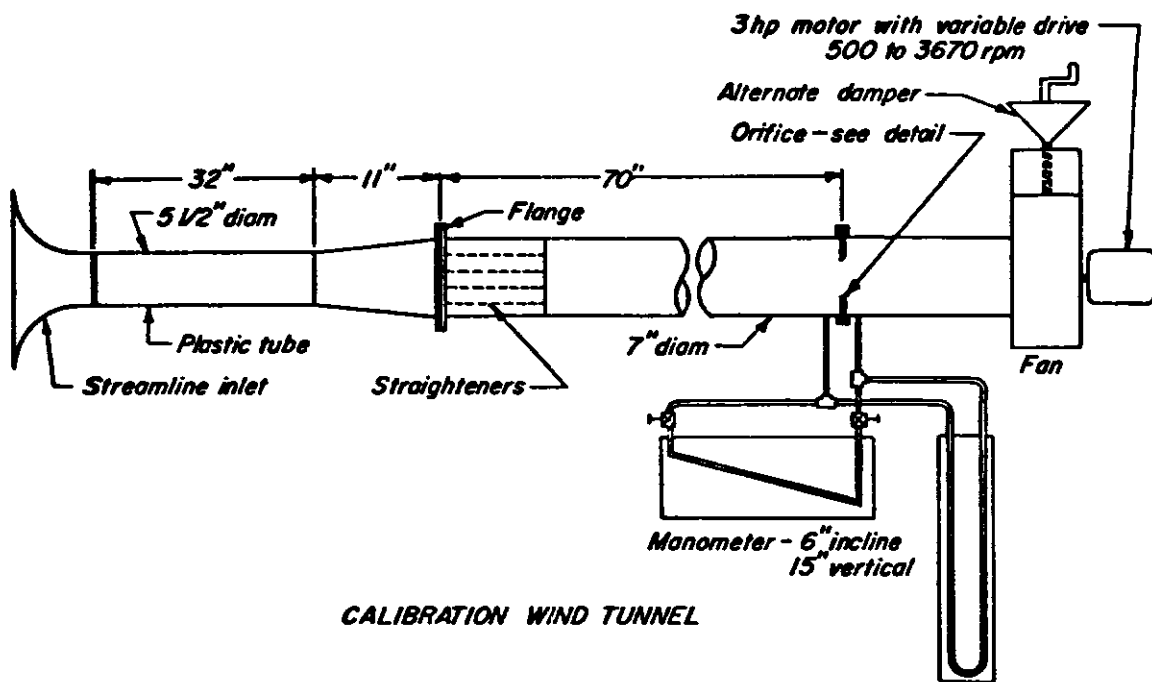
Any ventilation system, be it local exhaust for contaminant control or general for comfort, is designed in terms of removing or distributing a specified quantity of air at a specified velocity at a total system pressure which is the sum of the parts. An initial survey of the system is the only time a valid comparison can be made between the design basis and optimum system performance.

Sketch of the system. A sketch not necessarily to scale but representative of dimensions should be drawn noting such items as hoods, elbows, branchings, air cleaner, fan and stack. Supply ducts, plenums, and diffusers should be shown for general systems. Figure 40-1 and 40-2 represent gross simplifications of this concept.

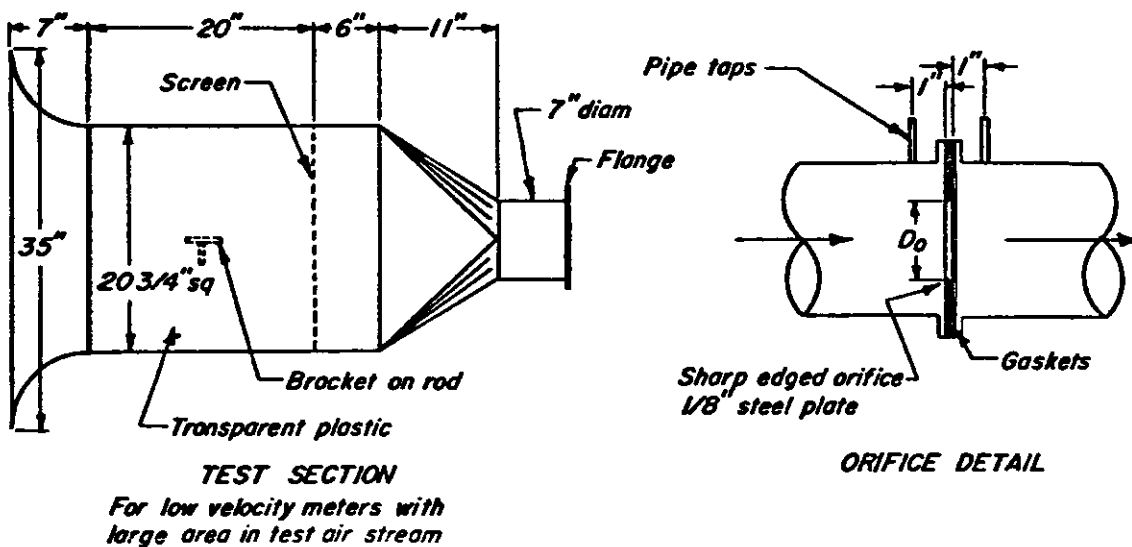
The sketch should be considered as part of the permanent record on which future changes in the systems may be recorded.

Specific air flow measurements. Measurements in terms of air flow, velocity, and static pressure must be made to determine that the system is adequately balanced and performing according to the design basis. These measurements include:

1. Static pressure measurements at:
 - a) hoods
 - b) up and downstream of the air cleaner
 - c) up and downstream of the fan
2. Air flow in cfm at:
 - a) hoods (throat suction method)
 - b) branches and mains (Pitot tube)
 - c) up and downstream of fan (Pitot tube)
3. Supply, capture, and conveying velocities at:
 - a) diffuser outlets (supply velocity)
 - b) face or opening of hood (capture velocity)
 - c) branches and mains (conveying velocity)
4. Fan performance
 - a) fan speed in rpm
 - b) horsepower (BHP) calculated using cfm (Q), total pressure (TP), and mechanical efficiency (ME) of fan.



CALIBRATION WIND TUNNEL



TEST SECTION

For low velocity meters with large area in test air stream

ORIFICE DETAIL

American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation Manual, 11th Edition: Lansing, Michigan, 1970.

Figure 40-8. The Calibration Wind Tunnel.

Equation 7:
$$\text{BHP} = \frac{(Q) (TP)}{6356 \times \text{ME}}$$

The locations of the measurements must be identified on the sketch and a record kept for future comparisons. A sample form can be found in reference 4.

The measurements obtained should agree within 10% of the design basis. If not, system modification should be made until such agreement is obtained.

Other Checks. Local exhaust systems are installed

for the singular purpose of removing some contaminant from the work environment. Visualization techniques using smoke tubes or candles can be most helpful in verifying the system exerts a sphere of control over a sufficient area to prevent excessive exposures to operating personnel. Air evaluation for specific contaminants is also recommended to verify the system will control contaminants to levels known to be safe. Air samples taken in the breathing zone of operating personnel will be most helpful in assessing the adequacy of contaminant control.

As with the previous measurements, photographic records of smoke tests and the results of air evaluation tests should be maintained for future reference.

System Operation vs. System Start-up

Once systems are started up and determined to perform satisfactorily, the degree of evaluation *can be reduced as long as good records of start-up or initial conditions have been made.* Experience with air flow systems clearly indicates periodic surveys are required to assure system performance is adequate. Operating personnel cannot be relied upon as an "indicator" of system performance. Also, ventilation systems are rarely an integral part of the operation in terms of quality and production, and all too often receive inadequate maintenance.

For most systems simple velocity measurements at exhaust hoods and supply ducts will provide a crude indication of system performance when compared with start-up evaluations. For local exhaust systems, the throat suction method applied to exhaust hoods and static pressure differentials for air cleaners and fans will suffice in confirming the system is performing satisfactorily.

The throat suction method will provide valid information unless:

1. The hood entry has been modified/damaged;
2. There are obstructions ahead of the point of measurement; or
3. The system has been modified.

However, a reduction in throat suction can provide valuable information, such as an indication that there has been:

1. Accumulations of material in an elbow, branch, or main, thus clogging or restricting air flow. Build-up in the elbows result from impaction, while build-ups in straight runs result from insufficient conveying velocity or overloading the system.
2. A change in blast gate setting if the system is balanced using blast gates.
3. Additional branches and hoods added to the system. "Adding on" to a system is a real temptation. It is not sound economics when it renders the entire system deficient.
4. Excessive build-up on the filter. It is best to monitor filter build-up by attaching a static pressure measuring device across the filter.
5. Reduced fan output resulting from belt slippage, damaged or worn rotor, or build-up on the fan blades.

Data Handling and Recording

The sketch of the system made at start-up or for the initial air evaluation survey and the results of the ensuing air flow survey must be recorded and filed in such a manner that future air flow surveys can be conducted in a similar manner. The periodicity of air flow surveys can only be determined by such conditions as:

1. Nature of the materials being controlled. The more hazardous the materials, the more frequently the system should be checked.

2. Nature of the system. A blast gate system will require more frequent checks than other systems.
3. The degree of maintenance. Air flow surveys can be used to indicate the need for more frequent and improved maintenance.

Reference 4 provides a sample of a diagram, check list and additional information regarding checking and testing systems.

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Preferred Reading

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CHAPTER 41

LOCAL EXHAUST SYSTEMS

John E. Mutchler

INTRODUCTION

Local exhaust systems are employed to capture air contaminants — dusts, fumes, mists, vapors, hot air and even odors — at or near their point of generation or dispersion, to reduce contamination of the breathing zone of workers. Local ventilation is frequently used and is generally the preferred method for controlling atmospheric concentrations of airborne materials that present potential health hazards in the work environment. As discussed in Chapter 39, this type of ventilation is preferred over general exhaust ventilation for the following reasons:¹⁻²

1. If the local exhaust system is properly designed, the control of a contaminant can be complete; therefore, the exposure of workmen to contaminants from the sources exhausted can be prevented. With general ventilation the contaminant concentration has been diluted where the exposure occurs, and at any given workplace this dilution may be highly variable, and therefore inadequate at certain times.
2. The volume of required exhaust is usually much less with local ventilation; therefore, the required volume of make-up air is less. A saving in both capital investment and heating and cooling costs is realized.
3. The contaminant is concentrated in a smaller volume of air; therefore, if a dust collector or other air pollution control device is needed, it is less costly. As a first approximation the costs of air pollution control are proportional to the volumetric rate of air handled.
4. Many local exhaust systems can be designed to capture large settleable particles or at least confine them within an enclosure, and thus greatly reduce the labor required for housekeeping.
5. Auxiliary equipment in the workroom is better protected from the deleterious effects of the contaminant, such as corrosion and abrasion.
6. Local exhaust systems usually require a fan of higher pressure characteristics to overcome pressure losses in the ventilation system. Therefore, the performance of the fan system is not likely to be grossly affected by wind velocity or an inadequate supply of make-up air. This is in contrast to general ventilation which can be affected severely by seasonal factors or an inadequate supply of make-up air.

COMPONENTS OF A LOCAL EXHAUST SYSTEM

A local exhaust system consists of four elements as shown in Figure 41-1: 1) hoods, 2) ducts, 3) air cleaning device (cleaner) and 4) air moving device (fan).

Typically, the system is a network of branch ducts connected to hoods or enclosures, main ducts, air cleaner for separating solid contaminants from the air stream, an exhaust fan, and a discharge stack to the outside atmosphere.

Hoods

A hood is a structure designed to enclose or partially enclose a contaminant-producing operation and to guide air flow in an efficient manner to capture a contaminant. The hood is connected to the ventilation system via a duct which removes the contaminant from the hood. The design and location of the hood is crucial in determining the success of a local exhaust system.

Ductwork

The function of the ductwork in an exhaust system is to provide a channel for flow of the contaminated air exhausted from the hood to the point of discharge. The importance of the ductwork design is underscored in the following points:

- a. In the case of dust, the duct velocity must be high enough to prevent the dust from settling out and plugging the ductwork.
- b. In the absence of dust, the duct velocity should strike an economic balance between ductwork cost and fan, motor and power costs.
- c. The location and construction of the ductwork must provide sufficient protection against external damage, corrosion and erosion, to provide a long, useful life for the local exhaust system.

Air Cleaner

Most exhaust systems for contaminants other than hot air need an air cleaner. Occasionally the collected material has some economic reuse value, but usually this is not the case. To collect and dispose of the contaminant is usually inconvenient and an added expense.

This subject is discussed in greater detail in Chapter 43; it is beyond the scope of this chapter to elaborate on the details of air cleaning for exhaust gas streams. Obviously, the growing concern with air pollution control, and attainment of air quality goals by legal restriction of emissions from sources of atmospheric discharge, place new importance on the air cleaning device within a local exhaust system.

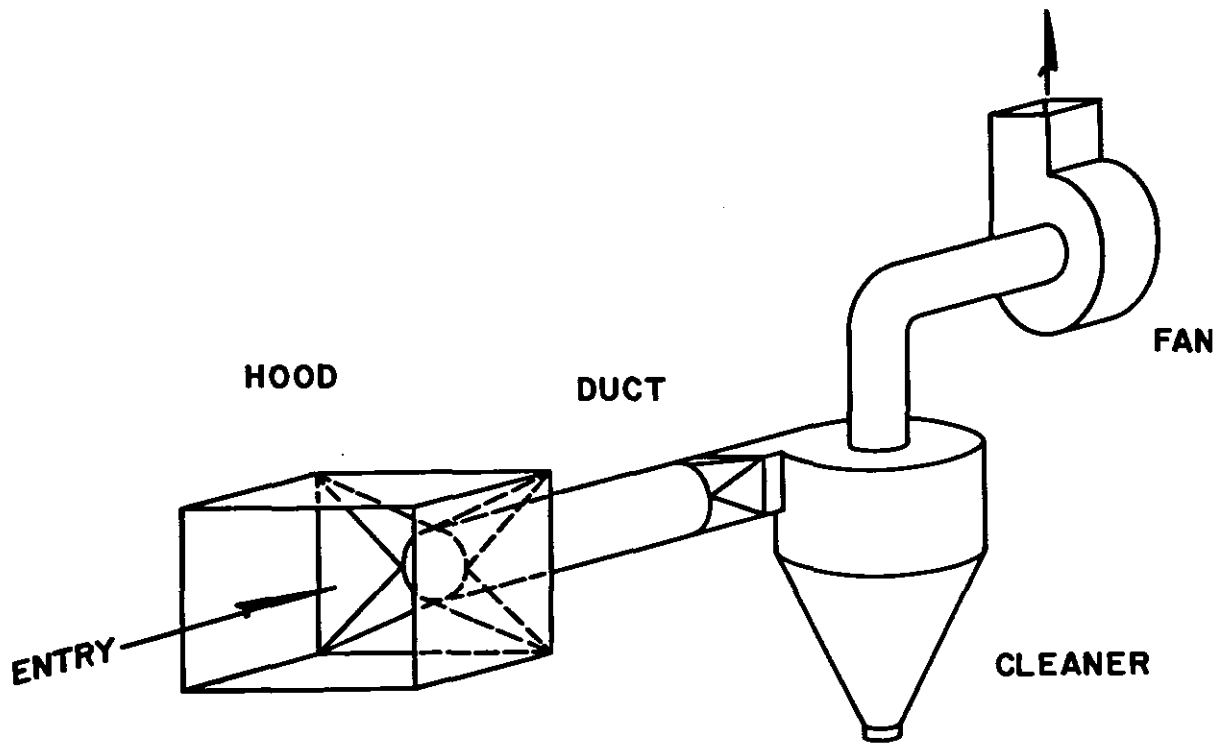


Figure 41-1. Elements of a Local Exhaust System

Air Moving Device

Centrifugal fans are the mainstay of air movers for local exhaust systems. Wherever practicable a fan should be placed downstream from the collector so that it will handle clean air. In such an arrangement, the fan wheel can be the backward curved blade type which has a relatively high efficiency and low power cost. For equivalent air handling the forward curved blade impellers run at somewhat lower speeds, and where noise is a factor, this may be important. Where chips and other particulate matter have to pass through the impeller, the straight blade or paddle wheel type fan is best because it is least likely to clog.

Fans and motors should be mounted on substantial platforms or bases and isolated by anti-vibration mounts. At the fan inlet and outlet the main duct should attach through a vibration isolator — a sleeve or band of very flexible material, such as rubber or fabric.

When the system has several branch connections, consideration should be given to using a belt drive instead of direct connected motor. The need for increased air flow at a future date can then be accommodated, to some degree, by adjusting the fan speed. The subject of air movers is covered in greater detail in Chapter 42.

PRINCIPLES OF LOCAL EXHAUST

When applying local exhaust ventilation to a specific problem, control of the contaminant is more effective if the following basic principles are followed:

1. Enclose the source as completely as practicable;

2. Capture the contaminant with adequate velocities;
3. Keep the contaminant out of worker's breathing zone;
4. Supply adequate make-up air; and
5. Discharge the exhausted air away from air inlet systems.

Enclose the Source

A process to be exhausted by local ventilation should be enclosed as much as possible. This will generally provide better control per unit volume of air exhausted. This principle is illustrated in Figure 41-2. Nevertheless, the requirement of adequate access to the process must always be considered. An enclosed process may be costly in terms of operating efficiency or capital expenditure, but the savings gained by exhausting smaller air volumes may make the enclosure worthwhile.

Capture the Contaminant with Adequate Velocities

Air velocity through all hood openings must be high enough to contain the contaminant and, moreover, remove the contaminant from the hood. The importance of optimum capture and control velocity is discussed further in the following sections.

Keep the Contaminant Out of Worker's Breathing Zone

Exhaust hoods that do not completely enclose the process should be located as near as possible to the point of contaminant generation and should provide air flow in a direction away from the worker toward the contaminant source (see Figure 41-3).

ADVANTAGES OF ENCLOSURE

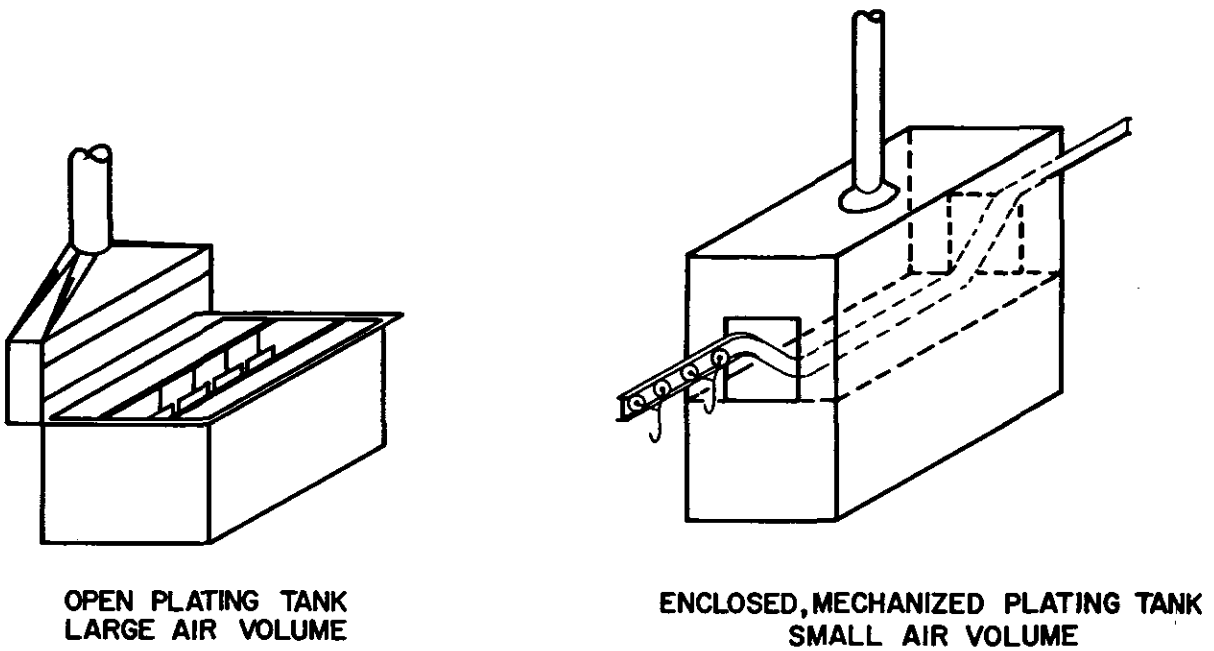


Figure 41-2. Advantages of Enclosure.

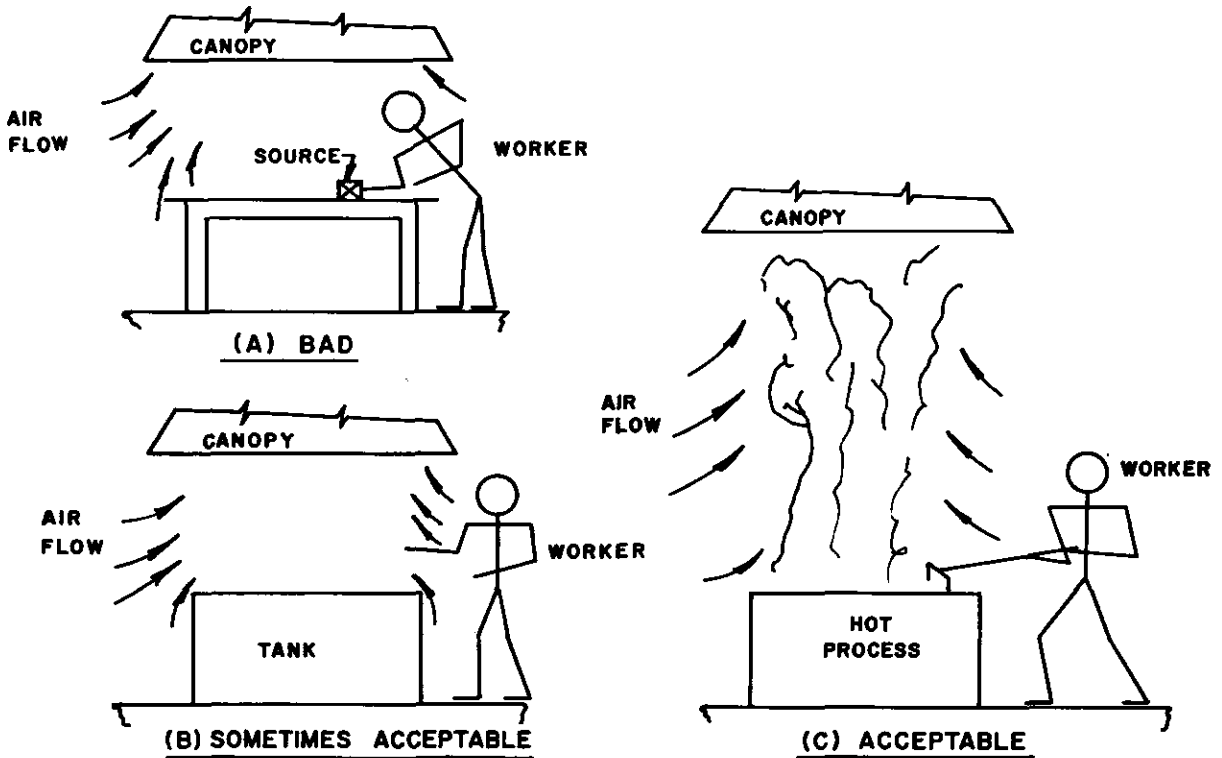


Figure 41-3. Use and Misuse of Canopy Hoods.

This item is closely related to the characteristics of blowing and exhausting from openings in ductwork and is also considered in more detail in the following sections.

Provide Adequate Air Supply

Every cubic foot of air that is exhausted from a building or enclosure must be replaced to keep the building from operating under negative pressure. This applies to local exhaust systems as well as general exhaust systems. Additionally, the incoming air must be tempered by a make-up air system before being distributed inside the processing area. Without sufficient make-up air, exhaust ventilation systems cannot work as efficiently as intended.

Discharge the Exhausted Air Away from Air Inlets

The beneficial effect of a well-designed local-exhaust system can be offset by undesired recirculation of contaminated air back into the work area. Such recirculation can occur if the exhausted air is not discharged away from supply air inlets. The location of the exhaust stack, its height, and the type of stack weather cap all can have a significant effect on the likelihood of contaminated air re-entering through nearby windows and supply air intakes. This subject is treated in more detail in Chapter 42.

FUNDAMENTAL CONCEPTS IN LOCAL EXHAUST VENTILATION

Capture and Control Velocities

All local exhaust hoods perform their function in one of two ways. One way is by creating air movement which draws the contaminant into the

hood. The air velocity created at a point outside a non-enclosing hood, which accomplishes this objective, is called "capture velocity." Other exhaust hoods essentially enclose the contaminant source and create an air movement which prevents the contaminant from escaping from the enclosure. The air velocity created at the openings of such hoods is called the "control velocity."

The determination of the two quantities, control velocity and capture velocity, is the basis for the successful design of any exhaust hood. The air velocity which must be developed by the exhaust hood at the point or in the area of desired control is based on the magnitude and direction of the air motion to be overcome and is not subject to direct and exact evaluation (see Table 41-1). Many empirical ventilation standards, especially concerning dusty equipment like screens and conveyor belt transfers, are based on "cfm per foot of belt width" or similar parameters. These are called exhausted rate standards. They are easily applied, are usually based on successful experience, and usually give satisfactory results if not extrapolated too far. In addition, they minimize the effort and uncertainty involved in calculating the fan action of falling material, thermal heads within hoods, air currents, etc. However, such standards have three major pitfalls:

1. They are not fundamental.
2. They presuppose a certain minimum quality of hood or enclosure design although it may not be possible or practical to achieve the same quality of hood design in a new installation.
3. They are valid only for circumstances sim-

TABLE 41-1
RANGE OF CAPTURE VELOCITIES*

Condition of Dispersion of Contaminant	Examples	Capture Velocity, fpm
Released with practically no velocity into quiet air.	Evaporation from tanks; degreasing, etc.	50-100 f
Released at low velocity into moderately still air.	Spray booths; intermittent container filling; low speed conveyor transfers; welding; plating; pickling.	100-200
Active generation into zone of rapid air motion.	Spray painting in shallow booths; barrel filling; conveyor loading; crushers.	200-500
Released at high initial velocity into zone of very rapid air motion.	Grinding; abrasive blasting,	500-2000

In each category above, a range of capture velocity is shown. The proper choice of values depends on several factors:

- | <i>Lower End of Range</i> | <i>Upper End of Range</i> |
|--|-------------------------------------|
| 1. Room air currents minimal or favorable to capture. | 1. Disturbing room air current. |
| 2. Contaminants of low toxicity or of nuisance value only. | 2. Contaminants of high toxicity. |
| 3. Intermittent, low production. | 3. High production, heavy use. |
| 4. Large hood — large air mass in motion. | 4. Small hood — local control only. |

*Comm. on Industrial Ventilation, *Industrial Ventilation*, 12th edition, ACGIH, p. 4-5.

ilar to those which led to their adoption. It should be clear then, that the nature of the process generating the contaminant will have an important role in determining the required capture velocity.

Air Flow Characteristics of Blowing and Exhausting

The flow characteristics at a suction opening are much different from the flow pattern on a supply or discharge opening. Air blown from an opening maintains its directional effect in a fashion similar to water squirting from a hose. The effect is so pronounced that it is often called "throw." However, if the flow of air through the same opening is changed such that it operates as an exhaust or intake opening with the same volumetric rate of air flow, the flow becomes almost completely non-directional and its range of influence is greatly reduced. As a first approximation, when air is blown from a small opening, the velocity thirty diameters in front of the plane of the opening is about 10% of the velocity at the discharge. However, the same reduction in velocity is achieved at a much smaller distance in the case of exhausted openings, such that the velocity equals 10% of the face velocity at a distance of one diameter from the exhaust opening. Figure 41-4 illustrates this point. For this reason, local exhaust hoods must not be applied for any operation which cannot be conducted in the immediate vicinity of the hood.

Air Flow into Openings

Air flow into round openings was studied extensively by DallaValle.³ His theory of air flow into openings is based on a point source of suction which draws air from all directions. The velocity at any point in front (distance X) of such a source is equivalent to the quantity of air (Q) flowing to the source divided by the effective area

of the sphere of the same radius.

Conversely,

$$Q = VA$$

$$A = 4\pi X^2$$

$$\text{So, } Q = V(12.57 X^2)$$

Where Q = air flow, cfm

V = velocity at point X, fpm

X = centerline distance, ft

A = pipe area, ft²

$\pi = 3.1416$, dimensionless constant

Postulating that a point source is approximated by the end of an open pipe, Dalla Valle³ and Brandt⁴ determined the actual velocity contours for a circular opening, as shown in Figure 41-5. These contours, or lines of constant velocity, are best described by the following equation:

$$Q = V(10 X^2 + A)$$

Effects of Flanging

Flanges surrounding a hood opening force air to flow mostly from the zone directly in front of the hood. Thus, the addition of a flange to an open duct or pipe improves the efficiency of the duct as a hood for a distance of about one diameter as shown in the following equation:

$$Q = 0.75 V(10 X^2 + A)$$

For a flanged opening on a table or bench:

$$Q = 0.5 V(10 X^2 + A)$$

Table 41-2 illustrates other hood types and gives the air volume formulae which apply.²

Slots

Caution must be used in applying the generalized continuity equation when the width to length ratio (aspect ratio) of an exhaust opening approaches 0.1, since the opening becomes more like a slot. Using the same line of reasoning as

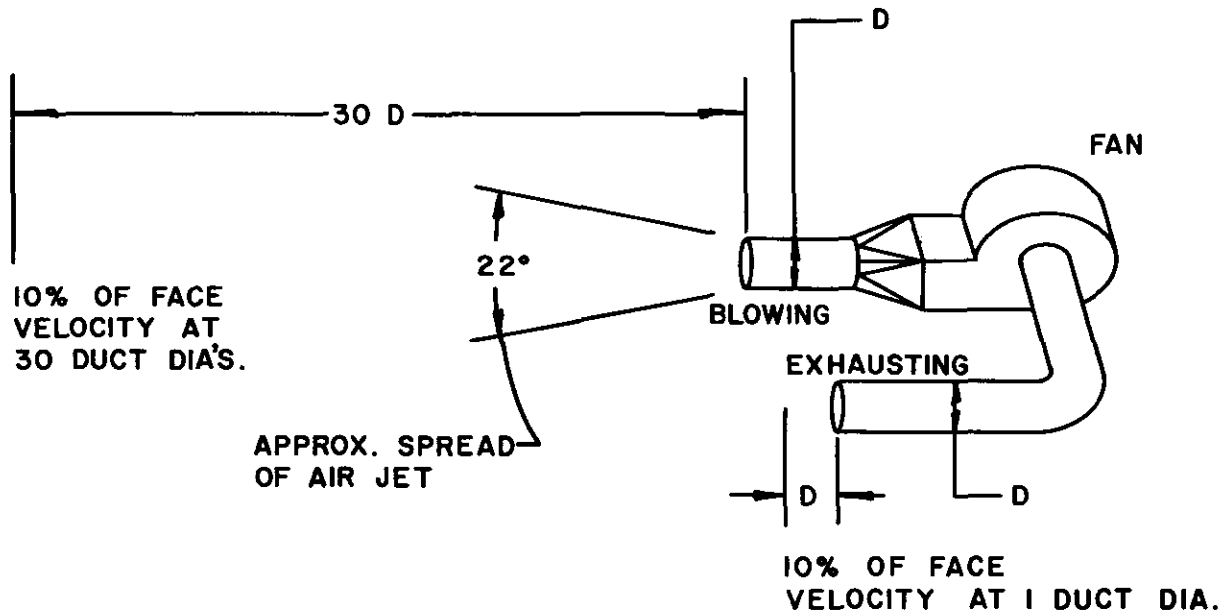
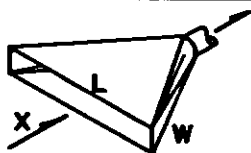
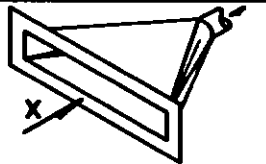
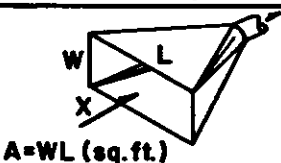
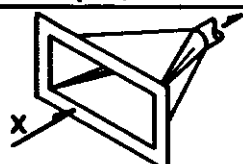
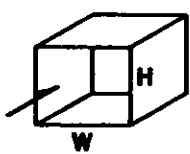
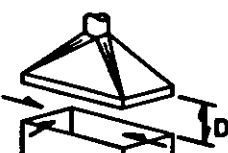


Figure 41-4. Air Flow Characteristics of Blowing and Exhausting.

**TABLE 41-2
INDUSTRIAL VENTILATION***

HOOD EXHAUST VS. CAPTURE VELOCITY

HOOD TYPE	DESCRIPTION	ASPECT RATIO $\frac{W}{L}$	AIR VOLUME
	SLOT	0.2 OR LESS	$Q=3.7 LVX$
	FLANGED SLOT	0.2 OR LESS	$Q=2.8 LVX$
	PLAIN OPENING	0.2 OR GREATER AND ROUND	$Q=V(10X^2 + A)$
	FLANGED OPENING	0.2 OR GREATER AND ROUND	$Q=0.75V(10X^2 + A)$
	BOOTH	TO SUIT WORK	$Q=VA=VWH$
	CANOPY	TO SUIT WORK	$Q=1.4 PVD$ P=PERIMETER D=HEIGHT

*Comm. on Industrial Ventilation, *Industrial Ventilation*, 12th edition, ACGIH, p. 4-4.

DallaValle, Silverman^s considered the slot to be a line source of suction. Disregarding the end, the area of influence then approaches a cylinder and the velocity is given by:

$$V = \frac{Q}{2\pi XL}$$

Where: L = length of slot, ft.
X = centerline distance, ft.
 $\pi = 3.1416$, dimensionless constant

Correcting for empirical versus theoretical considerations, the design equation which best applies for freely suspended slots is:

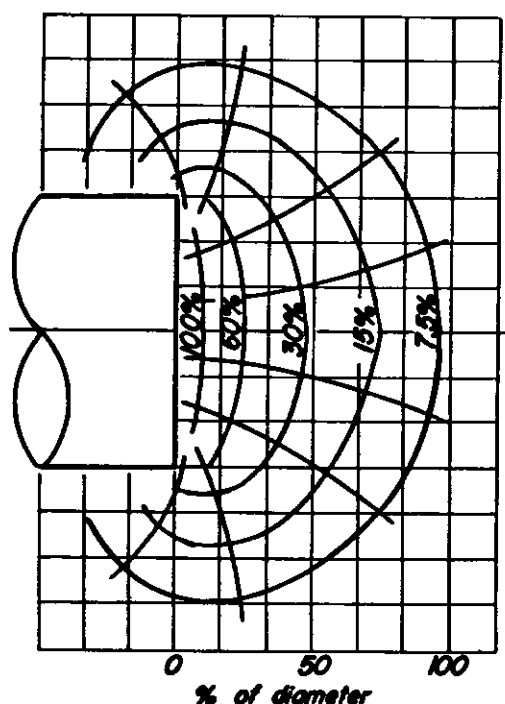
$$V = \frac{Q}{3.7 XL}$$

Flanging the slots will give the same benefits as flanging an open pipe so that only 75% of the air is required to produce the same velocity at a given point. Therefore, for a flanged slot:

$$V = \frac{Q}{2.8 XL}$$

Air Distribution in Hoods

To provide efficient capture with a minimum expenditure of energy, the air flow across the face of a hood should be uniform throughout its cross section. For slots and lateral exhaust applications this can be done by a "fish tailing" design. An easier method of design is to provide a velocity of 2,000-2,500 feet per minute into the slot with a low velocity plenum or large area chamber behind it. For large, shallow hoods, such as paint spray



American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation — A Manual of Recommended Practice, 12th Edition. Lansing, Michigan, 1972.

Figure 41-5. Velocity Contours for a Circular Opening.

booths, lab hoods, and draft shake-out hoods, the same principle may be used. In these cases unequal flow may occur with a concentration of higher velocities near the take-offs. Baffles provided for the hood improve the air distribution and reduce pressure drop in the hood giving the plenum effect. Where the face velocity over the whole hood is relatively high or where the hood or booth is quite deep, baffles may not be required.

Entrance Losses in Hoods

The negative static pressure that is exhibited in the ductwork a short distance downstream from the hood is called the "hood static pressure," SP_h . This term represents the energy needed to:

1. Accelerate the air from ambient velocity (often near zero) to the duct velocity;
2. Overcome the frictional losses resulting from turbulence of the air upon entering the hood and ductwork.

Therefore, $SP_h = VP + h_e$

where VP = velocity pressure in the duct
and h_e = hood entry loss

The hood entry loss, h_e is expressed as a function of the velocity pressure, VP . For most types of hoods $h_e = F_h VP$, where F_h is the hood entry loss factor. For plain hoods where the hood entry loss

is a single expression, $F_h VP$, the VP referred to is the duct velocity pressure. The hood static pressure can be expressed as:

$$SP_h = VP_{duct} + h_e$$

$$\text{or } SP_h = VP_{duct} + F_h VP_{duct} = (1 + F_h) VP_{duct}$$

However, for slot and plenum or compound hoods there are two entry losses; one through the slot and the other into the duct. Thus,

$$SP_h = h_{e_{slot}} + VP_{duct} + h_{e_{duct}} =$$

$$F_{slot} \times VP_{slot} + VP_{duct} + F_{duct} \times VP_{duct}$$

The velocity pressure resulting from acceleration through the slot is not lost as long as the slot velocity is less than the duct velocity, as is usually the case.

Another constant used to define the performance of a hood is "coefficient of entry," C_e . This is defined as a ratio of the actual air flow to the flow that would exist if all the static pressure were present as velocity pressure. Thus,

$$C_e = \frac{Q_{actual}}{Q_{VP = SP_h}} = \frac{4,005 A \sqrt{VP}}{4,005 A \sqrt{SP_h}} = \sqrt{\frac{VP}{SP_h}}$$

This quantity is constant for a given shape of hood and is very useful for determining the flow into a hood by a single hood static pressure reading. The coefficient of entry, C_e , is related to the hood entry loss factor, F_h , by the following equation only where the hood entry loss is a single expression:

$$C_e = \sqrt{\frac{1}{1 + F_h}}$$

Page 4-12 (Figure 4-8) of *Industrial Ventilation* provides a listing of the entry loss coefficient (C_e) and the entry loss (h_e) in terms of velocity pressure (VP). Most of the more complicated hoods have coefficients obtained by combining some of these simpler shapes.

Static Suction

One method of specifying the air volume for a hood is to specify the hood static pressure, SP_h , and duct size. The hood static pressure at a typical grinding wheel hood is two inches of water. This reflects a conveying velocity of 4500 feet per minute and entrance coefficient (C_e) of 0.78. For other types of machinery where the type of exhaust hood is relatively standard, a specification of the static suction and the duct size is given in Alden⁶ and other reference sources. Specification of the static suction without duct size is, of course, meaningless because decreased size increases velocity pressure and static suction, while actually decreasing the total flow and the degree of control. Therefore, static suction measurements for standard hoods or for systems where the air flow has been measured previously are quite useful to estimate, in a comparative way, the quantity of air flowing through the hood.

Duct Velocity for Dusts and Fumes

The air velocity for transporting dusts and fumes through ductwork must be high enough that the particles will not settle and plug the ducts. This minimum velocity, called "transport velocity," is typically 3,500 to 4,000 linear feet per minute. At these velocities, frictional loss from air moving

along the surface of the ducts becomes significant; therefore, all fittings, such as elbows and branches, must be wide-swept, gradual, and with smooth interior surfaces. The cross-sectional area of the main duct generally will equal the sum of the areas of cross sections for all branches upstream, plus a safety factor of approximately twenty percent. When the main duct is enlarged to accommodate an additional branch, the connection should be tapered and not abrupt.

Local exhaust systems for gases and vapors may have lower duct velocities (1,500 to 2,500 feet per minute) because there is little to settle and plug the ducts. Lower velocities reduce markedly the frictional and pressure losses against which the fan must operate, thereby realizing a saving in power cost for the same air flow.

EXHAUST HOODS AND THEIR APPLICATIONS

The local exhaust "hood" is the point at which air enters the exhaust system, and the term is used in a broad sense to include all suction openings, regardless of their shape or their physical disposition. Hoods in the context of this discussion embrace all types of such openings including suspended, canopy-type hoods, booths, exhausts through grille work in the floor or bench top, slots along the edge of a tank or table, the open end of a pipe, and, in a general sense, exhaust from most enclosures.

Hoods ventilate process equipment by capturing emissions of heat or air contaminants which are then conveyed through ductwork to a more convenient discharge point or to air pollution control equipment. The quantity of air required to capture and convey the air contaminants depends upon the size and shape of the hood, its position relative to the points of emission and the nature and quantity of the air contaminants.

Exhaust hoods should enclose as effectively as practical the points where the contaminant is released. They should create air flow through the zone of contaminant release of such magnitude and direction so as to carry the contaminated air into the exhaust system. Exhaust hoods and enclosures may also serve the important function of keeping materials in the process by preventing their dispersion.

Hoods can be classified conveniently into three broad groups: enclosures, receiving hoods, and exterior hoods. Booths, such as the common spray-painting enclosure, are a special case of enclosing hoods and will be discussed separately.

Enclosures

Enclosures normally surround the point of emission or contaminant generation, either completely or partially. In essence, they surround the contaminant source to such a degree that all dispersive actions take place within the confines of the hood. Because of this, enclosures require the lowest exhaust rate of the three hood types. A typical enclosed hood is illustrated in Figure 41-6.

Enclosure hoods are economical and efficient. They should be used whenever possible, especially when the contaminant is a hazardous material.

Materials having high toxicity or corrosiveness and fine dusts must be effectively controlled for workers' health and safety. Hoods handling these materials should be carefully designed so as not to accumulate the contaminants.

Booth Type Hoods

Booths are typified by the common laboratory hood or spray painting booth in which one face of an otherwise complete enclosure is open for access. Air contamination takes place inside the enclosure and air is exhausted from it at such a rate as to induce an average velocity through the opening that will be sufficient to overcome escape tendencies of the air within it. The three walls of the booth greatly reduce exhaust requirements, but not to the extent of a complete enclosure.

A list of several enclosure hoods and their application is shown in Table 41-3.

TABLE 41-3.
ENCLOSURE HOODS AND THEIR APPLICATIONS

Hood	Application
Booth	Laboratory Paint and metal spraying Arc welding Bagging machines
Machine Enclosure	Bucket elevators (complete enclosure) Vibrating screens Storage bins Mullers — Mixers Crushers Belt conveyor (transfer points) Packaging machines Abrasive blast cabinets

Receiving Hoods

The term "receiving hoods" refers to those hoods in which a stream of contaminated air from a process is exhausted by a hood located specifically for that purpose. Two common types of receiving hoods are canopies and grinding hoods. Canopy hoods frequently are located directly above various hot processes. A canopy hood is shown in Figure 41-7. They receive contaminated air which rises into the hood primarily by reason of its own buoyancy. This type of receiving hood is similar to an exterior hood in that the contaminated air originates beyond the physical boundaries of the hood. The fundamental difference between receiving and exterior hoods is in the way air moves to the hood; i.e., the entire air flow is induced by the receiving hood, but flows more freely to the exterior hoods. However, canopy hoods are adversely affected by crossdrafts and are less efficient than total enclosures. They cannot be used to capture toxic vapors if people must work in a position between the source of contamination and the hood.

Contaminants from a grinding or polishing wheel are too heavy to be captured by conventional air-flow patterns created by exhaust hoods.

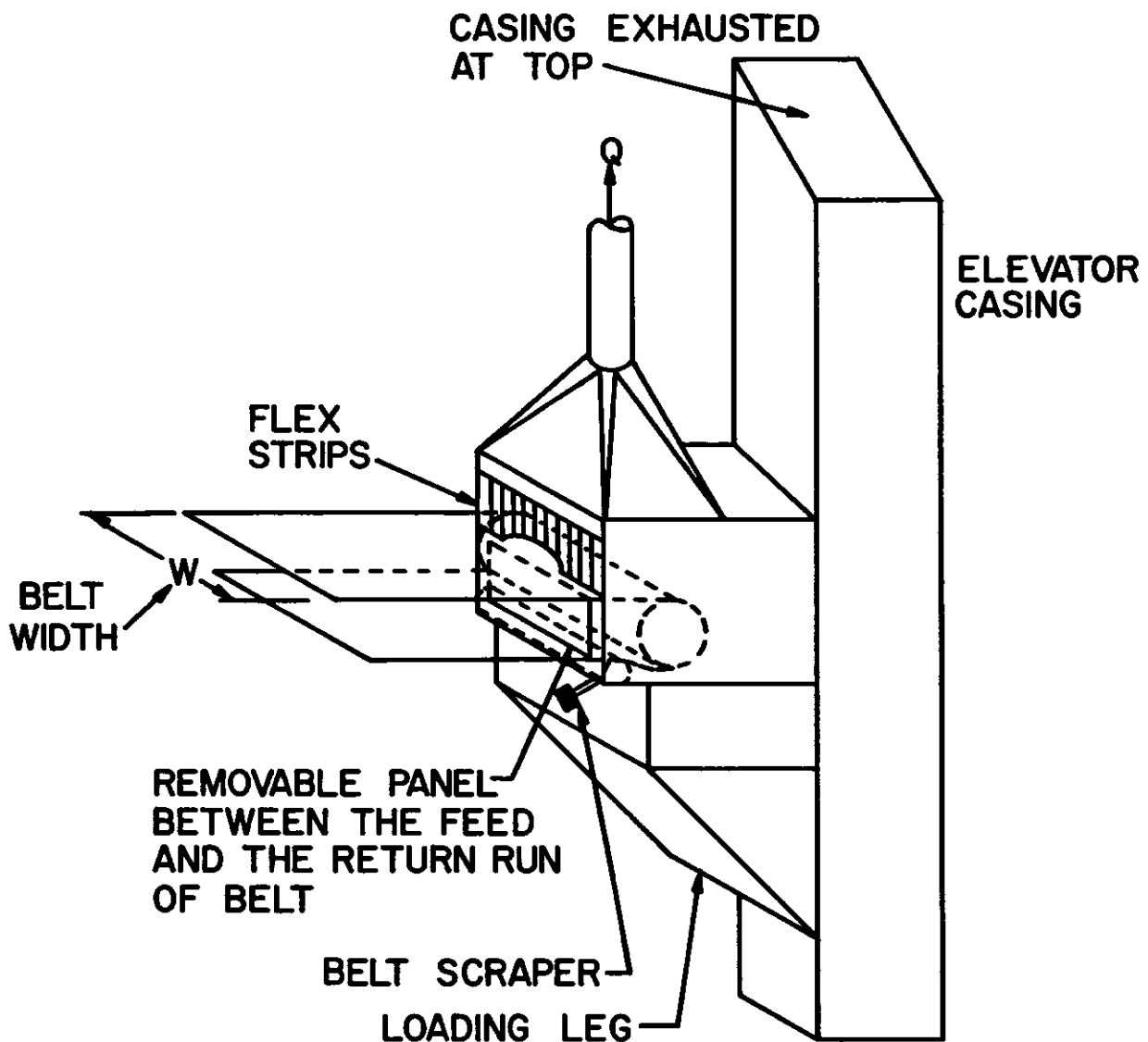


Figure 41-6. A Typical Enclosed Hood.

Hence, this type of hood is also located in the pathway of the contaminant. Heavy particulates are released into the hood by inertial forces from the grinding (or polishing) wheel. If hood space is limited by the process, baffles or shields may be placed across the line of throw of the particles to remove their kinetic energy. Then, lower air velocities are required to capture and carry the particles into the hood. A typical grinding wheel hood is shown in Figure 41-8.

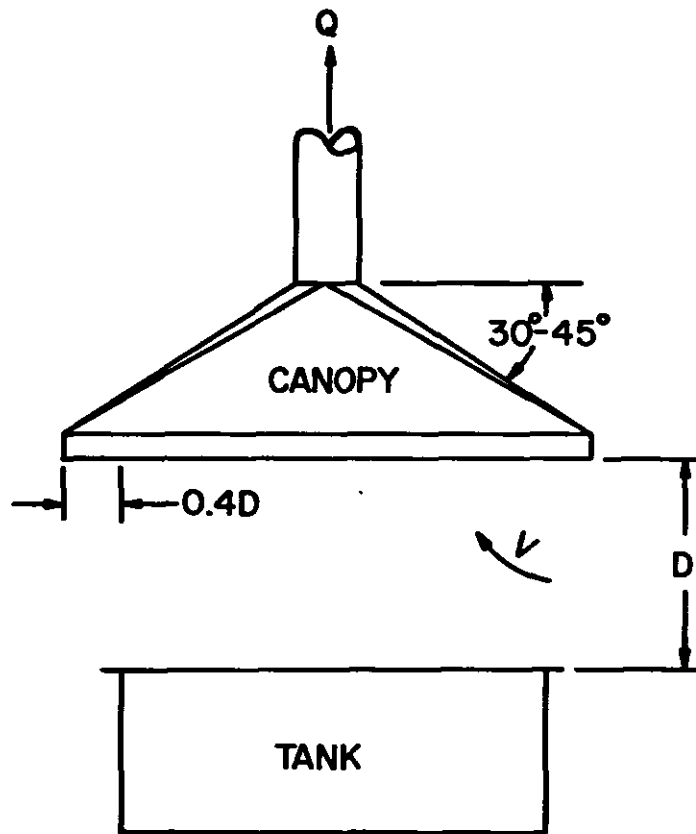
Some common receiving hoods are listed in Table 41-4.

Exterior Hoods

Exterior hoods must capture air contaminants being generated from a point outside the hood itself — sometimes relatively far away. These differ from enclosures or receiving hoods in that they must “reach” beyond their own dimensions and capture contaminants without the aid of natural phenomena (e.g., natural drafts, buoyancy

TABLE 41-4.
RECEIVING HOODS AND THEIR APPLICATIONS

Hood	Application
Grinding	Surface grinders Stone and metal polishing
Woodworking	Shapers, stickers, saws, jointers, molders, planers
Stone cutting	Granite and marble cutters and grinders. Granite surfacing
Sanding	Belt and drum sanding operations
Portable	Hand grinding, chipping
Canopy	Hot processes evolving fumes



$$Q=1.4 PDV$$

where

Q=RATE OF AIR EXHAUSTED, cfm.

P=PERIMETER OF SOURCE, ft.

D=VERTICAL DISTANCE BETWEEN SOURCE AND CANOPY, ft.

V=REQUIRED AVERAGE AIR VELOCITY THROUGH AREA BETWEEN SOURCE AND CANOPY, fpm.

Figure 41-7. A Canopy Hood.

inertia, etc.). Exterior hoods must create directional air currents adjacent to the suction opening to provide exhausting action. They are sensitive to external conditions and may be rendered completely ineffectual by even a slight draft through the area. They also require the most air to control a given process. Of the three hood types, exterior hoods are the most difficult to design. They are used when the mechanical requirements of a process will not permit the obstruction that total or partial enclosure would entail. This class of hood includes the numerous types of suction openings located adjacent to sources of contamination which are not enclosed. These hoods include exhaust slots on the edges of tanks (see Figure 41-2)

or surrounding a work bench, exhaust duct ends located close to a small area source, large exhaust hoods arranged for lateral exhaust across an adjacent area, exhaust grilles in the floor or bench work below the contaminating action, certain canopy hoods and large propeller exhaust fans on outer walls adjacent to a zone of contamination.

A more complete list of external hoods and their applications is given in Table 41-5.

VENTILATION STANDARDS AND REGULATIONS

Regulations resulting from the Occupational Safety and Health Act of 1970 include several standards for local ventilation, both for the pre-

GRINDER OR POLISHER

Side opening should be minimum.
 $\frac{1}{4}$ " maximum is desirable.

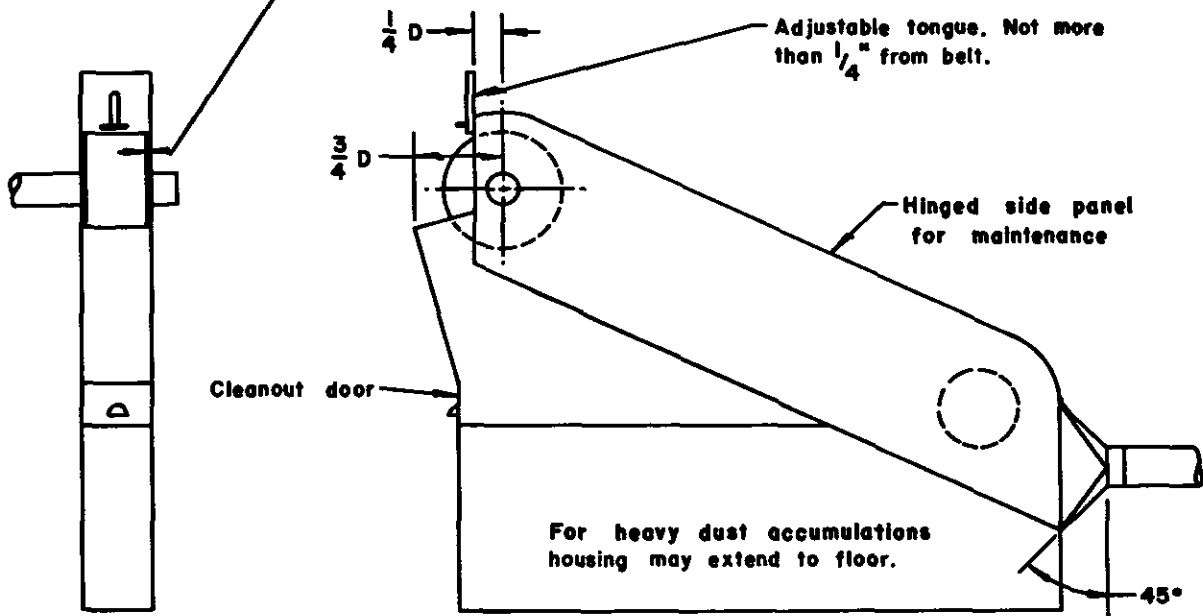


Figure 41-8. A Grinding Wheel Hood.

vention of fire and explosion and for controlling hazardous materials in the workroom to prevent illness or injury. In late 1972, such regulations included specific ventilation requirements for:

1. Abrasive blasting;
2. Grinding, polishing and buffing;
3. Spray finishing operations;
4. Open surface tanks;
5. Welding, cutting and brazing;
6. Gaseous hydrogen;
7. Oxygen;
8. Flammable and combustible liquids in storage rooms and enclosures; and
9. Dip tanks containing flammable or combustible liquids.

The bases of these OSHA standards have been the consensus-type standards developed by organizations such as the American National Standards Institute and the National Fire Protection Association. It is quite likely that the number and specificity of ventilation standards will increase with time, both under the regulations of the Occupational Safety and Health Administration and by the added interest in occupational health and safety at all levels of government.

It is important to understand that standards and codes define minimum standards of ventilation. Most of these have developed as "rule-of-thumb" values, usually based on successful experience. As a result, they tend to be inflexible and can be inadequate for design purposes. If not

**TABLE 41-5
 EXTERNAL HOODS AND THEIR
 APPLICATIONS**

Hood	Application
Slot	Open tanks
Push-Pull	Plating tanks Cementing and lay-up tables
Down draft	Floor or bench type grinding, welding, low fog painting
Side draft	Some open surface tanks Shakeout grates
Small canopy	Cool to warm processes
Wall fan (hood)	Some plastics operations Feed mill

used with caution, especially in new installations they can cause a false sense of security and result in excessive expense when it is found necessary to modify or replace inadequate ventilation equipment.

References

1. AMERICAN IRON and STEEL INSTITUTE. Committee on Industrial Hygiene, *Steel Mill Ventilation*, AISI, 150 East 42nd Street, New York, New York, 1965.
2. AMERICAN CONFERENCE OF GOVERNMENTAL INDUSTRIAL HYGIENISTS. Committee on Industrial Ventilation, *Industrial Ventilation — a*

- Manual of Recommended Practice*, ACGIH, P.O. Box 453, Lansing, Michigan, 12th Edition, 1972.
3. DALLAVALLE, J. M. "Velocity Characteristics of Hoods Under Suction," *ASHVE Transactions*, 38, p. 387, 1932.
 4. BRANDT, A. D. *Industrial Health Engineering*, John Wiley and Sons, New York, New York, 1947.
 5. SILVERMAN, L. "Velocity Characteristics of Narrow Exhaust Slots." *Industrial Hygiene and Toxicology J.*, 24, 267, 1942.
 6. ALDEN, JOHN L. *Design of Industrial Exhaust Systems*, The Industrial Press, New York, New York, 1949.

DESIGN OF VENTILATION SYSTEMS*Engineering Staff***George D. Clayton & Associates***INTRODUCTION**

Not too many years ago the design of ventilation systems was an art, but with the accumulation of knowledge today it has "come of age" and may be classified as an engineering science. Various "rule-of-thumb" methods have been replaced with new rules based on theory, supported by experimentation, and validated by experience. When properly designed and installed, a good ventilation system often can add to productivity and the general well-being of workers. In some cases, a system with adequate collection devices can recover enough valuable materials to pay for itself in a reasonably short time.

It should be emphasized that in industrial hygiene the primary purpose for designing a ventilation system is to protect the health and well-being of workers.

The design of any ventilation system should include consideration of materials that will withstand normal mechanical abuse inherent to the environment in which it is operated. Frequently, extra design capacity in fans, control equipment and motors which allows for future expansion of the system at minimum cost is desirable.

There are generally two types of ventilation systems: (1) general, and (2) local exhaust. For the purpose of this chapter make-up air is considered part of local exhaust ventilation.

GENERAL VENTILATION

General ventilation refers to the commonly encountered process of flushing a working environment with a constant supply of fresh air. General ventilation differs from local ventilation in that it is a dilution process rather than strictly an exhausting process. General ventilation may be accomplished by natural infiltration of air, or with the aid of some type of air moving device.

Office Buildings

For office buildings to maintain comfortable work conditions, the proper environmental atmosphere must be achieved. This usually occurs as a result of a properly designed general ventilation system. Whereas the design criteria for local exhaust systems are relatively clear-cut, this is not necessarily the case for general systems. Here design is based on human comfort requirements, noise considerations and ease of distribution of fresh air.

*The following staff members participated in writing this chapter: Donald K. Russell, Quentin Keeny, John E. Mutchler and George D. Clayton.

Worker Comfort. The comfort of office workers is subject to the following environmental conditions:

1. Air temperature;
2. Humidity;
3. Radiant heat;
4. Concentrations of tobacco smoke;
5. Concentration of body odors; and
6. Air movement.

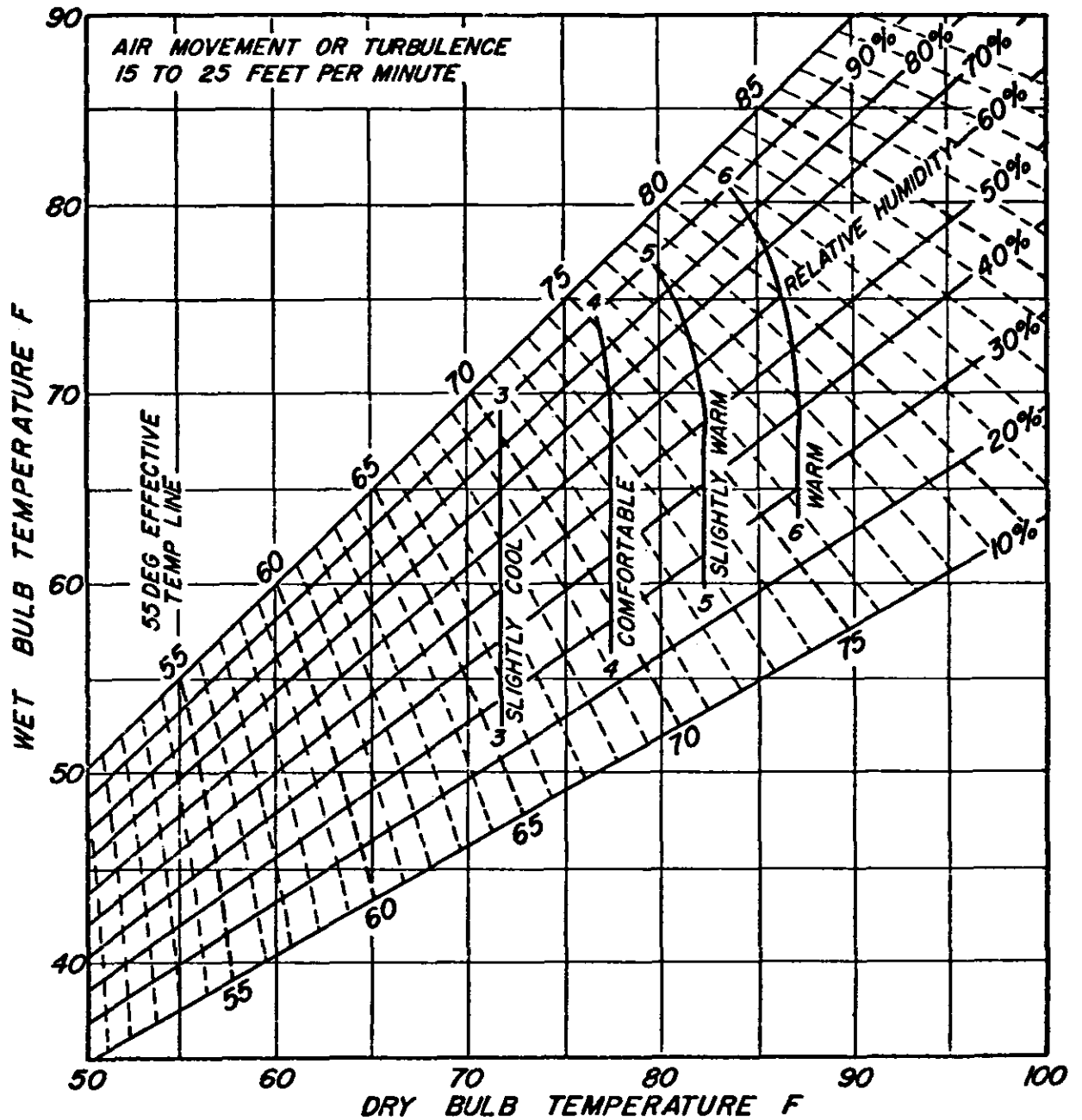
Before designing any general ventilation system, the aforementioned conditions must be measured or estimated. Then a fresh air flowrate can be calculated which will reduce undesirable air qualities to tolerable levels.

Comfort Zone. Various indices have been devised by investigators to describe a "comfortable" environment. A comfort chart has been developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. which uses wet- and dry-bulb air temperatures as parameters (See Figure 42-1). The comfort zone is that combination of environmental conditions which is thermally neutral to the human body. Specifically, the comfortable temperature range for office workers is 68 — 74°F during the winter months and 75-82°F in summer with moderate humidities. A summary of minimum ventilation requirements for various conditions is included in Table 42-1.

Odor Control. Air exchange rates are dictated in part by the concentration of body and tobacco odors in a room. These concentrations are affected by air supply, space allowed per person, odor absorbing capacity of the air conditioning process, temperature and relative humidity.

Conditioning of Air. Comfort conditions can be met by the proper selection of air conditioning equipment. Such equipment can maintain proper conditions of temperature, humidity, and odor levels when comfort indices have been determined. The subject of air heating and conditioning is beyond the scope of this chapter; however, the reader is urged to consult the references listed at the end of this chapter, specifically 5, 6 and 7, for more information.

To summarize briefly, the criteria for design calculations for general office ventilation systems include the determination of worker comfort, zone parameters (temperature, humidity), tolerable odor levels, space allowed per person in room and the odor-absorbing capacity of the air conditioning unit to be installed. In addition, it should be stressed that fan noise is an extremely important



American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation — A Manual of Recommended Practice, 12th Edition. Lansing, Michigan, 1972.

Figure 42-1. Comfort Chart for Still Air (from: Industrial Ventilation Manual). Notes: 1. Effective Temperature (dashed) lines indicate sensation of warmth immediately after entering conditioned space. 2. Solid lines 3, 4, 5, and 6 indicate sensations experienced after three hour occupancy. 3. Both sets of curves apply to people at rest and normally clothed.

TABLE 42-1.
Summary of Minimum Outdoor Air Requirements
for Ventilation Under Various Conditions

Type of occupants	Air space per person (cubic feet)	Requirements based on primary* impressions (cfm per person)	Requirements based on impressions of occupants† (cfm per person)
Heating season with or without recirculation. Air not conditioned.			
Sedentary adults of average socio-economic status	100	25	23
	200	16	11
	300	12	----
	500	7	>5
Laborers	200	23	----
Grade school children of average class	100	29	----
	200	21	15
	300	17	----
	500	11	----
Grade school children (low income)	200	38	----
Grade school children (medium income)	200	18	----
Grade school children (high income)	100	22	----
Heating season. Air humidified by means of centrifugal humidifier. Total air circulation 30 cfm per person.			
Sedentary adults	200	12	----
Summer season. Air cooled and dehumidified by means of a spray dehumidifier. Total air circulation 30 cfm per person.			
Sedentary adults	200	>4‡	6‡

*Impressions upon entering room from relatively clean air at threshold odor intensity.

†Corresponding to an air quality of fair to good.

‡Values provisionally restricted to the conditions of the tests.

"The Industrial Environment and Its Control," J. M. DallaValle, p. 105, Pitman Publishing Corporation, New York, N.Y., 1948.

design consideration of office ventilation systems. Usually a forward-curved blade fan is chosen over the more efficient backward-curved blade fan simply because of noise considerations. More detailed information on fans and noise problems are given in a later section of this chapter and in several references^{1, 2, 3, 4, 5}.

Industrial Buildings

General ventilation systems employed in industrial buildings are of two types — natural and mechanical.

Natural Ventilation. The two forces which are responsible for natural ventilation are wind and thermal head. Realizing this, in the past, architects devised sawtooth and monitor type roofs to achieve maximum ventilation and lighting, although with greater use of mechanical ventilation, these building designs are slowly becoming outdated. More recently, windows such as the double hung sash and center-pin-swing-hinge type have been utilized to achieve maximum natural air flow. In buildings such as warehouses, powerhouses and pump-rooms, where few people are employed, wall or roof openings generally provide enough fresh air for good ventilation. Mushroom, gooseneck, or louvered penthouse roof ventilators are reasonably

effective supply ports regardless of wind direction. **Mechanical Ventilation.** Although general ventilation by natural means is the most economical, it is limited in usefulness. Ventilation by mechanical devices (i.e., fans) is seldom limited, and, when used in conjunction with ductwork, air can be distributed to all parts of the building. Equipment and design considerations for general ventilation systems of this type are discussed in the following section and later in this chapter.

Design Considerations. General ventilation systems are used in industry in conjunction with local exhaust ventilation systems to achieve maximum effectiveness (for additional discussion see Chapter 39). Besides providing for a comfortable atmosphere in which to work, general ventilation systems may be employed to control vapors within acceptable limits from organic liquids of low-level toxicity. This is successfully accomplished by dilution. Table 42-2 lists the dilution air volumes for several commonly used solvents. Threshold Limit Values (TLV) represent guides to allowable toxic material concentrations in air. When the maximum allowable concentrations of the contaminant are known and the generation rate has been estimated, the quantity of dilution air re-

TABLE 42-2.
Dilution Air Volumes for Vapors
 (based on 1971 TLV Values which are shown as ppm in parentheses)

Liquid	Cu. ft. of air (STP) required for dilution to TLV*	
	Per Pint Evaporation	Per Pound Evaporation
Acetone (1000)	5,500	6,650
n-Amyl acetate (100)	27,200	29,800
Isoamyl alcohol (100)	37,200	43,900
Benzol (25)	Not Recommended	
n-Butanol (butyl alcohol) (100)	44,000	52,200
n-Butyl acetate (150)	20,400	22,200
Butyl cellosolve (50)	61,600	65,600
Carbon disulfide (20)	Not Recommended	
Carbon tetrachloride (10)	Not Recommended	
Cellosolve (2-Ethoxyethanol) (200)**	20,800	21,500
Cellosolve acetate (2-ethoxyethyl-acetate) (100)	29,700	29,300
Chloroform (50)**	Not Recommended	
1-2 Dichloroethane (50)** (ethylene dichloride)	Not Recommended	
1-2 Dichloroethylene (200)	26,900	20,000
Dioxane (100)	47,300	43,900
Ethyl acetate (400)	10,300	11,000
Ethyl alcohol (1000)	6,900	8,400
Ethyl ether (400)	9,630	13,100
Gasoline	Requires special consideration	
Methyl acetate (200)	25,000	26,100
Methyl alcohol (200)	49,100	60,500
Methyl butyl ketone (100)	33,500	38,700
Methyl cellosolve (25)	Not Recommended	
Methyl cellosolve acetate (25)	Not Recommended	
Methyl ethyl ketone (200)	22,500	26,900
Methyl isobutyl ketone (100)	32,300	38,700
Methyl propyl ketone (200)	19,000	22,400
Naptha (coal tar) (100)	30,000-38,000	40,000-50,000
Naptha (petroleum) (500)	Requires special consideration	
Nitrobenzene (1)	Not Recommended	
n-Propyl acetate (200)	17,500	18,900
Isopropyl alcohol (400)	13,200	16,100
Isopropyl ether (500)**	5,700	7,570
Stoddard solvent (200)	15,000-17,500	20,000-25,000
1,1,2,2-Tetrachloroethane (5)	Not Recommended	
Tetrachloroethylene (100)	39,600	23,400
Toluol (Toluene) (200)**	19,000	21,000
Trichloroethylene (100)	45,000	29,400
Xylol (xylene) (100)	33,000	36,400

*The tabulated dilution air quantities must be multiplied by the selected K value.

**See Notice of Intended Changes in TLV List for 1971.

The K value is merely a safety factor between 3 and 10 (usually 6) which is multiplied by the dilution air quantities to assure air concentrations well below the TLV.

"Industrial Ventilation — A Manual of Recommended Practice" 12th Edition, American Conference of Governmental Industrial Hygienists, Committee on Industrial Ventilation, Lansing, Michigan, 1972.

quired may be calculated using the equations given in Chapter 39. Although this method of ventilation may be used effectively to deal with low toxicity gases and vapors, it is not advisable to treat particulate contaminants or toxic vapors or gases with general ventilation. Whenever possible, local exhaust systems should be used to minimize the total amount of hazardous material released.

LOCAL EXHAUST VENTILATION

Local exhaust systems are primarily concerned with contaminant control at the point of emission and/or dispersion (for additional information see Chapter 41). As mentioned earlier, local exhaust systems usually complement (rather than replace) general ventilation systems. The components of all local exhaust systems are similar, but the total design of each system is unique. The components include a hood, ductwork, an air moving device, an air cleaning device, and special fittings. The processes to which these components are applied are numerous and varied. Therefore the size, shape and material of construction of each component will vary with the contaminated air being handled.

Hood Design

The design of any local exhaust system begins with the proper selection of an exhaust hood. Over the years, many types of hood designs have evolved, with only one purpose in mind — to confine or capture the contaminant with a minimum rate of air flow into the hood. In most instances, the more complete the hood enclosure, the more economical and effective the installation will be.

Exhaust hoods are designed to work in one of two ways: (1) they can induce an air movement which draws the contaminant into the hood or (2) they can enclose the contaminant source and induce an air movement which prevents the contaminant from escaping the enclosure. In either case, a certain air velocity in front of the hood is required for effective removal of contamination. This required air velocity in front of the hood must be determined before the exhaust system can be designed.

Unfortunately, the determination of required air velocity is not subject to direct and exact evaluation. In the past, three methods have been used to approximate a required velocity: (1) evaluation of and comparison with existing operations, (2) experimental tests, and (3) calculations based on theoretical air requirements. These methods and practical experience enable the design engineer to estimate a required air velocity in most cases. Tables 41-1 and 42-3 are helpful for estimating required control velocities.

Hood types. Exhaust hoods can be categorized as enclosures, receiving hoods, or exterior hoods.

Enclosures, such as paint-spray booths, surround the point of emission either completely or partially. They are the most effective hoods to use, but they are seldom utilized for any manual operations where workers must also be enclosed.

Receiving hoods are used on processes where contaminants may be conveniently "thrown" into the hood. For example, inertial forces carry air

contaminants from a grinding wheel into a hood located in the pathway of the particles. If the hood cannot be located directly in the path of the escaping particles, baffles or shields may be placed across the line of throw of the particles to destroy their kinetic energy. Then, lower air velocities will suffice to capture and carry them into the hood.

Unlike enclosures and receiving hoods, exterior hoods must capture air contaminants that are generated from a point *outside* the hood. Exterior hoods require the most air to control a given process, are most sensitive to external conditions, and thus are the most difficult to design.

Hood Design Considerations. Before designing a hood, several principles should be considered. Some of the most important ones are listed below:

- a. An attempt should be made to minimize or eliminate all air motion in the area of the contaminant source. This will reduce the amount of air needed to be exhausted and subsequently reduce system power and equipment requirements.
- b. Air currents which necessarily exist should be utilized by the hood whenever possible.
- c. The hood should enclose the process as much as possible without endangering workers' safety.
- d. When enclosure is impractical, the hood should be located as close to the contaminant source as possible. The air velocity created by an exhaust hood varies inversely with the *square* of the distance for all but long, slot-type hoods.
- e. The hood should be located so that the contaminant is removed *away* from the breathing zone of the worker.
- f. The use of flanges and baffles should be considered. Flanges can increase hood effectiveness and may reduce air requirements by 25%.¹
- g. Use of a hood larger than required should be considered. Large hoods can reduce danger of "spills" by diluting them rapidly to safe levels. It has also been shown that small hoods require higher capture velocities to be as effective as large hoods.

Exhaust Duct Design

The design of an exhaust duct system is the second stage of a total ventilation system design. Initially, a rough duct layout should be prepared which shows branches, expansions, contractions, elbows, air moving and air cleaning devices. Using this as a basis, pressure drop calculations can be made and duct sizing can be estimated.

Transport Velocity. At this stage of design, the required exhaust rate for each hood has been determined. The problem now is to determine the minimum transport-velocity — i.e., the air velocity required to move the contaminant through the duct system. Information pertaining to transport velocities may be obtained by the following methods: (1) by reference to data published in the literature (See Tables 42-4 and 42-5), (2) by actual laboratory tests with the material to be conveyed, or (3) by theoretical considerations involving particle size, density and shape.

TABLE 42-3
Minimum Control Velocities and Exhaust Rates
for Typical Specific Operations

Where both control velocity and exhaust rate are given, the air volume exhausted shall be based on the method which requires the larger volume.

Operation	Control Velocity, fpm	Control Velocity Basis	Exhaust Rate, cfm	Exhaust Rate Basis
Abrasive blasting				
Cabinets	500	Openings in enclosure	—	
Rooms	60-100	Downdraft in room	—	
Bagging				
Paper bags	100	Openings in enclosure	—	
Cloth bags	200	Openings in enclosure	—	
Pulverized sand	400	Point of origin	—	
Barrel filling	100	Point of origin	100	Per sq. ft. barrel top, semi-enclosure
Bin and hopper	150-200	Openings in enclosure	0.5	Per cu. ft. bin volume
Belt conveyors				
Transfer point				
Belt speed <200 fpm	150	Openings in enclosure	350	Per ft. belt width
>200 fpm	200	Openings in enclosure	500	Per ft. belt width
Belt wiper			200	Per ft. belt width
Bottle washing	150-250	Face of booth or enclosure openings	—	
Bucket elevators	—		100-200	Per sq. ft. casing cross section Tight casing required
Core sanding lathe	100	Point of origin	—	
Foundry screens				
Cylindrical	400	Openings in enclosure	100	Per sq. ft. circular cross section
Flat deck	150-200	Openings in enclosure	25-50	Per sq. ft. screen area
Foundry shakeout				
Enclosure	200	Openings in enclosure	200	Per sq. ft. grate area
Side draft	—		350-400	Cool castings per sq. ft. grate area
Downdraft			400-500	Hot castings
			250	Cool castings
			600	Hot castings
				Per sq. ft. grate area
Furnaces, melting				
Aluminum	150-200	Openings in enclosure	—	
Brass	200-250	Openings in enclosure	—	
Granite cutting				
Hand tool	200	Point of origin	—	
Surfacing machine	1500	Point of origin	—	
All tools	1500	Face of enclosing hood		
Grinding				
General	—	See applicable American National Standards	200	Per sq. ft. plan area of bench downdraft grille
Disc and portable	—		400	Per sq. ft. plan area of floor downdraft grille
Swing frame	150	Face of booth		
Kitchen range	100-150	Face of canopy	—	
Laboratory hood	100-150	Face of hood, door open. Less for "air supplied" hoods	—	
Metallizing				
Toxic material	200	Face of booth		Additional respiratory protection required
Nontoxic	125	Face of booth	—	
Nontoxic	200	Point of origin	—	
Mixer	100-200	Openings in enclosure	—	

TABLE 42-3 Continued
Minimum Control Velocities and Exhaust Rates
for Typical Specific Operations

Where both control velocity and exhaust rate are given, the air volume exhausted shall be based on the method which requires the larger volume.

Operation	Control Velocity fpm	Control Velocity Basis	Exhaust Rate, cfm	Exhaust Rate Basis
Packaging machines	100-400	Openings in enclosure	25	Per sq. ft. plan area of enclosure
	50-150	Face of booth	—	
	75-150	Downdraft	—	
Paint spray	100-200	Face of booth	—	
Pharmaceutical coating pans	100-200	At opening of pan	—	
Quartz fusing	150-200	Face of booth	—	
Rubber calendar rolls	75-100	Openings in enclosure	—	
Silver soldering	100	Point of origin	—	
Steam kettles	150	Face of canopy	—	
Tanks				
Open surface	50-150	See applicable American National Standards		
Closed	150	Manhole or inspection opening		
Welding, arc	100-200	Point of origin	—	
	100	Face of booth	—	
Woodworking		See applicable American National Standards		

TABLE 42-4
Classification of Transport Velocities
for Dust Collection

Material	Minimum Transport Velocity, fpm
Very fine, light dusts	2000
Fine, dry dusts and powders	3000
Average industrial dusts	3500
Coarse dusts	4000-4500
Heavy or moist dust loading	4500 and up

The minimum transport velocity is not used for duct design; rather, a design velocity is estimated which includes a safety factor based on practical considerations. These include considerations for material buildup, duct damage, corrosion, duct leakage, etc. As shown in Tables 42-4 and 42-5, transport velocities for dust-laden air vary from 2000 fpm to 4500 fpm or higher.⁸

Balance Methods. After the preliminary duct layout has been made, the duct system pressure losses can be calculated. Two methods are used to "balance" the system — that is, adjust the duct design so that the total system will function properly. Each method has advantages and disadvantages as described below.

The first is known as the "Static Pressure Balance" method. Some texts³ refer to this as "Air Balance without Blast Gate Adjustment" because it is a procedure for achieving desired air flow without the use of dampers or blast gates. At

each junction of two air streams the static suction necessary to produce the required flow in one stream must match the static suction needed to produce the required flow in the other stream. Because there are no blast gates for workers to tamper with, this method is usually selected for use where highly toxic materials are to be controlled.

The other method is "Balance with Blast Gates." This type of system uses adjustable blast gates to balance the system and thus achieve the desired air flow at each hood. Calculations begin at the branch of greatest resistance. Pressure drops are calculated through the various sections of the main, on up to the fan. This design method is theoretically superior to the "Static Pressure Balance" method in that it is flexible enough to allow air volume changes without duct redesign. However, if blast gates are tampered with by unauthorized personnel, ducts may become plugged and the exhaust system rendered ineffectual.

Pressure Losses. Pressure losses in an exhaust duct system occur as a result of (1) hood entry, (2) special fittings, (3) duct friction, and (4) air cleaning devices. Various methods and charts are available to aid in estimating pressure losses from these sources.^{1,3} Because most charts and reference tables are based on standard air (0.075 lb./cu. ft.) corrections for altitude, temperature, and density must be made if conditions vary greatly from standard (See Table 42-6). Design calculations are based on volumes increased by the reciprocal of the density factor. System pressure losses will decrease directly as d , the density factor.

TABLE 42-5
Examples of Transport Velocities

Material, Operation, or Industry	Minimum Transport Velocity, fpm	Material, Operation, or Industry	Minimum Transport Velocity, fpm
Abrasive blasting	3500-4000	Jute	
Aluminum dust, coarse	4000	Dust	2500-3000
Asbestos carding	3000	Lint	3000
Bakelite molding powder dust	2500	Dust shaker waste	3200
Barrel filling or dumping	3500-4000	Pickerstock	3000
Belt conveyors	3500	Lead dust	4000
Bins and hoppers	3500	with small chips	5000
Brass turnings	4000	Leather dust	3500
Bucket elevators	3500	Limestone dust	3500
Buffing and polishing		Lint	2000
Dry	3000-3500	Magnesium dust, coarse	4000
Sticky	3500-4500	Metal turnings	4000-5000
Cast iron boring dust	4000	Packaging, weighing, etc.	3000
Ceramics, general		Downdraft grille	3500
Glaze spraying	2500	Pharmaceutical coating pans	3000
Brushing	3500	Plastics dust (buffing)	3800
Fettling	3500	Plating	2000
Dry pan mixing	3500	Rubber dust	
Dry press	3500	Fine	2500
Sagger filling	3500	Coarse	4000
Clay dust	3500	Screens	
Coal (powdered) dust	4000	Cylindrical	3500
Cocoa dust	3000	Flat deck	3500
Cork (ground) dust	2500	Silica dust	3500-4500
Cotton dust	3000	Soap dust	3000
Crushers	3000 or higher	Soapstone dust	3500
Flour dust	2500	Soldering and tinning	2500
Foundry, general	3500	Spray painting	2000
Sand mixer	3500-4000	Starch dust	3000
Shakeout	3500-4000	Stone cutting and finishing	3500
Swing grinding booth exhaust	3000	Tobacco dust	3500
Tumbling mills	4000-5000	Woodworking	
Grain dust	2500-3000	Wood flour, light dry sawdust	
Grinding, general	3500-4500	and shavings	2500
Portable hand grinding	3500	Heavy shavings, damp sawdust	3500
		Heavy wood chips, waste,	
		green shavings	4000
		Hog waste	3000
		Wool	3000
		Zinc oxide fume	2000

Material in Tables 42-3, 42-4 & 42-5 is reproduced with permission from ANSI Z9.2 copyright 1971, by the American National Standards Institute, copies of which may be purchased from American National Standards Institute at 1430 Broadway, New York, N.Y. 10018.

Hood Entry Losses

A loss in pressure occurs when air enters a hood opening. This loss is indicated by the coefficient of entry for the hood, C_e . This coefficient represents the ratio of actual to theoretical flow; i.e., $C_e = 1.0$ for a theoretically "perfect" hood. Several examples of entry coefficients are shown in Figure 42-2.

The design equation used in determining the static suction at the hood throat is derived from the classical orifice theory. For standard air it becomes:

$$Q = 4005 A C_e \sqrt{SP_h} \quad (1)$$

where: Q = air flow rate, ft³/min.

A = area of opening, ft²

C_e = entry coefficient, dimensionless

SP_h = static suction at hood throat, in. w.g.

Static suction, SP_h , is related to hood entry loss according to the following equation:

$$SP_h = h_e + VP \quad (2)$$

where: VP = velocity pressure in throat, in. w.g.

h_e = hood entry loss, in. w.g.

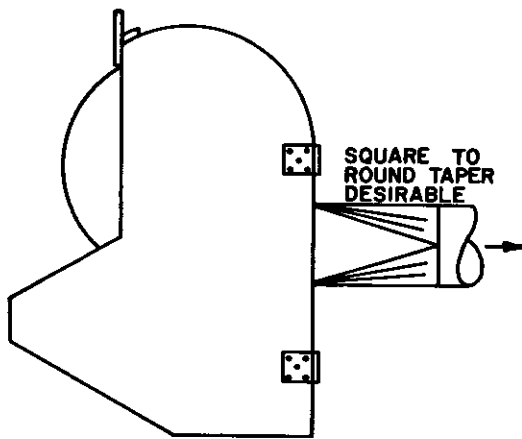
Velocity pressure (for standard air) may be calculated using the following equation:

$$VP = \left(\frac{V}{4005} \right)^2 \quad (3)$$

where: VP = velocity pressure, in. w.g.

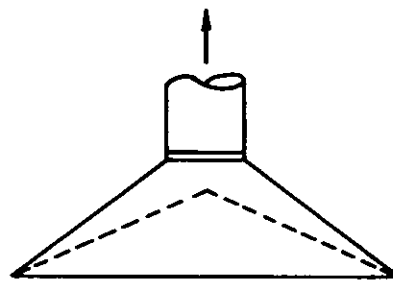
V = air velocity, fpm

Letting F be the fraction of the throat velocity



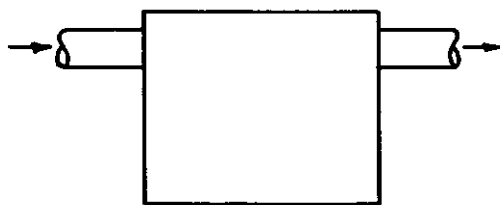
STANDARD GRINDER HOOD

$C_e = 0.78$



DOUBLE (INNER CONE) HOOD

$C_e = 0.70$ (APPROX)



TRAP OR SETTLING CHAMBER

$C_e = 0.63$ (APPROX)



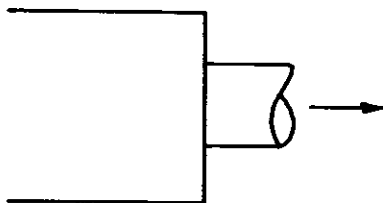
SHARP-EDGED ORIFICE

$C_e = 0.60$



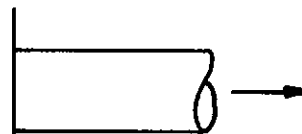
PLAIN DUCT END

$C_e = 0.72$



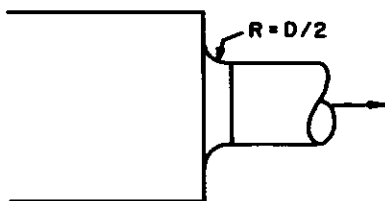
DIRECT BRANCH-BOOTH

$C_e = 0.82$



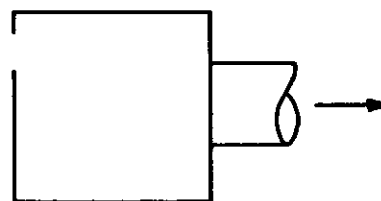
FLANGED DUCT END

$C_e = 0.82$



BOOTH PLUS ROUNDED ENTRANCE

$C_e = 0.97$



ORIFICE PLUS FLANGED DUCT
(MANY SLOT TYPES)

$C_e = 0.55$ (WHEN DUCT VELOCITY = SLOT VELOCITY)

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Figure 42-2. Hood Entry Loss Coefficients.

TABLE 42-6
Air Density Correction Factor, d

Altitude, ft.		—1000	Sea Level	1000	2000	3000	4000	5000	6000	7000	8000	9000	10,000
Barometer	"Hg	31.02	29.92	28.86	27.82	26.82	25.84	24.90	23.98	23.09	22.22	21.39	20.58
	"Wg	422.2	407.5	392.8	378.6	365.0	351.7	338.9	326.4	314.3	302.1	291.1	280.1
Air Temp.	—40	1.31	1.26	1.22	1.17	1.13	1.09	1.05	1.01	0.97	0.93	0.90	0.87
	F	0	1.19	1.15	1.11	1.07	1.03	0.99	0.95	0.91	0.89	0.85	0.82
		40	1.10	1.06	1.02	0.99	0.95	0.92	0.88	0.85	0.82	0.79	0.76
		70	1.04	1.00	0.96	0.93	0.89	0.86	0.83	0.80	0.77	0.74	0.71
		100	0.98	0.95	0.92	0.88	0.86	0.81	0.78	0.75	0.73	0.70	0.68
		150	0.90	0.87	0.84	0.81	0.78	0.75	0.72	0.69	0.67	0.65	0.62
		200	0.83	0.80	0.77	0.74	0.71	0.69	0.66	0.64	0.62	0.60	0.57
		250	0.77	0.75	0.72	0.70	0.67	0.64	0.62	0.60	0.58	0.56	0.54
		300	0.72	0.70	0.67	0.65	0.62	0.60	0.58	0.56	0.54	0.52	0.50
		350	0.68	0.65	0.62	0.60	0.58	0.56	0.54	0.52	0.51	0.49	0.47
		400	0.64	0.62	0.60	0.57	0.55	0.53	0.51	0.49	0.48	0.46	0.44
		450	0.60	0.58	0.56	0.54	0.52	0.50	0.48	0.46	0.45	0.43	0.42
		500	0.57	0.55	0.53	0.51	0.49	0.47	0.45	0.44	0.43	0.41	0.39
		550	0.54	0.53	0.51	0.49	0.47	0.45	0.44	0.42	0.41	0.39	0.38
		600	0.52	0.50	0.48	0.46	0.45	0.43	0.41	0.40	0.39	0.37	0.35
		700	0.47	0.46	0.44	0.43	0.41	0.39	0.38	0.37	0.35	0.34	0.33
		800	0.44	0.42	0.40	0.39	0.37	0.36	0.35	0.33	0.32	0.31	0.30
		900	0.40	0.39	0.37	0.36	0.35	0.33	0.32	0.31	0.30	0.29	0.28
		1000	0.37	0.36	0.35	0.33	0.32	0.31	0.30	0.29	0.28	0.27	0.26

Standard Air Density, Sea Level, 70 F = 0.075 lb./ft.³

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pressure loss in entry, and combining equations,

$$h_e = (F_b) (VP) \quad (4)$$

Whenever a hood is made combining basic shapes, Equation 4 applies only to the parts and not to the hood as a whole.

Losses from Special Fittings

Pressure is lost when air travels through the various fittings in an exhaust system. Elbows, branch entries, enlargements and contractions are the main fittings to be considered. Pressure loss across these fittings is conveniently expressed as a fraction of the velocity pressure, VP. Tables giving pressure regain and loss values (fractions) for expansions and contractions are included, see Tables 42-7 and 42-8.^{1,2}

Resistance of elbows and branch entries may also be expressed in terms of equivalent feet of straight duct (of the same diameter) that will produce the same pressure loss as the fitting. An example table (Table 42-9) is included.¹

Duct Friction Losses

Many graphs are available which give friction losses in straight ducts. However, most graphs are

based on new, clean duct. The chart included here (see Figure 42-3) allows for a typical amount of roughness, and is more practical for use in general application. Four quantities are plotted on the chart. If any two are given, the other two can be read directly from the chart.

Additional Pressure Losses

In addition to the pressure losses mentioned above, the pressure drop across collection equipment (if used) must be known in order to insure proper operation. This can vary widely, but usually data are available from the manufacturer to minimize guess work. Where data are unavailable, comparisons with known values for similar equipment should be used. Dust collection equipment is covered more extensively in Chapter 43.

Design Suggestions. A few suggestions pertaining to duct design and location are listed below:

- a. Duct mains should be arranged in such a way that smaller branches enter the main near the high-suction end — closer to the fan inlet.
- b. Long runs of small diameter duct should be avoided.

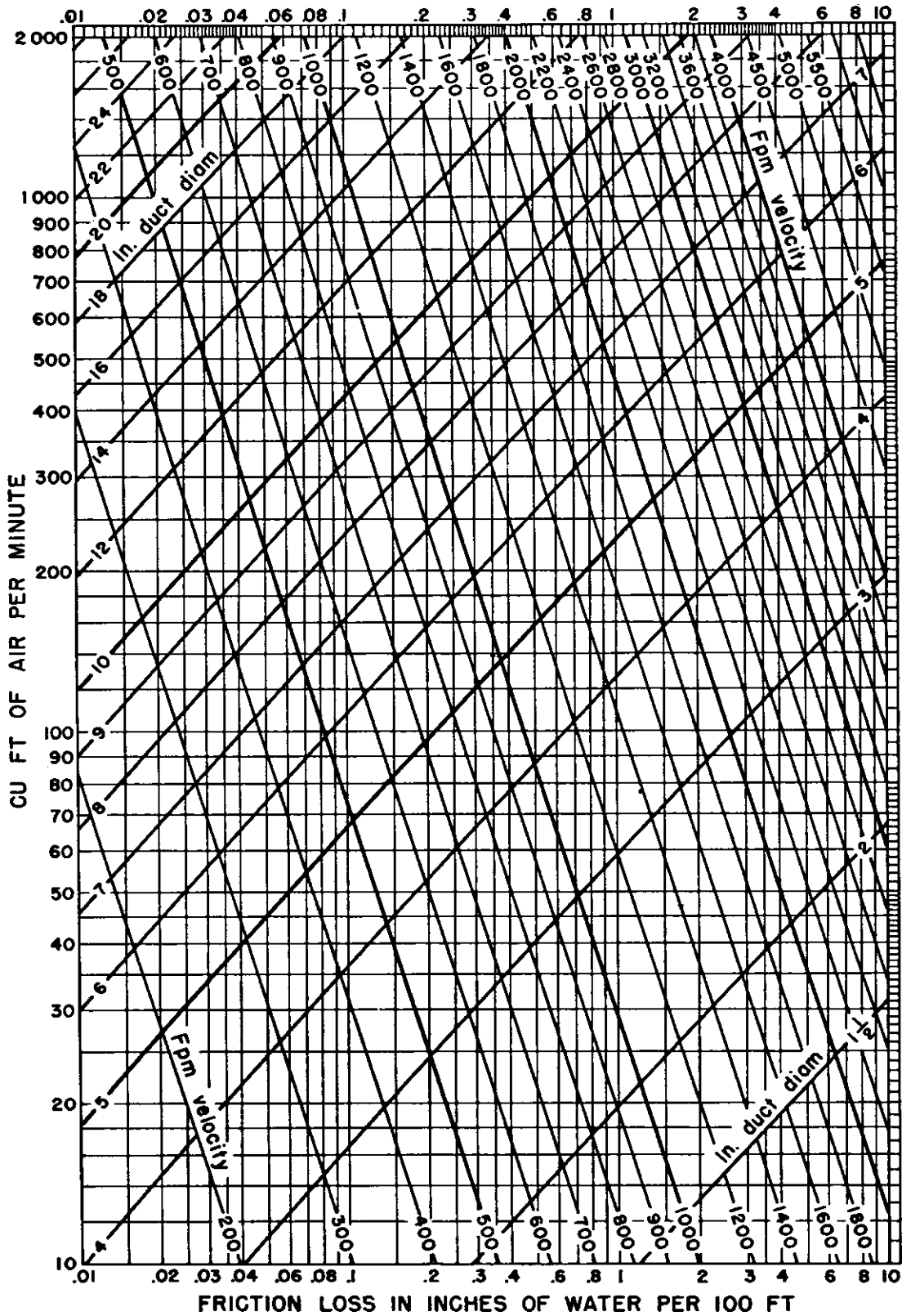
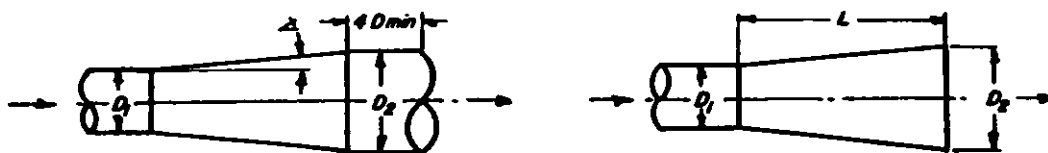


Figure 42-3. Friction of Air in Straight Ducts for Volumes of 10 to 2000 Cfm. (Based on Standard Air of 0.075 lb per cu ft density flowing through average, clean, round, galvanized metal ducts having approximately 40 joints per 100 ft.) Caution: Do not extrapolate below chart.

TABLE 42-7.
Static Pressure Regains for Expansions



Within duct

Regain (R), fraction of VP difference					
Taper angle degrees	Diameter ratios D_2/D_1				
	1.25:1	1.5:1	1.75:1	2:1	2.5:1
3 1/2	0.92	0.88	0.84	0.81	0.75
5	0.88	0.84	0.80	0.76	0.68
10	0.85	0.76	0.70	0.63	0.53
15	0.83	0.70	0.62	0.55	0.43
20	0.81	0.67	0.57	0.48	0.43
25	0.80	0.65	0.53	0.44	0.28
30	0.79	0.63	0.51	0.41	0.25
Abrupt 90	0.77	0.62	0.50	0.40	0.25

Where: $SP_2 = SP_1 + R(VP_1 - VP_2)$

At end of duct

Regain (R), fraction of inlet VP						
Taper length to inlet diam L/D	Diameter ratios D_2/D_1					
	1.2:1	1.3:1	1.4:1	1.5:1	1.6:1	1.7:1
10:1	0.37	0.39	0.38	0.35	0.31	0.27
1.5:1	0.39	0.46	0.47	0.46	0.44	0.41
20:1	0.42	0.49	0.52	0.52	0.51	0.49
3.0:1	0.44	0.52	0.57	0.59	0.60	0.59
4.0:1	0.45	0.55	0.60	0.63	0.63	0.64
5.0:1	0.47	0.56	0.62	0.65	0.66	0.68
7.5:1	0.48	0.58	0.64	0.68	0.70	0.72

Where: $SP_1 = SP_2 - R(VP_1)$

When $SP_2 = 0$ (atmosphere) SP_1 will be (-)

The regain (R) will only be 70% of value shown above when expansion follows a disturbance or elbow (including a fan) by less than 5 duct diameters.

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- Extending an exhaust system to reach an isolated hood increases fan power consumption. To avoid this problem, it may be more economical to install a separate system for that hood.
- If possible, locate the fan near the middle of an array of exhaust hoods rather than at one end.
- If long rows of equipment are to be served, the main header duct should be located near the middle of the system to equalize runs of branch duct.
- Ductwork should be located so that it is readily accessible for inspection, cleaning and repairs.
- Ductwork should be out of the way of elevators, lift-trucks, cranes, etc., to avoid mechanical damage.
- Duct cleanout areas should be provided.

AIR MOVING DEVICES

Various power-driven machines are capable of creating the required flow of air in an exhaust system. These machines are generally known as "air moving devices." Included under this general heading are fans, turbo-compressors, ejectors and positive displacement blowers.

As mentioned in Chapter 39, the air moving device manufacturer, to gain acceptance for his product, generally must earn membership in the Air Moving and Conditioning Association (AMCA). Membership is contingent upon sub-

jecting his product to the AMCA test code for air moving devices. In addition, the manufacturer must furnish a prospective buyer of his product, certain data relative to the product and its applications. This information should include the following.

- Classification according to static pressure limitations
- Multirating tables — performance curves
- Specifications — AMCA standards
- Drive arrangement
- Designations for rotation and discharge
- Dimensional data
- Materials and methods of construction
- Sound level ratings
- Accessories
- Temperature limitations.

Fans are the most commonly used exhausters in the field of industrial ventilation. They are divided into two main classifications: axial flow or propeller type, and radial flow or centrifugal type. A summary of fan types is given in Chapter 39. A list of fan types appears below.

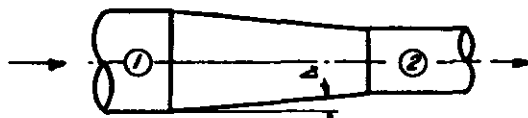
Axial Flow Fans

- Propeller
- Duct
- Tube Axial
- Vane Axial
- Axial Centrifugal

Centrifugal Fans

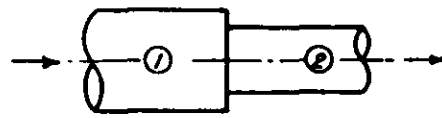
- Radial Wheel
- Forward-Curved Blade
- Backward-Inclined Blade
- Airfoil

TABLE 42-8.
Static Pressure Losses for Contractions



Tapered contraction
 $SP_2 = SP_1 - (VP_2 - VP_1) - L(VP_2 - VP_1)$

Taper angle degrees	L(loss)
5	0.05
10	0.06
15	0.08
20	0.10
25	0.11
30	0.13
45	0.20
60	0.30
over 60	Abrupt contraction



Abrupt contraction
 $SP_2 = SP_1 - (VP_2 - VP_1) - K(VP_2)$

Ratio A_2/A_1	K
0.1	0.48
0.2	0.46
0.3	0.42
0.4	0.37
0.5	0.32
0.6	0.26
0.7	0.20

A = duct area, sq ft

Note:

In calculating SP for expansion or contraction use algebraic signs:

VP is (+)

and usually

SP is (+) in discharge duct from fan

SP is (-) in inlet duct to fan

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Turbo-compressors and positive displacement blowers are used in systems having relatively low volume and high velocity and high static pressure. Turbo-compressors are typically used for industrial vacuum-cleaning systems where air must be transported through small diameter ducts at high velocities. Positive displacement blowers are used where a fixed quantity of air is required to be supplied or exhausted through an increasingly long duct, as in pneumatic conveying. Both exhausters can handle only clean, filtered air, due to the rigid design tolerances of their moving parts.

Ejectors are used in exhaust systems handling gases which are too hot, corrosive, abrasive, or sticky to be handled by a fan. Because ejectors are mechanically very inefficient, they require a much higher horsepower expenditure than equivalent fan installations.

Fan Laws and System Curves

Before selecting the proper fan, it is necessary to be familiar with the fan laws and system curves. These are listed in Table 42-10.

A fan or system curve shows graphically all possible combinations of volumetric flow and static

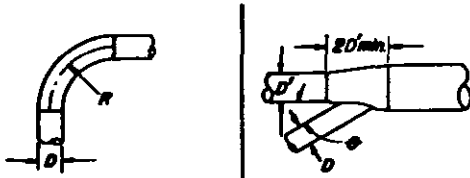
pressure for a given system. Because the fan and system can each operate only at a point on their own curve, the combination can operate only where their curves intersect. See Figure 42-4) If the fan speed is changed, the operating point will move up toward the right (increased speed) or down toward the left (decreased speed) on the system curve. (See Figure 42-5)

Fan Selection

A fan is chosen on the basis of its characteristics and the requirements of the system to which it will be applied. Each fan is characterized by five features: 1) volume of gas flow, 2) pressure at which this flow is produced, 3) speed of rotation, 4) power required, and 5) efficiency. These quantities are measured by the fan manufacturer with testing methods sponsored by the Air Moving and Conditioning Association or the American Society of Mechanical Engineers. Test results are plotted to provide the characteristic fan curves supplied by most fan manufacturers.

The designer chooses the fan he needs from multirating tables. Each different entry in the table has a unique performance characteristic —

TABLE 42-9.
Equivalent Resistance in Feet of Straight Pipe



Pipe D	90° Elbow * Centerline Radius			Angle of Entry	
	15D	20D	25D	30°	45°
3"	5	3	3	2	3
4"	6	4	4	3	5
5"	9	6	5	4	6
6"	12	7	6	5	7
7"	13	9	7	6	9
8"	15	10	8	7	11
10"	20	14	11	9	14
12"	25	17	14	11	17
14"	30	21	17	13	21
16"	36	24	20	16	25
18"	41	28	23	18	28
20"	46	32	26	20	32
24"	57	40	32		
30"	74	51	41		
36"	93	64	52		
40"	105	72	59		
48"	130	89	73		

* For 60° elbows — 0.67 x loss for 90°
45° elbows — 0.5 x loss for 90°
30° elbows — 0.33 x loss for 90°

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TABLE 42-10.

Fan Laws
(Q = CFM P = Pressure)

- Variation in Fan Speed:**
Constant Air Density—Constant System
(a) Q: Varies as fan speed.
(b) P: Varies as square of fan speed.
(c) Power: Varies as cube of fan speed.
- Variation in Fan Size:**
Constant Tip Speed—Constant Air Density
Constant Fan Proportions—Fixed Point of Rating
(a) Q: Varies as square of wheel diameter.
(b) P: Remains constant.
(c) RPM: Varies inversely as wheel diameter.
(d) Power: Varies as square of wheel diameter.
- Variation in Fan Size:**
At Constant RPM—Constant Air Density
Constant Fan Proportions—Fixed Point of Rating
(a) Q: Varies as cube of wheel diameter.
(b) P: Varies as square of wheel diameter.
(c) Tip Speed: Varies as wheel diameter.
(d) Power: Varies as fifth power of diameter.
- Variation in Air Density:**
Constant Volume—Constant System
Fixed Fan Size—Constant Fan Speed
(a) Q: Constant.
(b) P: Varies as density.
(c) Power: Varies as density.
- Variation in Air Density:**
Constant Pressure—Constant System
Fixed Fan Size—Variable Fan Speed
(a) Q: Varies inversely as square root of density.
(b) P: Constant.
(c) RPM: Varies inversely as square root of density.
(d) Power: Varies inversely as square root of density.
- Variation in Air Density:**
Constant Weight of Air—Constant System
Fixed Fan Size—Variable Fan Speed
(a) Q: Varies inversely as density.
(b) P: Varies inversely as density.
(c) RPM: Varies inversely as density.
(d) Power: Varies inversely as square of density.

that is, each entry describes a corresponding performance curve. Usually the fan required will have characteristics between two values given in the table. A linear interpolation is necessary to determine the right fan size, speed, horsepower, etc. needed to do the job. (See Table 42-11.)

Noise Vibration Control

The possibility of noise problems arising in exhaust systems should not be overlooked at any stage of the design process. If the system has been designed improperly, or if the wrong fan has been chosen, it is likely that a noise or vibration problem will arise. It is usually a simple matter to foresee such problems and prevent them from occurring.

The potential source of noise in any exhaust system is the fan. It is a pliable piece of equipment, is often forced to operate at high speeds, and is inherently prone to vibrate. Fan vibration is of two types: aerodynamic or mechanical.

Aerodynamic vibration varies distinctly with the volume of air drawn through the fan. This usually occurs when fans are operated at a point to the left of the peak of their static pressure curves. If the system pressure estimate is low, a smaller fan than actually needed may be specified, and forced to operate at a point other than the one for which it was selected. This type of vibration may also be caused by poor inlet connections to the fan. If possible, inlet boxes and inlet elbows should be avoided, or at least vanned to reduce fan inlet spin. (When air is forced to flow through a sharp turn as it enters the fan, it tends to load just part of the fan wheel and pulsation can occur.) Similarly, good outlet design will minimize pulsation.

Mechanical vibration cannot be foreseen by the design engineer except in cases where the structural support for the fan is inadequate. Frequently fans are supported on mounts having a natural vibration frequency near that of the fan. Under such conditions vibration is almost impossible to stop. The best support to use is an inertial mass such as a concrete pad supported by steel springs. The most common mount is the integral base — a structural steel platform built to fit

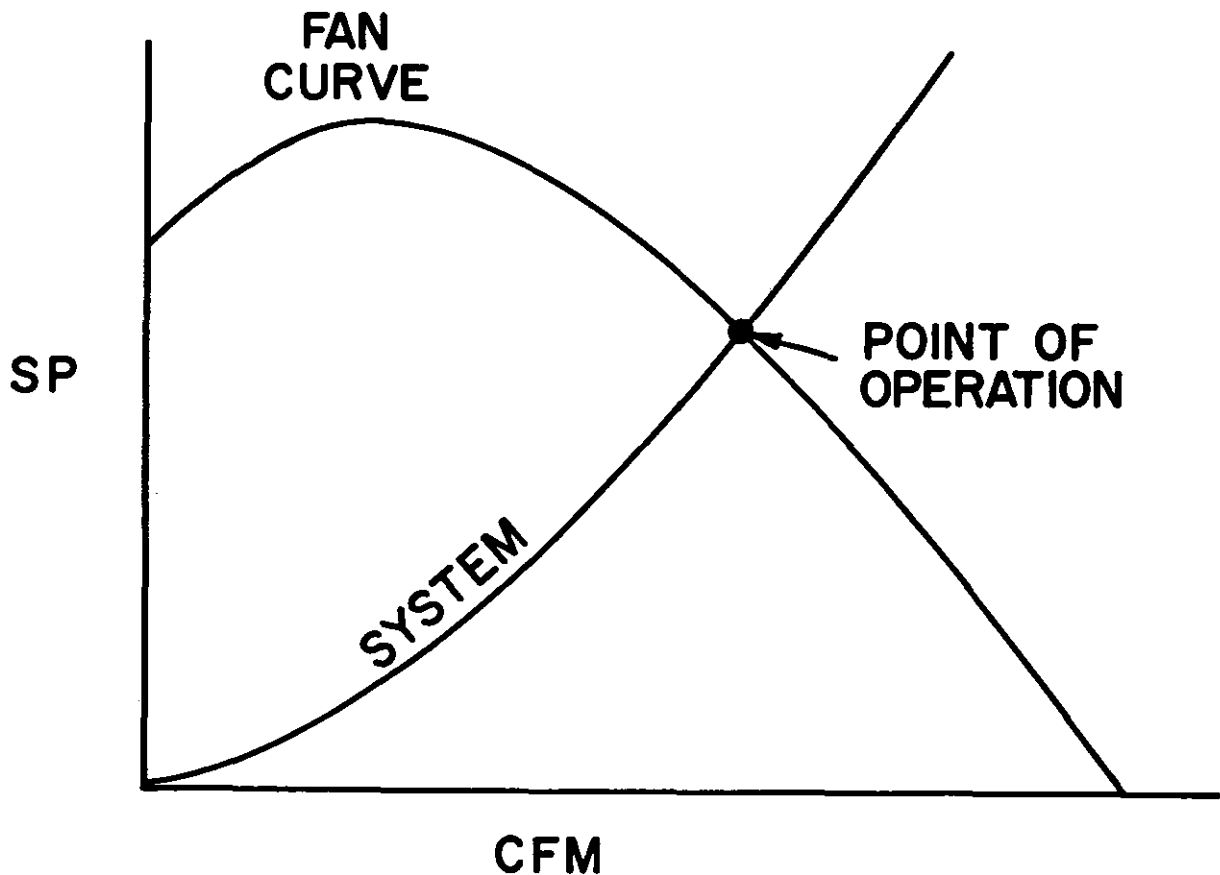


Figure 42-4. Fan and System Curves.

under the fan and motor, supported on steel spring or rubber-in-shear mounts. When the integral base is used, fan inlet and outlet vibration-elimination connections are required. In addition, a flexible conduit supplying power to the motor is essential.

The type of fan chosen for an exhaust system has a great influence on noise levels. For instance, axial flow fans are louder than centrifugal, and radial blade centrifugal fans are louder than other centrifugal types. The relatively new, airfoil-blade wheel centrifugal fans are the most quiet fans available today. This type is a modification of the backwardly-inclined-blade wheel.

Fans are now available with silencers to match the fan's aerodynamic characteristics. (Until recently fans and silencers were not designed to operate as an aerodynamic and acoustical unit.) Silencers impose additional resistance, the loss for which must be allowed in design calculations. In addition, streamlined duct transitions before and after the silencer must be considered. Silencers should always be installed on the clean air side of the system.

Finally, flexible duct-fan connections should be considered. Whenever fans are rigidly connected to ducts, the system can carry the fan's sound and vibration to remote areas. Use of duct lining can also reduce noise levels, but it is generally not used on medium to high velocity sys-

tems. Low velocity air conditioning systems usually employ linings to some degree.

MAKE-UP AIR

For a ventilation system to work effectively, the air exhausted from a room should be replaced in an amount at least equal to the exhausted volume. For best results, the supply air should exceed the exhaust volume; common practice is to allow 10% excess make-up air. The actual amount of make-up air needed depends upon the type of process involved, the amount of air exhausted, and the age and construction of the building.

The process to be exhausted may require low air exchange rates — six per hour or less. If exchange rates are small enough and the building is old and not tightly constructed, there may be no need for other make-up air. However, if the process calls for high air change rates, e.g., 60 per hour, or the building is modern and tightly sealed, then make-up air is definitely required. A negative pressure in a building is a common result of inadequate provision for make-up air.

Importance of Make-up Air. There are many reasons for providing make-up air; the most important ones are involved with the proper functioning of men and equipment. Make-up air should be provided for the following reasons:

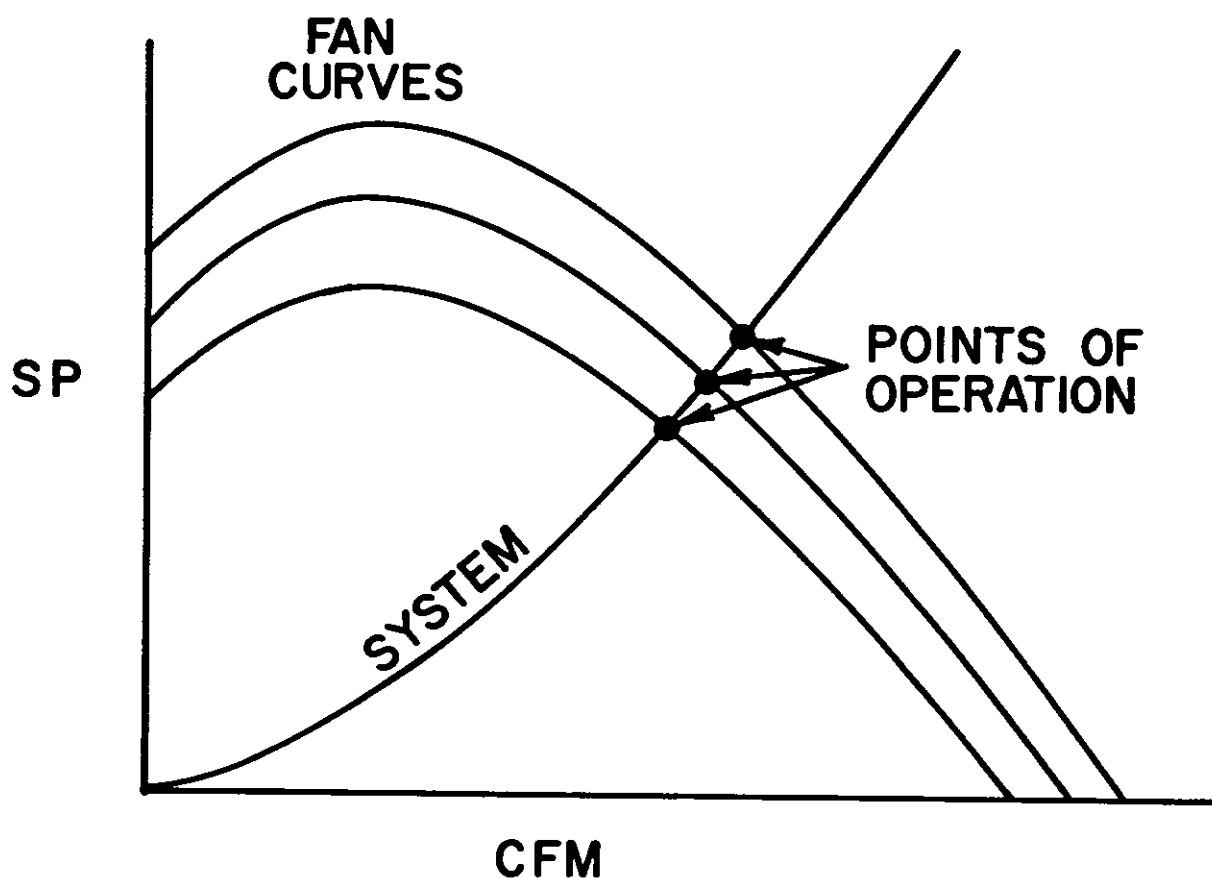


Figure 42-5. Fan and System Curves.

1. To insure that exhaust hoods operate properly. Exhaust volumes needed for proper operation of hoods may be drastically reduced under negative building pressures. If the exhaust system uses propeller fans, the flow may actually be reversed, entering instead of exhausting.
2. To insure proper operation of natural stacks. Some combustion exhaust stacks operate on natural drafts as low as 0.01 in. w.g. Under negative building pressures, flue gases, such as carbon monoxide, will not be able to leave via the stack. These gases may eventually infiltrate work areas and cause potential health hazards.
3. To eliminate high velocity cross drafts. A negative pressure as low as 0.01 to 0.02 in. w.g. may result in high velocity drafts through doors and windows. Drafts can: cause discomfort for workers; bring in or stir up dust; disrupt hood operation. Drafts also tend to cause uneven heating and adverse humidity conditions as well as poor temperature control.
4. To eliminate differential pressure on doors. A negative pressure of 0.05 to 0.10 in. w.g. is enough to make doors difficult to open. This situation is not only unpleasant for employees to deal with daily, but can

also lead to injury from slamming doors. The location and application of make-up air equipment also requires careful consideration. The following recommendations should be considered:

1. The fresh air intake should be located as far as possible from contaminant sources.
2. Exhaust stacks should be tall enough and properly located so that waste air will not re-enter the plant make-up air system.
3. Avoid the use of canopy type weather caps. By forcing air downward, weather caps on stack heads reduce the advantages gained by increasing stack height.
4. Where necessary, make-up air should be filtered to protect equipment, prevent plugging, and provide maximum heat exchange efficiency.

Equipment. The equipment used for providing and tempering make-up air is similar to or identical with that used for conventional heating and cooling systems. For heating make-up air, there are three basic equipment types: 1) heat exchangers using steam or hot water, 2) direct-fired heaters which burn gas or oil, and 3) open-flame heaters.

1. Steam heating coils are among the most common types of make-up air heaters. Moreover, if an ample steam supply is available, this type of heating may result in

TABLE 42-11.
Typical Fan Multirating Table

Vol- ume, cfm	Outlet veloc- ity, fpm	Veloc- ity pres- sure, in. WC	1 in. SP		2 in. SP		3 in. SP		4 in. SP		5 in. SP		6 in. SP		7 in. SP		8 in. SP		9 in. SP	
			rmp	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp
2,520	1,000	0.063	437	0.63	595	1.27	728	2.00	837	2.66										
3,120	1,200	0.090	459	0.85	610	1.55	735	2.30	842	3.10										
3,530	1,400	0.122	483	1.05	626	1.87	746	2.72	847	3.57	943	4.60								
4,030	1,600	0.160	513	1.33	642	2.18	759	3.17	858	4.12	950	5.21	1,030	6.29						
4,530	1,800	0.202	532	1.61	666	2.56	774	3.63	876	4.63	964	5.82	1,040	6.92	1,125	8.18				
5,040	2,000	0.250	572	2.00	688	2.97	797	4.12	890	5.30	976	6.50	1,052	7.75	1,134	8.96	1,208	10.15	1,270	11.67
5,540	2,200	0.302	603	2.36	712	3.43	816	4.66	910	5.93	999	7.38	1,068	8.60	1,145	9.93	1,210	11.18	1,279	12.82
6,040	2,400	0.360	637	2.79	746	3.99	840	5.33	926	6.73	1,017	8.17	1,088	9.50	1,160	10.88	1,230	12.25	1,288	13.92
6,550	2,600	0.422	670	3.27	762	4.62	866	6.05	954	7.83	1,032	9.08	1,095	10.50	1,171	11.98	1,245	13.50	1,298	15.10
7,060	2,800	0.489	708	3.81	795	5.32	892	6.72	963	8.78	1,050	9.97	1,125	11.60	1,188	13.06	1,257	14.70	1,310	16.48
7,560	3,000	0.560	746	4.42	833	6.05	920	7.70	993	9.32	1,068	11.00	1,142	12.75	1,210	14.28	1,277	15.98	1,328	17.80
8,060	3,200	0.638			866	6.96	943	8.71	1,020	10.40	1,097	12.10	1,168	14.02	1,228	15.50	1,292	17.36	1,340	19.12
8,560	3,400	0.721			900	7.93	964	9.80	1,053	11.48	1,120	13.30	1,188	15.35	1,248	16.93	1,310	19.00	1,360	20.90
9,070	3,600	0.808					1,010	11.00	1,078	12.70	1,148	14.65	1,213	16.70	1,270	18.42	1,335	20.75	1,380	22.60
9,570	3,800	0.900					1,038	12.25	1,108	14.15	1,170	14.90	1,240	18.80	1,292	19.46	1,355	22.35	1,405	24.40
10,080	4,000	0.998					1,162	13.60	1,138	15.40	1,200	17.35	1,270	19.70	1,320	21.70	1,380	23.15	1,430	26.40
10,580	4,200	1.100							1,168	16.90	1,230	19.05	1,283	21.50	1,348	23.50	1,405	26.10	1,450	28.42
11,100	4,400	1.210							1,198	18.58	1,258	20.55	1,322	22.50	1,373	25.40	1,430	27.95	1,478	30.60
11,600	4,600	1.310							1,232	20.30	1,290	22.50	1,355	23.80	1,405	27.40	1,450	30.15	1,500	32.90
12,100	4,800	1.450							1,270	21.00	1,321	24.40	1,383	25.65	1,432	29.60	1,482	32.40	1,528	35.20
12,600	5,000	1.570							1,301	24.20	1,355	26.40	1,410	28.80	1,462	31.80	1,513	34.60	1,555	37.80
15,120	6,000	2.230													1,622	45.90	1,670	49.00	1,702	51.50

Design of Local Exhaust Systems

"Air Pollution Engineering Manual", Public Health Service, U.S.D.H.E.W., Cincinnati, Ohio 1967, data from New York Blower Company, 1948.

- the lowest fuel cost. The major drawback to steam coils is their potential to freeze and burst when the outside air is below freezing.
- 2. Direct fired heaters may be used where safety regulations permit (i.e., where there are no fire or explosion hazards). Here natural gas or liquified petroleum gas is burned directly in the air stream. Direct fired heating is used extensively for tempering make-up air.
- 3. Open flame, or indirect-fired heaters provide a heat exchange surface between the combustion chamber and the air being heated. The gaseous products of combustion are sent out through a flue. The drawback to this heating system is that condensation occurs on the heat transfer surface on every startup when using cold, outside air.

Finally, when natural infiltration can effectively provide all the required make-up air, infra-red unit heaters can be used.

Heating costs can be minimized if good engineering judgment is used in the make-up air supply design. The following recommendations should be considered:

- 1. Make-up air should be mixed with warmer building air before it reaches the work zone.

- 2. If possible, air should be delivered directly to the work zone. Make-up air should be introduced in the plant below the 8-10 foot level. In this way, the workers are constantly exposed to fresh air, and better circulation of air is achieved.
- 3. Sometimes it is possible to design a make-up air system that serves a dual purpose. Supply air may be used for spot cooling during warm weather, or in winter, waste heat can be recovered by cooling process equipment, motors, generators, etc. with this air.
- 4. Internal waste heat from a building can be recovered by using recirculated air to temper make-up air.

Supply Duct Design. The principles and methods involved in designing the supply duct are the same as explained earlier for the "Balance with Blast Gate" method. The difference is that the major portion of the ductwork is on the pressure side of the fan instead of the exhaust side. Also, only clean air will be handled by this ductwork.

Design velocities are based solely on economical factors; minimum transport velocities are not critical here. Velocities in the range of 2000 fpm are commonly used as they are most feasible.

Supply air systems are made up of rectangular ducts and branch takeoffs to save space. Light gauge construction materials are used with me-

chanical joints because leakage is of little consequence.

EXAMPLE PROBLEM

To assist the reader in better comprehension of this chapter, an example is presented herewith illustrating the various considerations a design engineer must give to a specific problem. This example is presented purely for illustrative purposes — no consideration has been given to the possibility that interfering machinery, trusses, etc. may alter the final design.

The problem: Design an exhaust system to control particulate residue from a 16-inch industrial disc sander. The system, shown in Figure 42-6, includes a disc sander, ductwork, fabric dust collector, and fan.

The following assumptions are derived from information presented earlier in this chapter.

1. $Q = 440$ cfm. The air volume required to properly exhaust the disc sander.

2. $v = 3500$ fpm. The transport velocity required for this system.

3. Hood losses = $1.0 \text{ slot VP} + 0.25 \text{ duct VP}$
In addition, assume that the pressure loss across the dust collector is 2 inches of water.

It is required to design an appropriate local exhaust system for the sander and select an appropriate fan.

The first step in designing the system is to develop a systematic approach to the problem. Table 42-12, taken from the "Industrial Ventilation Manual," assists in the orderly design of a ventilation system. At the top of this table are columns numbered 1-19. The required information is inserted into the various columns as shown. An explanation of how the various data shown in the table were obtained is presented in the section of this chapter entitled "Explanation of Answer Chart."

To assist the reader in following the various steps necessary to solve this problem, please refer to column numbers and to the diagram.

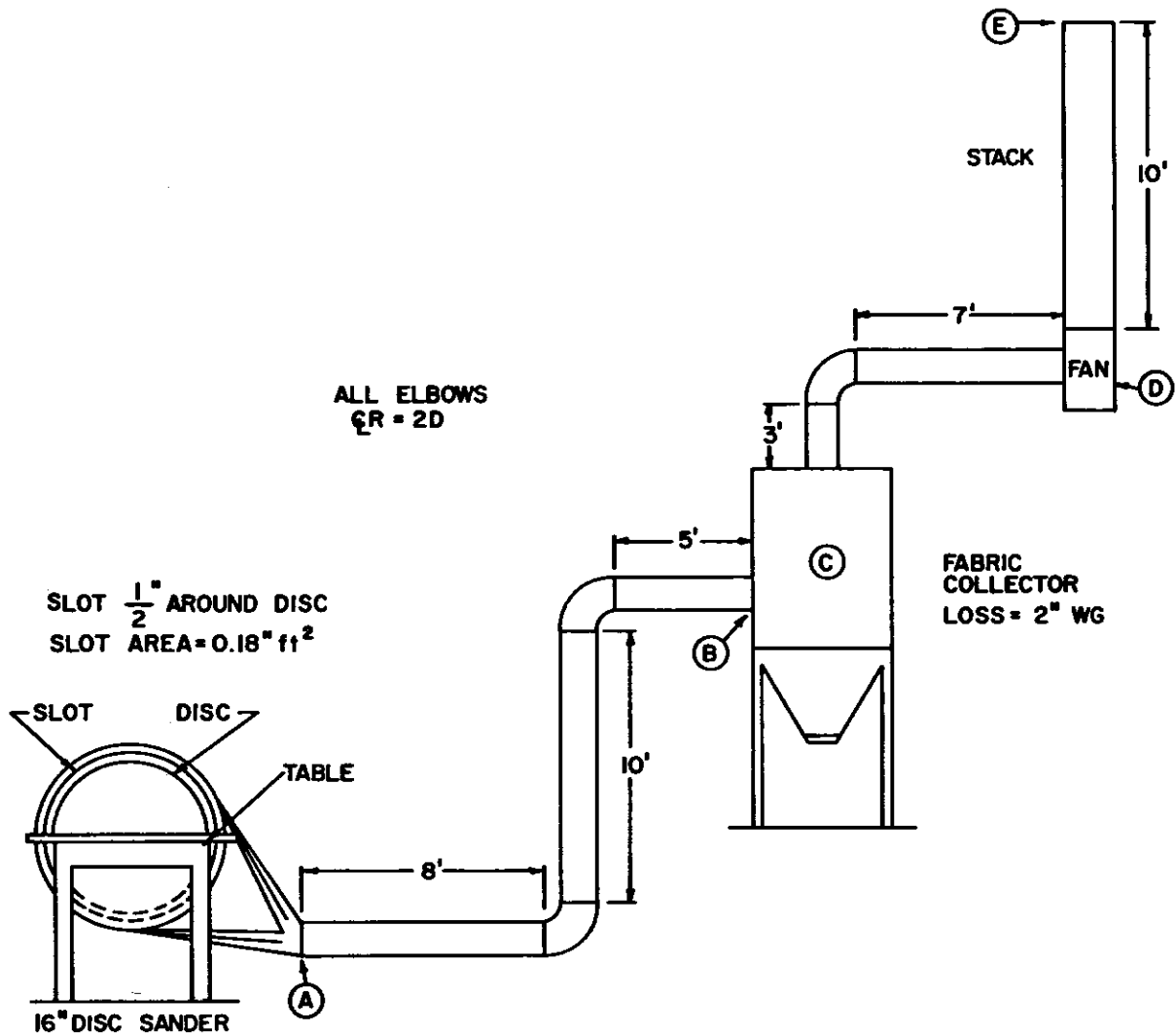


Figure 42-6. Controlling Dust from a 16" Disc Sander.

TABLE 42-12.
Answer Chart — A Worksheet for Answers to Problem

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
									Col. 7 plus Col. 9	Col. 10 x Col. 11 100		1.00 plus Col. 14	Col. 13 times Col. 15	Col. 12 plus Col. 16				At junction
No. of br. or main	Dia. in in.	Area duct sq. ft.	Air volume CFM in in.	Vel. in FPM	Length of duct in feet				Resistance in inches water gauge			Resistance in inches of water				cor- rected CFM		
					straight runs	Number of elbows	equiv. entries	total length	per 100	of run	one VP	entry hood loss suct.	hood suct.	static press.	gov. SP			
A-B	5	0.1364	475	3500	23'	2-90°	12'	35'	4.0	1.40	0.76	.25	1.25	0.95				
Slot		0.18		2640								0.44	1.0	0.44	2.79			
Collector										2.0					4.79			
C-D	5	0.1364	475	3500	10	1-90°	6'	16'	4.0	0.64	0.76				5.43	= SP in		
D-E	5	0.1364	475	3500	10			10	4.0	0.40	0.76				0.40	= SP out		

Column	Entry	Explanation
1	A-B	Considering section of duct from point A to B.
2	5	Example states that Q=440 cfm and v=3500 fpm. Using this information, choose duct diameter of 5". This diameter gives Q=475 cfm at v=3500 fpm — see Column 5.
3	0.1364	The area of a 5" circular duct is 0.1364 sq. ft.
5	475	Duct diameter=5" and duct velocity=3500 fpm. Hence, the air volume in the duct is 475 cfm.
6	3500	Determined previously.
7	23	The length of straight pipe between points A and B is 23 feet.
8	2/90°	From A to B there are two 90° elbows.
9	12	The equivalent length of each elbow is 6 feet. (See Table 42-10.)
10	35	The total length of straight pipe equivalent from A to B is 35 feet.
11	4.0	Friction loss is read directly from Figure 42-3 knowing duct diameter and air volume.
12	1.40	To determine total resistance of run from A to B, take 1/100 of the product of Column 10 x Column 11.
13	0.76	Convert from velocity to velocity pressure $VP = \left(\frac{v}{4005} \right)^2$
14	0.25	Entry loss was given in problem statement.
15	1.25	The hood loss is 1 velocity pressure. This represents the amount of energy needed to get air to flow into the hood. NOTE: Because the 1 velocity pressure has been added on here, it will not be considered when calculations are made on the slot.
1	Slot	Considering slot opening only.
3	0.18	Given slot area in example description.
6	2640	Know slot area and air volume to be moved. Velocity can be determined from $v = Q/A = 475/0.18 = 2640$ fpm.
13	0.44	Velocity pressure conversion as before.
14	1.0	This entry loss is given in problem statement.
17	2.79	Combining all duct and slot losses Column 12 + Column 16 + Column 16 = 2.79 in. w.g.
1	Collector	Considering only the collector.
12	2	Given that the pressure drop across the collector was 2 in. w.g.
17	4.79	The cumulative resistance in the system to this point.
1	C-D	Considering the duct between points C and D.
12	0.64	Resistance from duct friction is 0.64 in. w.g.

TABLE 42-12 Continued
Answer Chart — A Worksheet for Answers to Problem

Column	Entry	Explanation
17	5.43	Cumulative resistance in the system up to the fan. Quantity represents inlet static pressure.
1	D-E	Considering only the straight length of duct from the fan.
12	0.40	Duct resistance.
17	0.40	Static pressure after the fan.

It is important to note that in filling out Table 42-12, you start your design in Column No. 1 and complete the design horizontally through Column No. 17 in this particular problem.

EXPLANATION OF ANSWER CHART

Start entries in Column 1 and go across horizontally to Column 17. Columns 14, 15, and 16 need to be filled in only where air initially enters duct (i.e., through a hood). Section A-B will be considered in detail.

Fan static pressure is calculated from the following equation:

$$\begin{aligned} \text{Fan SP} &= \text{SP (Fan Inlet)} + \text{SP (Fan Outlet)} - \text{VP (Fan Inlet)} \\ &= 5.43 + 0.40 - 0.76 \\ &= 5.07 \text{ in. w.g.} \end{aligned}$$

The fan and motor selected should be able to handle a static pressure of 5.25 to 5.5 inches of water.

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CHAPTER 43

CONTROL OF INDUSTRIAL STACK EMISSIONS

*Engineering Staff**

George D. Clayton & Associates

INTRODUCTION

Simply defined, pollution is the wrong substance in the wrong place at the wrong time. Air pollution existed long before man discovered fire. Volcanic eruptions, dust storms, forest fires and other natural phenomena have released millions of tons of pollutants into the air since the beginning of time.

With the advent of the industrial revolution, continuous exposure to a variety of gaseous and particulate materials became commonplace. The synergistic effects of these chemicals on health has led to several air pollution disasters throughout the United States. The first recorded episode oc-

curred in Donora, Pennsylvania in 1948, when 20 people died during a five-day atmospheric inversion.

In addition to health effects, pollutants in the air can cause extensive economic damage. The poisoning of livestock by lead and zinc, the destruction of crops by sulfur dioxide, ozone and fluorides, and the damage to neighborhoods by smoke, dust and gaseous pollutants combined carry an economic price tag ranging between 10 and 60 billion dollars per year. One estimate given for the personal cost to a resident living in a relatively polluted community is \$84 per year. This figure includes only those costs resulting from the maintenance of the household itself.

The cost to industry of reducing emissions to the level required by the Clean Air Act will entail

*The following staff members participated in writing this chapter: George T. McCollough, Delno Malzahn, John E. Mutchler and George D. Clayton.

TABLE 43-1.
Stationary Sources
Estimates of Potential and Reduced Emission
Levels and Associated Costs
[298 Metropolitan Areas]

Source	Year	Quantity of Emissions ¹ (Thousands of Tons per Year)						Control Costs (Millions of Dollars)	
		Part	SO _x	CO	HC	F	Pb	Investment	Annual
Solid Waste Disposal	1967	1,110	—	3,770	1,400	—	—		
	FY 76 W/O ²	1,500	—	5,450	2,020	—	—		
	FY 76 W ³	185	—	414	293	—	—	201	113
Stationary Fuel Combustion	1967	3,247	11,416	—	—	—	—		
	FY 76 W/O	3,867	14,447	—	—	—	—		
	FY 76 W	930	4,697	—	—	—	—	2,432	1,006
Industrial Processes	1967	4,601	5,156	7,520	1,412	53	20		
	FY 76 W/O	6,053	6,229	10,040	1,736	73	30		
	FY 76 W	453	1,720	539	849	9	10	3,877	1,095
TOTAL	1967	8,958	16,572	11,290	2,812	53	20		
	FY 76 W/O	11,420	20,676	15,490	3,756	73	30		
	FY 76 W	1,568	6,417	953	1,142	9	10	6,510	2,214

¹Emission abbreviations are: particulates (Part), sulfur oxides (SO_x), carbon monoxide (CO), hydrocarbons (HC), fluorides (F), and lead (Pb). Blanks in the table indicate the emission levels meet the applicable regulation or that emissions are negligible or do not exist.

²Estimates without implementation of the Clean Air Act, for fiscal year 1976.

³Estimates with implementation of the Clean Air Act, for fiscal year 1976.

From "The Economics of Clean Air, Senate Document No. 92-67" annual report of the Administration of the EPA to Congress.

a total investment of \$6.5 billion by 1976, according to one estimate. By that year the associated total annual control cost including depreciation, operating and maintenance costs will amount to an estimated \$2.2 billion (Table 43-1).

LEGISLATION

Federal air pollution legislation was enacted because of the inconsistency of local air pollution control regulations and the increasing deterioration of the nation's air quality. The first Federal legislation concerning air pollution (Public Law 84-159) was enacted in 1955; it authorized a program of research and technical assistance to the states. This legislation was amended and strengthened in 1963, 1965 and again in 1966.

The Air Quality Act of 1967, more commonly called the "Clean Air Act" represented a major shift in the enforcement level of air pollution regulations. Introduced into this Act was the concept of "air quality control regions" within a single state or interstate area. The state or states having jurisdiction in a particular region were empowered to set standards of air quality, based on desired ambient air levels and guided by criteria published by the Department of Health, Education and Welfare. Initial and ongoing emission standards were also established so that compliance would insure the attainment and maintenance of desired air quality.

Within three years, the discrepancies arising in ambient standards among different air quality regions and the lack of national air quality standards led to the Clean Air Amendments of 1970. Under these amendments, states are required to adopt implementation plans (emission limitations) for the entire air region, with priority to be given to development of plans for areas where air pollution is most serious. National emission standards or limits have been established for certain new or newly-modified stationary sources for particulate, sulfur dioxide, sulfuric acid, nitrogen dioxide and plume opacity. In addition, national emission standards for hazardous chemicals such as beryllium, mercury and asbestos were set on existing sources.

CONTROL CONSIDERATIONS

The aggregate demands for improvement of air quality created by the existence of health hazards, economic damage, public pressure and legal requirements would seem to place industry in a position of "clean-up or shut-down." The degree of control necessary to fulfill these demands dictates the efficiency and sophistication of required abatement systems.

Once the required collection efficiency is determined for a single emission source, five basic factors of the source process must be characterized before proper design of an appropriate system can be undertaken:

- 1) The chemical and physical properties of the atmospheric effluent must be measured. These include size, density, shape, size-spectrum, chemical composition and corrosiveness.

- 2) The carrier exhaust gas must be characterized, including temperature, humidity, density and pressure.
- 3) Estimation of process factors such as volumetric flowrate, velocity and particulate gaseous concentrations must be made.
- 4) Construction factors including equipment size, layout, materials of construction and safety requirements must be determined.
- 5) Operational factors, such as maintenance, utility and disposal costs must be obtained.

Comparative cost data for collector designs is based on a variety of process variables. Emission abatement costs increase as the total volume of gas to be treated is increased. Careful analysis of the equipment included in the collector system, plus the installation and maintenance costs, must be made for an optimum design choice between alternative systems. Table 43-2 presents curves to obtain preliminary cost estimates. It is important to note that the installed cost may exceed the cost of the collection device as shipped by the manufacturer by a factor ranging between 100 and 400 percent.

Equipment modification and the substitution of process materials can often be the most effective means of solving air pollution problems. Substantial reduction of the loading in effluent air streams can be brought about by replacement of raw materials or fuel types used. For example, conversion from coal to natural gas as a combustion fuel dramatically reduces sulfur dioxide and particulate emissions.

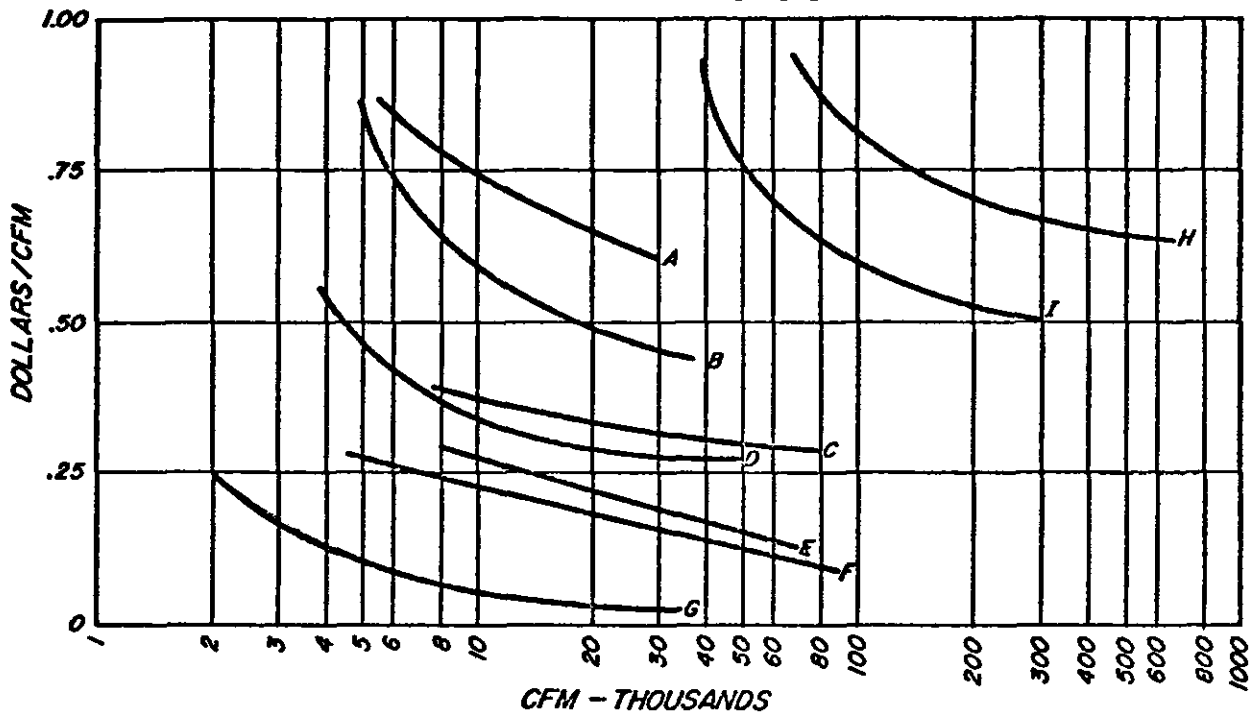
Modifications to the plant design which suppress contaminant formation at the source are, of course, the ideal solution. In addition, any design change which concentrates the contaminant loading to the collecting device into a smaller air volume, reduces the size and cost of the collector needed, since most collecting devices are designed on the volume rate of air to be handled and are relatively insensitive to changes in contaminant loading.

Good plant layout, construction and house-keeping can be an effective system for contaminant suppression. The prevention of leaks, periodic vacuuming and "hosing down" procedures and the elimination of open piles of chemicals are a few of the many possible methods for lowering emissions within the plant area.

The engineer, after carefully studying the costs related to such factors as: 1) the need for controls; 2) the degree of control required; and 3) potential process changes, has available to him a variety of types, designs and manufacturers of control devices. Proper selection of the optimum system requires a thorough understanding of the characteristics of process factors, along with a fundamental knowledge of the principles associated with each type of control equipment.

Table 43-3 includes a summary of the characteristics of particles and the effective range of certain collection devices. Table 43-4 includes the operating mechanisms and minimum size data for 90% collection efficiency. For a more detailed discussion, the equipment types are divided into

TABLE 43-2.
Cost Estimates of Dust Collecting Equipment



- A—High temperature fabric collector (continuous duty)
- B—Reverse jet fabric collector (continuous duty)
- C—Wet collector (maximum cost range)
- D—Intermittent duty fabric collector
- E—High efficiency centrifugal collector
- F—Wet collector (minimum cost range)
- G—Low pressure drop cyclone (maximum cost range)
- H—High voltage precipitators

- I—High voltage precipitators (minimum cost range)

Note 1: Cost based on collector section only. Cost does not include ducting, water requirement, power requirement or exhausters (unless exhaust is integral part of secondary air circuit.)

"Industrial Ventilation — A manual of Recommended Practice" 12th Edition, Committee on Industrial Ventilation, American Conference of Governmental Industrial Hygienists, Lansing, Michigan.

six broad, general categories: 1) mechanical separators; 2) filtration devices; 3) wet collectors; 4) electrostatic precipitators; 5) gas adsorbers; and 6) combustion incinerators.

Mechanical Separators

These devices impart either inertial or gravitational forces on the particle to remove it from the carrier stream. The range of particle sizes consistent with effective collection efficiencies is 15 to 40 microns in diameter; a sharp dropoff of collection efficiency occurs with particles smaller than 15 microns in diameter. Industrial use is limited to applications where the particulate is very coarse or the separator is used in series with other devices.

The many varieties of mechanical separators can be divided into three broad categories: gravity chambers, cyclone collectors and impingement separators.

Gravity Chambers. These chambers are the oldest and least efficient method of dust collection. They consist of a low-velocity enclosure where the larger contaminant particles are removed by the force of gravity. Particles smaller than 40 μ in diameter usually pass through, uncollected.

Collection efficiency is related to the terminal settling velocity, U_t , and is expressed in the following equation:

$$\eta = \frac{100 U_t A_h}{Q}$$

where: η = % collection efficiency by weight

U_t = particle terminal settling velocity, ft./min.

A_h = horizontal area of chamber, ft²

Q = volumetric flowrate of gas, ft³/min.

An increase in the effective horizontal area, A_h , through the use of horizontal baffles, or a decrease in volumetric flowrate and velocity profile, favorably affects collection efficiency.

Advantages of gravity settlers include: low initial cost (between 5¢ and 25¢ per cfm), simple construction and a slight pressure drop. These advantages are offset by an inability to remove particles smaller than 40 microns in diameter and large space requirements.

Gravity chambers are most useful as a pre-cleaning stage before treatment by a higher collection efficiency device. The removal of large-

TABLE 43-3.
Properties of Aerosols

		Particle Diameter, microns (μ)									
		0.0001	0.001	0.01	0.1	1	10	100	1,000	10,000	
Equivalent Sizes		Angstrom Units, Å									
		Theoretical Mesh (Used very infrequently)									
Electromagnetic Waves		X-Rays									
		Ultraviolet									
Technical Definitions	Gas Dispersals	Fume									
	Liquid	Mist									
Common Atmospheric Dispersals	Soil:	Clay									
		Salt									
Typical Particles and Gas Dispersoids		Fine Sand									
		Coarse Sand									
Methods for Particle Size Analysis		Gravel									
		Smog									
Types of Gas Cleaning Equipment		Clouds and Fog									
		Mist-Drizzle									
Terminal Gravitational Settling [for spheres, sp. gr. 2.0]	In Air at 25°C, 1 atm.	Rain									
	In Water at 25°C.										
Particle Diffusion Coefficient, $\text{cm}^2/\text{sec.}$	In Air at 25°C, 1 atm.										
	In H ₂ O at 25°C.										
<p>Molecular diameters calculated from viscosity data at 0°C.</p>		<p>Rosin Smoke</p> <p>Tobacco Smoke</p> <p>Metallogurgical Dusts and Fumes</p> <p>Ammonium Oxide fume</p> <p>Sulfur Concentrator Mist</p> <p>Fertilizer, Ground Limestone</p> <p>Fly Ash</p> <p>Coal Dust</p> <p>Cement Dust</p> <p>Beach Sand</p> <p>Carbon Black</p> <p>Contact Sulfuric Mist</p> <p>Paint Pigments</p> <p>Insecticide Dusts</p> <p>Ground Talk</p> <p>Spray Dried Milk</p> <p>Alkali Fume</p> <p>Milled Flour</p> <p>Plant Spores</p> <p>Pollens</p> <p>Hydraulic Nozzle Drops</p> <p>Zinc Oxide Fume</p> <p>Cellulose Silica</p> <p>Atmospheric Dust</p> <p>See Salt Nuclei</p> <p>Nebulizer Drops</p> <p>Lung Damaging Dust</p> <p>Pneumatic Nozzle Drops</p> <p>Red Blood Cell Diameter (Adults): $7.5\mu \pm 0.3\mu$</p> <p>Bacteria</p> <p>Human Hair</p> <p>Viruses</p> <p>Impingers</p> <p>Electroformed Sieves</p> <p>Sieving</p> <p>Ultramicroscope</p> <p>Microscope</p> <p>Electron Microscope</p> <p>Centrifuge</p> <p>Elutriation</p> <p>Ultracentrifuge</p> <p>Turbidimetry**</p> <p>Sedimentation</p> <p>X-Ray Diffraction</p> <p>Absorption</p> <p>Permeability*</p> <p>Visible to Eye</p> <p>Nuclei Counter</p> <p>Light Scattering**</p> <p>Electrical Conductivity</p> <p>Machine Tools (micrometers, Calipers, etc.)</p> <p>Ultrasonics (very limited industrial applications)</p> <p>Setting Chambers</p> <p>Centrifugal Separators</p> <p>Liquid Scrubbers</p> <p>Cloth Collectors</p> <p>Packed Beds</p> <p>Common Air Filters</p> <p>High Efficiency Air Filters</p> <p>Impingement Separators</p> <p>Thermal Precipitation (used only for sampling)</p> <p>Mechanical Separators</p> <p>Electrical Precipitators</p>									
<p>* Stokes-Cunningham factor included in values given for air but not included for water</p>		<p>† Furnishes average particle diameter but no size distribution.</p> <p>** Size distribution may be obtained by special collection.</p>									
		Particle Diameter, microns (μ)									
		0.0001	0.001	0.01	0.1	1	10	100	1,000	10,000	

Reprinted by permission of Stanford Research Inst. J. 8, 95 (1961).

Characteristics of particles and particle dispersions. Courtesy Stanford Research Institute.

Source: "Air Pollution Manual". Part II, p. 13, American Industrial Hygiene Association, Akron, Ohio.

TABLE 43-4.
General Classification of Particulate Collectors

Control Device	Class	Force	Particle Diameter for 90% Removal in Microns
Settling Chamber	Mechanical	Gravity	50
Impingement Separator	Mechanical	Inertial Impingement	25
Cyclone (Small Diameter)	Mechanical	Centrifugal	>5
Cyclone (Large Diameter)	Mechanical	Centrifugal	25
Baghouse	Filtration	Inertial Impingement + Electrostatic + Diffusional	>1
Panel Filters	Filtration	Inertial Impingement + Electrostatic + Diffusional	>1
Mat Filters	Filtration	Inertial Impingement + Electrostatic + Diffusional	10
Deep Filter Beds	Filtration	Inertial Impingement + Electrostatic + Diffusional	1
Spray Chamber	Scrubber	Inertial Impingement	25
Packed Tower	Scrubber	Inertial Impingement	5
Cyclone Scrubbers	Scrubber	Inertial Impingement + Centrifugal	5
Venturi	Scrubber	Inertial Impingement + Centrifugal	>1
Wet Inertial (Mechanical)	Scrubber	Inertial Impingement + Centrifugal	5
Orifice	Scrubber	Inertial Impingement + Centrifugal	5
Single-Stage High Voltage	Electrostatic Precipitators	Electrostatic Attraction	>1
Two-Stage Low Voltage	Electrostatic Precipitators	Electrostatic Attraction	>1

Source: "Air Pollution Manual". Part II, p. 13, American Industrial Hygiene Association, Akron, Ohio.

size particulates which may prove erosive to a second-stage cleaner optimizes the system by increasing the efficiency and life of the second collector.

Impingement Separators. Impingement separators encompass a large, heterogeneous group of collection devices, all of which are based on the inertial force of a particle to accomplish its removal from the carrier gas stream.

The separator utilizes a network of baffles to collect or concentrate the particulates, as depicted in Figure 43-1. As the particles moving in the gas stream approach a stationary target, the air will deflect around the impingement target, carrying with it the lighter particles. The inertial force of the heavier particles causes them to cross the fluid streamlines, strike the target, and be removed, as shown in Figure 43-2.

The target efficiency of impingement is the percentage of particles which collide with the stationary object. This value can be obtained graphically from the separation number, N_s , which is a dimensionless value obtained from classical hydrodynamics and reported graphically in Figure 43-3.

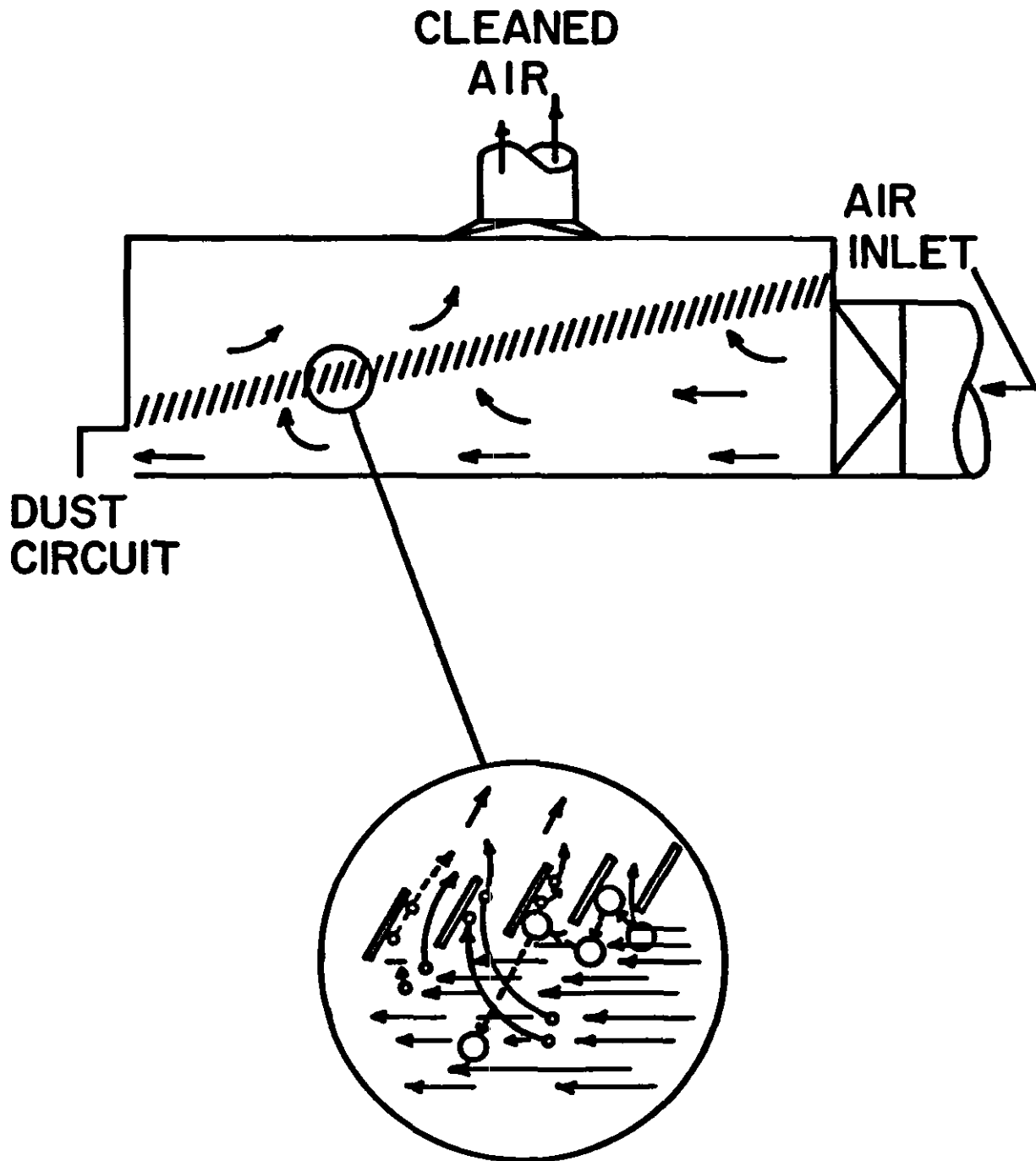
$$N_s = \frac{D_p^2 V \rho_p}{18\mu D_b}$$

where: N_s = Separation number, dimensionless
 D_p = particle diameter, feet
 V = relative velocity gas to target, ft./sec.
 ρ_p = particle density, lb./ft.³
 μ = gas viscosity, lb./ft.-sec.
 D_b = target diameter, ft.

The collection efficiency increases with increasing particle size, gas velocity and particle density; but overall efficiency is quite low, in the range of 50-80%, with particles smaller than 20 microns uncollected. Optimum designs, therefore, utilize small openings between baffles and high gas velocities.

Advantages of impingement separators include: low cost (from 15¢ to 30¢ per cfm), simple construction and trouble-free operation. Disadvantages include low overall efficiency, erosion of baffles and corrosion.

Impingement collectors find use throughout industry as: precleaners for more elaborate devices, collection devices where large particles are involved and devices that concentrate the particulates, in a smaller percentage of the gas stream. *Cyclone Collectors.* The most prevalent type of mechanical collector in use today is the cyclone. It operates on the principle of creating a vortex from the inlet gas stream velocity.



American Industrial Hygiene Association: Air Pollution Manual. Akron, Ohio, 1968, part II, p. 34.

Figure 43-1. Flat Lower Impingement Separator.

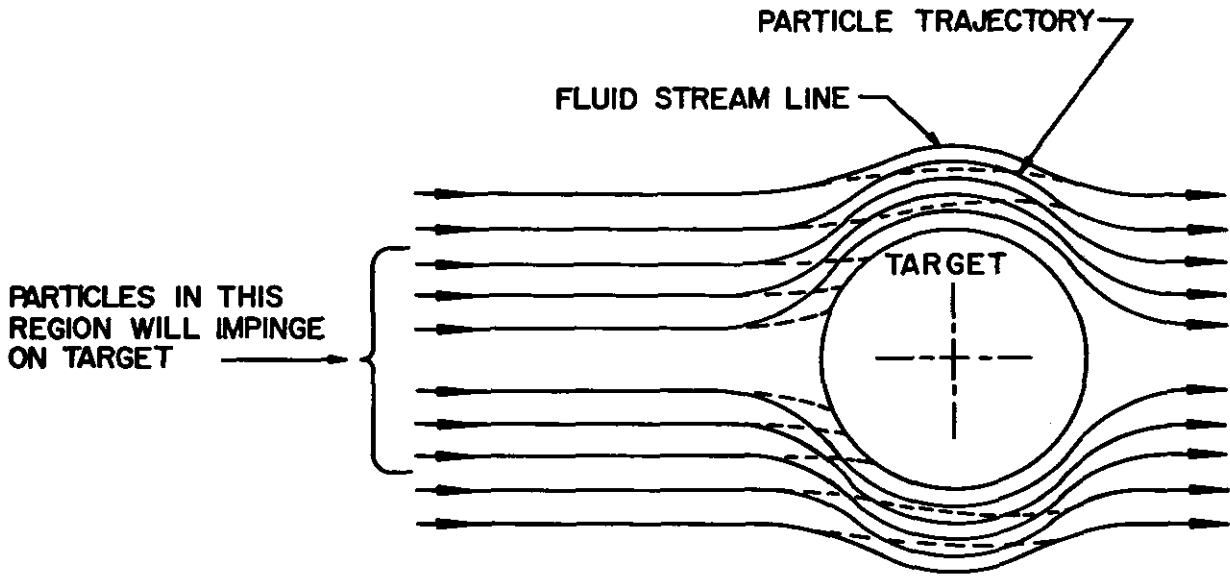
The entrained particles are drawn outward by centrifugal force, where they impinge on the wall surface and are removed by gravity to a collection point. The air flows in a double vortex, spiraling downward at the outside periphery and returning upward through the inside regions as shown in Figure 43-4.

During cyclonic separation, the gas stream velocity may increase several times over the inlet conditions. The separation mechanism is similar

to gravitational settling except that the force acts centrifugally instead of gravitationally, resulting in an increased force on the particle. In small-diameter cyclones, this value may reach upwards of 2500 times the force of gravity.

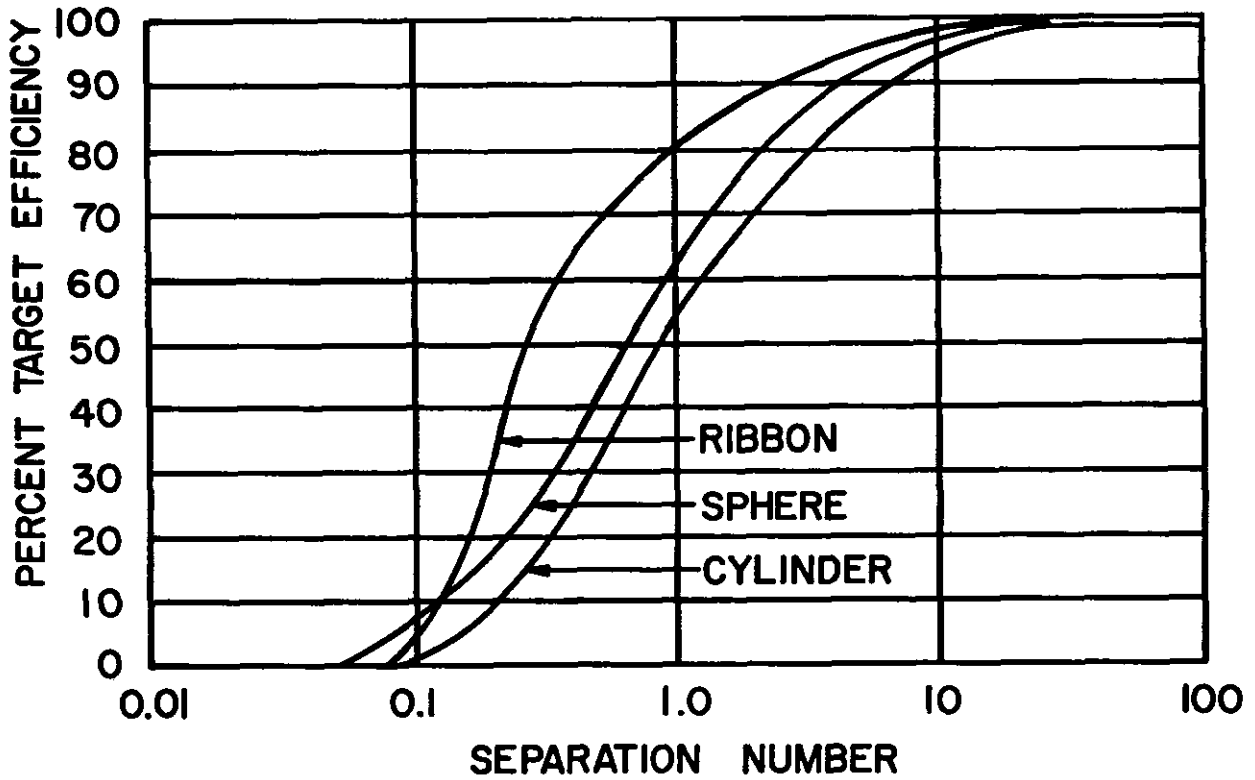
One typical equation for calculation of the size of particles collected is listed below:

$$D_{pc} = \sqrt{\frac{9 \mu b}{2\pi N_e V_1 (\rho_p - \rho_e)}}$$



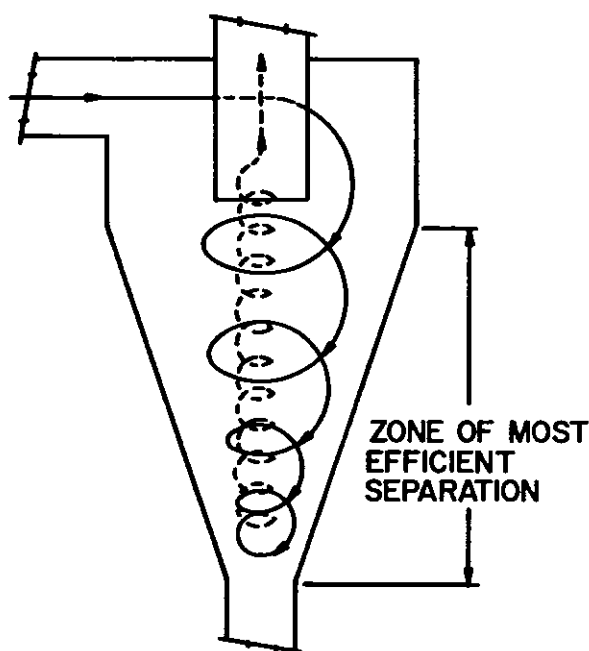
Stern: Air Pollution, 2nd Edition. Academic Press, p. 401.

Figure 43.2. Physics of Impingement.



Stern: Air Pollution, 2nd Edition. Academic Press, p. 401.

Figure 43-3. Target Efficiency of Impingement.



Air Pollution Engineering Manual, Department of Health, Education and Welfare, 1967, p. 93.

Figure 43-4. A Simplified Cyclone Collector.

where: D_{50} = diameter of particle collected at 50% efficiency

μ = gas viscosity, lbs./sec.-ft.

b = cyclone inlet, ft.

N_t = number of turns within the cyclone (approximately 5)

V_1 = inlet gas velocity, ft./sec.

ρ_p = particle density, lb./ft.³

ρ_g = gas density, lb./ft.³.

Caution is recommended in applying this equation to a design problem since the cyclone may be a poor classifier by particle size due to the variation of factors such as radius of rotation, distance from the wall and tangential velocity.

In design consideration, the factor of primary importance is the cyclone's radius. Collection efficiency increases as the radius is reduced. This is due to the increased centrifugal force created on the particle. Pressure drop increases with efficiency.

Small diameter or high efficiency cyclones have seen increased application in the last few years. Often, an arrangement of cyclones in parallel is used to handle high-volumetric flowrates rather than one large-diameter cyclone.

Cyclones have widespread use due to several inherent advantages: low initial cost (from 10¢ to 50¢/cfm) for simple construction, moderate pressure drop and low maintenance requirements. Disadvantages include: low collection efficiencies for particles below 5 microns and erosion from impingement of particulate matter.

Filtration Devices

Filtration is an effective technique for control-

ling emissions in the form of dust or fume from a carrier stream. Collection efficiencies of over 99.9% have been recorded in some applications. Three classes of filters exist: mat filters, ultrafilters and fabric filters. Of the three, the latter is the most important for industrial applications of air pollution control.

Mat filters are extremely porous, containing 97-99% void space. They have limited life and are usually used as process air cleaners. Ultrafiltration involves deep filter beds used for high efficiency removal requirements such as radio-active wastes. Baghouses or panel filters utilize fabrics to effect separation and are common throughout industry for a multitude of applications.

Fabric filters are employed in two basic designs, panel filters and baghouses. Panel filters are composed of individual filters, one or two inches thick. These panels filter out the particulate, as the gas flows through the medium. Baghouses are composed of long sleeves of fabric, up to 45 feet in length. These bags filter the air as it passes through the cloth. Periodic cleaning is important to both types to prevent excessive pressure drops from developing. Some mechanisms used for reducing the filter buildup of particulates are mechanical shaking, reverse air jet and low-frequency sound generation. A typical baghouse is shown in Figure 43-5.

The fabric weave often has interstices on the order of 100 microns, yet collection efficiencies of over 90% are reached on particles of one micron in diameter. Obviously, the filtering mechanism cannot be simple sieving. The theory of fabric filtration is not well developed. Empirically, the cloth openings quickly fill, as large-diameter particles "bridge over" the openings. Forces of electrostatic attraction appear to exert the greatest influence, but other forces, such as Brownian diffusion, impingement and gravitational settling may contribute to the overall process.

The cake of particles that develops becomes the filtering medium. As this cake grows thicker, increasingly smaller particles are collected and the pressure drop increases. Periodic cleaning must be performed to limit the pressure drop to design levels.

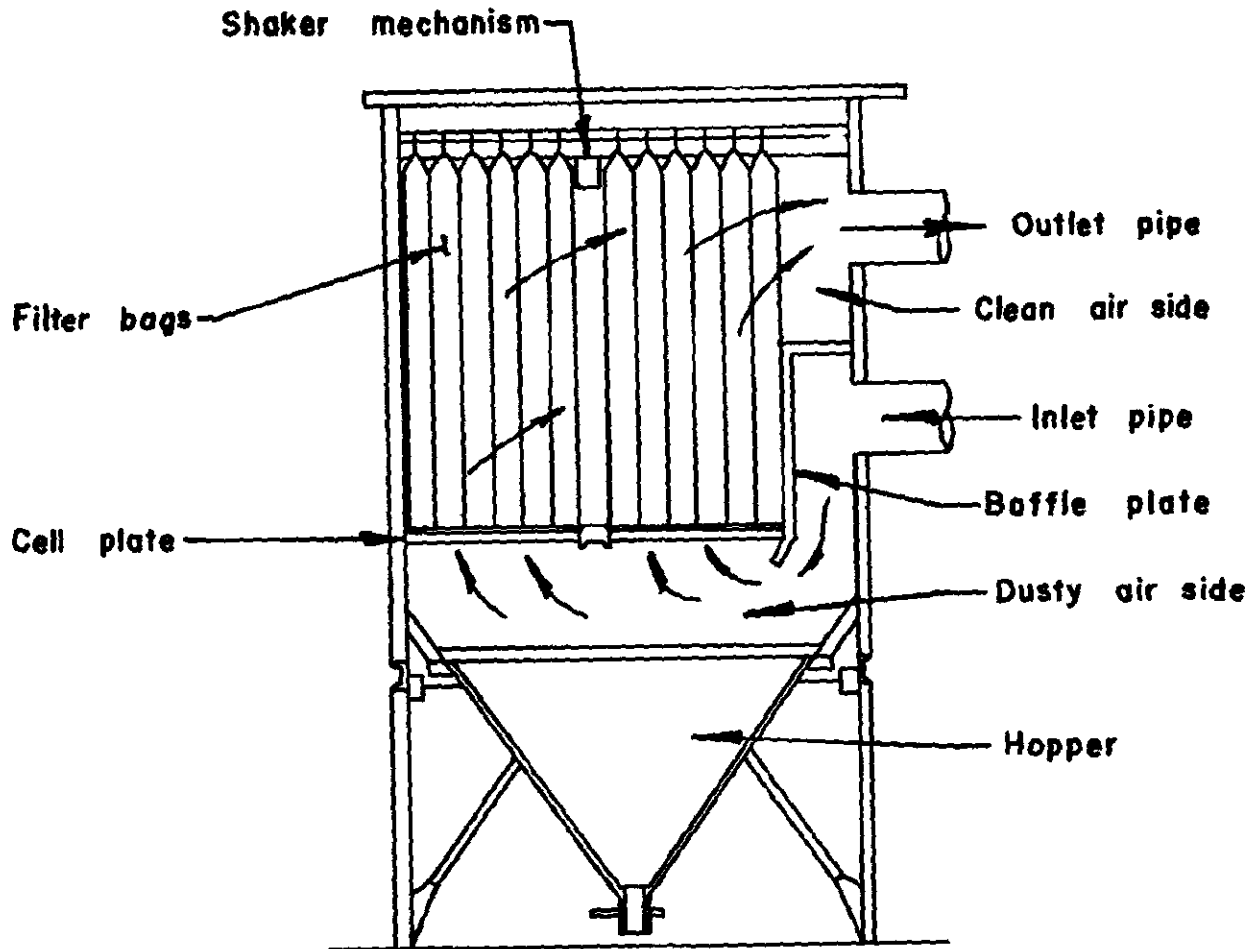
The pressure drop through a fabric filter and the cost of the device are the two most important factors in the design of a collection system for fabric filters. Generally, an increase in cloth area will enhance efficiency, lower the pressure drop and lengthen the fabric life through a reduced cleaning interval, but it also increases the cost of the device.

Three variables of design are used to determine the ultimate pressure drop in the system:

1. Filter ratio, which is the ratio of carrier gas volumetric flowrate to filter area;
2. Type of cloth and weave selected;
3. Time period of cleaning and method utilized.

The pressure drop is the sum of the resistances of the cloth and the filter cake and can be calculated from the following formula:

$$\Delta P_t = \Delta P_f + \Delta P_c = K_2 L_1 V^2$$



American Industrial Hygiene Association: Air Pollution Manual. Akron, Ohio, 1968, part II, p. 48.

Figure 43-5. Single Compartment Baghouse Filter.

where: ΔP_t = Pressure drop at time t due to dust cake, lb_f/ft^2

ΔP_r = total filter resistance at time t , lb_f/ft^2

ΔP_1 = initial filter resistance of cleaned filter, lb_f/ft^2

K_z = proportionality constant, $\frac{\text{lb}_f \text{ sec}^2}{\text{lb}_m \text{ ft}}$

L_x = dust concentration in carrier gas, lb_m/ft^3

t = time since cleaning

V = superficial filtering velocity, ft/sec .

The filter ratio affects the pressure drop by determining the loading rate on the filter. A ratio of three cubic feet per minute per square foot of cloth area is an average value for common dusts. Excessive loading leads to rapid filter buildup. This, in turn, requires a shorter cleaning interval and lowers the life of the cloth. The resistance of the cleaned cloth is determined by material and weave pattern.

The selection of cloth type depends on the

temperature of the gas stream and the abrasive characteristics of the particulate. Table 43-5 illustrates some of the more common fabric materials.

Advantages of fabric filters include:

- 1) Upwards of 99% collection efficiency for virtually all particle sizes;
- 2) Moderate power requirements; and
- 3) Dry disposal of collection efficiency.

Disadvantages include:

- 1) High cost (between 30¢ and \$2.50/cfm);
- 2) Large space requirements;
- 3) High maintenance and replacement costs;
- 4) Control of moisture in the dusts; and
- 5) Cooling for high temperature gas streams.

Wet Collectors

Wet collectors or scrubbers effect separation of both particulate and gaseous phase contaminants. Particle removal is accomplished by mechanisms similar to those operating in mechanical separators. In a wet collector the particles first impinge upon discrete droplets or sheets of liquid, and then subsequent separation of the liquid removes the particulates from the gas stream. Removal of gaseous components takes place by the

TABLE 43-5
Properties of Fiber Materials Used as Filters

Fiber	Physical characteristics							
	Relative strength	Specific gravity	Normal moisture content (%)	Maximum usable temperature (°F)	Relative resistance to attack by			Other attribute
					Acid	Base	Organic solvent	
Cotton	Strong	1.6	7	180	Poor	Medium	Good	Low cost
Wool	Medium	1.3	15	210	Medium	Poor	Good	—
Paper	Weak	1.5	10	180	Poor	Medium	Good	Low cost
Polyamide (nylon)	Strong	1.1	5	220	Medium	Good	Good ^a	Easy to clean
Polyester (Dacron)	Strong	1.4	0.4	280	Good	Medium	Good ^b	—
Acrylonitrile (Orlon)	Medium	1.2	1	250	Good	Medium	Good ^c	—
Vinylidene chloride	Medium	1.7	10	210	Good	Medium	Good	—
Polyethylene	Strong	1.0	0	250	Medium	Medium	Medium	—
Tetrafluoroethylene	Medium	2.3	0	500	Good	Good	Good	Expensive
Polyvinyl acetate	Strong	1.3	5	250	Medium	Good	Poor	—
Glass	Strong	2.5	0	550	Medium	Medium	Good	Poor resistance to abrasion
Graphitized fiber	Weak	2.0	10	500	Medium	Good	Good	Expensive
Asbestos	Weak	3.0	1	500	Medium ^d	Medium	Good	—
"Nomex" nylon	Strong	1.4	5	450	Good	Medium	Good	Poor resistance to moisture

^a"Air Pollution" 2nd Edition, Stern, A. C. ed., Academic Press, New York, N. Y., 1968.

^bExcept phenol and formic acid.

^cExcept phenol.

^dExcept heated acetone.

^eExcept SO₂.

principle of absorption. This process proceeds through diffusional movement of the gas component towards the liquid upon which it absorbs by a concentration gradient across the interface region.

Wet collectors find industrial applications where one or more of the following conditions exist:

- 1) Polluting gaseous components need to be controlled;
- 2) Combustible situations would occur if dry collection were used;
- 3) A humid gas effluent is encountered; and
- 4) Cooling of the effluent is desired.

Gas Absorption. Gas absorption occurs either through a chemical reaction with the contacting liquid or by simple physical equilibrium of solubility. In a system where a reaction occurs, equilibrium between the gas and liquid phases for a component is impossible, since in the liquid phase a reaction removes the component from solution. This allows for separation of the component in excess of equilibrium values.

In a system involving simple gas solubility in water, Henry's Law can be used to calculate the equilibrium mole fractions in the liquid and vapor phases.

$$P_A = H X_A$$

where: P_A = partial pressure of gas A

H = Henry's Law constant

X_A = mole fraction of gas A dissolved in the liquid.

Mass transfer of the gas to the liquid controls the rate at which this equilibrium is approached. A concentration profile exists across both the liquid and gas interface (Figure 43-6). This driving force causes the molecules of the absorbent gas to diffuse from an area of higher gas concentration to an area of lower concentration, the interface.

Since the gas phase diffusion is usually the rate-determining step, the flux at the interface can be determined by the following equation:

$$N_A = K_G A P \Delta Y$$

where: N_A = moles transferred per hour, m/hr.

K_G = mass transfer coefficient, hr./lb.-ft.²

P = total pressure, lb./ft.²

A = interface area, ft.²

ΔY = driving force, lb.-ft.

Gas Absorption Equipment. Absorption equipment operates on the principles of gaseous or liquid dispersion. Packed towers, venturi scrubbers and spray towers operate by liquid dispersion. Tray towers and sparging equipment operate by

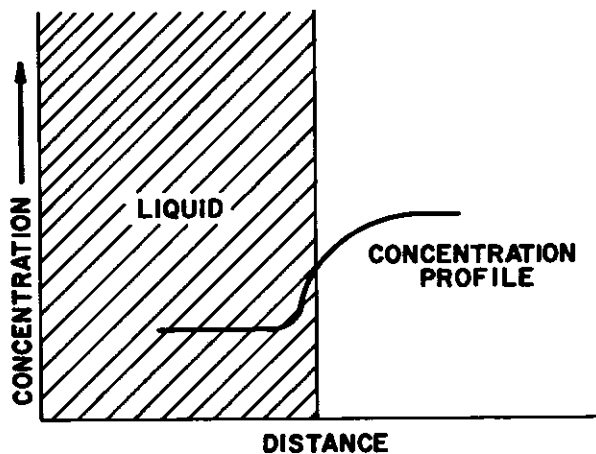


Figure 43-6. Concentration vs. Position in Liquid and Gas.

gas dispersion.

Particle Collection. Particle collection proceeds by a two-step process. First, the particle is contacted by a liquid droplet and is "wetted"; then the wetted particles are removed from the carrier gas. In some collectors, the liquid serves only to clean the impingement surfaces. Mechanisms for wetting the particle include:

- 1) Impingement upon liquid droplets;
- 2) Brownian diffusion;
- 3) Condensation of water around a particle as the gas dips below its dewpoint; and
- 4) Electrostatic attraction between the droplet and the particle.

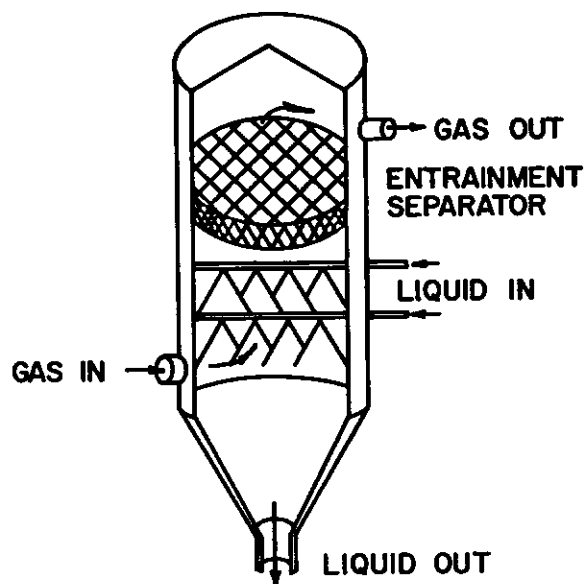
The wetted particles are removed through impingement and/or centrifugal force, depending on the type of device. The wetting of the particle increases its mass, allowing it to be readily removed by inertial force. Overall design and collection efficiency equations are not well developed and depend on the type of equipment. Decreasing water droplet size and increasing relative gas velocities will improve collection efficiency.

Particle Collection Equipment. All types of wet scrubbers including those that are used for gas absorption remove particulates to some degree. Generally, those devices that utilize high energy contact between the gas stream and small spray droplets achieve the greatest particle collection efficiency. A list of wet collecting devices is included below:

1. spray chambers
2. cyclone-type scrubbers
3. orifice-type scrubbers
4. mechanical scrubbers
5. mechanical-centrifugal collectors
6. venturi scrubbers
7. packed towers
8. wet filters.

Simplified drawings of several of the devices are depicted in Figures 43-7 through 43-10.

Discussion of Wet Collectors. Water pollution problems are always associated with wet scrubbers



Stern: Air Pollution, 2nd Edition. Academic Press, p. 474.

Figure 43-7. Spray Tower.

and should be considered when evaluating possible systems. It is often necessary to settle out the particulate sludge with flocculants and to adjust the pH before the water can be returned on-stream. Other problems include: freezing of process water, corrosion and increased opacity of the plume due to condensing liquid. Advantages of a wet collector include:

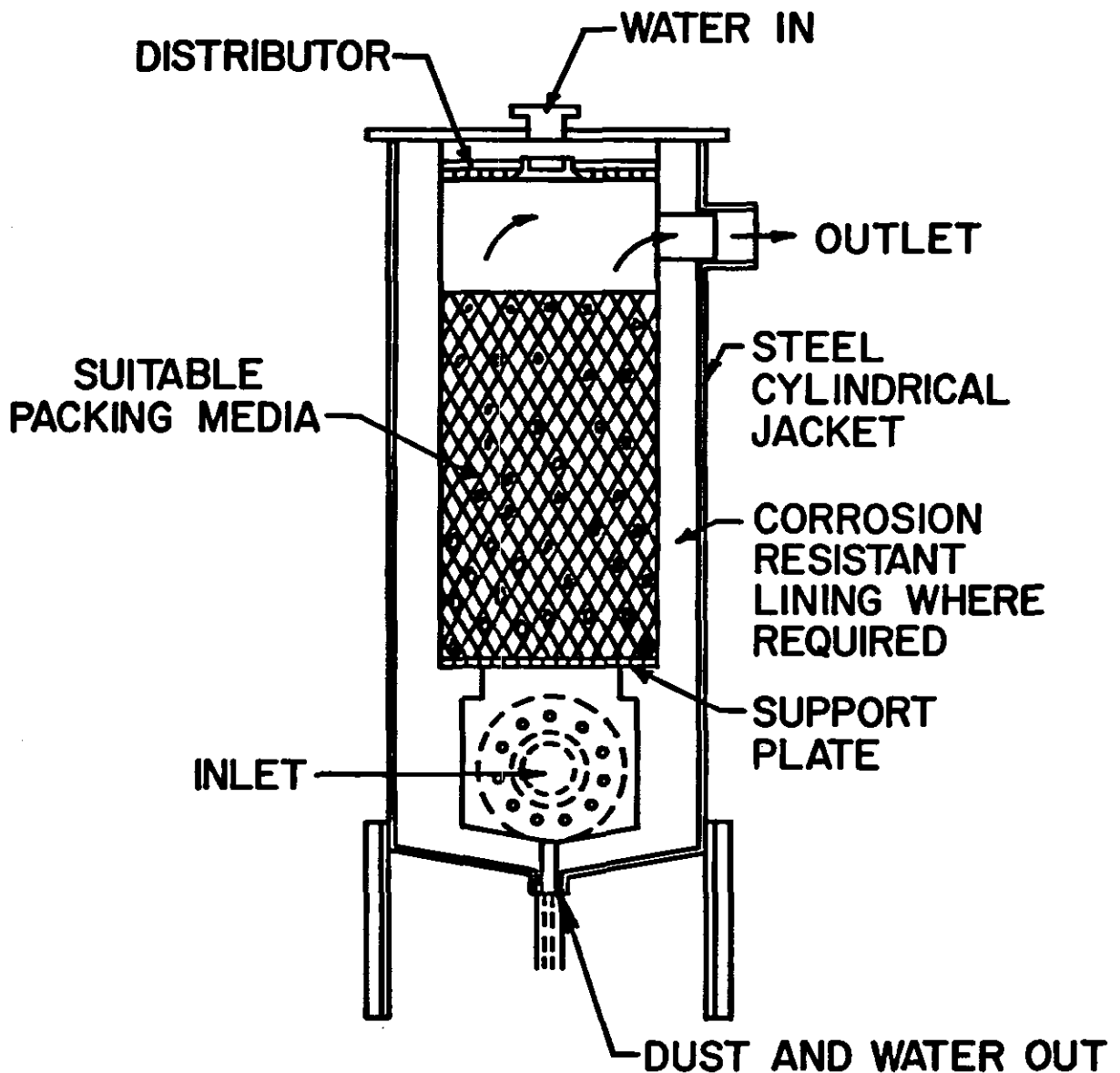
1. constant pressure drop
2. dust removal problems eliminated
3. treatment of high temperature and humid gases
4. compact design
5. moderate costs (between 25¢ and 75¢/cfm).

Electrostatic Precipitators

Electrostatic precipitation is a collection process that utilizes a field of charged gas ions to charge the particle followed by attraction to a collection electrode. This device is sometimes called the Cottrell Process, after Frederick Gardner Cottrell, who invented and designed the first electrostatic precipitator.

Three processes are involved in the operation of all electrostatic precipitators: particle charging, particle collection and removal of collected material. If particle charging and collection are separated, a two-stage precipitator results; otherwise, the unit is a single-stage precipitator. Most industrial use is of the latter design, as shown in Figure 43-11.

Particle charging occurs through the formation of a highly-charged region of unipolar gas ions called the corona field. The corona field forms from the electrical voltage potential between the electrodes. If this voltage potential becomes too large, sparking will occur and the corona field will



American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation — A Manual of Recommended Practice, 12th Edition. Lansing, Michigan, 1972, p. 474.

Figure 43-8. Packed Scrubber.

be disturbed. The particles flowing through the corona field charge themselves by collision with charged gas ions and move towards the oppositely charged electrode where collection occurs. Removal from the electrode is effected by a mechanical shaker.

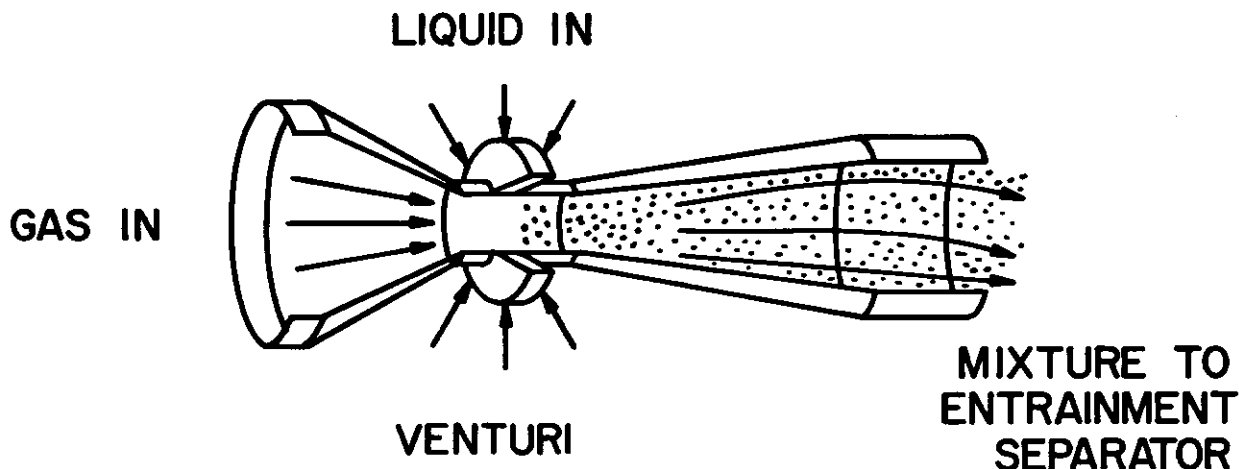
There is no theoretical limit to the size of the particles that can be collected. Collection efficiencies are related to the size of the equipment, with efficiencies of over 99% obtainable. The following equation can be used to calculate the efficiency of collection:

$$E_f = 100 - 100 \left[\exp \frac{-A E_o E_p a}{V 2 \pi \eta} \right]$$

where: E_f = percent efficiency
 A = surface area of collecting electrodes, ft^2
 V = volumetric flowrate, ft^3/min .
 E_o = charging field, volts/ft.
 E_p = collecting field, volts/ft.
 a = particle radius, ft.
 η = gas viscosity, lb./hr. ft .

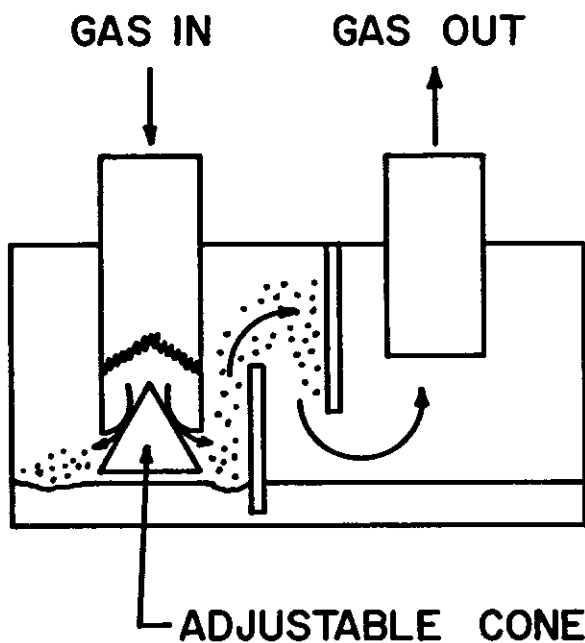
From the equation, it can be seen that an increase in voltage and surface area coupled with a decrease in volumetric flowrate gives optimum operating conditions.

Initial cost for an electrostatic collector runs



Stern: Air Pollution, 2nd Edition. Academic Press, p. 474 (9, 10) and p. 440 (11).

Figure 43-9. Venturi Scrubber.



Stern: Air Pollution, 2nd Edition. Academic Press, p. 474 (9, 10) and p. 440 (11).

Figure 43-10. Doyle Impingement Scrubber.

from 80¢ to \$2.50/cfm, with erected cost approximately 1.7 times the initial cost. Power costs are quite low, since energy is required only to separate the particle without having to do work on the carrier gas.

Electrostatic precipitators have many advantages, including:

1. high efficiency
2. dry collection of dusts
3. low pressure drop
4. ability to collect mists and corrosive acids
5. low maintenance costs
6. low operating costs

7. collection efficiency can be adjusted by unit size
 8. ability to handle gases up to 1500°F.
- Disadvantages include:
1. high initial cost (between 80¢ and \$2.50/cfm)
 2. frequent need for a precleaner
 3. large space requirements
 4. difficulty in collecting materials with extremely high or low electrical resistivity.

Gas Adsorbers

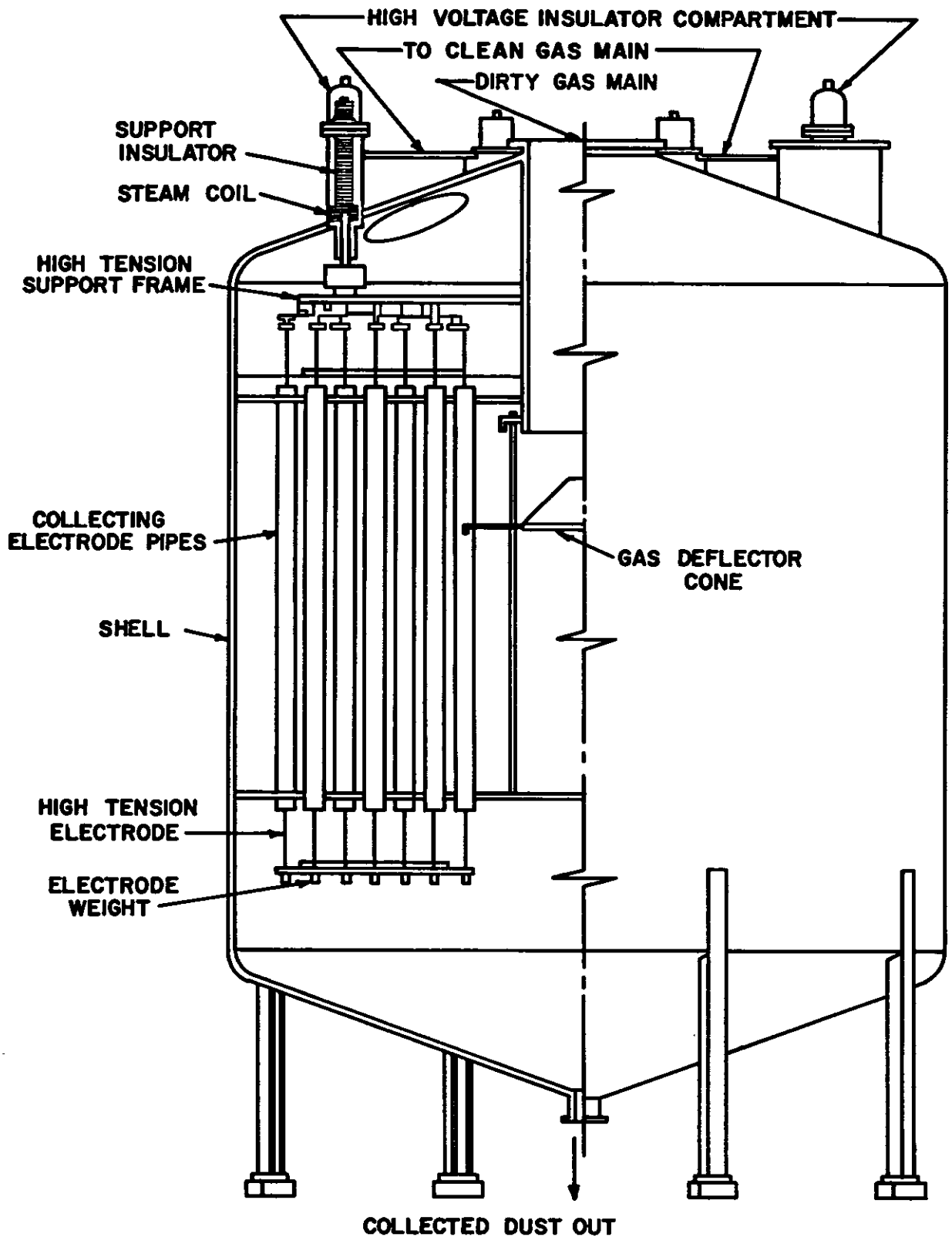
Adsorption is a useful process for controlling highly odorous, radioactive or toxic gases. This process involves retention of molecules from the gas phase onto a solid surface. Van Der Waals' forces, ionic attraction, secondary chemical bonds and capillary condensation — all have a role in the adsorption of the gas onto the solid surface.

Two general types of adsorbers exist: fixed bed and regenerative. In addition, recirculation may be utilized to increase the effectiveness of the device. Fixed bed adsorbers are economical only when the average contaminant concentration is less than a few parts per million. Regenerative adsorbers are designed to handle much heavier loadings with the additional advantage of recovery of the contaminant solvent which may have a high economic value. A typical fixed bed adsorber is shown in Figure 43-12.

The mechanism of adsorption progresses in three distinct steps:

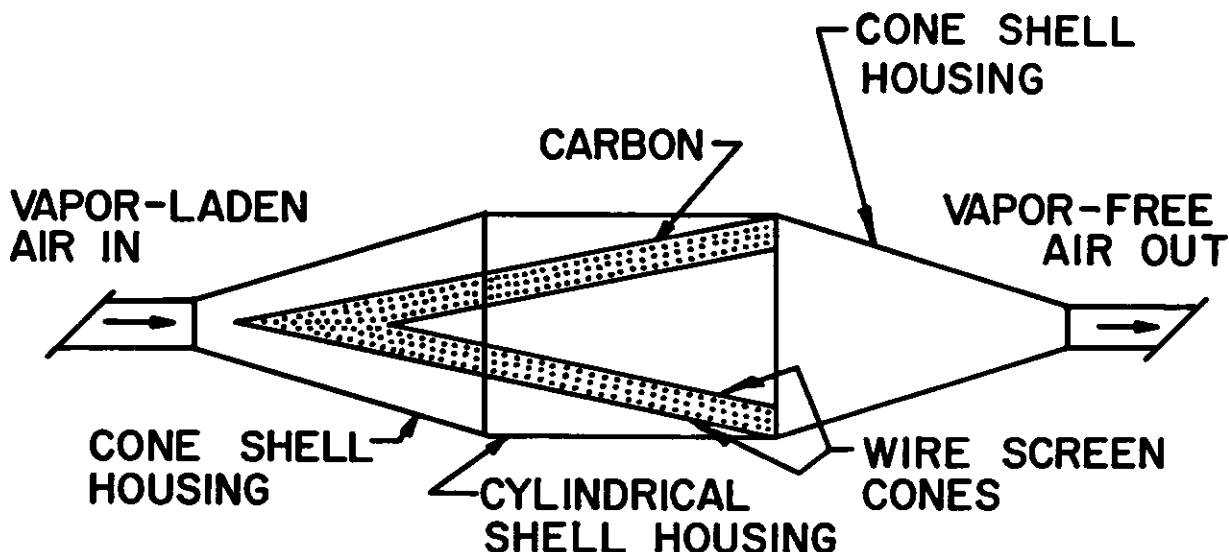
- 1) The adsorbent moves to the solid surface;
- 2) Physical bonding occurs; and
- 3) Adsorbent is removed through treatment with steam, hot brines or other methods.

In design of adsorbent systems, increased removal efficiency is often obtained if conditions of high pressure and low temperature are maintained. The high efficiency of adsorbers is offset by the many associated problems. Equipment costs may run as high as \$35.00 per pound of vapor removed with operating costs running about five dollars per pound of vapor removed. Other prob-



Stern: Air Pollution, 2nd Edition. Academic Press, p. 474 (9, 10) and p. 440 (11).

Figure 43-11. Tube-Type Electrostatic Precipitator.



Air Pollution Engineering Manual, Department of Health, Education and Welfare, 1967, p. 197 and p. 172.

Figure 43-12. Fixed Bed Adsorber.

lems include corrosion and particulate contamination of the device.

Combustion Incinerators

Combustion incineration is a process that utilizes oxidation reactions for emission control. Combustion afterburners find numerous industrial applications and can be used for any of the following situations:

1. odor control
2. reduction in opacity of the plume
3. conversion of carbon monoxide to carbon dioxide
4. reduction of organic vapors and particulate emissions.

Combustion devices come in two types, direct flame and catalytic combustion. Direct flame incineration involves the burning of additional fuel to reach temperatures high enough for destruction of the gas or aerosol mixtures. Complete combustion yields H_2O and CO_2 , whereas incomplete combustion may produce even more offensive compounds than originally found. A typical direct flame incinerator is shown in Figure 43-13.

Catalytic combustion utilizes a catalyst, normally a noble metal, to lower the activation energy of the oxidizing reactions to reduce the temperature and fuel costs required for oxidation. Combustion may even become self-sustaining if the concentration of combustibles in the gas stream is sufficiently high.

In designing or operating a flame combustion device, care should be taken to see that the temperature, residence time and turbulent mixing are sufficient for complete oxidation. One satisfactory method of achieving this goal is to admit the contaminant gases into a throat where the burner is located. High velocities can be obtained for thorough mixing of the gases in the region of highest temperature. A retention time of 0.3 to 0.5 second and operating temperature ranges between $850^{\circ}F$ - $1500^{\circ}F$ have been found to be satisfactory for most applications. Efficiencies of

98% or higher can often be obtained in a well-designed incinerator.

The decision of whether to use flame or catalytic combustion is based on economic considerations and operational characteristics. Costs for flame and catalytic combustion vary widely, depending on the amount, types and concentration of pollutants to be burned. Some of the operational differences are listed below:

- 1) Generation of nitrogen oxides is reduced using catalytic combustion;
- 2) Catalysts require periodic cleaning and regeneration;
- 3) Integration of catalysts into the design of equipment permitting heat recovery is much easier.

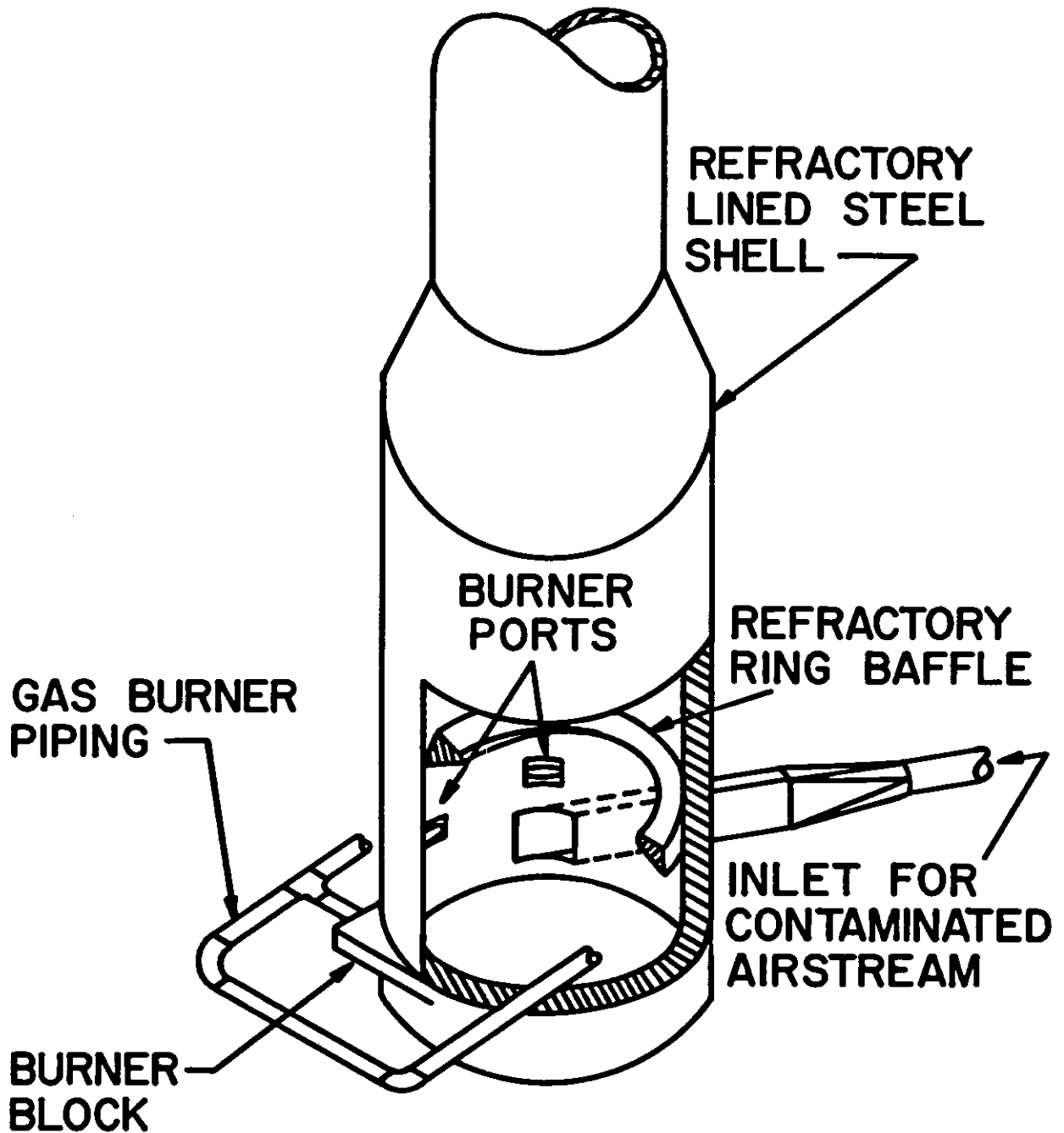
SUMMARY

This chapter has stressed the standard pollution control equipment in existence today: mechanical separators, filtration devices, wet collectors, electrostatic precipitators, gas adsorbers and combustion incinerators. These devices are listed and evaluated for comparison in Table 43-6.

One area which has been neglected is the water pollution and solid waste potential of air pollution control devices. Obviously, devices which reduce atmospheric emissions must eventually accumulate materials that must be disposed of by other means. A frequent argument against the use of wet collectors is the resulting liquid waste.

In many cases the collected materials can be used productively. They may be recycled back into the process stream, put to use in another plant application or (rarely) sold. All too frequently, however, the liquid wastes are simply discharged to city waste treatment systems, or directly into the waterways, while solid wastes are hauled away to landfills or incinerators.

The design of any air pollution control system must include consideration for potential pollution effects. A control system for one specific



Air Pollution Engineering Manual, Department of Health, Education and Welfare, 1967, p. 197 and p. 172.

Figure 43-13. Direct-Fired Afterburner.

airborne contaminant may involve more than just the design of an air pollution control device. An evaluation of the overall waste disposal system for the total operation may result in numerous additional modifications before all potential pollution sources are adequately controlled.

Preferred Reading

1. STRAUSS, W. *Industrial Gas Cleaning*, International Series of Monographs in Chemical Engineering, Volume 8, Pergamon Press, New York (1966).
2. STERN, A. C. *Air Pollution, Volume III — Sources of Air Pollution and Their Control*, Environmental

Science Monograph Series, Academic Press, New York (1968).

3. DANIELSON, J. A. *Air Pollution Engineering Manual*, U. S. Department of Health, Education and Welfare, Public Health Service, Cincinnati, Ohio (1967).
4. LUND, H. F. *Industrial Pollution Control Handbook*, McGraw-Hill Book Company, New York (1971).
5. *Air Pollution Manual, Part II: Control Equipment*, American Industrial Hygiene Association, 66 South Miller Road, Akron, Ohio 44313 (1968).
6. *Journal of the Air Pollution Control Association*, Pittsburgh, Pennsylvania.

TABLE 43-6.
Comparison of Pollution Control Equipment

Device	To Control	Advantages	Disadvantages	Costs	Examples
Mechanical Separators	Medium to large diameter particles	<ol style="list-style-type: none"> 1) Low initial cost 2) Simple construction 3) Ease of operation 4) Use as precleaners 	<ol style="list-style-type: none"> 1) Low efficiency 2) Erosion of components 3) Cannot remove small particles 4) Large space requirements 	Low initial cost (5¢-25¢ per cfm)	<ol style="list-style-type: none"> 1) Gravity Chambers 2) Impingement Separators 3) Cyclone Collectors
Filtration Devices	Dusts, fumes	<ol style="list-style-type: none"> 1) High collection efficiency on small particles 2) Moderate power requirements 3) Dry disposal 	<ol style="list-style-type: none"> 1) High costs 2) Large space requirements 3) Must control moisture and temperature of gas stream 	High costs (30¢-\$2.50 per cfm)	<ol style="list-style-type: none"> 1) Fabric Filters 2) Mat Filters 3) Ultrafilters
Wet Collectors	High-temperature, moisture-laden gases	<ol style="list-style-type: none"> 1) Constant pressure drop 2) Elimination of dust removal problems 3) Compact design 	<ol style="list-style-type: none"> 1) Disposal of waste water may be expensive and troublesome 	Moderate (between 25¢ and 75¢ per cfm)	<ol style="list-style-type: none"> 1) Spray Chambers 2) Cyclone, Orifice, Venturi Scrubbers 3) Mechanical Scrubbers 4) Mechanical-Centrifugal Collectors
Electrostatic Precipitators	All sizes of particles—even very small mists which form free-running liquids	<ol style="list-style-type: none"> 1) High efficiency 2) Dry dust collection 3) Low pressure drop 4) Can collect mists and corrosive acids 	<ol style="list-style-type: none"> 1) Often requires precleaner 2) Large space requirements 3) Cannot collect some high/low resistivity materials 4) High initial cost 	High initial costs—low operating costs & low maintenance costs	<ol style="list-style-type: none"> 1) Single-stage Precipitators 2) Two-stage Precipitators
Gas Adsorbers	Highly odorous, radioactive or toxic gases	<ol style="list-style-type: none"> 1) Contaminant solvent may be recovered 	<ol style="list-style-type: none"> 1) High equipment & operating costs 2) Corrosion 3) Contamination 	High equipment and operating costs	<ol style="list-style-type: none"> 1) Fixed Bed 2) Regenerative
Combustion Incinerators	Odors, plume opacity, carbon monoxide, organic vapors	<ol style="list-style-type: none"> 1) Capable of reaching high efficiency operation 2) Catalytic combustion reduces NO_x pollutants 	<ol style="list-style-type: none"> 1) Must burn additional fuel or add catalyst 2) Incomplete combustion can further complicate original problem 3) Catalysts require periodic cleaning & regeneration 	Vary widely depending upon application	<ol style="list-style-type: none"> 1) Direct Flame 2) Catalytic Combustion

CONTROL OF INDUSTRIAL WATER EMISSIONS

Thomas J. Powers

INTRODUCTION

Industry uses water for almost every conceivable purpose from nuclear shielding to washing down floors. Every water use is important and each source of used water must be known and evaluated. By far the greatest volume of industrial water use is for heat exchange. The smallest water use is in products such as beverages and water-based latex paints.

Man cannot use water without adding something to it. That "something" may be heat, suspended materials or dissolved substances. The more water is used, the more materials are added to it until its usefulness is impaired and a condition of pollution exists. Industrial water use must be so managed that pollution is avoided.

Control of water emissions from industry to

the environment requires a thorough knowledge of the volume of water used per unit time and the quality of the used water. Adequate control also demands a knowledge of the quality standards for both emitted water and receiving water.

Water emissions may best be identified and categorized by the service from which the used water originates. There would then be used water from (Fig. 44-1):

1. Treatment of incoming water
2. Sanitary services
3. Boiler operation
4. Housekeeping
5. Heat exchange
6. Unit processes
7. Roof and yard drainages.

Having identified all used water sources and

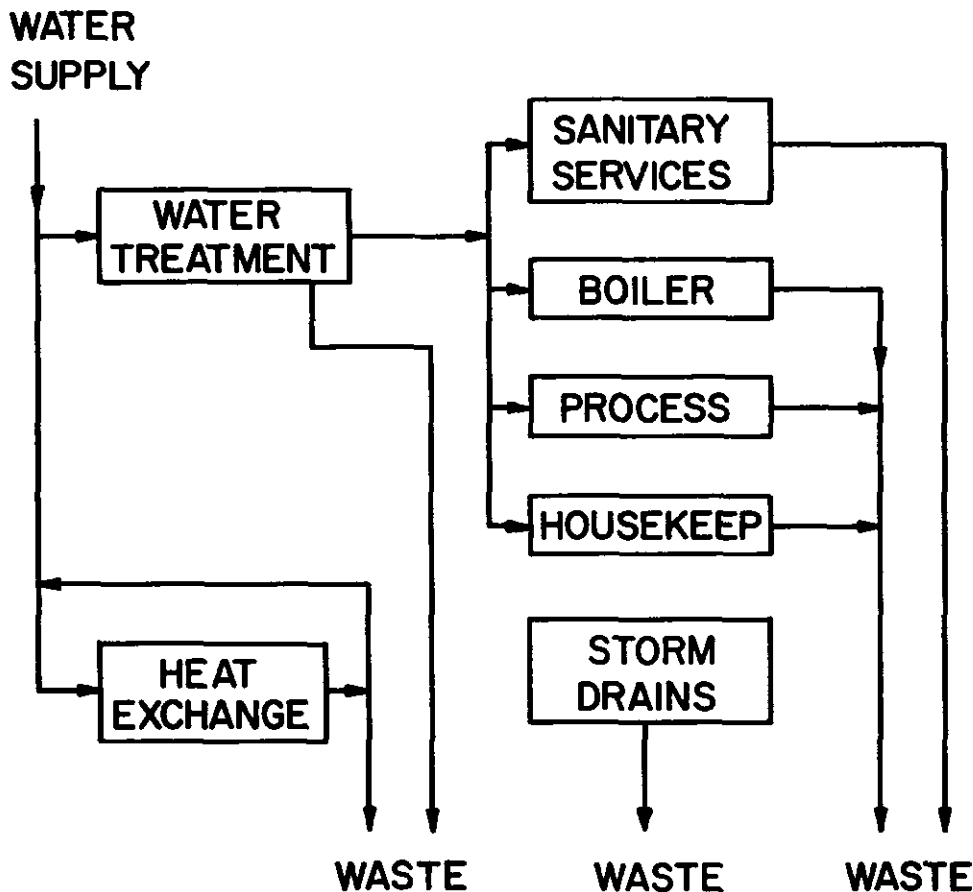


Figure 44-1. Origins of Industrial Water Emissions.

quality, the environmental engineer must review the control methods most applicable and economic for each waste water source. Combinations of waste waters are quite often possible and desirable, but careful analysis of the water quality and the control methods are necessary to indicate compatibility.

Modern small industry will probably find it most economic to purchase potable water from a public supply and to purchase waste water treatment services for those wastes which are compatible with biologic systems. Extreme caution must be used on the potable water supply to avoid any cross-connections. It is also necessary to know accurately the waste water flowrate and quality so that design is adequate to insure control of water emissions to meet standards.

The discussions presented here are not referenced. The author has presented a list of excellent texts which answer almost all of the specific questions which might arise. The references in the texts will guide the reader to articles covering almost every type of waste water problem encountered in industry.

Throughout this chapter emphasis is placed on the necessity for proper measurement of waste flows, proper sampling and accurate analyses together with laboratory experiments to arrive at sound judgments. There is no substitute for sound engineering based on facts derived in this manner.

IDENTIFICATION OF USED WATER SOURCES

Wastes from Water Treatment

Treatment of incoming water to achieve the water quality necessary for each use is a necessity for many industries. Whenever solids must be removed, a waste water source results.

Clarifier Underflows. Ordinary sedimentation using coagulants such as aluminum or iron salts and flocculant aids is practiced widely on water from surface sources. The settled material removed from the bottom of the settling tank is called sludge and is usually about 8% solids and 92% water. The composition of the solids is the same as the solids in the incoming water plus the coagulant hydrates and filter aids. The sludges can be further dewatered by settling in ponds, by vacuum filtration or by centrifugation. The water resulting from further dewatering should be recycled to the raw water source. The only water lost is to the sludge cake, usually 50% to 75% of the cake weight.

Water softening is the removal of calcium and magnesium ions from the water and can be accomplished by a cation exchanger or by the treatment of the water with lime followed by soda ash. The settled sludge from lime-soda softening will contain calcium carbonate and magnesium hydroxide. By recycling the sludge in the process a final concentration for disposal might contain up to 25% solids and 75% water. Further dewatering can yield up to 50% solids.

Sedimentation, even with flocculant aids, seldom results in a water with less than 20.0 mg/l of suspended solids. Usually sedimentation is fol-

lowed by filtration to remove particles down to about 20 microns.

Filter Backwash. Filter backwash is a waste water which contains the solids washed from a filter usually in a concentration about ten times the concentration fed to the filters. This water should be recycled back to a sedimentation tank inflow so that the water is not lost and the solids become a part of the sedimentation tank underflow sludge.

Filters are also used to separate precipitated iron from well water which has been aerated to oxidize the ferrous iron to the ferric state. The wash water from these filters should be ponded and the water returned to the system.

Ion-Exchange Regeneration. Water treatment by ion-exchange is widely used for water softening where a cation exchange material removes the calcium and magnesium by replacement with sodium. The regenerant is common NaCl and the waste water resulting from regeneration contains CaCl₂, MgCl₂, and the excess NaCl used. The waste water volume resulting from regeneration is usually about 4 bed volumes and the frequency of regeneration depends on the amount of calcium and magnesium in the incoming water.

Complete demineralization using both cation and anion exchangers produces water very close to distilled water. The regenerants may be ammonium hydroxide, caustic, sulfuric acid or hydrochloric acid. The cation exchange replaces all cations with hydrogen giving an acid water which is degassed to remove CO₂ and SO₂, and the anion exchanger then replaces regenerant anions with hydroxyl ion. The regenerant streams contain all of the substances contained in the original water less the acid gases blown out plus the excess of regenerant added. The waste volume is usually of the order of 6 bed volumes per regeneration.

The regeneration brines from ion-exchange water treatment are of no value and cannot be recycled; they are true waste waters.

Waste Waters from Sanitary Services

Every industry must provide potable water approved by the State Health Department for sanitary services. Drinking water, washbasins, laundry, toilets, showers (including safety showers) and kitchens should be furnished with potable water. The environmental engineer should constantly be on the lookout for cross connections between potable and non-potable sources. Whenever it is necessary to use potable water as an alternate in a non-potable system, the potable water should be delivered to a head tank and re-pumped to the non-potable system (Fig. 44-2). A suitable color code for each water system can help prevent erroneous connections. Toilets, washrooms and showers should be sewered separately together with laundry and kitchen wastes, to a segregated system called the sanitary sewer. Drinking fountains, safety showers and eye baths are usually placed strategically for workmen's maximum convenience and need not be sewered to the sanitary system.

The waste water resulting from sanitary ser-

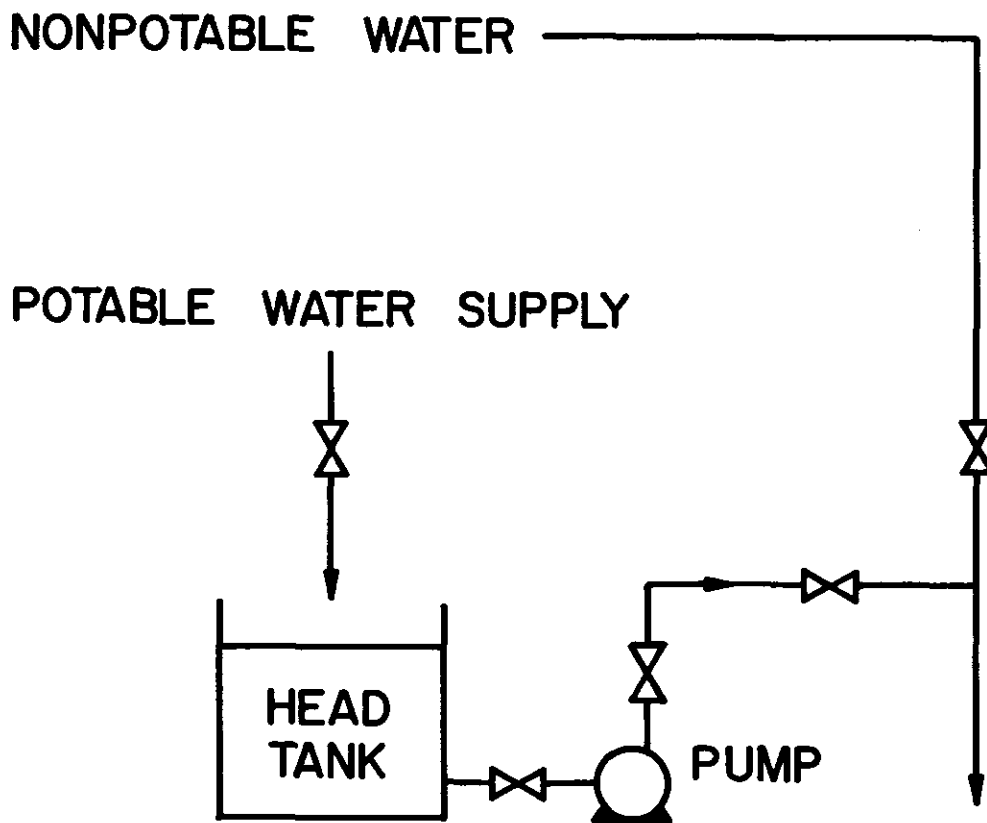


Figure 44-2. Equipment to Avoid Cross-Connections.

vices will be about 20 gallons per person per shift. The waste water should be limited to 100 mg/l of suspended solids and a B.O.D. of about 120 mg/l. If laundry and kitchen wastes are added, the volume will be about 30 gallons per person per shift.

Waste Waters from Boiler Operation

Many industries operate boilers to produce process steam and plant heat. These boilers are usually low pressure boilers (150 psi) and do not require demineralized water for make-up, but almost all use internal boiler treatment. The chemicals added to boiler feed are for the purpose of holding compounds in solution as water is evaporated and to prevent water entrainment in the steam.

Boiler Blow-Down. In order to maintain the solids in the boiler at a manageable level it is necessary to purge the boiler periodically. This is called boiler blow-down. Naturally this represents a considerable heat loss which can be minimized by exchanging the heat to the boiler feed. The resulting water is highly mineralized and must be considered a waste. The total dissolved solids will be 3500-5000 mg/l.

Ash Sluice Water from Combustion of Coal. Most low pressure coal fired boilers are stoker fed and seldom require fly ash control. Ashes are usually sluiced with water to an ash pit. The overflow water from ash handling is alkaline and must be considered as waste water. If fly ash is collected,

it also is usually sluiced to a pit.

Boiler Cleaning Solutions. Fouled boiler tubes result in decreased efficiency and must be cleaned periodically (1-2 years). Chemical cleaning is widely used and the low pressure boiler can be cleaned using hydrochloric acid which contains substances to inhibit its attack on metallic iron. Many industries require that the cleaning contractor haul spent cleaning solutions off-site although in some instances the spent solutions are discharged to the ash pit where residual alkali neutralizes some of the acid and iron is precipitated.

High pressure boilers require more sophisticated cleaning methods using organic materials such as citric acid and versines since hydrochloric acid should not be used on stainless type steels. These spent cleaning solutions contain copper and nickel chelates and require separate handling.

Waste Waters from Housekeeping

Almost every industry maintains service hoses which are used to wash down equipment and floors. This is not only for appearance but also for personnel safety and product quality control. The food industries in particular must shut down all production periodically and remove all traces of putrescible substances from materials handling equipment and floors. It is common practice to run production for two shifts and use the third shift for a complete clean-up.

Service hoses with 50 psi water pressure will

deliver from 15 to 30 gpm. Several hoses being used at a time will result in a considerable flow from the building.

The engineer should attempt to minimize water use and yet accomplish the purpose. Leaving hoses running is a very common mistake which must be corrected constantly.

Water Used for Heat Exchange

As stated previously the use of water as a heat exchange medium is by far the greatest industrial water use. Once-through cooling is extensively practiced because it is the simplest and cheapest system as long as sufficient water is available. Heat has become known as a pollutant because of the changes in the water biota due to increased temperatures. Heat added to surface waters is slowly transferred to the atmosphere until the water and air above it reach equilibrium.

Once-through cooling adds very little to a water except heat; however, a 20-25°F rise in the water temperature is common.

Cooling Towers. Heat exchange water which is in short supply or which may cause thermal pollution is recovered for re-use by causing the heat to be rapidly dissipated to the atmosphere through use of cooling towers. The recycle of cooling water over cooling towers necessitates treatment of the water to prevent scale and corrosion in the heat exchange piping. The cooling tower will lose about 2.0% of the water by evaporation, about 1.0% by entrainment and 10% by the purge required to maintain a constant solids content (Fig. 44-3). The purge loss will contain about 1000 mg/l of total solids, plus the amount of zinc, chromium and other chemicals added to condition the water.

Barometric Condensers. It is quite common to use a steam jet to pull a vacuum on a distillation or evaporation process. One source of heat exchange water which may not be included in the cooling water system is the barometric quench condenser (Fig. 44-4). This type of condenser can contain sizable quantities of product if a small vacuum leak develops in the system. It is advisable to use an inner-after condenser rather than the quench condenser when the product being handled is a major pollutant (Fig. 44-5).

Product Heat Exchangers. Heat exchangers which are used to cool a product should have readily accessible water sampling points downstream from the units. A small leak in a tube can account for a sizable product loss even though the pressure is greater on the water side. The velocity of the water past a pin hole leak can create a suction, causing product to enter the cooling water stream.

Unit Processes

The water which comes in direct contact with raw materials, intermediates, by-products or products is called process water. The inadvertent loss of materials to heat exchange equipment and clean-up of floors has previously been discussed.

Raw Material Purification. Many raw materials are transported by water and unwanted impurities are washed or dissolved away. Many examples of this water use are found in the food industry. Sugar beets are sluiced to screens ahead of slicers. The flume water washes dirt and debris from the beets and also dissolves some sugar depending on the condition of the beet.

The quality of the process water from the canning industry can be directly related to the condition of the vegetables or fruit as received.

COOLING TOWER

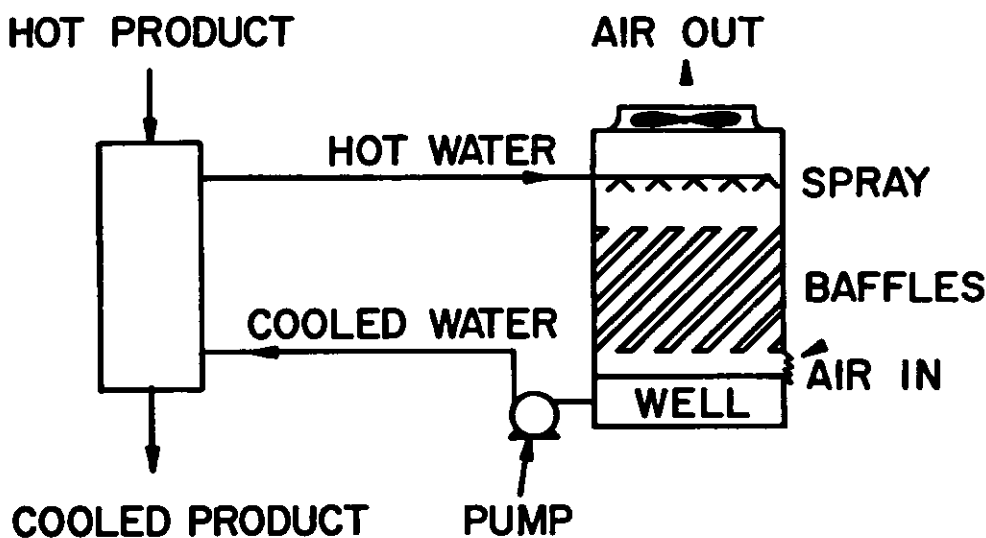


Figure 44-3. Cooling Tower.

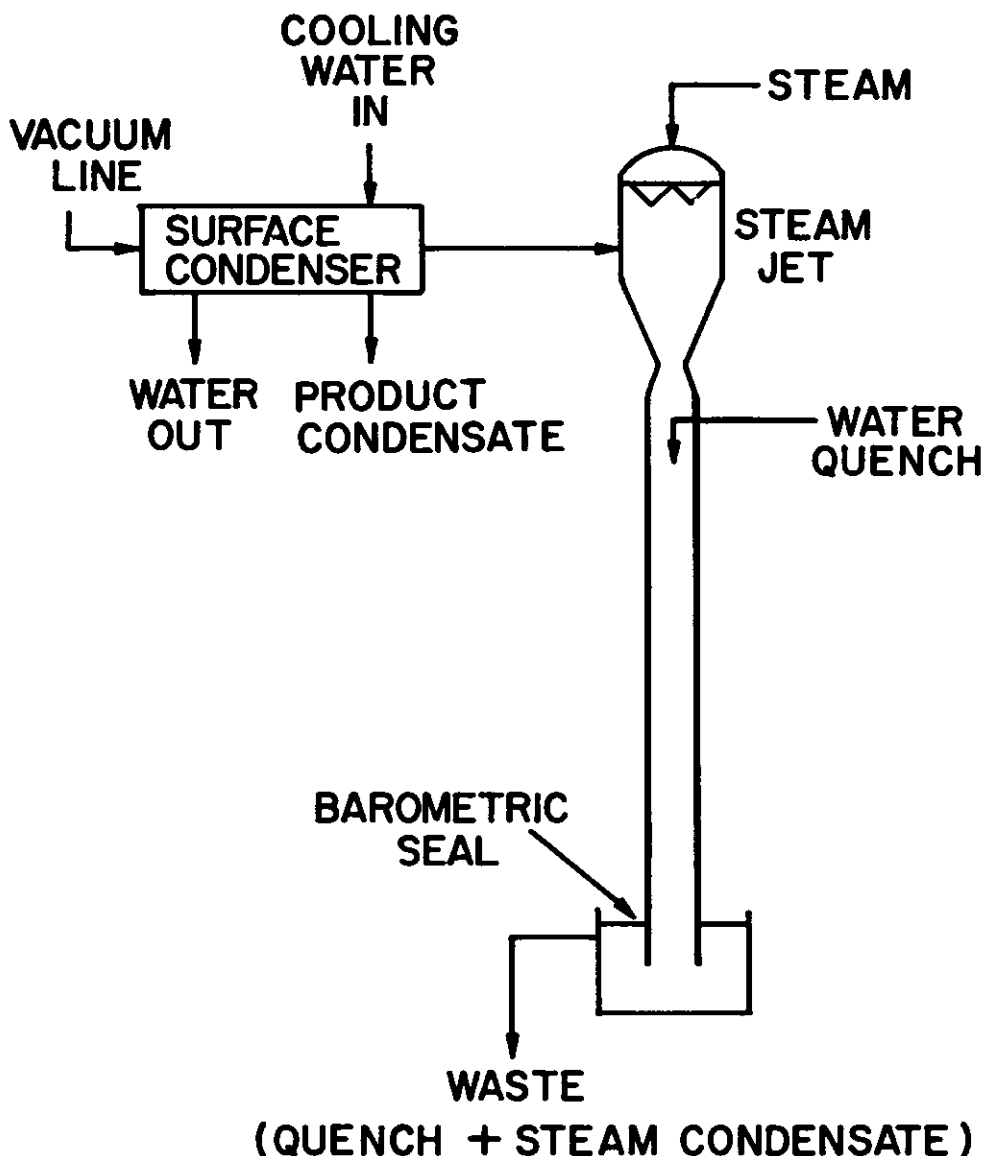


Figure 44-4. Barometric Quench Condenser.

Reaction Vessel Cleaning. One of the most important waste water sources from unit processes is the clean-up of vessels from batch reactions. These waters are usually quite concentrated, are discharged intermittently and often require special handling.

Raffinates. Solvent extraction of materials from water is a common industrial process. The water remaining after the extraction is called a raffinate. As a rule these are strong wastes containing by-products, some product and some solvent.

Vent Gas Scrubbers. Whenever gases are released from a process they are usually scrubbed with water. If the gas is valuable, such as hydrogen, it may be scrubbed to remove impurities and recovered for use. Many vent gases such as chlorine, hydrogen cyanide, hydrogen sulfide or phosgene may be dangerous and must be removed by efficient scrubbing equipment (see Chapter 43). The water wastes from vent scrubbers can be the most important waste water to measure and evaluate

for control.

Condensates. Whenever steam is used or is formed in a process it is generally condensed using a heat exchanger or a quench condenser. Many condensates are pure water and can be re-used, but almost all condensates are subject to receiving impurities. Continuous monitoring of condensates is a must to achieve process control as well as control of water emission.

Roof and Yard Drainage

The design of the sewer system should provide a segregation of water run-off from factory roofs and yards. Raw materials and products are often lost to roofs or grounds. Pressure reaction vessels with frangible reliefs often vent materials to roofs. Tank car loading is bound to result in some spills. Storage tanks develop leaks. If control of water emission is to be achieved the environmental engineer cannot overlook roof and yard drainage. These waste waters should be monitored and the necessary controls installed and maintained.

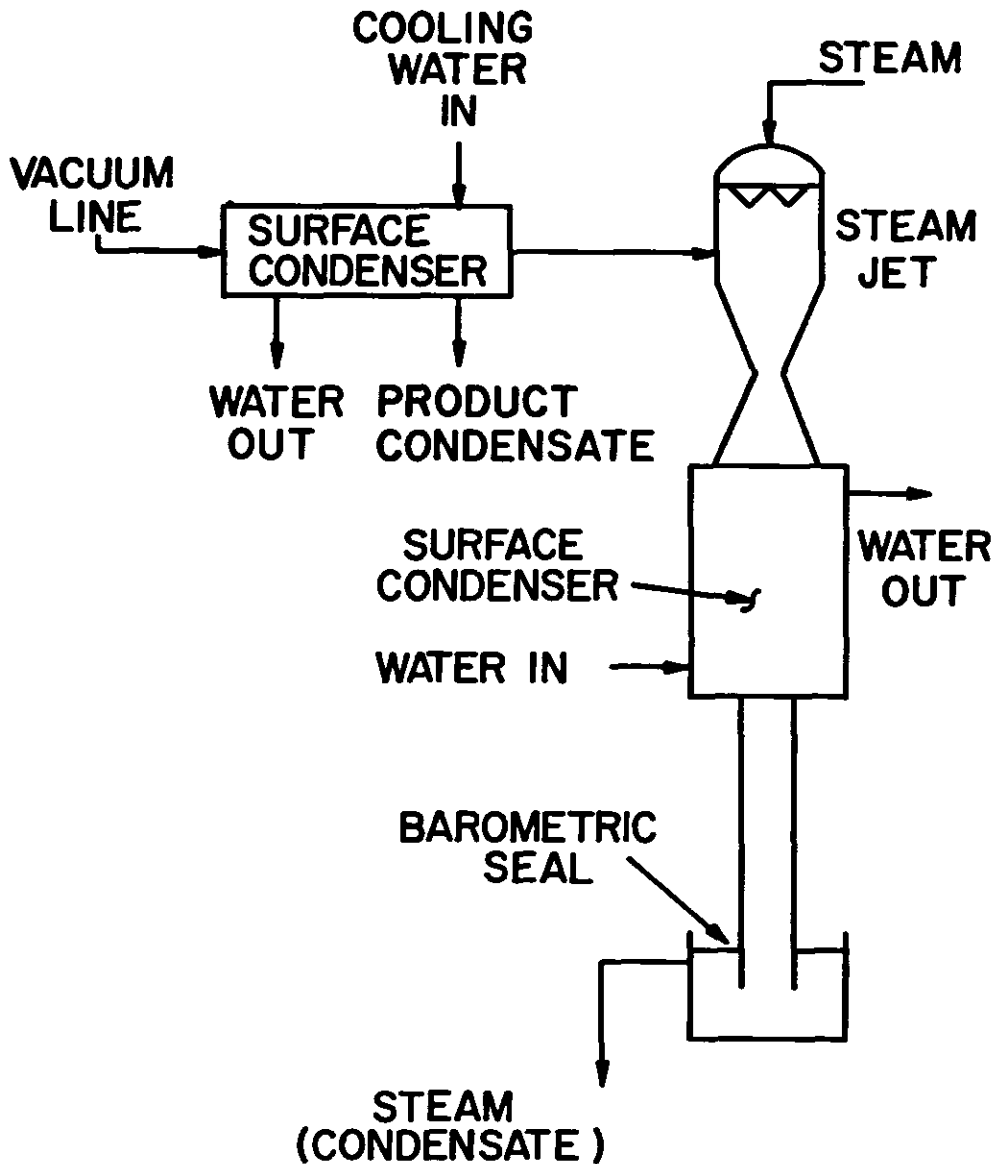


Figure 44-5. Barometric Inner Condenser.

CONTROL METHODS FOR WATER EMISSIONS

Waste Inventory

In considering the control of industrial water emissions it is well to remember that things happen in industry. A good philosophy to follow in design is that if it can happen, it will. One of the most valuable and useful tools in the control of water emissions is impervious storage facilities into which high concentration, low volume and intermittent waste waters may be inventoried and from which waste may be monitored, recycled or treated to achieve control. Where land is at a premium, waste inventory can be achieved by pumping to holding tanks. It may be advisable to inventory each process waste separately near the production equipment and feed from these at a steady rate to the proper control method.

The chemical industry has used waste storage

of brines with controlled discharge to streams at high flows for many years.

Raw Material Change

As is the case in control of air pollutant emissions it is sometimes necessary and feasible to avoid the production of a waste by changing the raw material. For instance, a tannery might change from salted hides to fresh hides and avoid the problem created by washing salt from the preserved hides. If the purification of the raw material creates a waste water problem it may be possible to have the supplier remove the impurity prior to shipping.

Process Change

There are many processes which have inherent losses to water. Most of these are in the wet process industries where raw materials are dissolved in water or transported by water. It is possible in some instances to change the process and relieve

the losses to the waste water. The environmental engineer should review each process with process engineers to minimize water contact and the production of waste materials. Major process changes may take years to accomplish and be very costly, but if a waste can be avoided or made into a useful product, the long term economics can be favorable.

Direct Burning

The direct burning of organic residues from industrial processes is a common method of ultimate disposal. Minimizing water and concentrating the waste water stream to more than 10% organic content permits the use of direct burning at reasonable cost. A very good example of this is the waste liquor from sulfite pulp mills. Both fluidized bed combustion and direct burning have been used.

Wet combustion using air or oxygen to 300°C resulting in pressures up to 1750 psi has also been used on sludges in some municipalities, but has not yet been used extensively on strong industrial wastes.

Vaporization and Catalytic Burning

The catalytic burner is used extensively to control odorous air emissions (Chapter 43) and can also be used to destroy organic matter if the water waste is first vaporized. This technique has been used on nonrecoverable solutions of lower alcohols.

Control of Water Emissions by Recycle

The containment and utilization of waste waters by recycle is common to most industries. Water conservation practices such as counter-current washing and the re-use of cooling water does not mean the reduction of pollutants but rather a concentration in a smaller volume.

Recycle of water usually entails the addition of chemicals to control corrosion, scaling and bacterial growths. However, the recycle of weak solutions which contain raw materials, intermediates or product may be an economic necessity and should be investigated thoroughly.

Subsurface Disposal

The loss of polluted water to fresh ground water must be avoided. This is not easy and requires a knowledge of subsurface geology and hydrology. Sewers collecting acid wastes must be designed to carry that waste without loss to the ground. Sewers subject to hot water release must not break due to thermal shock. Dyked areas which might retain polluted water should be made impervious.

Disposal by deep well is an engineered method of ultimate disposal which is politically and geologically possible in many parts of the country where porous and permeable sedimentary formations containing connate brines exist. The waste waters which have been so disposed are usually brines or waters containing highly toxic or odorous materials which cannot be treated effectively and which should not be allowed to pollute the ground or surface water. The chemical and oil refining industries have used deep well disposal in Texas, Indiana, Ohio, Louisiana and Florida. The depth of these wells is usually 1500 to 6000 feet.

While deep well disposal is not exactly a last resort method, most State agencies will demand a review of alternate control techniques. The volume of waste water a formation can accept safely is finite. The deep formation disposal capacity is a valuable resource and should be reserved for those wastes which must not be allowed to invade man's environment.

If deep well disposal is being considered, a competent hydrologist or geologist should be employed to develop a feasibility report and preliminary costs. Starting with the State Water Pollution Control agency, all regulatory agencies must approve. The design of surface equipment and the well design cannot be trusted to inexperienced engineers. Drilling of the well and its completion should be closely supervised by an engineer knowledgeable in these matters. Too many failures have been the result of poor design and execution.

Treatment to Standard Quality

Very seldom is it possible to eliminate, contain or destroy waste waters to a degree which will permit release to public waters without treatment of some sort to meet a quality standard.

Most municipal waste water treatment plants control the quality of industrial waste discharge to municipal sewers through ordinances establishing limits on pH, suspended solids and biochemical oxygen demand. Industries producing waste waters exceeding the standards are required to pre-treat the waste or to pay a surcharge or both. Sanitary sewage is described as having pH 6-9, suspended solids — 350 mg/l, B.O.D. — 300 mg/l. In addition to the control of these three parameters, it is necessary to restrict the waste waters from industry to those wastes containing substances which are compatible with the treatment process being used. Practically all municipal waste water treatment systems use biologic processes. Since the municipality must also treat to a standard quality it cannot afford to receive wastes which will upset or poison the biologic process. Substances highly toxic to bacteria must not be allowed to reach the treatment process. Other substances which may not be toxic but which have a high chlorine demand may also be refused.

Physical and Chemical Treatment Methods: Neutralization. The first treatment step toward control will probably be neutralization to achieve an effluent stream having a pH between 6-9. Aside from proper inventory, neutralization may be the only treatment needed in some instances. On the other hand, neutralization may cause precipitation of insoluble materials and require further treatment. It is also possible to use the neutralizing power of one waste when properly mixed with another. The cheapest alkali usually available is finely ground limestone, CaCO_3 , and next is CaO , which should be slaked to Ca(OH)_2 . One source of waste Ca(OH)_2 is from the manufacture of acetylene from calcium carbide. Laboratory experiments should be performed to develop the most economic neutralization system.

Screening. The use of coarse and fine screens to remove large suspended particles is a first treatment step in many industries, especially the food

industry. Screening may also be the only pretreatment required before discharge to a municipal system. Fine screens remove those particles which may overload skimming and sludge handling equipment in further treatment steps. Sometimes screenings will be of some value as stock feed but mostly they are hauled off-site for burial or spreading on the land.

Sedimentation-Flotation. Solids removal by settling is the universal primary treatment step. All settling systems should be designed, although many small industries dig a hole in the ground and hope for miracles. Flow-through settling ponds are used extensively in the mineral processing industries. These ponds must be designed to give adequate solids storage for long periods of time before settling capability is lost. Dual ponds permit the use of a fresh pond while the filled pond is being excavated.

Where land is costly, the use of designed clarifiers permits the continuous use of a stable settling capacity and the dewatering of solids for off-site disposal.

Clarifiers are usually designed to receive water at 600-1000 gallons per square foot per day. Flocculation chambers can also be included so that coagulants and flocculants can readily be applied to upgrade not only the solids removal efficiency but also hydraulic capacity. It is usually most economical to remove as many settleable and colloidal materials as possible in the primary settling step. Here again laboratory experiments with various coagulants and flocculants guide the engineer's judgment of the best system and engineering parameters.

A well designed and properly operated clarifier should deliver an effluent of about 25 mg/l suspended solids.

Sludges from the underflow of clarifiers will usually contain about 5-8% solids. The accumulation of inorganic sludges in dyked areas is common industrial practice. Dewatering by vacuum filters, sand beds or centrifuges permits hauling sludges off-site or, in the case of organic solids, prepares them for sanitary landfill or incineration. The safe disposal of sludges from waste water treatment can account for 50% of the total treatment cost and therefore requires detailed study.

In some cases the character of the solids in a waste water may cause the engineer to select flotation as the solids-separation process. Oily and greasy materials having a specific gravity close to water can be made to trap other particles and, by using dissolved air under pressure, the fine bubbles which are released to a flotation tank cause the suspended materials to rise to the top of the tank where they can be skimmed off readily.

Laboratory experiments can quickly evaluate flotation efficiency and the effectiveness of adding coagulants. Most water treatment equipment suppliers have flotation equipment which can be engineered after design parameters are established.

Chemical Treatment. The use of chemicals for neutralization and as aids in the sedimentation process has been mentioned. Chemicals are also used to precipitate undesirable ions such as mer-

cury and other heavy metals, fluorides and phosphates. Hexavalent chromium can be reduced by SO_2 and precipitated as trivalent chromium.

The use of chlorine as a disinfectant for municipal waste water prior to discharge is a requisite in most states.

Chlorination of industrial wastes for disinfection may be important in some industries where the dissemination of disease organisms to the environment is likely. The most important use of chlorine in industrial waste treatment is as an oxidant to destroy highly toxic or odorous substances. The standard treatment of cyanides from the plating industry is oxidation by alkaline chlorination. One pound of cyanide requires 7.35 pounds of chlorine. Chemical oxidation using chlorine, ozone or permanganate will cost more than 50 cents per pound of organic matter destroyed. This cost usually dictates that chemical oxidation be used only as a final polishing method after the bulk of the organic matter has been removed by some less expensive method.

Adsorption. There has been a renewed interest in the use of activated carbon for the removal of soluble organic materials from waste waters. Activated carbon has a broad spectrum of pore size, but is most effective in the removal of larger molecules (C_2 and above). The cost of granular activated carbon is usually more than 30 cents per pound. It is evident that at least ten regenerations must be effected if the adsorption cost is to be made competitive with chemical oxidation. Here again the use of activated carbon is usually limited to threshold treatment.

Extraction. Solvent extraction is a production technique used extensively in the chemical industry. The extraction of phenol from water using caustic-washed benzene is a classic example. Since most solvents are soluble in water to some degree, it is then necessary to strip the solvent from the waste. An ideal situation might be the use of water-insoluble waste from one process to extract the water-soluble waste material from another process water.

Biological Waste Treatment Methods

General. Bacteria can utilize an amazing number of organic compounds as the carbon source in their metabolism, which is the basis for many systems to remove organic materials from water. By providing an environment conducive to bacterial growth one can achieve rapid utilization of complex mixtures of soluble organic materials. End products of bacterial carbon utilization are carbon dioxide and protein.

Since biological treatment depends on the production of protein, it is necessary that nitrogen and phosphorus in a usable form be available to build protein molecules. All living cells require carbon, nitrogen, oxygen and phosphorus. Oxygen can come from the free oxygen dissolved in water in which case the biologic system is called *aerobic*. If the oxygen comes from a combined source such as NO_3 or SO_4 , the system is *anaerobic*.

Anaerobic Biological Treatment. Anaerobic bacteria use combined oxygen, and the entire system is one of reduction. The end products of anaerobic bacterial action are CO_2 , CH_4 , NH_3 , H_2S and

fatty acids. The CO_2 is in excess of the NH_3 production and the NH_3 combines with the CO_2 to form ammonium bicarbonate. Material equivalent to one pound of Chemical Oxygen Demand (COD) fed to the anaerobic process should yield about 5.6 cubic feet of CH_4 .

The use of anaerobic treatment by industry has been restricted largely to the food industry. Too often the industry has used merely an open pond and let nature take its course. Improper design and control have resulted in the uncontrolled production of H_2S and amino acids causing odor nuisances.

Properly designed and contained anaerobic treatment plants can remove effectively and cheaply as much as 90% of the B.O.D. from a strong organic waste. Proper mixing, recycled solids, off-gas containment and temperature control are requisite to achieve 90% removal in as little as 24 hours retention time. Anaerobic treatment should be considered for any waste which has a B.O.D. of more than 2000 mg/l. Temperature should be maintained at about 95°F.

Usually anaerobic treatment is followed by aerobic treatment for two reasons. The anaerobic process develops considerable non-settleable solids and produces acetic and propionic acids. The aerobic process then metabolizes the organic acids and flocculates the colloidal particles.

The best example of anaerobic treatment is the stabilization of the organic matter contained in municipal waste water treatment plant sludges. The digester effectively removes about 50% of the total organic matter contained in sludges. The gas from a well-operated digester will contain about 65% methane and 34% CO_2 with variable amounts of H_2S .

An interesting adaptation of the anaerobic process is the removal of nitrogen from a waste water containing nitrates. A low molecular-weight carbon source such as methanol is fed to an acclimatized system to reduce the nitrate to gaseous nitrogen. The single carbon minimizes sludge production, but other soluble organics can be used.

Sludge lagoons can be rendered odorless if sufficient sodium nitrate is present in the water over the sludge.

Aerobic Biological Treatment. Aerobic biological treatment of high volume, low organic, industrial waste waters is quite common, primarily because of low cost. Oxygen from air can, through biologic oxidation, be made to oxidize a pound of carbon for about 10 cents, including amortization and operation of the facilities. The cheapest chemical methods range upward from 50 cents per pound of carbon oxidized. Then too, bacteria can readily metabolize materials such as acetates which are extremely difficult to oxidize chemically.

Many methods are used to accomplish biological oxidation.

(a) The earliest method was the *oxidation pond* which is still effective in warm climates if sufficient surface area and depth are provided. Without continuous sludge removal, a pond quickly becomes anaerobic on the bottom. Sufficient

retention time for solids permits the flow-through part of the pond to remain aerobic. Many pulp and paper mills have used aerated ponds to assure sufficient oxygen and minimize the land area needed. All biological reactions are temperature dependent, so in order to maintain effective treatment the water should remain above 50°F or the retention time required to achieve a standard quality becomes too great and economy is lost. Another factor in the retention time is the amount of biological solids kept in suspension. The aerated pond usually has no more solids in suspension than one half the B.O.D. concentration.

With proper depth for sludge, observations on oxidation ponds have led engineers to design for about 50 lbs. B.O.D. loading per acre per day.

(b) The *trickling filter* was an outgrowth of the old contact tank. It was observed that biological slimes adhered to surfaces in natural streams. The contact tank was merely a tank filled with large stones into which the waste water was directed and operated on the fill and draw principle. The slimes on the rocks obtained oxygen from the air drawn into the tank on the discharge cycle. By spraying the waste water and permitting it to trickle down through a bed of stones, the process permitted more air to contact the waste and hence increased the loading as well as the oxidation efficiency. There is no filtering action as such in the so-called trickling filter. Soluble organics are converted to protein; colloidal matter, if present, can be absorbed in the slimes. The slimes adhering to the media will become anaerobic next to the media surface. As the slimes become thicker, they slough away from the media and become suspended solids in the effluent.

The development of the rotary distributor further increased the usefulness of the trickling filter by insuring complete and uniform distribution over the entire rock surface.

The use of plastic shapes which provide a known surface-volume relationship have improved removal efficiencies and have permitted the use of increased depths so that these units have become known as oxidation towers.

The trickling filter should not be used on wastes which have a high suspended organic solids content. Solids absorbed in the slimes can quickly go anaerobic, and the odors can be a nuisance. The oxidation tower has its best place in the rapid conversion of soluble materials to insoluble protein. In this case the indicated removals are in the neighborhood of 50%. The unit then serves to pre-treat medium strength wastes ahead of activated sludge.

Rock trickling filters can seldom be loaded to more than 50 lbs. B.O.D. per day per 1000 cu. ft. of media. The plastic media-units have been used with loadings of 500 lbs. B.O.D. per day per 1000 cu. ft.

(c) *Activated sludge* is a process in which flocculated biological slimes are settled and returned to the aeration tank to maintain a high ratio of acclimatized sludge mass to carbon.

The activated sludge process has been the subject of much research since 1914. Each year

investigators have added a little to our understanding of the process until we now can formulate the various relationships and design facilities with a fair amount of accuracy.

With highly concentrated waste waters containing rapidly metabolized substances the main problem is to dissolve oxygen as fast as the bacteria can use it. A well acclimated return sludge will convert soluble organic material to protein as rapidly as oxygen is made available. A limited oxygen supply will increase the time of conversion to the point that the protein growth phase is still in progress at the end of the aeration tank. When this condition occurs sludge will be lost over the settling tank weirs and effluent quality is poor. An overloaded activated plant is extremely difficult to manage and usually goes from bad to worse because of the inability to condition properly the return sludge so that flocculation

takes place before reaching the settling tanks.

Accurate evaluation of waste waters and laboratory experimentation are necessary to define the design and operation of an efficient activated sludge system.

Recommended Reading

1. ECKENFELDER, W. WESLEY, JR.: *Industrial Water Pollution Control*. McGraw-Hill Book Company — New York, 1966.
(Laboratory procedures to develop design criteria with excellent recent references.)
2. NEMEROW, NELSON M.: *Liquid Wastes of Industry*. Addison-Wesley Publishing Co., Reading, Mass., 1971.
(Theories, Practices and Treatment — replete with specific industry references.)
3. *Principles of Industrial Waste Treatment*. John Wiley & Sons, New York, 1955.
(General review of industrial waste problems and solutions.)

CONTROL OF INDUSTRIAL SOLID WASTE

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C. G. Golueke

SCOPE OF INDUSTRIAL WASTE
GENERATING ACTIVITIES**The Problem of Definition**

In reducing to comprehensible terms the vast spectrum of residues of resource utilization which comprise solid waste, it is necessary to resort to some scheme of classification.

At the broadest level of definition, relating wastes to the general sector of human activity in which they originate has been the most common approach. Thus municipal, agricultural, and industrial wastes commonly appear in both the literature and the language of solid waste management as categories which by implication, at least, are essentially of the same order. That they are not in fact of the same order is of little significance when the primary concern is for municipal wastes. However, when industrial waste is the problem, some distinctions between the three classes must be clearly understood.

1. *Municipal Wastes.* The domestic and commercial activities which generate municipal wastes are characteristic of cultural and social patterns which are national in scope. Thus, with some variations in regional and climatological factors which result in ashes in one community and year-round grass trimmings in another, the term "municipal wastes" has an identifiable meaning without great refinement of definition.
2. *Agricultural Wastes.* In the case of agricultural wastes there is currently some confusion of definition. Some individuals still consider the term to include everything from crop residues left in the fields to animal manures and the residues produced in processing food and fiber grown on the land. However, much of agriculture is organized and managed in the same manner as are factories. Land is prepared, and many crops are harvested, with sophisticated machinery. Thousands of animals are concentrated in milk, egg, and meat production enterprises. The distinction between a processing plant utilizing farm products as its raw material and one processing crude petroleum, for example, is quite artificial. Therefore, except for plant residues left in the fields and animal wastes deposited in the pastures, it seems appropriate to include much of what is now classed as agricultural waste in the industrial waste category. In fact there is already a trend to consider animal manures as a source of industrial pollution.¹

3. *Industrial Wastes.* Although, as previously noted, there is a certain logic in classifying solid wastes as municipal, agricultural, and industrial, the logic breaks down when control of industrial wastes is the problem of concern. Consequently, in terms of control there is no way to define "industrial wastes" in the context of the simple classification cited. It is everything that is not included in "municipal wastes" and a large percentage of what is included in "agricultural wastes." Therefore, it can best be isolated only in relation to certain types of human activity.

**Nature of Human Activity
Involved in Industry**

The range of human activities which might be described by the word "industry" is so broad and varied that essentially the only thing all industries have in common is that they generate residues they do not want. Although in the aggregate these unwanted residues comprise industrial solid waste, no one approach can resolve the waste control problem it presents, for the simple reason that there is no single identifiable problem. There are, however, types of activity which generate broad types of industrial solid waste problems, each amenable to some typical approach although not to a universal solution. For the purpose of this discussion these activities are divided into three classes: 1) extractive industries; 2) basic industries, and 3) conversion and fabricating industries.

Obviously these three classes are not mutually exclusive. Processing, for example, may be a feature of any type of industry, but each class has identifiable characteristic waste generating features which differentiate it from the other two.

**INDUSTRY AS A GENERATOR
OF SOLID WASTES****Extractive Industries**

The normal concept of an extractive industry is, as the name implies, one in which raw materials are taken from the earth and marketed in essentially their original state with little or no value added by manufacture or processing. Consequently it is to be expected that the solid wastes generated by such industries are but components or products of the earth. Four extractive industries, namely mining, quarrying, logging, and farming are of particular significance as generators of solid wastes. A fifth, the petroleum industry, is a major contribution to industrial solid waste problems, but not in the extraction process itself.

1. *Mining.* In terms of the quantity of solid wastes generated, mining probably exceeds all other industries, estimates ranging as high as 1.6 billion tons per year.²⁻³ Shaft and tunnel mining of coal and metal ores necessitates bringing to the surface large quantities of earth materials associated with the particular mineral sought, or overlaying it. Convenience, economics, and sheer weight and volume of materials dictate that these tailings be discarded near the mine head. Thus the major waste problem is fundamentally the local creation of an extremely large pile of inert material which is usually unsightly, destructive of the land resource it occupies, and may contribute to water pollution by leaching over a long period of time. Sometimes this waste pile is a menace to human life as well, as a result of instability due to fine particles, which may run as high as 40 percent.² A notable example is the 1966 tragedy in Aberfen, Wales, where 150 persons (mostly school children) were killed by a slide of an 800-foot-high pile of coal mine waste.

Mine tailings are proving to be stockpiles of valuable resources, albeit by inadvertence rather than design.³⁻⁴ A major example is the early discarding of tungsten and vanadium ores in iron mining operations. When later a use was found for these metals, more wealth was extracted from the waste pile than was originally generated from iron. However, this secondary extraction did little to diminish the size of the original heap of wastes.

Concentration of solid wastes often occurs at locations which are relatively close to the mine where crushing, flotation, and other processing of ores is essential to the extraction process. Such secondary waste concentrations are generally smaller than those at the mine head but they are by no means insignificant in volume. For example, about 1.3 tons of wastes are generated for each ton of pelletized iron ore processed.⁵ However, they still represent materials taken from the earth's crust and simply relocated and concentrated on the land surface.

2. *Quarrying.* Quarrying is often classified separately from underground mining. Open pit, or strip mining and the quarrying of glass sand, stone, and sand and gravel are typical of this type of extractive industry. In comparison with other types of mining, sand and stone quarrying displaces and concentrates smaller amounts of unwanted materials (approximately 0.5 to 5.0 percent).⁶ Otherwise the solid waste problem is the same; i.e., inert earth materials piled on the surface. Although quarrying wastes may be deplored by citizens on the basis of effects on nearby property values, or of aesthetics or other emotional response, quarrying is more an environmental problem of noise, dust, traffic, and aesthetics than one of solid waste generation.
3. *Logging.* As a generator of solid wastes the harvesting of timber differs from mining and

quarrying in that its residues are organic. Hence, in a matter of years rather than of geologic time they are returned to the soil by the biochemical processes of nature. It is estimated that traditional logging procedures leave in the woods some 30 to 40 percent of the original weight of the tree, or about one ton of debris per 1,000 board feet of logs harvested.⁷ As a solid waste problem this material is scattered over a wide area, is unsightly, constitutes a fire hazard to the forest, may be a reservoir of tree-destroying diseases and insects, and represents a wastage of natural resources.

4. *Farming.* The solid waste generating aspects of farming include both plant and animal wastes, the estimated per capita production averaging 43 to 60 lb./day.⁸⁻⁹ Plant residues of significance include unharvested or unharvestable crops, vines, straw and stubble, and orchard prunings. Here a variety of solid waste control problems accrue largely as a result of air pollution and other environmental considerations. Unfortunately, burning of certain seed grass stubble is necessary to control plant diseases. Straw and stubble plowed into soil increase the cost of nitrogen fertilizer to offset the carbon surplus. Unharvested products such as melons and tomatoes produce unpleasant odors and may attract insects and rodents. Tree prunings are both a physical problem and a reservoir of crop and tree-destroying pests if burning is not allowed. Burning of sugar cane remains an economic and technological necessity in eliminating leaves prior to processing.

Disposal of manure and dead fowl constitutes an extremely difficult problem to the poultry and egg production industry. Although the wastes are organic and capable of incorporation into soil by natural processes, they are concentrated in location, 10,000 to 100,000 birds being housed in a single location. Moreover, they are aesthetically objectionable, uneconomical to collect, and unwanted by agriculturists. The same situation exists in dairy and animal fattening installations, the latter of which involve as many as 20,000 animals in a single operation and may soon involve 100,000.¹ Concentration of decomposable wastes, pollution of water, fly production, aesthetics, and economic and technological problems of collection and disposal are among the solid waste problems generated by animal husbandry as an extractive aspect of the farming industry.

In evaluating extractive industries as generators of wastes, the four examples cited have several things in common. They concentrate wastes at specific locations on the surface of the earth; the wastes are normal products of the earth and its living things; and they do little to multiply the basic value of the product. They differ, however, in nature, some being inert materials whereas others are biodegradable organic matter. Consequently, no single approach to solid waste con-

trol can overcome the problems man associates with the wastes of extractive industry.

Basic Industries

For the purpose of this analysis, basic industries are considered those which take raw materials from extractive industry and produce from them the refined materials which other industries convert into consumer goods. Basic industries differ from extractive in several ways, the most significant being in the value added by manufacture.

Products of the basic sector of industry are such things as metal ingots, sheets, tubes, wire, and structural shapes; industrial chemicals; coke; paper and paperboard; plastics materials; glass; natural and synthetic fabrics; and lumber and plywood. From the farming industry there is a tendency for fiber to go into basic industry, and food to conversion industries or directly into commercial channels. Exceptions might be the hulling of rice and the production of raw sugar from sugar cane, although these two might better be classed as conversion industries.

The solid wastes generated by basic industries may be said to differ from those generated by extractive industries in three major aspects: They are more diverse in composition; they differ markedly from the normal mineral and plant residues found in nature; and the industry itself generates a fraction of its own wastes. The solid waste generated by any type of industry in its business offices is, of course, considered a part of the normal commercial component of municipal wastes.

Eight basic industries are perhaps the major generators of solid wastes in their class: metals, chemicals, paper, plastics, glass, textiles, wood product, and power.

1. *Metals.* Blast furnace slag and ashes from the smelting of iron ore probably rank second only to mining wastes in volume of waste produced by industry. Slag produced in steel production is estimated to be more than 1,000 tons per day per furnace, or about 21 percent of the steel ingot production^{10,11}. Similarly, the smelting of copper and the production of aluminum result in significant amounts (more than 5 million tons each in 1965)^{10,12} of waste materials essentially of an inert nature, although subject to leaching if carelessly discarded in the environment. Like extractive industry wastes, basic metal wastes are concentrated at the points of generation. Here, however, the similarity begins to lessen. Mining wastes, for example, tend to occur in areas remote from any community which does not depend almost entirely upon mining for its livelihood. In contrast, smelting is more likely to be done in a community which through the years has diversified until it harbors many diverse urban interests. Thus both the physical freedom to create a large pile of slag at the smelter site and the willingness of people to accept it, become serious aspects of the problem of control of solid wastes from the metals industry.

At the second level of the basic metals industry, where ingots are formed into

shapes, smaller amounts of mill scale and spalls characteristic of the metal being processed appear as solid wastes. At this level of industry new types of solid waste appear: trimmings from the product itself; residues from the on-site use of other refined products associated with the process (e.g., lime sludges from the neutralization of spent pickling liquor); and miscellaneous wastes from the handling and shipping of the item produced.

2. *Chemicals.* For variety of wastes the chemical industry exceeds all other basic industries and generates some of the most economically and technologically difficult problems of solid waste management. The nature of these problems in any particular chemical plant, of course, depends upon the processes and the products involved. Producers of less exotic materials such as portland cement, carbon black, and lime have tended to locate in areas remote from urban communities. Their principal solid wastes have been air-transported particulates, deposited over a large downwind area, plus ashes and mineral residues accumulating at the plant site. In contrast, such industries as petro-chemicals have generally located in urban centers or have been overrun by urban expansion. The same may be said of producers of sulfuric acid, fertilizers, and many other basic chemicals.

The range of waste materials generated by the more complex chemical industries is too extensive to catalog in detail in this summary. However, it includes off-specification material, tars, process sludges, and a vast variety of chemical residues. Although roughly one-third of industrial wastes are generated by the chemical processing industries,¹³ the wastes are significant because of their particular chemical properties and their environmental effects.

Generally, solid wastes from the more sophisticated chemical processes are generated in a liquid stream which, in many cases, has been discharged to the ocean or to surface streams, or injected into deep underground strata. Nevertheless, some are generated directly in the solid state. These include chemical residues, precipitated sludges, and the miscellaneous refuse associated with the import of necessary processing materials and shipment of the finished products. In the environmental climate of the 1970's an increasing fraction of air-borne particulates and water-borne process brines and sludges will have to be collected as solids and controlled by solid waste management techniques.

3. *Paper.* Although much public attention has been directed to paper as a waste material, most of the problems associated with its original production have been in the context of water pollution rather than solid waste control. As a generator of solid wastes the production of paper and paperboard is similar to other basic industries in that residues of materials used in the process and residues of the product itself must be dealt with. In the first category

are such things as tree bark, wood fiber, paper pulp, and inert filler, which are not difficult to remove from transporting water; and process chemicals and wood extractives which can be isolated as solids only with difficulty, at considerable expense. As in the case of basic chemicals, both components of this first category of residues are destined to be controlled as solids if they are allowed to become wastes.

The second category of wastes — residues of the product — consists primarily of trimmings of paper or paperboard, plus wastage occasioned by malfunction of the processing equipment. Much of this material may be reprocessed; some may be incinerated or deposited in landfills as are similar residues from the paper fabricating industry and from commercial and domestic sources.

The total volume of solid waste produced by the basic paper industry, although not insignificant, is not as much of a management problem as is the separation of dissolved solids from liquids in the waste stream which has historically been a water pollutant.

4. *Plastics.* In the case of plastics, the residues associated with production of the basic material are essentially a problem of the chemical industry. Much of this material then goes directly to the conversion and fabricating industries, but some is converted by basic industry into sheets and other forms used by fabricators. Wastes from this segment of the industry are largely trimmings from the product itself. No estimate is available of the amount of such solid waste, but it is undoubtedly only a small fraction of the overall plastics disposal problem of a community.
5. *Glass.* Solid wastes generated by basic producers of glass include slag from the purifying of glass sand, plus miscellaneous containers and residues from products used in coloring and laminating glass, cullet (glass fragments) from breakage during manufacture and trimming of sheets, off-grade, resin coated fibrous glass, and residues from on-site crating of glass for shipment to conversion and fabricating industries. Except in situations where cullet of various colors becomes mixed, the major fraction of solid waste from the basic glass industry is reused and hence does not appear as a waste requiring control measures.
6. *Textiles.* Basic textile industries vary in the nature and spectrum of solid wastes generated, depending upon the type of material being processed. Trash from the ginning of cotton may be generated at the extractive industry level or as an intermediate step between extractive and basic industries. It is a fraction of the original cotton plant and is generally concentrated as a waste in comparatively small fractions of the total at a number of dispersed locations in cotton farming communities. Wastes specifically characteristic of the cotton textile mill are more commonly such things as strapping and burlap used in baling, plus comber wastes and fibers damaged during storage or

shipment which are generally reutilized in the industry.¹⁴

Linen textile manufacturers likewise must dispose of plant residues and materials used in shipment of the raw flax. Fiber, twine, dirt, and wool fat characterize the wastes from preparing wool for textile processing. In addition to waste fibers, synthetics generate special wastes in the form of containers used in shipping chemicals from the basic chemical producers.

Residues from spinning, weaving, and trimming operations occur with all types of fabrics. Dye containers and residues from on-site preparation of cloth for shipment are a fraction of the overall solid waste generated by the basic textiles industry.

7. *Wood Products.* Tree bark, sawdust, shavings, splintered wood, and trimmings constitute the major solid wastes of the lumber producing industry. In weight they amount to some 10 percent of that of the original tree in the forest, or about 1.26 tons per 1,000 board feet.¹⁵ Conversion of wood to plywood sheets contributes plywood trimmings, knots, and glue containers to the overall solid waste of the wood products industry at its basic level. Wood ashes are typical wastes of this industry as a result of on-site burning of wastes for power production or to dispose of sawdust and other wood wastes.

Typically, sawmills are located in smaller communities and are notable for their untidy appearance. Broken cable, discarded machinery, and miscellaneous debris often characterize the environment of a wood processing plant, albeit out of scale with the amount of such wastes generated.

Air pollution and aesthetic considerations may be expected to intensify the solid waste control problems of the basic wood products industry as particulates now discharged to the atmosphere by burning become converted to solid wastes in response to restrictive legislation.

8. *Power.* Fly ash, bottom ash, and boiler slag accompany the production of power by burning of coal. Production of these three wastes by the U.S. power industry in 1969 was 21, 7.6, and 2.9 million tons, respectively.¹⁶ Often such power plants are located in metropolitan areas, hence the objection to air-borne fly ash, dust, and ash heaps confronts the power producing industry with solid waste problems. Where high ash coals are utilized, the volume of ashes and clinkers may approach that of the original coal consumed, although, of course, its dry weight is generally appreciably less than 20 percent of that of the coal from which it was derived.

As generators of solid waste, basic industries such as those herein cited have several things in common. With few exceptions, they draw upon more than one extractive industry for raw materials; a fraction of the raw materials they refine appears as a solid waste; they utilize refined products of

other basic industries and of conversion industries, importing in the process things such as shipping containers which become wastes for which they must assume responsibility; a fraction of their own product must be handled as a waste; and a considerable value is added by manufacture, or processing by the basic industry. In comparison with a purely extractive industry, a basic industry produces more categories of solid waste, some of which it can recycle directly in its own processes. However, in comparing one basic industry with another, the things they have in common are not reflected in any similarity of waste generated. Hence no common approach to solid waste control characterizes the problem of basic industries.

Conversion and Fabricating Industries

It is beyond the scope of this chapter to attempt any listing of the myriad enterprises which convert the products of basic industry into the goods which characterize our economy and our standard of living. Value added by manufacture is a maximum in the conversion and fabricating industries. As generators of solid waste, such industries also have many things in common. Particularly significant is the extent to which the output of one type of industry comprises a combination of raw materials and solid waste for another. For example, one modest sized industry engaged in converting plate glass to windows and mirrors in the Los Angeles area estimates its cost of disposing of crating materials received from its suppliers at one thousand dollars per month.

A second common characteristic of the conversion and fabricating industries is that residues of the basic materials they utilize generally constitute the greatest fraction of the waste they generate. Moreover, unlike a basic industry which may directly recycle the trimmings and rejects of its own product, the conversion or fabricating industry must rely on some secondary enterprise to take such of its residues as are reclaimable. Thus broken glass, metal trimmings, imperfect castings, and similar salvable residues can seldom be utilized directly by the conversion industry which generates them.

To illustrate the type of solid waste problems associated with the conversion and fabricating industries, such broad categories of industry as packaging, automotive, electronics, paper products, hardware, soft goods, food processing, and construction may be cited as typical, though by no means all inclusive.

1. *Packaging.* For the purpose of this summary, production of packaging materials is classed as basic industry, hence only the conversion of packaging materials to containers is considered. However, the scope of this sector of the industry is itself extremely broad and varied as regards the nature and resource value of the waste it produces. Aluminum, steel, glass, plastics, cardboard, corrugated paperboard, plastic-paper laminates, and paper with or without any of a broad range of coatings are among the materials used by the container industry. Whether or not an appreciable num-

ber of these items appear in any industrial waste stream depends, of course, upon the range of activities engaged in by a single company or plant. Recoverability of residues often depends upon the cleanness and uniformity of the waste material. For example, conversion of glass to containers generates an appreciable amount of cullet; however, whether this is recoverable or useless, generally depends upon the extent to which colored and clear glass is mixed in the waste. Nevertheless it may be said that, at the industrial level, wastes from the packaging industry are primarily fractions of the material converted, although the range of possible materials is unlimited.

A secondary waste of any individual packaging plant is packages passed along to it by its suppliers, together with residues on its own on-site shipping preparations.

2. *Automotive.* There are two major waste-generating sectors of the automotive industry. One makes and ships specialty components; the other assembles the components into a finished vehicle. Conversion and fabricating industries in the first of these categories produce such things as tires, generators, carburetors, radios, speedometers, wheels, bumpers, hub caps, lamps, bearings, and other of the dozens of systems or devices that go to make up an automobile. In each of these the solid waste generated is a function of the special activity of the individual industry, and comprises residues of the materials used and the packaging received from suppliers.

Painting and upholstering of automobile bodies adds both container and material residues to the solid waste stream of the manufacturer. However, by far the greatest component of the automobile assembly plant waste is the discarded packaging and shipping materials associated with the delivery of components from other industrial suppliers. In fact, there is probably no other sector of industry which compares with automobile assembly in the amount of solid wastes it inherits from its relationship with other industrial activities.

3. *Electronics.* Like the automotive industry, the electronics industry includes both a components and an assembly sector. Plastics, glass, wire and sheet metal scrap and residues of a variety of other basic products appear as solid waste of the many industries associated with production of electronic components. However, in comparison with the waste from most other conversion and fabricating industries, the actual amount is relatively small.

Packaging materials, particularly cardboard, corrugated paperboard, polystyrene foams, and padding materials utilized in shipping electronic components is the major waste generating problem of the assembly activity of the electronics industry. Shipping of the assembled equipment is generally in specially designed containers, the manufacturing wastes of which are ascribable to the packaging industry.

4. *Paper Products.* Conversion of paper into products used in commerce and by the public largely results in solid waste in the form of paper trimmings. Facial and toilet tissue, paper towels and napkins, and similar products yield a high quality waste which may or may not be salvable through a secondary enterprise, depending upon whether white and colored paper residues are mixed together in the conversion process. Conversion of kraft paper into bags, for example, yields a readily salvageable waste. Publishing of books and magazines, which might be classed as a fabricating industry in the context of solid waste generation, is a major source of filled paper residues which are commonly disposed of as solid wastes.
5. *Hardware.* The term "hardware" rather than "hard goods" is used herein because the latter embraces many classes of basic as well as conversion and fabricating industries. "Hardware" is confined further herein to the metals industry which produces the machines and tools (with the exception of the automobile), and the utensils and gadgets used by all classes of industry and by the public. Solid waste from such hardware industry includes residues from boring and machining of metals; trimming and sizing of plates, tubes, and structural shapes; and miscellaneous residues from casting and forging processes. It also includes plating, etching, and similar liquid borne wastes which, like similar wastes from the basic chemical industry, must eventually be managed in the solid form.
6. *Soft Goods.* Conversion of such materials as textiles, leather, and plastics into articles of commerce constitutes the soft goods industry in the context of conversion and fabrication. As is characteristic of all industries in this classification, residues of the material processed represent the major item of solid waste generated, with incoming and outgoing goods yielding secondary wastes associated with shipping.
7. *Food Processing.* As a waste generating industry, food processing presents problems somewhat different from other conversion industries. Like extractive and basic industries concerned with material of plant and animal origin, food processing produces wastes which are subject to the normal recycling processes of nature. However, they are generated seasonally and in large amounts at locations which may be either urban or intermediate between farm and city. With the exception of a few residues such as rice hulls, food wastes are putrescible, attractive to insects, and occur in a semi-liquid or liquid state. Preparation of fruits and vegetables for canning yields a slurry of such things as leaves, soil, skins, peelings, pits, seeds, and cores, along with spoiled, out-sized, and damaged fruit. In California alone this type of cannery waste totaled 750,000 tons in 1967.⁷ Washing and cooking operations yield a companion stream of water-borne

dissolved and suspended solids. Because of water pollution problems, these solids increasingly are being removed from water for disposal by solid waste management techniques.

Processing of fish and animals for marketing or canning likewise generates putrescible liquid and semi-liquid wastes. The solids content of these waste streams, along with bones and other inedible fractions, are destined to be handled as solid wastes as water quality objectives become more restrictive.

Because the food processing industry is linked directly to extractive industry without an intermediate basic refining, containers coming to the plant are reused in the fields and orchards. Furthermore, shipment of the finished product makes use of containers already prepared by the packaging industry. Consequently, wastes from the food processing industry are predominantly fractions of the material processed.

8. *Construction.* Among the most significant generators of solid waste is the construction industry. In its purely fabricating activities its waste products are typical residues of the materials it employs — lumber, plasterboard, wire, paper, cement bags, sheet metal scrap, etc. However, unlike other industries in the conversion and fabricating category, most construction wastes result from peripheral activities essential to its production phase. Demolition of buildings, breaking up of pavement, and preparation of site produce very large volumes of such materials as earth; rock; broken concrete, tile, brick, lumber, and plaster; tree stumps, poles, and piling; and miscellaneous rubble.

The eight foregoing examples by no means cover the full range of activities which might be classed as conversion and fabricating industries. They illustrate, however, that the wastes generated by this class of industry are primarily residues of the materials they process or convert into consumer goods, and that the measures necessary to move products from one sector of industry to another impose a secondary solid waste burden on the receiver. More important, it is significant that at this most complex level of industrial solid waste generating activity the value added by manufacture is greatest. This suggests that the economic capability of conversion and fabricating industries should generally be greater than that of a basic or an extractive industry as such. Moreover, conversion and fabricating industries tend to be activities of a diverse urban community. Therefore, social pressure for solid waste control can be expected to be exerted most heavily upon such industries, especially since their products, along with the associated packaging, constitute the major solid waste which the citizen himself ultimately casts off.

MANAGEMENT OF SOLID WASTES

Earlier in this chapter it was found convenient to arrange industry into three categories, each having specific waste generating characteristics. These categories were presented in ascending order of magnitude of value added by manufacture,

responsibility for creating wastes, and degree to which their activities are conducted in urban communities. To evaluate each category, and type of industry within that category, as a generator of wastes it was necessary to treat extractive, basic, and conversion and fabricating industries as discrete entities. In the real world of industry, however, these three may be only sectors of a single large industry which owns and operates every aspect from raw material source to the finished consumer product. Thus the conclusion that no common waste management technique is applicable to all types of industry in a single category, although valid, is complicated by the fact that industry may be stratified vertically along ownership lines as well as horizontally along functional lines. To get at the general problem of solid wastes management in such a complex situation, it is convenient to consider waste control approaches in relation to the source of solid wastes rather than the composition of the waste itself.

Disposal as a Condition of Production

The simplest situation in solid waste control applies especially to an extractive industry in which the feasibility of operating at all is contingent upon satisfactory control of its solid wastes. In such a circumstance a mining, quarrying, or logging operation might be undertaken by industry only when waste control is not an economically overwhelming consideration. Feasibility may, of course, be based on geographic or topographic conditions, property holdings, access, or regulation by public law or public policy. It does not necessarily imply environmental perfection, although there is a tendency (1971) for aesthetics to be given increasing weight where public interest or public opinion is a factor. Uneconomical conditions, whether natural or man-imposed in a wastes management context, generally have discouraged an extractive industry operating entirely on its own resources. However, in an industry which covers the whole range from extraction to conversion, extraction of raw material may well be operated at a loss in order to produce profits at the higher industrial level where value added by manufacture is sufficient to offset losses. Moreover, control of solid wastes by an industry of this sort may be subject to considerable upgrading in technique and cost without causing the system to fail economically. Nevertheless, in such activities as mining there is no choice but to dispose of wastes upon the land, albeit under conditions acceptable to society.

In the case of farming as an extractive industry, constraints imposed by solid waste management have seldom been insurmountable unless urban environmental conditions are required of the farmer. Generally, he is not part of an industrial complex which can take a loss continually at the extractive level. Thus if society asks too much in the name of solid waste control or other environmental context, the agriculturist, unless subsidized, ceases operations and converts his land to urban development.

Incidental Residues Produced By An Industry

As noted in a preceding section, processing,

converting or fabricating activities within several types of industry result in slag, ashes, clinkers, and similar solid residues, as well as air-borne particulates or liquid carried process sludges, generated at the site of operation. For air and water-borne solids, control measures may include electrostatic precipitators, bag filters, wet scrubbers, sedimentation, chemical precipitation, or other conventional waste treatment processes. Disposal of bulky worthless solids involves simple deposition on the land in some location and under some conditions, acceptable to the public. More valuable incidental wastes may, however, be reclaimable or convertible to useful resource materials if the level of cost is acceptable. For example, about 14 percent of power plant solid wastes were utilized outside the power industry in 1969.¹⁶ Other measures which may assist in controlling the residues produced incidental to industrial output may include such expedients as abandoning on-site generation of power, or making changes in process. Abandonment of an entire plant, especially one with obsolescent processes, is a measure sometimes taken by industry confronted with solid wastes which are a by-product of its fundamental processes.

Product Residues Generated By A Basic Industry

When refinement rather than conversion of raw materials is the goal of production, product wastes occasioned by spillage, breakage, or malfunction of process may be managed by direct recycling within the plant. The same is true of metal trimmings, cullet, and paper trimmings in industries producing metal, glass, or paper as basic products.

Residues From Materials Conversion Or Fabricating

Cullet, metal trimmings, packaging materials, and other residues resulting from the conversion of basic industrial products into consumer goods cannot be directly reused by the waste producer. To him they represent a solid waste, some of which might be salvaged or reused economically; some of which he shall have to pay someone to remove for disposal. Metal scrap, clear glass, and uncoated corrugated paperboard are typical of the material which might be returned to more basic industries for reprocessing. Similar trimmings from plastics, fiberboard, laminated plastic-paper, lumber, cloth and a host of other materials are generally useless and are relegated to the landfill or incinerator.

Waste From Interindustry Transfer

Packaging and shipping of basic materials or finished products, a necessary part of industrial activity, require that most industries accept various amounts of materials, which immediately become a waste, in order to acquire the materials necessary to their enterprise. Thus each industry helps to create a solid waste management problem for those with which it does business. In general, the waste-to-product ratio goes up from basic to conversion industry, reaching its maximum value at the conversion industry-to-consumer level. Most of the waste generated by interindustry transfer of materials and components is waste, although there

are instances where intra- or inter-industry practices work to hold down waste production. Where producer and fabricator are favorably located with respect to each other, such things as cable spools and protective packaging for television tubes are commonly reused repeatedly for their original purpose.

Special Problem Materials

Waste materials which present especially difficult problems of management at present (1972) include both natural and synthetic products. Organic wastes, particularly food processing wastes, are a nuisance because they are putrescible, whereas plastics are a nuisance because they are not. Process sludges of a wide variety of activity, ranging from industrial waste treatment to saline water reclamation, present an unsolved problem both because of their high liquid content and because they are so newly recognized as solid waste problems that no economic technology for converting them to drier solids has been developed.

CONTROL OF INDUSTRIAL SOLID WASTES

In the preceding section attention is directed to the internal management of solid waste generated at various levels in the industrial scale. However, to determine what methods of control are needed in solving the overall problem of industrial solid wastes, it is first important to understand the relationship of industrial practice to the generation of society's total solid waste problem.

To a significant degree it is true that the entire industrial effort of the nation is dedicated to the production of solid wastes. The product of extractive industry is the raw material of basic industry; and the product of basic industry feeds the conversion and fabricating industry. Each sector of the system discards what it cannot pass along to the next in line. Finally, the entire product of the conversion and fabricating industry becomes the solid waste of all sectors of society — industry, commerce, and citizens. The rate at which the overall system functions governs the economy of the nation and depends upon the acceptance of goods by the consumer at the top of the scale. This encourages industry to mistake the act of physical acceptance of goods by the citizens for actual consumption of these goods. The next logical step is to create through advertising a dissatisfaction on the part of the consumer so that he discards his purchases on the basis of obsolescence rather than loss of utility. Thus it is clear that quite aside from any question of whether industry is giving the public what it demands, or the public is accepting what industry persuades it to demand, the overall waste generation of the commercial and municipal sectors of society is a function of what flows from industry into these sectors.

Carried to its logical conclusion, this system would eventually convert all nonrenewable resources into discarded wastes unless reuse and recycling are a matter of industrial practice and public policy. Therefore it seems logical to conclude that public agencies, industry, and education of the public each play a role in industrial solid waste control.

Role of Public Agencies in Industrial Solid Waste Control

In the absence of any public agency concerned with overall environmental quality, solid waste control would be a problem of individual enterprises in specific locations rather than one confronting the entire sector of human activity loosely described as "industrial." Thus, for example, a mining operation with land area for spoils would have no disposal problems, whereas waste disposal might be the most compelling problem of a less fortunately situated operator. Without public constraints, wastes generated incidental to production, and residues of materials conversion as well, might be hauled to some public or private dump and so pose no problem other than that of cost to the generating industry. The same may be said of particulates discharged to the atmosphere, or of process brines and sludges discharged to the water resource.

Industry would, of course, share in any ultimate disaster that wastes might bring upon mankind, but in the interval industry's wastes like those of everyone else would react only to degrade the general environment. In such a situation, responsibility for deciding what sort of a world society wants accrues to the public; and implementing public goals is the function of public agencies. Therefore, some agency of the public must decide what constitutes an environmental problem, at what level the problem is to be tolerated, and what measures should be taken to alleviate it.

In the context of problems associated with industrial solid wastes public agencies play a role in four distinct areas: public health, environmental quality, resource conservation, and economics.

1. *Protecting Public Health.* The concept that industrial solid waste poses a threat to public health apart from that of municipal refuse is of quite recent origin. It developed from a realization that air pollution is a menace to human health and that industrial pollution of water has health implications beyond that of historical water-borne disease. Constraints imposed on industry in the interests of health of workers and citizens in general are, therefore, currently reflected in the concept that air and water pollutants should be separated from their transporting media and dealt with directly as solid wastes. As with municipal refuse, however, industry is expected to handle its putrescible organic residues in such a manner as to keep down insect and rodent vectors of disease.

Thus, the role of the public health agency in industrial solid waste control is essentially regulatory.

2. *Attaining Environmental Objectives.* Environmental objectives which call for clean air, pure water, freedom from nuisance and affront to the aesthetic sensibilities of man, and a healthy ecological balance in nature are perhaps the major concern of public agencies in relation to industrial (and other) solid wastes. At the local level attainment of such objectives may be the responsibility of the health department, but at the federal level and in many

states protection of the environment is a role assigned to some agency with broader regulatory powers than the department of health. It is the role of this agency to determine where and under what conditions wastes may be deposited on land, burned, or otherwise disposed of by those who generate them. In carrying out this role the agency, in the long run, continuously must strike a balance between the environmental perfection desired by an emotional public and the industrial freedom considered necessary to an ever-expanding and changing civilization to arrive at a point at which environmental objectives are attainable at an acceptable reduction in our level of civilization.

3. *Implementing Resource Conservation Policies.* Resource conservation is a matter of public concern which has been assigned to numerous agencies with various powers and specific interests for more than half a century. In relation to solid waste, conservation has been interpreted^{17,18} in terms of both land resources and the value of resource materials in the solid waste. Thus, a public agency, alone or in concert with other public agencies, might decree in one case that a spoils dump or a slag heap in a certain location would be destructive of a land resource either by physical occupancy of land or by environmental degradation. In another case the conclusion might be that a properly constructed landfill in a particular location would create a new land resource.

Concern for the resource value of residues such as glass, metal, and paper wastes from the conversion and fabricating industries might lead a public agency to any of several alternate decisions. For example, the decision might be that enhancement of land resources is important enough to justify sacrificing resource residues as landfill material. In contrast, there might be reason to decide that resource residues should be stockpiled in a fill for reclamation at some future date; or that they should immediately be recycled in the interest of resource conservation regardless of cost.

Both the multiplicity of public agencies having interest in land use and in resource conservation, and the scope of possible policy decisions, gives the public agencies a broad and flexible role in determining the conditions industry must meet in managing its solid wastes.

4. *Overcoming Economic Constraints.* In the matter of economic constraints, public agencies may play either of two important roles. They may force industry into actions regarding solid waste control previously thought to be too costly by regulatory actions directed to resource conservation, environmental quality, or any other objective. At the other extreme, they may establish economic incentives for action by industry.

It is not likely that regulation of what conversion and fabricating industries must do with their solid wastes will be a deciding factor.

Instead, a requirement that resource materials be recycled will strike at the consumer-waste hinge of the system and so feed back through the entire industrial equilibrium. That is, it will change the kind of materials required by the conversion industry and, consequently, what basic industry produces and what amounts of specific raw materials are extracted.

In the matter of economic incentives, tax breaks or tax penalties,¹⁹ demonstration grants for exploring new processes, direct subsidy of recycling, and equalization of freight rates for new and scrap metal* are examples of actions which might be taken by public agencies under appropriate public policy. The result might be both a change in the nature of solid waste generated by industry, and in the ultimate fate of such wastes.

Role of Industry in Industrial Solid Waste Control

Because industry accounts for a very large fraction of the total solid wastes of society and the processes by which many wastes are generated are proprietary to industry, it is logical to expect that industry should play a significant role in the control of its wastes and, consequently, of the total waste load upon the land.

The Matter of Options. If all discarded material is considered as waste, the mining and basic metals industries appear as the major source of industrial waste. To deal with such things as mine tailings and blast furnace slag, however, man has few options. Thus at the lower end of the scale the role of industry in solid waste generation is relatively fixed. Similarly, the small value added by processing at the extractive level limits feasible disposal methods, unless higher levels of industry or government subsidize waste control.

Further up the scale, however, such rigidity no longer pertains. The material to be used for any given purpose, as well as the resulting waste-to-product ratio, is a function of the inventiveness and ingenuity of man. Competition for markets encourages the producer of consumer goods to use that ingenuity in finding better processes and cheaper materials and production methods. Constraints imposed by public policies concerning resources, environment, and waste management may likewise react to this same end. Therefore, at the higher end of the scale the role of industry in the overall waste problem is not fixed by circumstance.

Reducing the Amount of Waste. Better processes and cheaper materials do not lead necessarily to a lesser amount of wastes generated. In fact, it is possible that quite the opposite might result. Therefore, industry's role in controlling the amount of solid waste society generates is one of looking to its own design and materials selection activities with consideration for the final disposition of its product in the environment.

The concept that purchase is synonymous with consumption of goods leads logically to a limitation of the objectives of design to such traditional factors as ease of manufacture, saving in cost of fab-

*In Minnesota the 1970 freight rate for scrap was \$4.25/ton as contrasted with \$1.84 for raw material.²⁰

rication, appeal to the buyer, novelty, and obsolescence. Responsibility for solid waste control and for resource conservation, however, now requires that degradability of synthetic materials, ease of dismantling for segregating component materials, minimum number of types of material, and other materials recovery considerations or disposal objectives be among the specifications designers should seek to meet.

Role of Public Education

It is particularly important that people understand the inter-relationships within industry and the dependence of our level of civilization upon industrial activity.

An informed public plays an especially significant role in the control of industrial solid wastes, both because public opinion is respected by industrialists and because public attitudes are the basis of policy legislation which creates the institutions which carry out public policy. Public education is both important and urgent at such times in history as the 1970's when prophets of doom abound, and citizens are bombarded daily with propaganda and with naive and simplistic answers to complex environmental problems.

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CONTROL OF COMMUNITY NOISE FROM INDUSTRIAL SOURCES*Lewis S. Goodfriend***INTRODUCTION**

There are many potential sources of community noise in an industrial plant. However, there are only six general classes of noise sources: a) power generating units, b) fluid control systems, c) process equipment, d) atmospheric inlets and discharges, e) materials handling, and f) plant traffic. Although not a source, architectural and engineering deficiencies also contribute to community noise by allowing plant noise to escape into the community.

Within each of the above classes, there are several types of machines or processes that create the noise. The actual noise source within each machine or process is due to one of a very limited number of physical noise generating mechanisms.

Before describing each of the major industrial noise source categories, the physical generating mechanisms will be outlined, after which the machines, processes and systems in industry that generate community noise will be described. This will be followed by a discussion of the response of people to noise in the community and the methods for delineating or comparing community noise levels. The chapter concludes with a presentation of methods of reducing industrial noise in the community and the outlook for future needs and methods of noise control.

NOISE GENERATION

The noise generating mechanisms which occur in industrial machinery are: impact, gas flow phenomena, perturbations in fluid flow, combustion, friction, dynamic imbalance of reciprocating and rotating machines, and magnetic excitation. Each type will be discussed briefly with respect to the types of industrial machinery and processes and their particular systems of noise generation, transmission paths, and radiators.

Impact

The most familiar of the industrial impact phenomena are probably those from the forge hammer and the punch press. These produce intentional impacts which occur as a direct result of the energy in a flywheel or force of gravity on a drop hammer's mass being expended on the workpiece.

Other sources of impact include: repetitive chipping and scraping, bulk handling of small parts, e.g., tumbling, and the use of negative clearances in some processes. Another class of impacts is unintentional. This occurs when poor machine design, installation, or maintenance permits over-travel of machine elements.

Gas Flow Phenomena

The sound of escaping air or steam is probably the most familiar gas flow noise. However, other conditions associated with gas flow, such as turbulent flow and flow around obstacles, can produce noise. Where the obstacle is a sharp edge, it is possible to generate intense tones. Similar intense acoustic signals are generated by flow across spaced obstructions such as stiffeners in a duct. Flow across the face of a cavity will produce noise which can be amplified by other parts of the mechano-acoustic system.

Air flow causes noise. The hissing noise made by a high-pressure air line open to the atmosphere and the swishing noise of the air flowing past the open window of a car are both examples of air flow noise. There are two separate mechanisms at work here. In the open air-line case, the sound is generated by the non-uniform flow. In other words, the eddies or turbulences within the air stream generate noise, and the larger the difference in velocity between the air stream and the stagnant surrounding air, the more noise which is generated. In the second case, the obstacles in the air stream cause vortices downstream of the obstacle. Since it takes time for the vortices to form, be shed and be followed by another, a periodic system, the sound generated is characterized by tonal quality. Noise from such air flow generators can be amplified many times to produce intense whistles as will be discussed later. The usual sources associated with noise generation by air flow include fans, obstacles in air streams, leaks and open bypass valves in the air handling system, whether of high or low pressure.

The siren effect is responsible for many types of gas flow noise. A siren basically is a device which emits puffs of air in a cyclic pattern. Classically, it consists of an air supply and a rotating disc with holes that match one or more holes in the air supply. When the holes of the disc are aligned with those of the air supply or "wind box," air can escape freely. At other times, the air is essentially cut off. The repetitive release of air makes a sound of tonal character. The volume of air released at each matching of the holes determines the intensity of the noise produced. The siren effect is responsible for the noise of compressor inlets and air turbine discharges. Also, a similar sound is made by a power saw's teeth which cause perturbations in the air near the blade as the teeth pass fixed portions of the saw.

A special type of gas flow phenomenon which generates flow noises is the production of large volumes of hot, turbulent gases as a result of com-

bustion of fuels, whether solid, liquid or gaseous. The expansion of the gas as it is produced and heated causes intense local acoustical disturbances. This gives combustion noise its distinctive low-pitch rumbling sound. Where combustion takes place unevenly, the noise is rough and uneven. In some instances the acoustic signal is so strong as to extinguish the flame which is reignited by a pilot flame or the heat of the burner, and this cyclic behavior can generate serious vibration, often resulting in structural damage. The noise is often an intense low frequency pulsation.

Friction

Another source of noise generation is friction. Although we generally associate energy losses due to friction with heat, friction causes two kinds of noise generation. The first is a series of miniature impacts as the imperfections in one surface are forced over another surface without any lubrication. The sound is somewhat like that from air noise and the sound output is a function of surface smoothness and speed. The second type of friction noise is stick-slip noise. Here, the friction causes a moving part to stop or slow down imperceptibly and as the driving force builds up, the friction is overcome and the parts slip by each other for an instant. Then, they grab again. This action produces high stresses in the parts and the sticking and slipping phases occur at high speeds, thereby producing an intense, high frequency phenomenon. Where the combination of part size and shape permit effective radiation of this type of sound, an intense sound will be radiated.

Dynamic Imbalance

Almost any kind of dynamic imbalance in high speed machinery will cause mechanical vibrations. Where the appropriate acoustical conditions exist, the vibrations will be converted into acoustical energy. This energy may be radiated efficiently by some machine parts and housings. Typical sources are fans, pumps, engines, (both reciprocating and turbine) and compressors. Imbalance forces may be transmitted through bearings. Although bearing noise is partly friction noise, bearings can generate noise by the impact of imperfections in the bearings on other bearing parts at high speed. This causes vibrations which are readily converted to sound by the castings and housings. Generally, bearing noise is not a major source.

Magnetic Excitation

Although electrical machines are not generally considered as noise generators, motors, generators and transformers are capable of being major noise sources. The magneto-acoustic forces occur as a result of the magnetic forces on conductors and rotor and stator. Since there is no magnetic bias field like that due to the permanent magnet in a loudspeaker, the magnetic fields developed at both the positive and negative swings of the power supply line voltage in AC machines cause an unidirectional force. Thus, for each cycle of the line frequency there is a magneto-acoustic force of twice the frequency. Because of non-linearities in the magnetic and mechanical systems, the acoustic output can have a high harmonic content. The

radiated sound can, therefore, be rich in mid-frequency components. In some transformers and motors, the maximum levels occur for signals at six and eight times the line frequency.

In addition to the magnetic excitation, motors and generators produce noise from the radial blade fans used to cool the device by forcing air through or across the casing, and from the shear produced in the air as the slots on the rotor pass those on the stator.

Noise Amplification and Radiation

Except for a few of the sources mentioned such as fans, sirens, and air hoses, little noise would be radiated from equipment if it were not for subsystems which may be resonant or are efficient radiators. The most familiar resonant subsystem is the organ pipe. Without the pipe tuned to a resonance frequency desired, the noise made by the jet edge would be weak and would have little tonal quality. The pipe causes sound which has traveled to the far end to be reflected and transmitted just in time to reinforce the pressure variation at the jet, where a new, stronger signal is transmitted from the jet. The process repeats until an equilibrium situation occurs and a tone is radiated. There are other factors influencing the sound output of an organ pipe type of generator, such as the spacing of the nozzle and jet and their relative angular positions.

Cavities with small necks produce the familiar whistle when air is blown across the mouth. Castings can "ring like a bell," and machined parts such as gears can produce bell-like tones. Sheet metal panels can resonate over a wide frequency range, vibrating as either plates or membranes. The theory for these subsystems is presented in most vibration texts. Some specialized subsystems include machine shafts at the critical speed, gas furnace burners, cup burners, in which the source is inside the resonant structure, and machine room floors consisting of lightweight structural members.

Efficient radiators, formed by large surface area flexible bodies, may be combined with resonant subsystems. A small acoustical resonant subsystem, one side of which is formed by a large steel sheet, will drive the steel sheet as the coil in a loudspeaker drives the paper cone. The steel sheet will radiate the noise very effectively.

EXTERIOR SOURCES OF INDUSTRIAL NOISE

Power Sources

Furnaces and heaters provide the energy for a variety of industrial processes including the refining and fabricating of metals, generation of electricity, petro-chemical processes and a variety of kilns. In some new combined cycle plants, the hot gases operate gas turbines and then the same gases at lower temperature and velocity heat water in heat recovery boilers, the steam from which operates one or more steam turbines. Also, fossil fuel boilers generate steam for a wide variety of industrial processes. The basic process in all cases is combustion which by its nature produces thermal and pressure perturbations in the air which propagate as sound waves. Because of the slow

rate of flame-front propagation and the high energy release involved in the combustion, the perturbations, and thus, the sound waves produced, are of low frequency and high intensity.

Furnace and boiler noise is often mixed with induced or forced draft fan noise, but where combustion is rough, the low frequency rumble is often clearly distinguishable. The pressure pulsations can readily shake windows and cause doors to rattle against their stops.

Both steam and gas turbine systems radiate considerable noise from both turbine casing and the connected ducts and piping. The gas turbine's inlet and discharge are often open to atmosphere. Without mufflers they generate noise which is generally unacceptable. The inlet radiates the intense noise at compressor blade-passing frequency and the discharge radiates the combustion noise. The inlet blade-passing sound is a high pitched signal like a siren. The exhaust noise is like the sound of jet aircraft exhaust.

Electrical power transmission systems can cause three types of acoustical noise that can easily be heard in many rural and suburban locations at levels quite high, with respect to the ambient noise. These are substation transformer hum, high voltage corona and switch-gear and circuit breaker operations. Transformer noise is usually highest in level at light loads occurring generally late at night. Transformer noise is characterized by the pure tone harmonics of 120 Hz. As the load on the transformer is adjusted, the signal changes character. In open country, substations can be heard for distances up to half a mile or more. The levels at 1000 feet can run in the 45 dB (A) range.

Corona noise which sounds like frying has a range of 50 to 70 dB (A) below the lines, and approaches these levels at houses along the transmission line right-of-way. It is highest in level when the corona discharge is most severe, during periods of high humidity, rain and fog.

The noise from air quenched circuit breakers is an explosive sound like a gunshot. When the circuit breaker operates, air at over 800 pounds per square inch gauge is used to cool and quench the breaker gap as the breaker opens. The result is a high pressure acoustic pulse which can run as high as 95 dB (A) at 1500 feet.

Fluid Control Systems

Pumps, both within and outside of buildings in industrial plants, generate high level noise. Generation of noise in pumps is caused by sudden changes in any of the flow parameters, volume, velocity and pressure, by turbulence, and by the mechanical noise generated by the bearings, seals, couplings and loose parts. The noise is transmitted along piping and conduit and is readily radiated from the pump casing, equipment enclosures and lightweight structural and building shell components.

Compressors generate noise at the inlet because of the rapid changes in velocity that occur as the inlet is either opened or closed in a reciprocating compressor or as the blades pass the cutoff in a centrifugal compressor. In axial flow compressors, the noise originates through the inter-

action of the fixed and rotating blades at the blade passing frequency. This noise is radiated from the casing of the compressor, connected structural members, and housing elements as well as from the downstream piping and ducting.

Fans and blowers generate noise in a manner similar to compressors, but work at lower static pressures. Many fans are exhaust or induced draft devices which are ducted on one side, but open directly to atmosphere on the other side. The noise generated by a fan will, in general, be a minimum at the most efficient operating point for the fan. Materials-handling blowers have an additional noise source, the interaction of the blade and the material itself, e.g., the scrap blower in a paper-board plant.

Any obstruction in a fluid flow system causes a change in velocity and can generate vortices at the trailing edge of the obstacle. In addition, many flow control devices obstruct the flow, e.g., fire dampers, and may generate severe turbulence downstream. This results in the generation of vortex noise, turbulence noise, and in some cases, intense pure tones due to the interaction of the vortices with some resonance condition in the pipe or duct.

Process Equipment

The term process equipment encompasses a wide range of systems and machines. Typical examples will be given, but it should be fairly easy to compare any process or machine to the list of sources, radiating systems and resonators in order to determine the acoustical system responsible for the noise associated with the particular device or system in question.

There are numerous sizes of mills ranging from table-mounted units to those enclosed by a large building, with basically the same process in each. A number of heavy hard rods, balls or knives within the mill, work upon the material to be milled, dividing the substance under the pressure of the balls, rods or knives until the material is reduced in size to the range desired. It may then be separated by size using vibrating screens, mechanical separation or flotation separation. In any case, the housing of the mill is acted upon by a large number of impacts. Because of the large relative area, the housing radiates the milling sound quite well. Connected with the mill are sets of gears, belts and bearings, which also generate large forces because of the energy being transmitted is high. Thus, a mill may generate bearing and gear noise in addition to the sound of the milling itself.

Crushers, particularly ore and stone crushers, require large amounts of power which is released in the destruction of the bonds holding together the particles of the material being worked. The result is a rapid series of high energy impacts. Crushers are often located out-of-doors or in lightweight sheds, and in either case radiate low frequency noise as well as bearing and drive equipment noise from the crusher structure, enclosure, or building.

Saws

Circular saws generate noise by siren action as the teeth pass fixed elements in the saw and as

they pass into and out of the material being worked. Saws also ring in the manner of a gong, due to a plate resonance which can be excited readily by the teeth as they strike the work and by the siren tone. Even if used indoors, saws can generate noise which radiates into the community.

Cooling Towers

Among the major outdoor noise sources are the cooling towers used as heat exchangers in industrial processes, power generation and air conditioning. The cooling water is sprayed into an air stream resulting from the action of a powerful fan or blower. The water flows over a "fill" material which enhances evaporation by providing a large surface area for contact with the air stream. The combined heat transfer due to evaporation and conduction provide the required cooling. The noise generated by the fans and blowers is similar to what can be effected from such fans. However, they often generate low frequency noise because of low speeds and few blades. These conditions are dictated by the fact that these are low static pressure, large volume devices of great physical size. Another component which generates cooling tower noise is the water splash. This contributes a distinctive high frequency sound to cooling tower noise. When the fans are turned off, the splashing noise can be quite annoying.

Flare Stacks

In the petro-chemical field the disposal of waste gases is often accomplished by burning them at the top of a tower where the products of combustion can mix with ambient air and can diffuse sufficiently to reduce both concentration and temperature. The result is that the combustion takes place in the open at the top of a tower, providing clear line-of-sight sound propagation to the neighboring community. The sound is generated both by steam injection often used to suppress smoke, luminosity and instability of combustion, and by combustion instabilities often related to moderate and high wind velocities, flowrates and port characteristics.

Mechanical Power Transmission

The transmission of mechanical power can readily generate high noise levels as a result of friction and impact noise sources. Slight imperfections in gear teeth cause acoustically significant perturbations in the force transmitted. These perturbations are often amplified by resonators in the gear-shaft system and are effectively radiated by the machinery housing. The mechanical perturbations also shock-excite some components such as gears which then are free to vibrate at their resonance frequency. Here again, the part and its associated structure and housing may radiate the sound into the community.

Belted systems can generate noise by several means, the most common of which is friction noise. In general, belt generated noise is not a major problem until other noise sources are eliminated. Chain drive systems are basically impact generators as long as they are well lubricated, but if not lubricated, they can become friction noise generators and in some cases, the friction load on the bearings increases the bearing noise.

Bearings in transmission systems are usually designed to minimize friction. However, poor maintenance and overloading can soon turn bearings into high level noise sources. Since they are attached to the structure and often the machine housing, they can cause considerable noise to be radiated into the community.

High Pressure Atmospheric Inlet and Discharge

Rapid pressure fluctuations such as those occurring at the discharge of a diesel engine, or the inlet of a compressor, are radiated from the inlet or discharge as acoustic signals. The signal usually has a tonal quality or contains a pure tone (and harmonics) at the rate at which the port(s) open or close. At the engine discharge, the pulsations may have initial pressures at many times atmospheric pressure. In compressors, the large volume involved often leads to high velocities in attached piping. The pulsations from the compressor inlet are transmitted as high velocity perturbations down the pipe to the atmosphere where the pulses look very much like the exhaust pulsations from an engine.

Continuous flow discharge from steam, air and gas lines, and blow down from high pressure vessels and piping systems generate high level noise through turbulent mixing of the jet with the ambient air. At pressure about twice atmospheric, the flow from an air line becomes sonic; that is, the velocity at the outlet is at the speed of sound. At pressures above this, the velocity remains sonic, but the nature of the flow changes and can be supersonic downstream. In either case, high acoustic pressures are generated. The noise level is a function of the eighth power of the Mach Number below sonic velocity and depends mainly on the square of the pressure ratio across the opening above sonic velocity. The exact level is influenced, however, by the temperature (second power), molecular weight and compressibility factor for the gas (both inversely as the second power).

Materials Handling

The noise caused by materials handling is among that most often heard outside of many plants. Fork-lift trucks and front loaders and a variety of cranes moving around the yard generate noise with their motors and sometimes with their loads. Electrically operated cranes of large capacity can be heard over large distances late at night and are sources of complaint mainly because of the pure tone component. Conveyors make noise from two major sources, the material conveyed striking the sides of the chute or enclosure, and the bearings and rollers on which the moving belt, or in some cases, the material themselves move. Belt conveyors impose large loads on the bearings and rollers and these, in turn, can generate noise which is readily radiated by the enclosure and structure. The sound of the large number of wheels of the skate-wheel conveyor, because of the nature of the wheels and the structure, can radiate at levels which may exceed acceptable community goals.

Large vibrating shakers used to empty hopper cars radiate low frequency signals into the community by means of the large radiating area of the

side of the car. The noise is often a maximum level below 30 Hz and can rattle doors, windows and the china and glassware in a house at several hundred feet. The noise level at the house is usually 80 dB or more at the exciting frequency. At this level, no earth vibrations will be measured and the signal may only be heard by a skilled observer when the area is noisy at higher frequencies. This is due to the reduced sensitivity of the ear at low frequencies, as well as the masking of low frequency noise and tones by high frequency noise. However, the low frequency acoustic waves cause the walls of the building to vibrate and, in turn, cause relative motion between doors, windows and shelves and the rest of the structure. High frequency vibrators (actually 60 and 120 Hz) will also radiate effectively when attached to large sheet metal hoppers. However, the noise level can be six to 15 dB higher when internal springs and rubber dampers break or slip out of position.

Other out-of-doors noise sources are the impact of large parts on other parts of loading platforms, the operation of dockside and platform elevators, and the use of powered material handling tools.

Plant Traffic

One of the most difficult noises to define and control in a modern industrial plant is traffic noise. The sources are trucks for the delivery and shipping of goods, rail cars in the shipping and classifying yards, and the employee automobile traffic. These sources might be only a moderate contributor during the day, but at night they may stand out against a much quieter ambient noise level. This will be particularly true where the plant operates a second shift and plant noise drops in level just before the outward flow of cars. Also early morning deliveries, before plant opening, can cause distinctive and annoying noise.

Architectural Deficiencies

The design of industrial plants must take into account the types of noise that will be generated within the plant. Openings made in the plant to install new equipment create a problem to be dealt with carefully. Among the most important items to consider are the adequacy of the basic structure and enclosure, and the prevention of any openings through which noise can escape inadvertently. Plant ventilation must be accomplished without allowing the vent openings to act as transmission paths between the internal noise and the community.

THE RESPONSE OF THE COMMUNITY TO INDUSTRIAL NOISE

The noise which is heard in a given location from sources far and near, including readily identified noises such as passing cars or barking dogs, is the *ambient* noise for that location. Removal of, or shutting down, all local sources under investigation leaves the only sound arriving at the measuring location the *background ambient* noise. The background ambient noise in a community usually consists of distant transportation noise.

Acceptability of Noise in the Community

Noise in the community may or may not be

acceptable to the workers and citizens in the area. Without some "acceptable" noise to mask the more distant sounds and day-to-day activities of our neighbors, we should find life intolerable. Thus, the ambient noise serves a useful social function, as long as it stays within certain bounds. Noise becomes unacceptable in any particular situation when it is distracting, especially during creative activity and when it interferes with sleep or with speech communication. It is also unacceptable when it interferes with the ability to hear speech or the sound portion of television, radio or recorded programs. Industrial noise can probably be acceptable at these relatively high levels, 50 dB (A) or more, out-of-doors when it meets certain criteria:

- a) it is continuous,
- b) it does not interfere with speech communication (on the patio, at the dinner table, or in the office),
- c) it does not include pure tones or impacts,
- d) it does not vary rapidly,
- e) it does not interfere with getting to sleep, and
- f) it does not contain fear-producing elements.

There are many other parameters which influence the acceptability of noise by individual residents or groups of residents exposed to any particular noise. Thus, although physical measurement of the sound level is important, it cannot effectively predict the response of any specific neighborhood or community to a particular noise source. In fact, the relationships as will be determined later, between the community and the operator of the noise source, and the responsiveness of the local political authority, may have a greater influence on acceptability of a noise than the noise level or quality.

Measurement and Evaluation

Both the A-weighted sound level and octave band analyses have been the major physical methods for measuring noise for purposes of evaluating its effect on the community. Octave band analysis permits the comparison with contours such as the noise rating chart or a municipal code. Studies have shown that even though it was designed for another purpose, the A-weighting does rank human response to noisiness and loudness quite well over a wide range of levels. Other schemes using manipulation of octave band data such as the Perceived Noise Level (PNL or PNdB)¹ or loudness² in sones have been used with some success for particular applications. The PNL is derived from equal noisiness contours similar to equal loudness contours but with a sharp increase in sensitivity in the range 1500 and 8000 Hz. In an effort to provide a single reading comparable to the A-weighted measurement, the D-weighted curve based on the 40 Noys perceived noisiness contour has been used.

None of the methods used except Composite Noise Rating (CNR),³ based on the Noise Level Rank Curves (Figure 46-1) have shown any relation between noise and the community response.⁴ Recent efforts to use single number

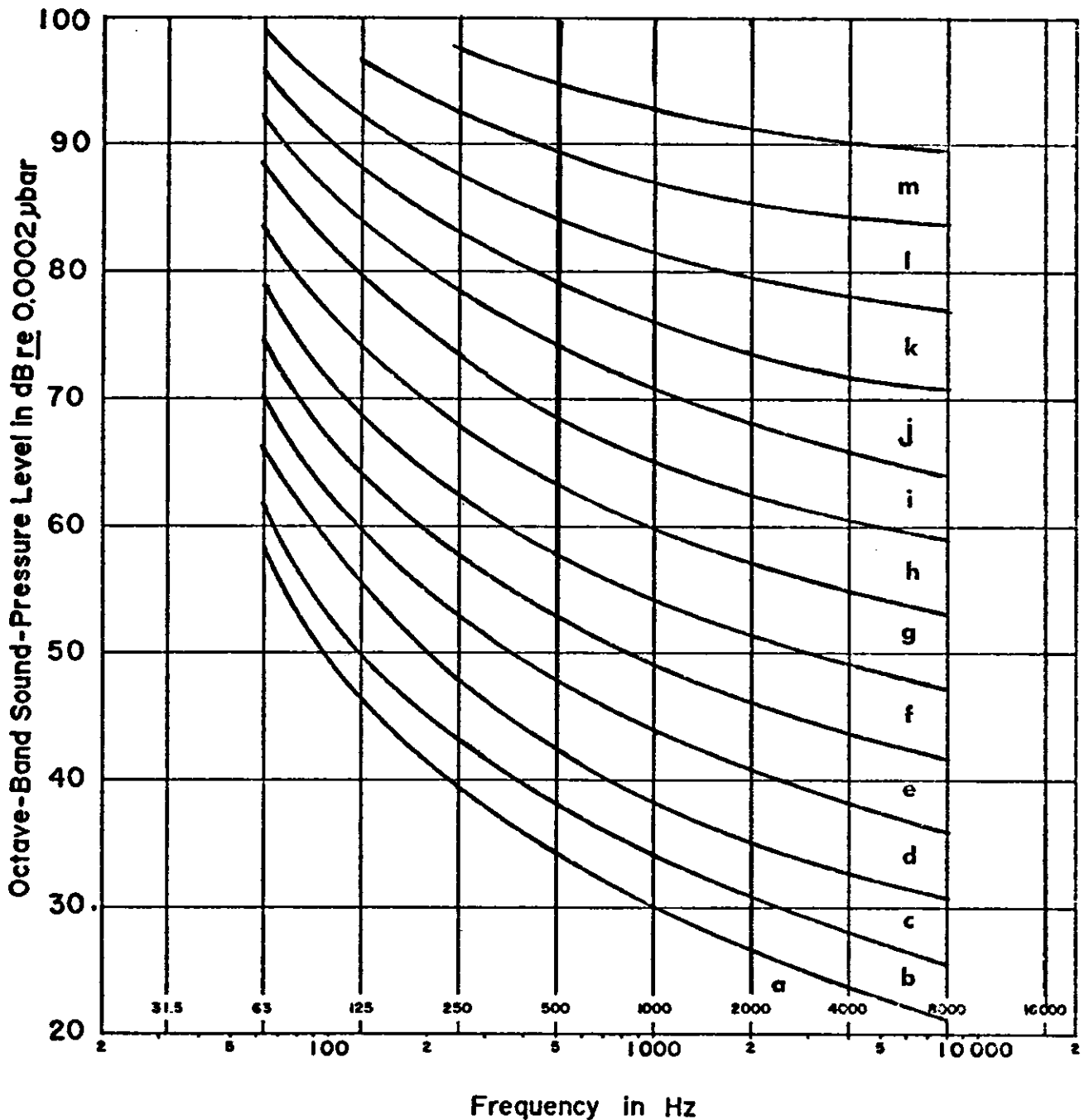


Figure 46-1. Noise Level Rank Curves.

measures such as the A-weighted level alone or Noise Pollution Level (NPL) have not been successful.⁵⁻⁶ A new effort using the A-weighted level modified by the same factors used in CNR has been proposed by Eldred and tested in a number of situations. Called "Normalized Community Noise Equivalent Level (NCNEL), this measure is based on the daily time history of the noise exposure expressed in terms of the A-weighted reading occurring in three periods: day, evening, and night. A table of adjustments covering the nature and extent of the exposure, the ambient

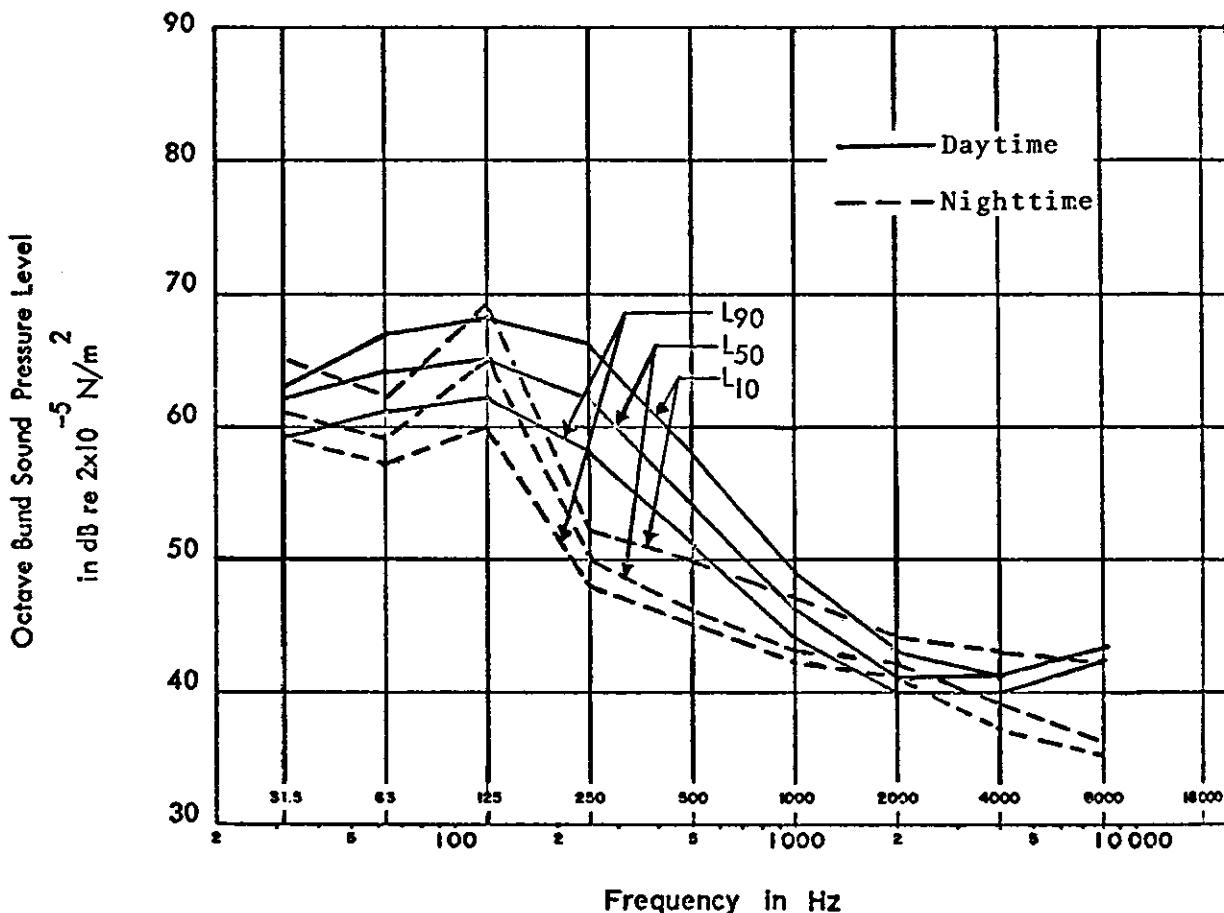
levels against which the noise is heard and the attitude of the persons exposed, is used to adjust measured values, (Table 46-1). When the adjustments are made, the NCNEL may be plotted on a chart that indicates the expected range of response of those exposed.

Noise Pollution Level (NPL),⁵ which is currently quite popular, attempts to use the statistical properties of the noise exposure to describe its noisiness. NPL is defined as $L_{eq} + 2.56 \times s$ where L_{eq} is the energy average of the noise as indicated on a level recorder or on a statistical

analyzer. Here, s is used as the standard deviation of the noise levels from a large number of one second samples taken during the measuring period. Unfortunately, NPL does not distinguish between the quiet residential background on which are superimposed many children at play and passing neighbors' cars versus the rather steady but high noise level of a downtown commercial area. There is not enough information in the statistics alone to describe the noises that do or do not cause a large standard deviation. One common treatment of data is the use of the tenth and ninetieth percentile of the measured levels to indicate the nature of the noise exposure. The 90 percentile values are considered to be the background ambient (the noise levels are above this value 90 percent of the time, while the 10 percentile values are those of the intrusions). The spread between the two is related to the standard deviation, but the absolute levels indicate its effect on speech communication.

Effect of Social-Political Environment

The response of a community or neighborhood to an industrial noise is, as has been noted above, not necessarily related to the level of the noise. There are many influences, not the least of which is an interaction between the industry and the municipal council and the citizens. It is sometimes two-sided and sometimes three-sided, but it is invariably a process of accommodation on each side. Whenever an industry proposes to locate a plant in a municipality, it has decided to do so on the basis of at least a preliminary investigation of the site. Corporate officials will have talked to local officials and there is some anticipation on both sides that the industry will provide jobs and tax income to the community and that the municipality will welcome the industry by accepting the gaseous, particulate, and liquid wastes and the increase in street traffic. However, after the initial decision to build a plant is made, the company must submit plans for zoning approval at one or



U.S. Environmental Protection Agency: Noise from Industrial Plants, Report NTID 300.2. Washington, D.C.

Figure 46-2. Example of Community Statistical Noise Spectra Obtained from Daytime and Nighttime Surveys. L_{90} , L_{50} , and L_{10} percentile values were obtained from 100 samples with one second integration time.

TABLE 46-1

Level Rank Chart. To Obtain Composite Noise Rating of a Noise Exposure (CNR), the Sound Spectrum is Plotted on the Chart and the Highest Level Rank Band Penetrated, Determine the Level Rank. The Level Rank is Then Adjusted One or More Steps According to the Table.

LEVEL RANK CORRECTIONS FOR CNR

a) Very Quiet Suburban	+1
Suburban	0
Residential Urban	-1
Urban Near Some Industry	-2
Heavy Industry Area	-3
b) Daytime Only	-1
Nighttime	0
c) Continuous Spectrum	0
Pure Tone(s) Present	+1
d) Smooth Temporal Character	0
Impulsive	+1
e) Prior Similar Exposure	0
Some Prior Exposure	-1
f) Signal Present: 20% of Time	-1
5% of Time	-2
2% of Time	-3

more public meetings. Officials must answer questions from municipal officials and the public. The process may have to be repeated four or five times. Finally, the plans must go to the municipal governing body where public and local officials can repeat the process. Some citizens groups have been known to arrive with lawyers and experts, while the company arrives with top officials and its experts. After appropriate parrying, each side offers some accommodation, and then the governing body may decide to approve the plans or ask for resubmittal. In all of these proceedings, noise is likely to be an important consideration. When the decision to accept the plant is given, the company involved may withdraw its plans and seek another site in a different municipality because it has sensed the hostility of the community that it will have to live with for many years. Even where the approval is granted, the municipality still maintains control. When the plant is completed it cannot be occupied without a certificate of occupancy. This must be issued by the building inspector who will have been monitoring construction. If he and the other officials are not satisfied, no Certificate of Occupancy will be issued until the "deficiencies" are "corrected." Finally, the municipal and state health officers and the state labor department must approve the plant and its operations.

Thus, the process of accommodation works to maintain some moderation of the noise radiated into a community neighboring an industrial plant (Figure 46-3). Even where a plant has existed for many years in reasonable harmony with its neighbors, a change in the plant that allows an increase in sound levels in the neighboring community is likely to cause an immediate response on the part of the neighbors. In some cases this results in demands for lower noise levels than ex-

isted prior to the change. In some cases the interpersonal relations between plant officials and neighbors may result in continuing skirmishes that preclude any satisfactory accommodation on the part of the parties involved. Even when the plant offers to buy neighboring homes at a premium, some neighbors may refuse, even if almost all of the remainder of the neighbors have left what was a substandard housing area.

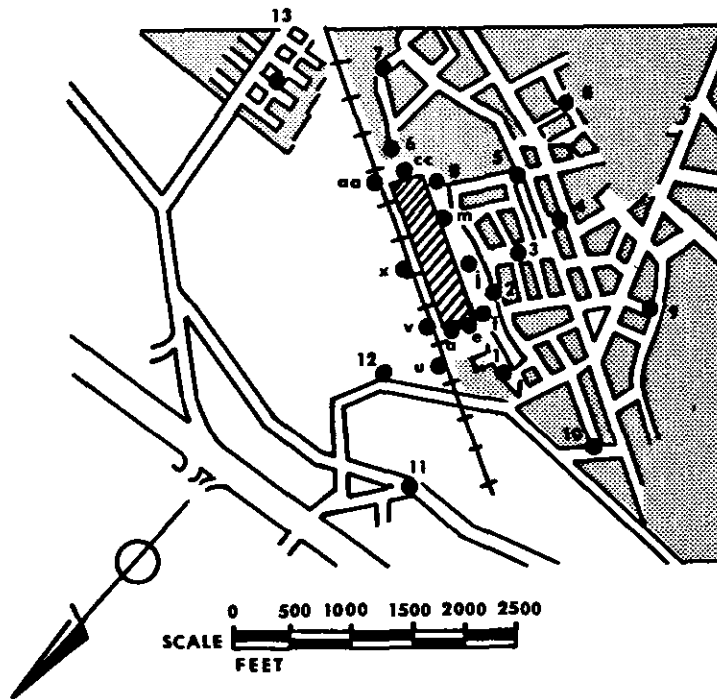
In some locations, single individuals have kept up such fights with major industries and have forced local officials to take legal action for violations of local health statutes even though the enforcement results from a personal vendetta. In general, the accommodation process has maintained the noise levels in communities across the country at levels just below that at which neighbors will complain (Figure 46-4). These noise levels may be higher than is socially desirable, but often they are also just below the noise from transportation noise sources, nearby highways, truck routes, and parkways.

The current effort to abate transportation noise may leave industrial noise as the major noise source in some areas. With the industries now clearly setting the ambient level, it may be that a new round of accommodation will occur.

THE CONTROL OF INDUSTRIAL NOISE SOURCES



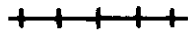


Industrial noise sources expose both the employees within the plant and the neighbors in the community. Often the same machine producing levels of 90 to 100 dB (A) around the machine indoors can be heard in the nearby residential neighborhood at levels from 40 to 60 dB (A). Some industrial noise sources as outlined earlier are out-of-doors and may or may not expose employees to hazardous noise levels, but because they can generate high levels of noise they can be heard at distances up to a mile from the plant. Close to the plant the noise levels may be well above the ambient, and can be unacceptable. The following section discusses the general methods of quieting industrial noise sources, and in some cases, mentions specific hardware.

The first requisite for a noise reduction program is a carefully done noise survey. Made at or near the plant boundary or closer, it should be possible to identify the major contributors to the noise in every direction around the plant. It may be necessary to make some measurements during a shutdown, and others close to small machines, to examine how much noise they might contribute to the total sound level in any given direction. With this information, the amount of noise reduction required at each machine may be evaluated. From the physics of the situation it is clear that if three or four different sources contribute about equal energy at a given point at the plant boundary, and thus, in the community beyond, all must be quieted to some degree. Clearly, if four machines generate roughly the same noise with about the same spectrum, eliminating the noise from two will only cause a three dB drop in level, and shutting down three would yield about



	Community Noise Levels in dB(A)												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Weekend	46	54	45	39	41	43	-	-	48	41	41	51	43
Weekday	50	59	44	42	42	40	44	40	41	44	39	53	43
Weeknight	52	61	46	40	43	45	43	40	41	41	42	49	42

	Plant Property Line Noise Levels in dB(A)										
	a	e	f	j	m	q	cc	aa	x	v	u
Weekend	50	62	59	68	55	41	44	40	60	65	52
Weekday	49	64	61	68	59	49	50	49	66	68	55
Weeknight	51	64	63	69	58	48	41	46	61	65	54

Key	
	Industrial Noise Source
	Residential Area
	Railroad Track
	Highway
	Measurement Location

U.S. Environmental Protection Agency: Noise from Industrial Plants, Report NTID 300.2. Washington, D.C.
 Figure 46-3. Example of a Noise Survey around an Industrial Plant. Levels were measured directly with a sound level meter.

Community Reaction

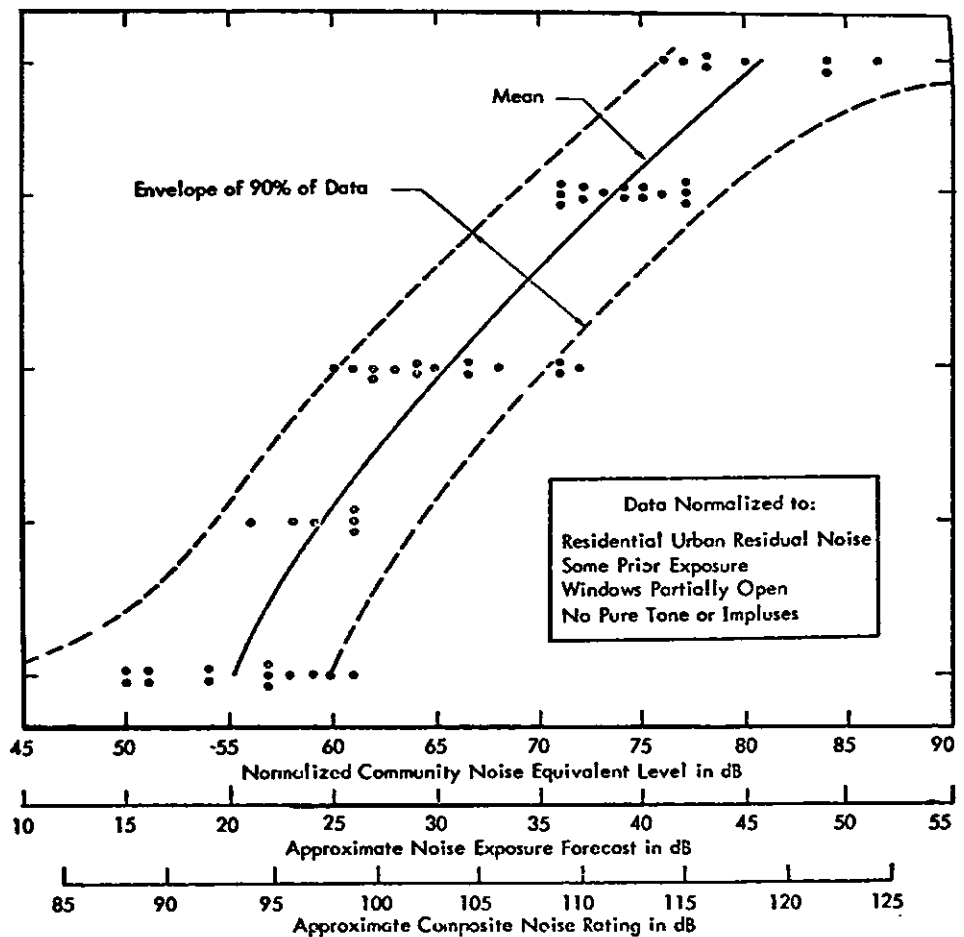
Vigorous community action

Several threats of legal action, or strong appeals to local officials to stop noise

Widespread complaints or single threat of legal action

Sporadic complaints

No reaction, although noise is generally noticeable



U.S. Environmental Protection Agency: Noise from Industrial Plants, Report NTID 300.2. Washington, D.C.

Figure 46-4. Relationship of Normalized Community Noise Levels and Other Human Response Scales and the Expected Community Response. (From Community Noise, U. S. Environmental Protection Agency Report NTID 300.2).

six dB reduction. Thus, a careful examination of the options is in order after the data are assembled.

Once the decision to quiet a given machine is made, detailed sound measurements and a study of the entire machine on a systems basis is in order. The sources within the machine must be identified, the various transmission paths for acoustic energy must be found by both inspection and measurement (acoustical and vibration), the radiators must be located, and finally, the resonators or feedback mechanisms must be found. When this study is completed, it will probably be clear what measures will provide the most noise abatement at the least cost. It may be possible to modify the source, leaving the path and radiators alone, or it may be possible to operate on two, three, or more of the system elements to varying degrees yielding an optimized-cost treatment of the system to produce a specific minimum required noise reduction.

Source Noise Reduction

Intentional impacts are used in forging, shearing and stamping. The desired result is achieved

only by an impact. Source reduction is difficult, although in shearing and stamping, die design and rate of operation do have a major influence on the noise. Also, the nature of the metal being worked strongly influences die design and noise output. Increasing the total time for the actual work on the material will usually reduce the sound output. This may reach a limit when the total stroke time is used for work. Any further change leads to a reduction in output. Many parts of presses and shears radiate the noise unnecessarily. It is possible to enclose partially some automatic presses; and large radiating surfaces, including belt and chain guards, can be damped as described below. The use of plastic shields and snap-out barriers close to the stamping dies should permit a reduction of several dB at the operator's position.

Unintentional impacts can be found by inspecting the clearances with the machine operating with illumination from a stroboscopic light source just off synchronism with the machine. Extreme care must be used not to touch parts that look like they are "standing still." It may be necessary to provide viewing ports or to use

mirrors to make the required inspection, but the results may be surprising. Rods and levers that appear to clear other parts when the machine is "turned over by hand" will whip at high speed with some being in mechanical resonance. Others may just be inadequately designed for the task. Rattling case parts can also be spotted by use of the strobe lamp. The obvious answer is redesign of the part, either using a more suitable section to prevent flexure or better connection at "crank-to-lever arm" connections that whip sideways. Each situation is different, and some will tax the designer's ingenuity. The problem is basically mechanical design, not acoustical.

Gas flow noise sources can often be controlled through the use of mufflers. Mufflers for high pressure lines are made in sizes for pipes from $\frac{1}{8}$ inch diameter up to 60 inches in diameter. They can provide extremely large reductions in noise level when correctly designed and made. The sizes from $2\frac{1}{2}$ inches up are often called snubbers and are offered in a wide range of styles including steam and water separator units. Units for compressor inlet and engine discharge are designed to operate in the appropriate temperature range while handling the pulsations encountered in the respective services. These differ from units designed to quiet continuous high pressure supersonic gas flow discharges where a special inlet diffuser section is required. In every case the muffler must be designed to withstand the high forces that occur both on the casing and on the internal baffles and tubing. Also, they must be fabricated from appropriate materials for the service intended.

Small and miniature mufflers find application on production line valve discharges. Spool valves are particularly easy to quiet using small units. The number of unintentional discharges through disconnected lines or bypass valves is surprising. In some cases these can be capped, thus preventing wastage. In other cases slight changes in process control can be made to eliminate the discharge.

Another solution to valve discharges to atmosphere is to manifold the discharge lines to a header which may serve as a muffler because of the large expansion ratio from the inlet pipe to the header. In other cases the collected discharge can be piped away to an outlet where the residual noise will be no problem or a single muffler of appropriate size used.

In some instances it is clear that the use of high pressure air is unnecessary, but it is used because it is available. A pressure reduction device (regulator) at or near the machine can reduce the sound output considerably.

Valve noise in high pressure systems and the noise from centrifugal compressors radiated by the piping can best be eliminated by "lagging" the piping or valve.⁷ The use of a two- to four-inch thick medium density mineral wool or glass fiber "spacer" covered by a one lb./sq. ft. jacket of lead can yield high frequency noise reductions of 30 to 50 dB. Higher reduction values may be obtained, but it is difficult to cover every valve and

pipe support. Actually, flanking transmission usually begins to predominate beyond about 50 dB of reduction. The jacket may be sheet metal or any appropriate weather resistant material providing the required weight. Asphalted roofing felt, leaded vinyl and leaded neoprene have been used in some applications.

The control of perturbations in fluid flow is usually a job for the machine designer. This involves the design and spacing of the fixed and stationary blades in compressors, the blade shape and cutoff design in centrifugal pumps and blowers and fans, and the nature of flow control in positive displacement pumps. In general, these devices lose efficiency rapidly when changes are made from the optimum design. However, casing design to minimize cavitation in pumps can yield lower noise output. Use of pressure equalization chambers, snubbers and mufflers in both liquid and gas systems and lagging have been the accepted methods to date.

In fans and blowers every effort made to reduce the tip speed of the unit does help to reduce noise, but tip speed alone is not an adequate index of fan noise output. Noise in fans and blowers may be increased by having struts or braces in the air stream such that, with axial flow units, the blades cut the wakes made by the obstruction. This can produce intense tones when the blade-passing frequency coincides with the vortex shedding frequency of the air-flow obstruction system. In low pressure air handling systems noise generated by turbulence at turns, dampers and mixing boxes can usually be avoided by good design. However, air conditioning style mufflers can be used. These are usually a series of sound absorbing baffles on six to 12 inch centers. The sheet metal work is relatively light for residential and commercial building use. Special industrial grade mufflers are available, fabricated from heavier gauge metal with better assembly. Here again, material of construction is governed by the environment and the gas handled. These mufflers have sometimes been applied to cooling tower inlets. Cooling tower discharges may be equipped with mufflers, but their effect on the fan characteristics may be so great as to raise the source noise and yield no net effect on the sound output.

One way to eliminate noise is to get rid of the source by modifying the process or system. Many industries faced with problems related to cooling tower noise use wells and return the water to the ground after passing it through a heat exchanger. In many cases local streams used for process water have been used for cooling, but current and proposed restrictions on thermal pollution will keep cooling towers in the picture for some time to come. The use of natural draft cooling towers solves most of the noise and discharge temperature problem, but these are large and costly structures.

A change in design and operation can often effect the appropriate noise reduction, sometimes at a cost in efficiency. In one case, when night operation of one cell of a three cell cooling tower caused neighbors to complain, the electrical cir-

cuits were modified, the motors rewound for two-speed operation and two cells were operated at about half-speed at night. The fan noise varies as the fifth power of velocity and operating two units only brings it back up three dB. This yields a net drop of about 12 dB.

Another case of changing processes is to switch from deep drawing to spinning for fabrication of large objects of circular section. A change from oil fired combustion with high pressure air for atomization and combustion to gas firing with a totally-enclosed muffled burner has been used successfully on single and multiple burner furnaces. Also, the switch from induced draft operation where muffling hot stack gases is difficult, to a forced draft system with inlet mufflers, results in considerable noise reduction. The noise radiation formerly from the top of the stack now takes place at ground level where buildings act as barriers.

Mechanical damping, most familiar as automobile undercoating, can reduce the amplitude at resonance frequencies in a panel or even in structural members, thus reducing radiation and feedback to the source, and in turn, reducing the driving forces. Damping can be effected by applied coatings of mastic or fibrous materials such as jute or wood fibers and foams. Also, friction between two metal surfaces not adhered to one another over their entire surface is used. Air trapped within the space between two plates may provide added damping. The most effective damping may be obtained with a thin layer of elastomeric damping compound between the sheet to be damped, and a thin constraining layer, such as metal foil or a lightweight metal sheet. Although damping is conventionally applied to large metal enclosures, it may also be used to control resonance of gears and sheaves by applying damping to the web or "spokes" as a constrained layer or a filler compound for hollow parts. With some components it may be possible to apply a damping disc or other mating form on one or both sides of a resonant part.

Considerable noise is generated by loose parts, rattling covers, worn bearings, and broken equipment. Reductions on the order of six to 10 dB may be achieved through maintenance alone, and in some cases, spectacular results are possible when cases are resealed or even just screwed back onto the structure.

Transmission Path Noise Control

It is sometimes difficult to determine what part of a system is the source and what is the transmission path. Sometimes the decision is arbitrary. In any case, a muffler may be used along the path or at the end of a line to eliminate not only noise generated at a given machine, but flow discontinuity noise generated at turns, dampers and valves along the way. It is sometimes necessary, especially in the case of high temperature exhausts, to split the muffling between a unit near the engine and one near the discharge. The unit near the engine will reduce the input to the exhaust pipe and minimize the possibility of shock wave formation, and the discharge unit will remove any noise

signals introduced along the way and clean up any small shocks formed. As mentioned above, manifolds are useful for collecting the discharge from several small lines and can act as mufflers. This does not always work because of resonances with the header or manifold. Appropriate baffles and inlet diffusers inside the header or manifold will prevent problems with resonance.

Inside plants, and out of doors, large barriers⁸ and partial enclosures provide considerable attenuation of noise, provided the barrier or enclosure is located close to the source and is not negated by reflections from a wall behind the equipment. Barriers with acoustical material on the surface facing the source with similar material on the wall behind can be quite effective. Enclosures are similar to barriers until they are fully sealed. Fully sealed enclosures provide varying degrees of noise reduction determined by the frequency of the noise and the transmission loss (TL) of the panel material. The TL is generally higher for more massive materials. However, even a one-to-four pound per square foot material such as damped sheet metal or cement asbestos board will yield a reduction in the A-weighted sound levels of 20 to 30 dB. If the seal on an enclosure is broken for ventilation, the TL will be reduced greatly, unless a vent muffler is installed. Such mufflers are produced as standard hardware by several manufacturers who also manufacture complete enclosures, and duct and blow-off mufflers. The vent mufflers may be equipped with fans having explosion-proof motors as required.

The use of acoustically absorbing material similar to acoustical ceiling tile can provide some reduction for interior noises heard out of doors and for some out-of-doors operations such as at loading docks. The materials used for industrial application must be fire resistant and should be applicable to large areas. Spray-on materials were popular for some time, and the recent trend away from asbestos fibers toward open cell urethane foams and cellulose materials should also provide appropriate results. Sheets of mineral or glass fiber board with perforated or decorative open-faced material (expanded metal) are also useful although they require structural support. The perforated metal must have relatively small holes on close centers, typically no more than one-half inch centers and holes from 0.06 to 0.15 in diameter. The holes and spacing should yield an open area of more than 15 percent, preferably 30 to 40 percent. The most effective acoustical materials will have high sound absorption coefficients in the frequency range in which the noise levels are highest. However, good high frequency absorption is usually desirable. For industrial applications it is not sufficient to look at the "Noise Reduction Coefficient" because this is the average of the individual coefficients for the test frequencies 250, 500, 1000, and 2000 Hz, and since the noise to be controlled is in the 2000 to 4000 Hz range (air discharges and cleaning jets), the sound absorption values at 2000 and 4000 Hz are critical to the noise reduction.

An interesting and useful facet of area noise

control with acoustical material is that the entire ceiling and walls of the plant need not be covered. A coverage of 60 percent spread over the entire area of the ceiling is almost as effective as the entire ceiling and usually a lot less expensive. Wall treatment near the source of noise is always effective. Examples have indicated 12 dB reduction at remote locations due to corner treatment close to a machine.

There are some situations where muffling, enclosure, or machine modification are not readily feasible, but moving the machine is quite simple. Moving a small positive displacement blower from one side of a plant building to another can yield 20 to 30 dB reduction at the fence on the side of the building facing its original location. This works as long as the other side does not face a residential area also. This uses the plant as an acoustical barrier. There are numerous applications of this barrier effect, and they are an economical way of accomplishing the desired purpose. It may take some ingenuity. As an example, many plants face highways and other transportation complexes, while the rear faces nearby residential zones. Although routine plant design does not locate major items of equipment along the face of the plant, it may turn out to be a reasonable design; suitable decorative screening is a low price to pay for the acoustical benefit.

Because plant buildings are designed for the protection of employees and equipment from the weather, they often do not include noise control considerations. Louvers, windows and doors may all serve to provide effective ventilation and materials flow. However, they also permit noise flow from the interior to the neighboring community. There is much to favor gravity flow ventilation, and employees in some plants resist the use of mechanical ventilation unless it is accompanied by air conditioning. However, closing up the louvers or using acoustically treated louvers and forced draft ventilation with muffled fans will solve many noise problems. Curtain wall plants using corrugated sheet skins that are not sealed, or damped, may let sound out through both the wall and leaks. Plant design must account for the high noise levels inside and the large radiating area provided by the walls. Also, loading dock and plant storage yards where active materials handling is carried out at night may require some planning in order to control noise. The use of perimeter storage sheds as barriers can effect noise control.

Administrative Procedures for Noise Control

Traffic noise, especially for the end of the second shift and early morning arrival, can readily be effected through an education or training program for the employees. This must be a positive and continuing program and make use of appropriate traffic control systems within the parking lot and around the plant. In some cases the use of multiple exits help. The problem of employees' talk at side yards adjacent to neighboring residential property can also be controlled through a continuing education and internal public relations program.

PLANT NOISE ABATEMENT

A number of sources discussed at the beginning of this chapter require a multistep approach or multielement approach in order to quiet the entire system. Steam power stations, for instance, require noise control of fans, blowers for forced and induced draft, materials handling systems, burner noise in fossil fuel systems, and steam and gas turbines when those facilities are used. Heaters and furnaces in petro-chemical and process industries may require mufflers for the high pressure blowers, cooling blowers and the burners themselves.

Transformers are extremely difficult to quiet internally, although premium transformers are available which provide a modest amount of noise reduction. The most common technique today is to build partial enclosures around the transformers using special sound absorbing concrete blocks which are "tuned" to absorb the transformer generated signals.

Circuit breakers have received moderate attention with respect to quieting, but because they are not activated frequently they should not be a consistent problem. Location in an appropriate area is probably the most convenient method of handling them. Corona noise is currently under study.

Another area in which a multielement approach must be used is in process industries where each machine or process element must be examined for noise generating capability and then quieted according to need. Large mills located inside buildings may cause no community noise problems so long as the building is well sealed. In some cases, the building supports the mill and radiates the noise. On the other hand, rock crushers located within a sand and gravel operation may be totally exposed to the neighbors. In this situation, a partial enclosure of appropriate sound absorbing and transmission loss material combined in one shell would reduce the noise sufficiently to eliminate community complaints. Such materials are commercially available. Items such as switch valves, blow down lines and high pressure air or gas bypass lines should all be equipped with appropriate mufflers.

Material handling devices such as fork lifts, motors, and cranes can be quieted by attention to the engine inlet and discharge mufflers. Electrically operated overhead cranes may require a small motor enclosure with forced air cooling if the unit is to operate out-of-doors at night and not be heard by neighbors. Conveyors are subject to both quieting through maintenance and improvement in bearings, or they may require partial or total enclosure. Conveyors that carry materials adjacent to or through a community overhead, may require a partial enclosure with only the top open.

These are but a few examples of the application of noise reduction techniques to the outdoor noise generators discussed at the beginning of this chapter. However, an examination of each piece of equipment or each process in the larger system or process being studied should make clear

those methods of noise control which are applicable and those which *may* be applicable if the effort is warranted.

FUTURE OUTLOOK FOR INDUSTRIAL NOISE CONTROL

As the citizens in the community become more conscious of noise and more aware of the noise in their environment, it appears that there will be an increasing demand for a quieter environment. Not every community today wants to increase its tax base at the expense of new industrial plants and their prospective noise sources. It thus appears that more stringent noise control requirements currently exist and are becoming commonplace.

In the light of the potential need for more stringent requirements, it is heartening to note that the knowledge in the field of industrial noise control is increasing and that a large body of technology is available to industrial machinery and industrial plant designers to achieve the desired acoustical goals. The payoff is an economic one. It costs money to carry out the design and development work for quieter machines and plants. The cost is not reasonable unless all industries within a given product area are required to meet the same criteria. This is discussed in detail in studies by the Environmental Protection Agency

in its report to Congress. For a discussion of the Environmental Noise Control Act of 1972 as passed by the House of Representatives see the October 18, 1972, issue of the Congressional Record, p. #10287.

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CHAPTER 47

SAFETY

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HISTORICAL PERSPECTIVE

Neil Armstrong's first step on the lunar surface on July 20, 1969, climaxed the stunning success of one of the greatest scientific achievements ever accomplished by man to that date. What made the Apollo XI program possible was a combination of loss control disciplines and engineering skills that brought about the design and assembly of the most reliable flight products ever produced. Of all contributions to this success, the application of a system approach was probably the overriding key. At all stages of design, manufacture and operation, the man-machine-environment subsystems were considered as interrelated, interdependent components of the overall system.

The meaning of safety in aerospace no longer represented the simple "freedom from hazard for man" as defined by Webster in the intercollegiate dictionary. Safety had come to mean "freedom from the man-machine-media interactions that result in: damage to the system, degradation of mission success, substantial time loss or injury to personnel." In effect, the desire to insure the gross safety of the system and the ultimate mission's success brought about a level of total safety confidence never before realized in the annals of industrial management.¹

With the accomplishments of space safety achievements well known, it is appropriate to take a brief look backward at the occupational safety movement to understand in part the direction taken in the past. The compensation-oriented specialist, largely influenced by attention focused on the appalling rate of death and disability associated with machinery and equipment, concentrated his attention on the man sub-system, with traumatic *injury prevention* as his primary target. To the early safety practitioner, the terms "accident" and "traumatic injury" were almost synonymous. While occupational disease, fire and property damage control were philosophically associated with industrial safety, actual accident prevention practices were largely devoid of these considerations.

Without doubt, the injury-oriented safety approach, with its concentration on the sources of trauma, brought about a tremendous reduction in death and disabling injury over the years, as discussed in the next section of this chapter. However, failure to recognize the total safety interrelationships of the occupational system's man-equipment-material-environment components has created other major problems, resulting in unprecedented pressures and controls on industry by external agencies. Products liability, air, stream,

and noise pollution are some of today's major problems highlighting the need to put loss control programs in tune with technological advances of our space age.

With this historical perspective in mind, let us set the stage by discussing the terms "safety" and "accident" as they are considered by an ever increasing number of safety leaders today. The word "safety," as used by loss control specialists, has broadened considerably in recent years because of the space age influences mentioned earlier. It has more appropriately come to mean "freedom from man-equipment-material-environment interactions that result in accidents." Similarly, the practical application of the term "accident" has also evolved to the broader meaning of "an undesired event resulting in personal physical harm, property damage or business interruption." The meaning of physical harm in this definition includes both traumatic injury and disease as well as adverse mental, neurological, or systemic effects resulting from workplace exposures.² Attention has been focused on the need to consider the "accident" as a "contact" with a source of energy (electrical, chemical, kinetic, thermal, ionizing radiation, etc.) above the threshold limit of the body or structure; or contact with a substance that interferes with normal body processes.³

Advocates of this view point out that the term "accident" is purely descriptive and has little etiological connotation in its use, while association with the word "contact" as used above gives more specific direction to control methodology. Utilizing this line of thinking, safety program activities can be directed at the PRE-CONTACT, CONTACT or POST CONTACT stages of accident or loss control. For optimum results, the modern safety specialist will design his program to include considerations at all three levels of the control process, with a logical concentration of effort at the PRE-CONTACT stage. As we consider the broader implications of these newer meanings of "safety" and "accident" we more clearly see the important relationship of the safety and environmental health disciplines and the increased import of interface between related specialists.

THE LOSS PROBLEM: THE HUMAN SIDE Death and Disability

While accidental injury rates in American industry have decreased through the years, the death and disability loss problem remained gross enough as late as 1970 that our nation selected occupational safety as a major legislative target.

In 1970, occupational accidents claimed the lives of 14,200 workers and injured 2,200,000 people to the extent they were unable to return to work the day following their injury.

To express the general trends over the past 35 years, the death and disabling injury rates from 1945 to 1970 are shown in Table 47-1.

TABLE 47-1.

Statistics on Work Fatalities and Disabling Injuries

Year (millions)	Employed Labor Force	Fatalities		Injuries	
		Fatalities	Per 100,000 Workers	Disabling Injuries	Per 100,000 Workers
1945	53	16,500	32	2,000,000	3,788
1950	60	15,500	27	1,950,000	3,211
1955	63	14,200	23	1,900,000	3,055
1960	66	13,800	21	1,950,000	2,964
1965	71	14,100	20	2,100,000	2,954
1970	80	14,200	18	2,200,000	2,824

THE LOSS PROBLEM: THE ECONOMIC SIDE

Injury Costs

The National Safety Council estimated that wage losses of workers due to accidents in 1970 were \$1,800,000,000, while related insurance administrative costs were approximately \$1,300,000,000 and medical costs, \$900,000,000. In addition, other costs such as the money value of time lost by workers (other than those with disabling injuries) who are directly or indirectly involved in accidents, and the value of the time needed to investigate accidents and write up accident reports amounted to the tidy sum of \$4,000,000,000.²

Other Costs

The number of legal suits involving accidents of people on the premises of the businessman, and product defects that resulted in injury, mushroomed in the past five years, presenting management with another big loss drain that exceeded \$885,000,000 in 1970.

Sources such as industrial associations and insurance records available on limited types of property damage, lead to the conservative estimate that building damage, tool and equipment damage, product and material damage, production delays and interruptions resulted in over \$4,500,000,000 during 1970. Fire property damage alone added another \$1,100,000,000 making a total property damage loss of \$5,600,000,000 for 1970.⁴

Total Accident Costs

The economic drain from accident losses is summarized in Table 47-2 as conclusive evidence of the tremendous loss problem faced by industrial America.

THE LOSS PROBLEM: SOURCE OF WORK INJURIES

The majority of injuries that cause workers to lose time but do not result in death, permanent total, or partial disability are referred to as temporary total injuries. State labor departments report that nearly half of this large group of com-

pensable work injuries result from two major sources -- handling objects and falls. On the other hand, machinery accidents account for only 6 percent of the temporary total injuries, but give rise to 19 percent of the injuries that cause permanent partial disability. This fact clearly indicates why emphasis on mechanical safeguarding and the elimination of catch points on moving machinery should be given emphasis in any safety program. The motor vehicle is as much a culprit on-the-job as it is off-the-job, and accounts for 18 percent of fatal, permanent total cases but only a very small percent of the permanent partial and temporary total injuries.

The chart below reveals the major sources of work injuries by their severity types.⁵

TABLE 47-2.

1970 Accident Losses

Workers' loss of wages	\$1,800,000,000
Insurance administrative costs	\$1,300,000,000
Medical Costs	\$ 900,000,000
Other costs related to above (time lost, investigation time, etc.)	\$4,000,000,000
Liability costs	\$ 885,000,000
Property damage costs (including fire loss)	\$5,600,000,000
Total loss	\$14,485,000,000

TABLE 47-3.

Source of Compensable Work Injuries

Source of Injury	All Cases	Fatal Perma- nent Total	Perma- nent Partial	Tempo- rary Total
	% of Cases	% of Cases	% of Cases	% of Cases
Total	100.0%	100.0%	100.0%	100.0%
Handling objects, manual	22.6	13.9	9.6	28.5
Falls	20.4	17.4	18.5	21.2
Struck by falling, moving objects	13.6	9.3	19.3	11.1
Machinery	10.2	3.1	19.2	6.3
Vehicles	7.1	20.7	7.1	6.9
Motor	5.0	18.0	4.3	5.2
Other	2.1	2.7	2.8	1.7
Stepping on, striking against objects	6.9	2.3	5.6	7.6
Hand tools	6.1	1.5	8.1	5.3
Elec., heat, explosives	2.5	7.7	2.2	2.6
Elevators, hoists, conveyors	2.2	3.6	3.8	1.5
Other	8.4	20.5	6.6	9.0

Source: Reports From State Labor Departments Tables 1, 2 and 3 from National Safety Council "Accident Facts" 1972, Chicago, Illinois.

THE PRE-CONTACT STAGE OF ACCIDENT CONTROL

In considering the "accident" as a "contact" with a source of energy above the threshold limit of the body or structure, it is logical that sufficient effective action at the pre-contact stage of accident control could prevent most accident contacts

from happening. Such action would eliminate the very potential for personal harm or property damage.

Recognizing that it is neither economically feasible nor practical to prevent all exposures to accident sources, action at this stage of loss control could include considerations to reduce or minimize the effects of such contacts at other stages in the loss process if and when they were to occur. A well-organized modern safety program would place great emphasis on such activities as good facility inspections, safety rules and regulations, group safety meetings, supervisory training, general promotion, hiring and placement practices, job analysis, job observation, skill training, personal communications, work standards, design engineering and maintenance and purchasing standards.

Since space does not permit a discussion of each of these and other important pre-contact stage program activity areas, the author has chosen the representative few that follow. They indicate well the need for a close inter-relationship of the safety and environmental health disciplines, and clearly highlight the enormous benefits of extended efforts at the pre-contact stage of accident control.

Facility Inspection

Why Inspect for Hazards? Every piece of equipment will wear out in time. Even with ideal care and usage, normal deterioration is inevitable. Materials and tools may be placed in unsafe positions or they may be abused and damaged.

While one can speculate that a perfect preventive maintenance engineering program should negate these problems, the question is, "Who has one?" Unless hazardous conditions are steadily "drained off" by regular hazard inspections, the average plant is continually "flooded" with hazards or sources of accidental contacts that have potential for personal harm and property damage.

The Occupational Safety and Health Act of 1970 has the purpose "... to assure as far as possible every man and woman in the nation safe and healthful working conditions and to preserve our human resources..." The Act also says that each employer "... shall furnish to each of his employees employment and a place of employment which are free from recognized hazards..."

It would seem appropriate at this point to define the word "hazard" as a *potential source of harmful contact*. The word harmful in this context includes traumatic injury and occupational disease exposures; adverse mental, neurological or systemic effects; and property damage.

While inspections may be of the FORMAL or INFORMAL variety, the formal type provides management with the most effective tool for the systematic detection and correction of hazardous conditions.

What to Inspect. Although every plant has different operations, equipment and physical layouts, there are certain important items that are quite common to most and deserve special mention. The following list presents the major categories of items that one should generally consider in making a safety inspection.

1. Atmospheric Conditions: Relates to dusts, gases, fumes, vapors, illumination, etc.
2. Pressurized Equipment: Relates to boilers, pots, tanks, piping, hosing, etc.
3. Containers: Relates to all objects for storage of materials, such as scrap bins, disposal receptacles, barrels, carboys, gas cylinders, solvent cans, etc.
4. Hazardous Supplies and Materials: Relates to flammables, explosives, gases, acids, caustics, toxic chemicals, etc.
5. Buildings and Structures: Relates to windows, doors, aisles, floors, stairs, roofs, walls, etc.
6. Electrical Conductors and Apparatus: Relates to wires, cables, switches, controls, transformers, lamps, batteries, fuses, etc.
7. Engines and Prime Movers: Relates to sources of mechanical power.
8. Elevators, Escalators and Manlifts: Relates to cables, controls, safety devices, etc.
9. Fire Fighting Equipment: Relates to extinguishers, hoses, hydrants, sprinkler systems, alarms, etc.
10. Machinery and Parts Thereof: Relates to power equipment that processes, machines or modifies materials, e.g., grinders, forging machines, power presses, drilling machines, shapers, cutters, lathes, etc.
11. Material-Handling Equipment: Relates to conveyors, cranes, hoists, lifts, etc.
12. Hand Tools: Relates to such items as bars, sledges, wrenches, hammers as well as power tools.
13. Structural Openings: Relates to shafts, sumps, pits, floor openings, trenches, etc.
14. Transportation Equipment: Relates to automobiles, trucks, railroad equipment, lift trucks, etc.
15. Personal Protective Clothing and Equipment: Relates to items such as goggles, gloves, aprons, leggings, etc.⁶

Detection System Components

The specific hazards and unique aspects of each industrial operation require the safety specialist to adopt a system of formal hazard detection that best meets his specific requirements. While there may be tremendous variation in his methods, he should attempt to fulfill two essential objectives. The first is to see that certain special items or parts are inspected at a frequency in accord with the criticality of the item to prevent hazardous conditions of significant severity. These special items or parts are frequently referred to as *critical parts* and could include such items as:

gear covers	shafts
workpoint guards	chains
railings	cables
safety valves	wires
limit switches	handles
stand-up switches	eyebolts
speed controls	lifting lugs
gears	grind wheels
cables	drill points
foundations	cutting points
belts	steps — rungs
drives	brackets

Special inspections of critical parts are usually much more frequent than general inspections and may be handled differently, even within the same plant. Frequently there are several different forms and inspection methods to meet the unique problems associated with the use and application of items being inspected.

The second important objective in any good program is to conduct regular, thorough general inspections of the entire facility. Several key guideposts essential to accomplishing this goal are as follows: (1) the critical parts inspection program for an area, or a checklist of hazards common to the area, should be reviewed before starting; (2) previous inspection reports should be reviewed carefully to help familiarize an inspector with all related problems in the area; (3) a good inspector will look for off-the-floor and out-of-the-way items as well as those right on the beaten track; (4) the good inspector will be methodical and thorough, and his notes will clearly describe specific hazards and their exact location; (5) a good inspector will classify each hazard by its "potential and loss severity" to aid management in its remedial decisions (see hazard classification below); (6) the good inspector will lend appropriate emphasis to those hazards (class "A") with imminent chance for loss of life or body part, seeking intermediate temporary remedy for these "critical" hazards immediately and diligently following up their permanent remedy promptly after his inspection is complete.

Hazard Classification

While a system of hazard classification has been used successfully by fire engineers for many years, application of this specific technique in general industry is relatively new. The extensive successful use of this tool in the aerospace program has unquestionably provided the motivation for its rapid adoption by an increasing number of companies in general industry. Since hazards do not all have the same potential for causing harmful effects, it is logical that a system for classifying them by their degree of probable loss severity potential can have considerable value. The following simple classification system has proven quite successful and is very similar to the one used by OSHA inspectors to assist them in establishing the gravity of violations:

Class "A" Hazard — A condition or practice with the realistic potential for causing loss of life or body part, permanent health disability, or extensive loss of structure, equipment, or material.

Example 1: Barrier guard missing on large press brake used for metal shearing operation.

Example 2: Maintenance worker observed in unventilated deep pit with running gasoline motor servicing large sump pump.

Class "B" Hazard — A condition or practice with potential for causing serious injury or illness resulting in temporary disabilities, or property damage that is disruptive but less severe than class "A".

Example 1: Slippery oil condition observed in main aisleway.

Example 2: Broken tread at bottom of office stairs.

Class "C" Hazard — A condition or practice with probable potential for causing non-disabling injury or illness or nondisruptive property damage.

Example 1: Carpenter without gloves observed handling rough lumber.

Example 2: Worker complained of strong odor from rancid cutting oil circulating in large lathe at north end of shop.

Classifying hazards into these three categories helps to put remedial planning in proper perspective, aids in motivating the action of others on the more serious conditions, and focuses hazard control attention on the critical areas requiring the greatest concentration of time, effort and resources.

Job Analysis

Job analysis⁷ is a tool that enables the supervisor to teach and direct his employees systematically in order to obtain optimum job efficiency. Since efficiency demands maximum use and control of the men, equipment, machines and environment involved in any job, the potential sources of traumatic injury and environmental health exposures are evaluated along with all other factors associated with production and quality control. Once completed, a good job analysis provides the blueprint to teach any worker how to do a critical job the safe, productive way. The actual preparation of a job analysis provides another enormous opportunity to *detect* actual or potential sources of occupational injury or health problems at the pre-contact stage of accident control.

Methodology. Jobs that are determined to be serious risks to safety, quality or production become the "critical few" first targets for analysis. Selection may be based on the frequency or severity of past loss history or the potential for loss. The regular maintenance and updating of the analysis is an important aspect of any job analysis program. A job analysis is best prepared by actual observations of a worker or workers doing the job. When infrequently performed jobs prevent the observation method of conducting a job analysis, the technique of group discussion can be employed as an alternative.

The four basic steps in conducting a job analysis are: (a) determining the job to be analyzed, (b) breaking the job down into a sequence of steps, (c) determining key factors related to each job step, and (d) performing an "efficiency check." The final step involves determining that each step of the job is done in the best and most efficient way. This final step frequently involves a job procedure or methods change, a job environment change or a technique to reduce the number of times the job must be done. The savings alone that result from the accomplishment of this step have consistently proved to be justification for introduction of the program.

JOB ANALYSIS

Instruction Standard

DIVISION Engineering
 DEPARTMENT Maintenance
 OCCUPATION Painter

JOB ANALYZED Painting a Chair
 DATE EFFECTIVE Nov. 1, 1970
 CODE NO. EM-72

SEQUENCE OF STEPS (NOT TOO FINE OR TOO BROAD)	KEY QUALITY OR PRODUCTION FACTORS (CLEARLY TELL WHAT TO DO AND WHY)	KEY SAFETY FACTORS (CLEARLY TELL WHAT TO DO AND WHY)
1. Select work area.	1. Should be as dust-free as possible to prevent dust from sticking to painted surface while wet. This can damage finish, requiring re-work.	1. Area should be well ventilated so that toxic fumes do not accumulate, possibly causing serious illness.
2. Bring tools and supplies to work area.	2. Have all needed tools at hand before starting to avoid delay.	2. Be sure all cans of thinner, paint remover, and paint are tightly closed when not in use to minimize the dangers from fire or explosion.
3. Prepare work area.	3. Place chair on newspapers to avoid delays caused by cleaning up spills.	3. Use at least six layers of paper to absorb spilled paint remover and paint. Both of these can cause extensive damage to the floor.
4. Remove old paint from chair with paint remover.	4. Be sure all paint is removed from cracks and crevices so final finish will be uniform. Otherwise, re-sanding may be necessary to smooth out rough surfaces.	4. Follow directions on paint remover container and do not allow smoking or open flame in area to prevent fire or explosion.
5. Sand chair with sandpaper.	5. Sand all surfaces with 00 sandpaper until smooth to the touch for best results. Wipe off dust. Dust left on surface will make finish rough, requiring re-sanding.	5. Gloves should be worn while sanding to prevent abrasions and splinters.
6. Apply first coat of paint.	6. Coat of paint should be light and applied with even strokes to minimize brush marks for most attractive results.	6. Follow directions on paint container. Same as #4, NO SMOKING OR OPEN FLAME.
7. Apply second coat of paint.	7. Same as #6.	7. Same as #6.
8. Clean up area and tools	8. Clean brushes thoroughly in paint thinner; then shake out thinner. Paint left in brush can ruin brush for further use if it is allowed to harden.	8. Dispose of all papers and wipe any spilled paint from floor or other surfaces. Papers left on floor can present fire or tripping hazards.
9. Store tools and supplies.	9. Brushes should be hung up by the handle to keep weight off the bristles. The weight of the brush on the bristles can deform them and ruin the brush.	9. All paint, thinner, and remover must be tightly sealed both to preserve them and to prevent escape of fumes which could cause fire or explosion.

International Safety Academy, Macon, Georgia.

Figure 47-1. Job Analysis — Instruction Standard (Form)

There are two basic approaches in doing a job analysis. One that has been used extensively in the past is the "Job Safety Analysis" technique that produces an end product dealing purely with safety. While there are unquestionable merits for treating this important subject in this manner, the author personally favors the complete approach referred to as "Proper Job Analysis," "Total Job Analysis" or just plain "Job Analysis," as the individual plant designates. This latter approach seems to have more appeal to management people at all levels, since it is based on the new concept of safety as one of the many inseparable parts of the supervisor's job. Figure 47-1 is an example of this approach.

Benefits. While there are many benefits that come with a Job Analysis program, none is more important than the peace of mind that a concerned management group has in knowing that it has provided a tool to insure that the actual potential sources of traumatic injury and environmental health exposures have been carefully analyzed and evaluated for all critical jobs.

Where complete elimination of hazards detected is not economically feasible or practical at the time a job analysis is accomplished, the completed job analysis provides the guidelines to accomplish the job safely by following the clearly defined method of procedure.

Engineering Controls

Most hazardous conditions can be predicted or anticipated at the design, purchase, maintenance or work-standard development stages of plant operation. Unsafe conditions, such as inadequate guards and devices, inadequate warning systems, fire and explosion hazards, projection hazards, congestion and close clearances, hazardous atmospheric conditions, and inadequate illumination or noise are good examples of the more common causes of accidents that can be prevented by effective engineering at the pre-contact stage of accident control.

Control Points. The design engineer naturally becomes a key to the control of hazardous conditions in any plant. Local standards that require the interface of engineers with safety and environmental health specialists at all stages of facility or equipment design and development provide the best avenue to prevention or control of potential injury or health problems at the point of optimum effectiveness. Additional local standards requiring the approving signature of safety and environmental health specialists on all drawings or plans increase the possibility that proper consideration was given this important subject.

In addition to all other guides suggested or required by the state, local government, associations, and local plant establishments, the Occupational Safety and Health Act of 1970 provides the engineer with a comprehensive source of minimum required standards.

The person(s) or department responsible for the purchase of materials/products/equipment also plays a major role in hazard prevention and control. Again, closely organized formal contact between purchasing personnel and those responsi-

ble for safety and health management at all stages of purchasing, planning and acquisition becomes a very important key to accident control. The required use of safety data sheets by suppliers on all materials with potentially hazardous properties can be an effective guide to decision-making in purchases, as well as provide local specialists with valuable information to develop safe-practice guides when the use of such potentially hazardous material cannot be avoided.

Maintenance and industrial engineering personnel are also among the vital few who play so important a role in the creation and control of a safe and healthful industrial environment. Local standards requiring safety and health considerations in all phases of related work activities must be designed into the job commitments of these key people. Safety and health personnel can maintain control of such standards by periodic audits and required approvals on such items as work permits and job standards being created.

Minimize Loss by Energy Control. Engineering considerations at the precontact stage can be directed toward the control of the energy exchange that could cause personal harm or property damage. Some of the various avenues open to prevent injurious loss through this means are:

1. Eliminate a potential injurious energy type by substitution or use of an alternative source; e.g., use of electrical motors instead of shafts and belts in powering machinery, or use of a solvent with a higher TLV than the one proposed.
2. Reduce the amount of energy used or released; e.g., reducing the temperature of a hot water system to reduce the danger of scalds to personnel in shower rooms, or slowing the speed of vehicles in a plant by periodic bumper pads in the road.
3. Separate the energy from persons or property that could be exposed by time or space; e.g., barricaded and locked safety space provision around radioactive isotope usage, or placing electric power lines outside of a building in a less accessible location.
4. Interpose barrier between energy and people or property potentially exposed; e.g., personal protective equipment, bumper guard on loading dock, cement base guard on column, or insulation on noise-emitting machine.⁸
5. Modify the contact surfaces of materials or structures to reduce injurious effects to people or property; e.g., placement of shock absorbing material on low ceiling point of stairway to minimize risk of head injury.
6. Strengthen the animate or inanimate structure to support the energy exchange; e.g., program of weight control and physical conditioning for railroad conductors to prevent spraining ankles while getting on and off moving cars, or reinforcing railroad cars to resist loads dropped on cars accidentally during crane handling.⁹

THE CONTACT STAGE OF ACCIDENT CONTROL

The safety or health specialist must be constantly alert to needs and applications of the principles of deflection, dilution, reinforcement, surface modification, segregation, barricading protection, absorption and shielding at the contact stage of accident control. While many applications of these principles are visually anticipated and provided for through effective engineering at the pre-contact stage, many others will escape the average system's design considerations. One must also keep in mind that the energy exchanges involved with normal wear and tear, as well as abnormal usage, will require continual repair and replacement of related materials, structures or equipment. The use and application of personal protective equipment provides one of the best examples of safety countermeasures at this stage of accident control.

Personal Protective Equipment

Four important considerations deserve special attention when the decision has been made that a need exists for personal protective equipment.

1. Selection of the proper type of protective device.
2. Employee fitting of the equipment and instruction on its proper use.
3. Enforcement of standards created.
4. An effective system of equipment sanitation and maintenance.

Proper selection involves a determination of the degree of protection desired, the practicality of its application for the job, the acceptance by the worker, as well as the elements of maintenance and cost. Of course, we must always be conscious that equipment selected meets the required standards of performance. Manufacturers whose products meet the standards of the Bureau of Mines and/or N.I.O.S.H., the National Fire Protection Association, American National Standards Institute and other standards organizations, will usually include an approval marking or label on the product.

To assure proper use, one should make sure that workers understand why protection is necessary, so they will *want* to use it. In addition, special attention should be given to the ease and comfort with which it can be used, so that it *will* be used. Personal protective equipment can be misused or disused to varying degrees depending on a variety of program factors. It, therefore, behooves the safety and health specialist to constantly recognize that this approach to hazard control should always be secondary to a sincere effort to eliminate the exposure. For additional coverage of this subject the reader is referred to Chapter 36 on "Personal Protective Devices."

Eye and Face Protection. Eye and face protection is required by the Occupational Safety and Health Act of 1970 "... where there is reasonable probability of injury that can be prevented by such equipment." Some of the typical operations where eye hazards exist are the pouring or handling of molten metals or corrosive liquids, cutting and welding, grinding, milling, chipping, sand blasting

and electric welding. It is not only necessary for the operator to wear such protection, but it may also be required by any person near the operation, including other workers, supervisors, or visitors. The ANSI Standard Z87 gives specifications for design as well as functional requirements. Specifications are given for types providing impact protection against flying objects, those providing protection against fine dust particles or liquid splashes, and those providing protection against glare, injurious radiation and impact.

Respiratory Protection. The Occupational Safety and Health Act of 1970 (OSHA) requires respiratory protection for the control of occupational hazards caused by breathing air contaminated by harmful dusts, fogs, fumes, mists, gases, smokes, sprays, or vapors which cannot otherwise be kept from contact with people. The potential extent of health problems that occur from misuse or disuse of respiratory equipment is so severe that every engineering means possible should be exhausted to avoid personal contact with harmful air contaminants.

When necessary, selection of respirators should be according to the guidance of the American National Standard Practices for Respiratory Protection Z88.2-1969. Some respirators are used to purify the air from contaminants, while others are used to supply fresh air to the worker. Selection involves the nature of the operation or process and the nature of the air contaminant, its concentration, and its physiological effects upon the body. One should also remember that some air contaminants can affect the skin, too, providing a double hazard. Other factors to consider include length of the exposure and the length of time the protective device must be worn.

Work in hazardous locations (such as tanks) requiring respirators to supply fresh air requires special safety precautions. For instance, in the event of equipment failure, it is essential to know the time required for escape, and the procedure for emergency escape. Standards also include the requirements for additional men to be present for special communication arrangements, and for the availability of rescue equipment and personnel in areas where self-contained breathing apparatus is used in atmospheres immediately hazardous to life or health.

Other Protective Devices. OSHA states that "Helmets for the protection of heads of occupational workers from impact and penetration from falling and flying objects and from limited electric shock and burn shall meet the requirements and specifications established in American National Standard Safety Requirements for Industrial Head Protection Z89.1-1969" and that "Safety toe footwear for employees shall meet the requirements and specification in the American National Standard for Men's Safety Footwear Z41.1-1967."

The Occupational Safety and Health Act also refers to ANSI Standards for rubber insulating gloves, rubber matting to be used around electrical apparatus, rubber insulating blankets, and rubber insulating sleeves to protect people working around electricity.

A wide variety of additional protective devices of special material is available and includes aprons, jackets, leggings and coats for protection against heat and splashes of hot metal in operations such as steelmaking and welding. Special protectors have been designed for almost all parts of the body, to protect against cuts, bruises and abrasions. Many types of hand and arm protectors are available. The material used in gloves depends upon what is being handled.

Impervious clothing is available to protect against toxic substances, dusts, vapors, moisture, and corrosive liquids. It ranges from aprons, bibs and gloves to full garments containing their own air supply. Natural rubber, neoprene, vinyl and other plastics are used to coat material used in this equipment.

By taking all the necessary steps to select, fit, enforce and maintain an effective personal protective equipment program, the safety or health specialist will have taken another giant step at the contact stage of accident control to prevent traumatic injury and environmental health problems.

THE POST-CONTACT STAGE OF ACCIDENT CONTROL

There is a tremendous reservoir of information to prove that the severity of losses involving physical harm and property damage can be minimized by the application of one or more countermeasures at the post-contact stage of accident control. These could include prompt first aid and rehabilitation in cases of physical harm, and prompt reparative action and salvage in cases of property damage.¹⁰

In addition to these countermeasures, the prompt investigation of any accident loss provides a significant opportunity to prevent similar future losses by remedying the causes involved. Emergency care and accident investigation are briefly discussed below, and represent two major post-contact measures to control accident losses.

Emergency Care

The logic of utilizing prompt emergency care as an effective countermeasure to reduce death and disability in industry is supported by many occupational medicine specialists. There is no way of knowing how many lives might have been saved last year had this care been more readily available. When we consider that one in every four disabling injuries involved some permanent loss of body part, the importance of this vital subject becomes even more evident. Expert consultants returning from Viet Nam have publicly asserted that, if seriously injured, their chances of survival would be better in the zone of combat than in most American cities. Excellence of prompt emergency care proved to be the major factor in the phenomenal decrease of death rates for battle casualties who reached medical facilities from 4.5% in World War II to less than 2% in Viet Nam.¹¹

The author suggests that the size of the death-and-disability problem in American industry justifies a much greater concentration of attention by everyone on this important post-contact acci-

dent control countermeasure. The emergency care requirements listed below are suggested as *minimum* for any general industrial establishment.

1. The existence of a properly-equipped central first aid area for the treatment of all general injuries.
2. The presence on all shifts of certified first aid attendants or medical professionals.
3. The existence and organization of a plan for handling serious or unusual cases.
4. The provision for assistance of a medical specialist to treat specific types of injuries.
5. The existence of an established, trained rescue or ambulance team on each shift.
6. The existence of an in-plant training program for key employees in urgently-necessary first aid cares.
7. Adequate distribution on the premises of "critical" first aid supplies to meet needs required by special exposures.

Authoritative sources give strong indication that a soon-to-be-released comprehensive study of first aid training and its effects on safe behavior, made in Toronto, Canada, will prove a significant correlation between the two. In effect, it is believed that this research will reveal that first aid training has significant value in the prevention of accidents and should be employed as a strong motivational factor in pre-contact accident control.

Accident Investigation

An accident investigation report is basically the supervisor's analysis and account of an accident, based on factual information gathered by a thorough and conscientious examination of all factors involved.

The time for accident investigation is always *as soon as possible*. The less time between the accident and the investigation, the better and more accurate the data which can be obtained. Facts are clearer, more details are remembered, and the conditions are nearest those at the time of the accident. Accident investigation report forms may differ from company to company, but the information they seek is fairly standard. An increasing number of companies use forms that provide a selection of numbered choices in the causal and remedial sections. Forms such as these are designed to minimize the amount of writing by the supervisor and to facilitate computerization of the data for analysis. The form displayed in Figure 47-2 at the end of this chapter is representative of the more common ones. The author would like to emphasize that many forms captioned "Accident Report" are really injury investigation reports. Their very design prohibits their use as a tool to gain valuable information on other accidents resulting in costly property damage that under slightly different circumstances could also have involved personal injury.

Obtaining Good Data

Reporting Cooperation Essential. No matter how conscientious a front line supervisor might be, he cannot investigate an accident unless he is aware of it. Since most accidents do not result in the dramatic "big loss," it is not difficult for workers to hide a large quantity of valuable data that

SUPERVISOR'S ACCIDENT INVESTIGATION REPORT

COMPANY OR BRANCH <i>Eastern Packing Company</i>		DEPARTMENT <i>Shipping</i>	
EXACT LOCATION <i>Bay #11, South side, West loading dock</i>		DATE OF OCCURRENCE <i>3-7-69</i>	TIME <i>2:45</i> <input checked="" type="checkbox"/> AM <input type="checkbox"/> PM
		DATE REPORTED <i>3-7-69</i>	

PERSONAL INJURY		PROPERTY DAMAGE	
INJURED'S NAME <i>Paul F. Riley</i>		PROPERTY DAMAGED <i>Left truck</i>	
OCCUPATION <i>Left truck operator</i>	INJURED PART OF BODY <i>right arm</i>	ESTIMATED COSTS <i>\$ 650.</i>	ACTUAL COSTS <i>\$ 785.90</i>
NATURE OF INJURY <i>Fracture of upper arm</i>		NATURE OF DAMAGE <i>rust & altering column bent</i>	
OBJECT/EQUIPMENT/SUBSTANCE/INFLECTING INJURY <i>Left truck</i>		OBJECT/EQUIPMENT/SUBSTANCE/INFLECTING DAMAGE <i>ground</i>	
PERSON WITH MOST CONTROL OF OBJECT/EQUIPMENT/SUBSTANCE <i>Paul F. Riley</i>		PERSON WITH MOST CONTROL OF OBJECT/EQUIPMENT/SUBSTANCE <i>Paul F. Riley</i>	

DESCRIPTION

DESCRIBE CLEARLY HOW THE ACCIDENT OCCURRED: ATTACH ACCIDENT DIAGRAM FOR ALL MOTOR VEHICLE ACCIDENTS.

Paul was backing left truck #26 North to clear aisleway in order for truck #22 to pass. He backed into bumping block without applying brakes causing block to break off dock resulting in his truck moving backward off dock to ground left. below on North side 35 feet from East end. Riley struck arm on truck as he attempted to jump free. He landed clear of truck on ground left. below dock.

ANALYSIS

WHAT ACTS, FAILURES TO ACT AND/OR CONDITIONS CONTRIBUTED MOST DIRECTLY TO THIS ACCIDENT?

Riley reported defective brake on Operator's Report form at start of tour on 3-7-69. He removed truck from garage and operated it from 11 a.m. with defective brake. Operator was using bumping block as stopping mechanism for truck. The bumping block on the dock was in unsafe condition. Condition of block was reported on inspection reports of 1-5-69 and 2-20-69.

WHAT ARE THE BASIC OR FUNDAMENTAL REASONS FOR THE EXISTENCE OF THESE ACTS AND/OR CONDITIONS?

Employee was not properly motivated to recognize seriousness of unsafe brake condition. Garage personnel did not properly follow up condition on Operator's report form. Maintenance control failed to effect prompt corrective action to bumper block. Area supervisor failed to properly follow up unsafe bumper condition.

LOSS SEVERITY POTENTIAL	PROBABLE RECURRENCE RATE
<input checked="" type="checkbox"/> Major <input type="checkbox"/> Serious <input type="checkbox"/> Minor	<input checked="" type="checkbox"/> Frequent <input type="checkbox"/> Occasional <input type="checkbox"/> Rare

PREVENTION

WHAT ACTION HAS OR WILL BE TAKEN TO PREVENT RECURRENCE? PLACE X BY ITEMS COMPLETED.

X Personnel dept. has been requested to assist in establishing left truck operators' training course. Left truck rules will be reviewed with all operators by 10-6-69. Riley will be included in both programs when he returns to work. X A statement of policy on handling of safety work orders has been issued by Vice President Matthews. X Maintenance control has issued a hazard classification coding system for use on all safety work orders. X All operators have been properly instructed not to operate equipment considered to be unsafe. X A follow-up system for inspection report items is being developed by Ad Hoc Committee headed by investigator.

INVESTIGATED BY <i>Ralph B. Jones</i>	DATE <i>3-7-69</i>	REVIEWED BY <i>Frank K. Roberts</i>	DATE <i>3-8-69</i>
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International Safety Academy, Macon, Georgia.

Figure 47-2. Supervisor's Accident Investigation Report (Form).

could provide effective insight to prevention and control of major accident problem areas. There are many reasons why people do not report these accidents that could provide valuable and usable data. Investigators have discovered that fear of medical treatment, red tape involved with the investigation of even minor incidents, concern about spoiling the company's safety record, or fearing the wrath of irate supervisors whose group record has been blemished are some of the more frequent reasons given for hiding accident information.

Guideposts to Good Investigation. The limited coverage of this important subject precludes a discussion of many important aspects regarding the actual investigation process. Several key guideposts essential to the process of completing a thorough job of investigation are:

- The scene of an accident should be kept as undisturbed as possible.
- Whenever possible, the initial phase should be at the scene of the accident, and as promptly as possible following its occurrence.
- As applicable, someone should take photographs and/or make drawings or measurements.
- All witnesses should be interviewed, one at a time and separately, as soon as practical.
- The real purpose of the investigation should be given each witness.
- No attempt should be made to fix blame, or fault-find during the investigation.
- The investigation should be objective and avoid questions that lead to biased answers.
- Data should be recorded accurately.

Benefits

Investigation Benefits and Data Use. The primary purpose and benefit of investigation could be expressed simply as PREVENTION AND CONTROL. Proper investigation, followed by effective remedial action, eliminates causal factors that could result in future injury, damage and lost production time. Prompt and thorough investigation of all accidents is concrete evidence of concern for the worker's safety and well-being, and can be a major contribution to improved group morale.

MEASUREMENTS OF PROGRAM EFFECTIVENESS

Measurements of safety program effectiveness can be placed in three categories. The first and most familiar would be "measurements of consequence." This could include major, serious, reportable, minor or other classifications of personal injury or property damage in terms of frequency and severity rates. Measurements of consequences could also be expressed as: (a) actual loss rates, as the above would be considered, or (b) potential loss rates. An example of a measurement of potential loss would be an incident or near-loss (near-miss) accident rate.

In considering the widely used and accepted measurements of consequence, it must be remembered that these are "after-the-fact" . . . in most cases, "after-the-loss." Complete reliance on this

one category of measurement frequently relegates safety program activity to one of reaction rather than preaction. There is no question that results the program is achieving must be known, but that management output is a direct result of management input must also be recognized. Measurement of both can be used effectively in a prevention and control effort. The need for good measurements of consequence must be accepted. A continual effort is required to broaden the statistical base of accident study by including an ever-enlarging group of injury, property damage and near-miss accidents. As program sophistication permits, this base should grow to include near-loss accidents (incidents) that could have resulted in the consequence of injury or damage.

"Measurements of cause" can be considered a second major category, and could take the form of actual or potential cause rates. The typical loss analysis of accident causes related to acts, conditions, or management deficiencies that resulted in loss, would best represent actual cause measurements. The results of sampling techniques applied to physical conditions or employee behavior could be classified as potential cause measurements. Any safety program activity based purely on measurement of actual causes is after-the-loss and reactive. The use of measurements of potential causes would be of substantial value, since resulting preventive activity could be instituted without the need for actual loss history.

The third classification that will receive enormous attention in the immediate future is "measurements of control." The first step in utilizing this important measurement class is to clearly define all activities in the safety program to which management gives input. Work activity areas could include hiring and selection, skill training, supervisory training, safety meetings, job analysis, job observation, engineering controls, etc. Management's safety work would vary from plant to plant, depending on the degree of program sophistication.

Assuming that a local standard or policy has been established for management's input into each of these activities, the remaining key step is to establish a method to quantify the degree of management effort in each activity area. For example, consider a hypothetical department of a plant that requires front line supervisors to investigate every accident that results in personal harm. A check at the first aid area indicates that 100 occupational injuries were treated during the previous month, and that investigation report forms were received on 69. By this actual count and comparison technique, it can be properly assumed that 69% of the required investigations were made during that month.

Measurement of control enables the safety specialist to provide his management team with a clear picture of its effectiveness in safety work activities that prevent or control loss. He is using measurements more easily understood, not necessarily dependent upon losses, suitable for inter- and intra-plant comparisons, more statistically reliable, less biased and certainly more inferential from a prevention and control standpoint.

While advantages and disadvantages can be cited for each category of measurement, the progressive safety specialist will probably use all three from time to time as cross checks and barometer of his program effectiveness.

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DESIGN AND OPERATION OF AN OCCUPATIONAL HEALTH PROGRAM

Jon L. Konzen, M.D.

GENERAL COMMENTS AND OBJECTIVES

An occupational health program has as its chief goal the preservation and, if possible, the improvement of the health of the work force. This work force includes everyone from the chief executive officer to the newest unskilled worker.

Such a program must contain the basic elements of prevention, acute clinical care, rehabilitation and counseling. The scope of an individual program will depend on the size of the business or industrial organization, its geographic location, the potential hazards inherent in the operation, and the philosophy of management and labor.

It is important that the scope of a program be defined in writing. This is true whether the plan is for a small single establishment involving only a few workers or a large multi-plant corporate program. The scope should include the basic objective of the program, the duties, authority and reporting relationships within the organization. Above all, the scope should clearly indicate that management understands and fully supports the program. Without the complete understanding, philosophical and financial support of management the best conceived program has little chance of success.

Occupational health programs involve multiple disciplines including occupational medicine, occupational health nursing, industrial hygiene, safety and health physics. These health professionals who are members of management must work closely not only with each other, but must have an effective relationship with other management members. This is especially true when working with members of the personnel and labor relations groups. This can be accomplished if the primary objective — the health of the worker — is continually kept in mind. This will have a positive effect not only on the worker, but it will favorably influence personnel and labor relations in such areas as workmen's compensation, sickness, absence and group insurance.

Two additional objectives are frequently being assigned to or closely coordinated with the health program in industry. One is to determine and make recommendations regarding possible effects of facility operations on the surrounding community. The second objective is to determine the health effects of the products on the consumer. The extent of the health involvement in these latter objectives will be dependent on the size, scope and level of the operation.

PRESERVATION OF EMPLOYEE HEALTH

Administration

General. Management plays a major role in any health program in industry, whether this be at the corporate level or at the plant level. The management must be fully aware and agree with the program, realize that it is preventive in nature and understand that it is not simply a tool to reduce compensation costs or improve the safety record. Management must be willing to give both the authority and the responsibility for carrying out the program to the chief health professional in the organization.

Position of Health Professionals in the Management Hierarchy

1. The physician should report to a senior member of management at both the plant and corporate level. The plant physician should report to the plant manager. The medical director at the corporate level should report either to the president or a senior vice-president.

2. The occupational health nurse, if there is a full-time physician, should report both administratively and technically to the physician. If the physician is associated with the company on a part-time basis, the nurse should report to him functionally on technical matters, but may report to the personnel manager administratively.

3. The industrial hygienist may report both at the plant and at the corporate level to the medical organizations or directly to the same reporting level as the physician. The reporting relationship is best determined on an individual company basis with consideration being given to the needs, philosophy, expertise and the full or part-time status of the personnel involved.

4. The safety professional has traditionally reported to the Personnel Department. As safety activities expand in the plant and the community, the reporting relationship must be re-examined and, if necessary, realigned to meet modern requirements.

5. The first aid personnel would report technically to the plant physician and administratively to the Personnel Department.

6. Para-medical personnel, who are also called physician's assistants, would report directly to the plant physician both technically and administratively, since a majority of such personnel are employed in plants with a full time physician.

7. The reporting relationships of other health professionals such as the health physicist and the psychologist should be determined in a similar

manner as outlined for the industrial hygienist.

It must be emphasized that whatever the reporting relationship, each health professional must be responsible for planning, justifying and administering his own budget.

There is a close interface among the disciplines of occupational medicine and nursing, industrial hygiene, safety, psychology and health physics. These disciplines may best serve the company and its employees through consolidation under one health professional, both at the local and corporate level.

Basic Concept of the Program

Pre-placement Health Evaluation. The pre-placement health evaluation should be an evaluation rather than "an examination." It has been traditional in many companies to carry out a pre-employment physical examination which consists of "seeing the doctor," a chest X ray and a urinalysis. This examination was frequently used to "weed out" hernias, bad backs or other obvious physical disabilities. The examination frequently had no other use.

A more rational approach to the pre-employment evaluation is to consider it a placement evaluation for intelligent assessment of the health status of the individual. In this era of wide medical coverage most job applicants have a reasonable knowledge of their health status. For this reason either an automated or a check-off type history will give the reviewing medical personnel sufficient information to categorize the man's health status without further examination.

Another approach to pre-employment evaluation is to combine the health questionnaire with a selected battery of tests to monitor specific organ systems such as cardiopulmonary, hemotologic and urinary systems. Paramedical personnel frequently can carry out at least part of the pre-placement evaluation. The results from such programs suggest that these types of pre-employment screening are as effective as the traditional doctor/applicant encounter in delineating health status of the applicant and in determining his physical capabilities to perform a job.

In industry where there are known hazards, it may be prudent to carry out in addition to the questionnaire and screening tests on selected organ systems, the traditional encounter with the physician so that a man's health can be further categorized. The examination will be used for job placement and as a baseline for further periodic health examinations based on work exposure.

Selective Job Placement. Practically no worker comes to a place of employment without some physical defect. Therefore, the pre-employment examination results should play a major role in the intelligent placement of a worker. If the physical requirements of the job are considered in relation to the physical limitations of the worker, it will frequently prevent accidents, ill health and increase productivity. Blanket policies should not be established for accepting or not accepting applicants with certain physical conditions. The individual's physical capabilities should be matched with the work he is expected to per-

form. This will permit utilization of a willing worker with some physical defects.

Periodic Health Evaluations Based on Job Exposure. The purpose of the periodic examination should be clearly defined and a program developed with the approval of management. The purpose of the periodic examination is to evaluate the health condition of the individual with emphasis placed on specific "target organs" which may be affected by actual or potential environmental exposures. Such a periodic health monitoring program will rely heavily on a carefully planned check-off questionnaire, selected tests such as audiometry for noise, spirometry for airborne particulate, and blood determinations for specific metals and/or chemicals. If all of the test parameters are normal, the physician may eliminate the personal examination and only review the record. Such a procedure lends itself to multiphasic screening.

A reasonable alternative is to broaden the scope of the periodic examination to make it a complete health appraisal of all body systems with emphasis on organ systems which may be harmed by the environmental exposures. The complete health appraisal is the more ideal approach; however, it may not be possible to carry out an in-depth health appraisal on all personnel.

Environmental Hazards in the Work Environment. Almost any environment has either potential or actual environmental hazards that need to be recognized, measured and monitored. Management and the health professionals must have a high index of suspicion in order to identify potential or actual environmental hazards. Physical agents, airborne particulate and vapors alone, or in combination, even at low concentrations, may be hazardous. First, one must consider the raw materials, the level of exposure to the worker and their potential to do harm. Next, consideration must be given as to how these raw materials are modified through intermediate steps and the exposures created. Finally, the finished product must be reviewed to determine possible effect on the worker. Each step from raw material to finished product must be evaluated under normal conditions and also under emergency conditions, such as spills, bursting or breaking.

An effective industrial hygiene baseline and periodic monitoring program can be developed by the industrial hygienist based on the above considerations.

It is important to assess the exposures in relation to the severity and length of the exposure. On this assessment, a rational approach to control by engineering methods can be undertaken. If it is demonstrated that the environment can be hazardous to health and that good engineering control cannot be effected, then an effective personal program must be initiated. Such a program must take into consideration the proper protective equipment, educational program to instruct the worker with regard to the hazards, and the necessity of wearing the protective equipment consistently and properly.

Integration of Environmental and Physical Ex-

amination Data. After in-plant environmental control has been achieved through engineering measures, or the much less desirable method of personal protective devices, continued surveillance of both the environment and the worker is necessary. The environment should be sampled periodically or, if necessary, continuously to provide an adequate characterization of breathing zone and general work area exposure concentrations. It is not adequate simply to measure the work atmosphere and on that basis conclude that there is no hazard to health "because the exposure is below the TLV."

The environmental exposure data must be integrated with the physical status data in a manner that considers length of exposure, average concentrations and peak exposures. The medical surveillance must evaluate the individual's physical condition in light of naturally occurring disease and the possibility of normal transitory physiological alterations in certain function studies. The periodic medical surveillance will generate considerable data on the exposed workers with emphasis on organ systems most likely to be affected by a given exposure.

We must characterize the exposures and physical findings in terms of the individual and the group. This characterization may be simple for the small operation with few potentially hazardous exposures. In large complex operations the characterization may involve a computerized, epidemiologically coordinated system. This system would utilize industrial engineering to characterize a worker's location and movements, continuous industrial hygiene monitoring to characterize the atmospheric exposures and multiphasic screening methods to examine the worker.

Personnel

Duties of the Health Professionals.

Plant Physician — The physician is the medical officer of the plant. In this capacity, he is responsible for advising management concerning the health condition of the workers, the health hazards that may exist in the plant and the safeguards to protect the health of the worker. In order to do his job effectively he must be fully cognizant of what the plant makes, how it is made, what raw materials are utilized, the potential and actual health hazards associated with this manufacturing and the physical requirements of the various types of jobs. The physician must have this information so he can adequately carry out the pre-placement health appraisals, periodic health examinations and the health education programs.

Most physicians who practice clinical medicine require additional orientation in the area of preventive occupational health programs. Sources of additional information for the development of a good occupational health program can be obtained from the organizations noted in the preferred reading list at the end of this chapter. Information concerning specific hazards, including the necessary industrial hygiene and medical monitoring as well as the required control measures can be obtained from the standards published by

the Department of Labor in the Federal Register, the ten regional offices of the Occupational Safety and Health Administration (OSHA), U. S. Department of HEW's National Institute for Occupational Safety and Health (NIOSH) regional offices, the company's insurance carrier, the firm supplying the particular chemical or material and private consultants in occupational medicine and industrial hygiene.

The plant physician, whether part or full time, should tour the plant a minimum of once a month to review the in-plant environment and the effectiveness of environmental control. He should direct the attention of management and, if there is one, the corporate medical director to conditions which may cause adverse health effects to the work force. The doctor should follow up until adequate controls are effected. The physician, as the chief health officer of the plant, is responsible for determining the significance of occupational and environmental sources of disease.

The plant physician is not expected to render any specialized treatment such as major surgery, treatment of severe eye injuries or other conditions beyond his field of training or experience. These cases should be referred to recognized medical specialists preferably those certified by the boards of the various specialties. However, all cases of occupational injury or disease should be examined by the plant physician at frequent intervals regardless of who is rendering the actual treatment.

Employees' physical impairments or diseases which are non-occupational are also an important phase of the plant physician's responsibilities. The physician should consult with the employees who seek his advice regarding non-occupational conditions, but should confine treatment to that which is necessary to relieve the emergency condition or to enable the employee to finish his shift. These employees should be referred promptly to their family physician. In some isolated areas the plant physician may care for both occupational and non-occupational related health conditions of the workers and possibly their families. In these situations there must be clear ground rules established between the physician, the company and the local medical society regarding delivery of health care.

It is the plant physician's responsibility to notify the local health department in cases of reportable communicable diseases.

All pre-placement, periodic, transfer and re-entrance health examinations are to be conducted or reviewed by the plant physician. All examinations should be conducted in privacy with only the patient present. Employees should not be examined "en masse." All female employees should be examined in the presence of a third party, preferably a nurse.

The plant physician should arrange and participate in First Aid courses for key plant personnel given under the auspices of the American Red Cross or other similar service organizations.

The plant physician should be responsible for and supervise the keeping of accurate, complete and legible medical records. The records of each individual employee are confidential. The

local company physician, in accordance with applicable policy, should determine the nature and amount of medical information that can be released to others. Medical personnel should not discuss an applicant's or an employee's health or medical records with other personnel except as required in the performance of their duty. Specific medical records of injury or occupational disease must be made available under the 1970 Occupational Safety and Health Act, and in cases involving workmen's compensation. Portions of the medical records dealing with occupational illness and injury must be discussed with the plant safety supervisor in order that he can carry out his functions.

The physician's opinions and recommendations should be based entirely upon the facts as determined by careful investigation of each incident, case or condition. Any biased judgment or opinion which might be used to further the company's or the employee's interest at the expense of the other party is considered unprofessional and highly inappropriate.

Occupational Health Nurse — The occupational health nurse is a part of the management team. As a health professional it is important that she be objective in all of her professional duties. The nurse should be trained, and if appropriate, certified to conduct the specialized in-plant testing required in the program. Her duties can be grouped in the areas of prevention, treatment, rehabilitation and education.

In the area of prevention, she plays a vital role in the pre-placement and periodic health examination programs by conducting preliminary testing and assisting in the completion of medical questionnaires. Her duties may include preliminary review of test results to screen out the obvious normal findings. This will permit the doctor to better utilize his time in reviewing the abnormal findings.

A good industrial nurse can handle many of the minor accidents and injuries which occur in any industrial setting. These treatments are carried out under the direction and written orders of the physician. It is most important that every health facility have a set of written orders defining the limits and responsibilities of the nurse with regard to treating the patient, and that the occupational health nurse is currently licensed to practice in the state in which she is employed.

The nurse plays a key role in rehabilitation of the injured worker by supervising appropriate exercises, whirlpool or heat treatments in the unit. This rehabilitation will aid in the early return to work of the injured employee.

The nurse plays a vital role in the educational program to inform the employee of potential health hazards of work and the signs and symptoms of over-exposure. Frequently she fits and instructs the worker in the proper use of personal protective equipment.

The nurse can serve as an effective health counselor for personal physical and mental health problems. She can be especially effective in the areas of alcohol and drug abuse.

The keeping of good clinical medical records

as well as the records prescribed under the Occupational Health and Safety Act fall largely to the nurse. She must have knowledge of the in-plant environment so she can intelligently assess complaints. This will permit proper recordkeeping and assist in early recognition, and prompt medical management of occupationally related health conditions.

Small plants frequently employ only part-time nursing service. The nurse coverage should be scheduled to cover more than one shift in a multi-shift operation. Her period in the plant should be long enough to accomplish all her duties. In most operations, each plant visit should be at least two hours in length.

Industrial Hygienist — The industrial hygienist in most companies will be located at either the central office or at a divisional office location. A few organizations have a qualified industrial hygienist located at the plant level. Many companies must rely on outside industrial hygiene consultation through their insurance carrier, state agencies or private consulting firms.

The duties of the industrial hygienist are to make the corporate management aware of potential in-plant environmental hazards, measure these hazards, recommend appropriate engineering control and periodically monitor the controlled environment. The industrial hygienist, physician and nurse must work closely together to achieve the proper control of the environment and maintain it. The industrial hygienist's specialized knowledge in the area of toxicology will be of great benefit to the physician and the nurse. He will often act as a liaison between the medical group and the actual plant production people in areas of common concern.

Safety Coordinator — The safety coordinator has the prime responsibility for the safety program of the plant. The two major areas of this responsibility are employee education in safe work practices and property safety.

The safety supervisor must work closely with the Medical Service of the plant to review all accidents and illnesses so unsafe conditions can be corrected and the affected employees be re-educated promptly to prevent further accidents.

First Aid Personnel — In all plants, and especially those without full nurse coverage, employees should be selected and trained as first aid personnel to provide emergency first aid when trained professionals are not present in the plant. These employees should attend and obtain certification from an approved first aid course such as is given under the auspices of the American Red Cross or other similar service organizations. The course must meet the standards for first aid training under the 1970 Occupational Safety and Health Act. The coordination of training these employees is the responsibility of the plant physician.

Other Health Professionals — Other health professionals who may be involved in plant operations from time to time include the health physicist and the doctor's assistant. The need for these personnel will be governed by the size and type of operation. The use of a physician's assistant must be governed by the availability of proper

physician supervision.

Facilities

The location, size, layout and equipment of an in-plant medical facility should be based on the size of the operation, the number of employees and the activities of the plant. It is especially important in new plant design to plan for possible future expansion.

The medical facility should be located on the first floor of a multi-floor complex with consideration given to proximity of elevator service which will accommodate a wheeled stretcher. An electric cart to serve as an in-plant ambulance may be necessary if the plant is unusually large. The medical facility should be located within easy access to the work areas. There should be a second entrance to a driveway which is free of architectural barriers where an ambulance can readily load an ill or injured employee.

The size of the unit is governed by the extent of the in-plant program. There are various formulas for determining unit size, but a reasonable rule of thumb is to include approximately 1 to 1.5 square feet for each employee up to 1000 employees. Over 1000 employees, the square footage per employee can be appropriately reduced.

The layout of the unit should permit wheeled stretchers to negotiate all turns and enter all rooms. It is important to remember that these units serve several functions: prevention, treatment and rehabilitation. In large units where there is one or more full time nurses as well as a full time physician, the floor plan should be designed to separate the preventive activities from the treatment activities. Various layouts have been devised for this purpose. There is no one best layout.

Privacy in an in-plant medical unit should equal that of the private physician's office. Privacy can be accomplished even when examining large numbers of pre-placement or periodic applicants. One commonly used method is to have two or three small dressing cubicles adjacent to the examining room. Each one of these cubicles has two doors. One door leads from the hall into the cubicle. The second door opens into the physician's examining room. The patient enters the cubicle, closes the hall door, locks it, disrobes and awaits the physician. The physician controls the movement from the cubicle into the examining room since no door knob is placed on the cubicle side of the door.

The larger units may have specialized rooms for minor treatment of illness or injury, a special room where minor suturing can be carried out under good aseptic conditions and a ward for observation of patients. It is most important that if there is more than one bed in a room that each bed be enclosed entirely by a cubicle curtain. All units, regardless of size, must have facilities for hand washing, toilet rooms and storage. In very small plants where there are fifty or less employees, the medical unit which is to serve primarily for first aid and health counseling may consist of only one room. The room requires a sink, dressing cabinet, industrial treatment chair, examination table, desk and files for maintaining

the confidential medical records. All other preventive, treatment and rehabilitative activities would be carried out at a nearby medical facility.

For a plant of 200 individuals or less, a three-room unit consisting of a doctor's office/examining room, minor treatment room and nurse's office/waiting room would be suitable. The doctor's office/examining room would also be used as a major treatment room for a severely injured patient prior to transport to the hospital. Each treatment and/or examination room should have running water, adequate lighting and ventilation.

In a small plant which employs less than 200 workers, where the physician does not come to the plant for other than monthly inspections, it may be appropriate for the nurse to carry out the preliminary health testing at the plant. The results would be forwarded to the physician's private office for completion of the examination. Most equipment commonly used in preliminary testing such as the mechanical sight screener, spirometer, audiometer and audiometric booth are not usually found in the average physician's private office. Blood can be drawn either at the physician's office or in the plant. X-ray studies would be made at an outside facility.

The effectiveness of the occupational medical program is usually increased by carrying out as much of the preventive, rehabilitative and educational program as possible in the plant. This would include all parts of the examination with the possible exception of X ray. Such a program would require frequent plant visits by the physician.

The training, background and length of time that the medical personnel are at the plant should determine the type and sophistication of emergency and therapeutic medical equipment and drugs that will be maintained on the premises.

Records

The medical records which must be maintained on an individual must characterize his health at the beginning, periodically throughout and at termination of employment. A record of all occupational injuries, illnesses and treatments must be maintained.

It is customary to have a pre-placement health examination form which includes a check-off health questionnaire that reviews the patient's past environmental exposures, family history, personal medical history and provides a section to record the objective medical findings. In designing such a form it is important to consider the educational status of the average applicant so that the history portion can be completed by the applicant with a minimum of assistance from the medical personnel. Newly designed forms should be computer compatible even if there are no immediate plans to use data processing equipment for storage, retrieval or use of the records.

A similar questionnaire and selected testing procedure approach may be used for the periodic health evaluation.

The forms should be designed with sufficient room so that all data can be entered easily and reviewed at a glance. The abnormal findings should stand out. There should be sufficient area for

comment and elaboration of all abnormal findings. Laboratory and other testing data may be displayed in tabular form.

Internal Statistical Reports. It is useful to have internal statistical reporting covering the costs, patient load and the various tests that are performed. An objective review of this data will permit an evaluation of the effectiveness of the program, enable determination of accurate costs for medical services and assist in realistic budget development.

Occupationally Related Accidents and Illness Investigation Reports. Early determination of the causes of occupational injury and illness is assisted by an intelligent accident or illness report that is completed jointly by the first-line supervisor, the plant safety coordinator and the medical service.

If each of these disciplines intelligently and accurately complete their portion of the report, unsuspected problem areas may be identified and controlled. They will assist in reducing accidents by making the entire plant more aware of the in-plant environment. It will also demonstrate to the employees that the company takes the matter of their health and safety seriously. Such reports with certain modifications can be used as workmen's compensation reports and the Occupational Safety and Health Administration Form #101.

Records for Compliance with the 1970 Williams-Steiger Occupational Safety and Health Act. The Occupational Safety and Health Act of 1970 states that all illnesses and injuries which require more than simple first aid must be recorded within six days after the illness or injury becomes known. OSHA Form 100 or an equivalent form or method approved by the Secretary of Labor may be used. The law further requires that an accident report be completed on each recordable injury or illness. OSHA Form 101 is provided for this purpose. Annually a summary which can be completed on OSHA Form 102 must be posted in a conspicuous place for not less than thirty days. This form must be posted not later than the first of February of the year following the covered period. Some selected plants will be requested to complete OSHA Form 103 for submission to the Department of Labor. This is a more detailed summary of the information reported on OSHA Form 102. The details for recordkeeping requirements are summarized by the Department of Labor in the booklet RECORDKEEPING REQUIREMENTS UNDER THE WILLIAMS-STEIGER OCCUPATIONAL SAFETY & HEALTH ACT OF 1970.

Industrial Hygiene Records. Industrial hygiene sampling records must be available for review by the Secretary of Labor or his representative. The samples should be taken in sufficient numbers and locations to characterize in-plant exposure to people.

Industrial hygiene reports which are made to management should be more than a list of numeric values. The report should interpret the data from the standpoint of ceiling values, time weighted exposures and excursion peaks. The

reports should discuss the corrective action which would be appropriate in relation to the exposures. It should be emphasized that the acceptable exposure concentration used in industrial hygiene, commonly called threshold limit values, are guidelines for reasonable exposures and are not absolute safe or unsafe limits. These levels should be discussed in terms of the standards which have been and are continuing to be published by the Secretary of Labor. The Federal Register should be consulted on a continuing basis for published changes.

Industrial Hygiene

There are three basic types of industrial hygiene surveys from a physician's standpoint. These include baselining of an operation, periodic monitoring of an operation and emergency monitoring of an operation. Baselining is an in-depth evaluation to characterize exposures throughout the manufacturing facilities. To carry out such a survey it is usually appropriate for the hygienist and frequently the physician to make a preliminary walk-through survey of the facilities to review raw, intermediate and end products of a manufacturing operation in order to identify actual and potential exposures under normal and abnormal conditions. After the walk-through has been completed and evaluated, the industrial hygienist will move in with the appropriate equipment and complete the baseline survey. Periodic monitoring of the plant is carried out in essentially the same way except the initial walk-through may be eliminated and the number of individual samples required usually can be reduced. The third type of industrial hygiene survey is the emergency survey. Medical review of the first-line supervisor's accident report may require immediate evaluation and sampling to determine if a particular operation or exposure is creating a hazardous condition. Such emergency surveys can be kept to a minimum if the baseline and periodic surveys are well planned and executed.

It is most important that the physician and industrial hygienist be consulted during initial planning and pilot stages of a new process or operation so that necessary environmental control and medical monitoring can be included in the economic feasibility study. It is possible that when the environmental concerns are considered, a product line may be unprofitable. Environmental and occupational health are necessary costs of doing business.

There should be a procedure by which the plant or corporate engineering coordinates with the medical and industrial hygiene services so that sufficient environmental consideration is given to a process change and to the purchase of new products and equipment. This will assure that engineering controls will be added or modified in order to control any potential environmental hazards. It is an old axiom that minimal changes in the process can cause maximal environmental problems.

Safety

Safety must play a major role in a well rounded health program (see Chapter 47). A

safety program should cover not only property, machine guarding, fire safety and the like, but must include the education of management as well as the work force in safe working procedures. The safety program begins when the worker is first employed. It is important to have on-the-job training programs that are directed to the individual to inform him of safety hazards in his particular job, as well as an indoctrination in the general aspects of safe work practices. This will require that a comprehensive job safety analysis be performed on all operations. Further, there must be a systematic inspection of new, revised and existing production and safety equipment to identify potential safety hazards and to assure compliance with governmental requirements. Another important task of the safety supervisor is a systematic accident investigation program coordinated with first-line supervision and the medical service.

Special Programs

Programs Directed at Specific Hazards. The pre-placement and periodic examinations mentioned earlier in this chapter are important but not all inclusive parts of special programs to protect workers from specific hazards in the work place. The examinations are limited to assisting in identification of workers who should not be exposed to certain hazards and reveal early adverse health effects. Special programs will vary in number and complexity depending on the hazard, type of exposure and number of workers involved. All the special programs have certain things in common which include recognition of the hazard, measurement of the hazard, control of hazard by engineering or personal protective devices, medical monitoring of the workers and education of the employee with regard to the health and safety implications presented by the hazard. It cannot be stressed too vigorously that the educational part of the program and its resulting motivational influence is one of the most important parts of any special program. If the worker cannot be properly motivated to cooperate in the protection of his health, costly industrial hygiene engineering, control devices, personal protection equipment and medical monitoring will have only limited effectiveness. The employee does have specific responsibilities under Public Law 91-596 (OSHA) to achieve and maintain safe and healthful working conditions.

Some of the more common specific hazard control programs include hearing conservation against noise; eye protection against flying particulate; respiratory protection against such airborne agents as lead, silica, asbestos, cotton and solvent vapor; thermal stress protection against heat or cold; and dermal protection against skin sensitizers or irritants (see Chapter 34). Immunization programs directed at such job related diseases as tetanus and in certain industries, typhoid, are often indicated. A well rehearsed and frequently reviewed tank entry program which incorporates segments of other hazard control is a common requirement in industry.

Medical Disaster Control. Medical disaster, either man-made or natural, can occur. All office com-

plexes and plants should have plans which will permit rapid evaluation, effective first aid, evacuation and transportation of injured personnel to a definitive treating facility. The elaborateness of the disaster control plan will depend on the size of the operation.

Alcohol and Drug Abuse. Programs to combat alcohol and drug abuse are important and necessary. These specialized programs require an interdisciplinary effort between personnel and medical departments and the community. Such programs should clearly define company policy, and include the detailed procedure for handling personnel involved in these abuses. These programs should be designed to treat drug and alcohol problems in the same manner as other chronic diseases.

Consultation to Management on Group Insurance Benefits. Management should review the group health insurance benefit plan with the medical service. Medical expertise will be of assistance in formulating the most comprehensive plan for the least amount of money.

Absentee Control. Absentee control is a by-product of a good medical program. Early recognition of job-related and non job-related conditions can assist in rapid treatment and early return to the job.

A day-to-day evaluation of sickness absence takes a careful, well thought out form to obtain the necessary confidential medical information and establish a good rapport between the private physician and the company medical service. The program will aid in preventing unwarranted and excessively long sickness absences. It will assist the plant physician in intelligently placing the returning worker if job change is necessary.

Occupational Mental Health. Mental health is an area of increasing concern of industry today. An emotionally affected worker who is troubled by home or work problems is not an efficient or safe worker. It is most important that the medical service programs train first-line supervision to recognize symptoms of emotional ill health, and refer employees promptly to the medical service. This will permit professional evaluation and counseling. If necessary, prompt referral to specialized mental health care can effectively be carried out by the medical service. It should be emphasized that the first-line supervisor should not try to diagnose or "treat" emotional illness, but should promptly refer the employee. Evaluation and counseling take time in the medical facility, but this service can render great dividends in terms of the individual as well as his value to the company.

Possible Health Effect of the Facility Operation on the Community

Effluents from a Facility. Effluents which are emitted from a plant to the atmosphere, to waste water, or by solid waste disposal must be monitored for legal reasons and to protect the health of the community. It is important to sample these effluents at the source of emission, as well as in the community since many materials may undergo a chemical change which would render them either more or less hazardous. Frequently emissions may be relatively unique to

a particular facility operation. For this reason, there must be close cooperation between the environmental engineering group and the medical group so that representative samples are obtained, and meaningful evaluation of the samples are carried out. At times by using toxicological consultation, the physician may be able to advise on the health effect of materials. At other times, it may be necessary to carry out animal studies or, in extreme cases, to evaluate the health effect on the community by epidemiological studies.

Social Impact of Opening or Enlarging Operations in a Community. The social impact of a plant on the community, particularly if it is a small community, may be appreciable. The medical service should be consulted during the initial planning stages of a new or enlarged facility to assist in the determination of adequate medical coverage for the in-plant operations and to assess the impact of the influx of a work force on the local medical support. In particularly small or isolated communities, it may be necessary to work with the local medical society in order to either encourage, and at times financially support expansion of local medical services, or offer comprehensive medical service to the employee and his family through the company.

Possible Health Effect of Products on the Consumer

Health Evaluation of New or Modified Products. For years many large progressive companies have carried out a joint effort with toxicologists and medical personnel to conduct studies on new or modified products from the conceptual stage through final product marketing. It is becoming increasingly clear that such procedures will have to be incorporated in product development programs of still more industries. Possible health effects must be considered as part of the normal product development process. The possible health effect evaluations of new or modified products may take place within the company or may be contracted to a variety of institutions who are equipped to carry out toxicological literature reviews, animal studies, human studies and limited field testing.

Whether evaluations are carried out within the company or through consultants, it is most important that a team within the company representing medical, technical and toxicological expertise be established to determine the need, scope and design of any research study.

Evaluation of Present Products. At times it is necessary to carry out a critical health effect evaluation of products which have been marketed for various periods of time. These health effect evaluations will utilize the same techniques as used for new or modified products. In addition, the health history of employees exposed to the finished product would be of value in assessing the health effect. An additional important tool in determining health effect on the consumer is an objective and representative analysis of customer complaints from a health standpoint. It is important when using customer complaints to carefully document the adverse health effects in relation to the use or

misuse of the product. It is also important to develop mechanisms which will surface customer complaints effectively in all areas where the product is marketed.

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THE DESIGN AND OPERATION OF OCCUPATIONAL HEALTH PROGRAMS IN GOVERNMENTAL AGENCIES

Victoria M. Trasko

BACKGROUND

Responsibility for occupational health and safety programs is dispersed among various federal and state governments. Goals are basically the same — the prevention and control of occupational injuries and illnesses, and the general improvement of the health of workers and the working environment; but missions are restricted to specific areas of authority or concern. For example, at the Federal level, health aspects of such programs have been viewed traditionally as the responsibility of the Public Health Service; safety aspects, the U.S. Department of Labor; and mine safety and health, the U.S. Bureau of Mines.

Functions of federal agencies have been confined to research and development, technical assistance to states and others, dissemination of information, and to various degrees, training and promotion of improved occupational health and safety programs at the state level. To these traditional functions has been added enforcement of national safety and health standards under recently enacted legislation. The role of state agencies, which have legal responsibility for health and safety of employed workers, is provision of direct services to industry in the solution of occupational health and safety problems. The application of research and of standards of good practice, and supervision of the health of its employees while at work is regarded as the responsibility of management. Over the years, a spirit of cooperation has existed among federal and state governments, and industry and labor which contributed greatly to the progress made in reducing the toll of occupational injuries and diseases which characterized the early decades of this century, and in making the job environment a safe and healthy place in which to work.

DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

National Institute for Occupational Safety and Health

The National Institute for Occupational Safety and Health (NIOSH) was established within the Department of Health, Education and Welfare (HEW) by the Occupational Safety and Health Act of 1970, PL 91-596 (see Chapter I) to carry out the functions specifically assigned to it, and the research and educational functions assigned to the Secretary of HEW and delegated to NIOSH. NIOSH formally came into being with the re-designation of the Bureau of Occupational Safety

and Health, Public Health Service. It is now located administratively within the Health Services and Mental Health Administration of HEW. The reconstituted Bureau itself had its origin in the establishment of the Office of Industrial Hygiene and Sanitation by the Public Health Service in 1914, and has been active as a continuous organization entity. The passage of the Occupational Safety and Health Act of 1970 provided for the first time a specific legislative base for occupational safety and health research and training activities.

In addition to broad responsibilities under PL 91-596, NIOSH has been delegated responsibilities for carrying out the health provisions of the Federal Coal Mine Health and Safety Act of 1969, PL 91-173.

Organization and Functions. NIOSH has its headquarters offices in Rockville, Maryland, and maintains primary research laboratories and other program functions in Cincinnati, Ohio, with specialized field laboratories at Salt Lake City and Morgantown, West Virginia. Staffs are also maintained in each of the 10 HEW Regional Offices.

The "Statement of Organizations, Functions and Delegations of Authority" (printed in the June 30, 1971, issue of the Federal Register), assigns the following major functions to the Institute: "Plans, directs, and coordinates the national program effort to develop and establish recommended occupational safety and health standards and to conduct research, training, and related activities to assure safe and healthful working conditions for every working man and woman:

"(1) Administers research in the field of occupational safety and health, including the psychological factors involved; (2) develops innovative methods and approaches for dealing with occupational safety and health problems; (3) provides medical criteria which will ensure, insofar as practicable, that no employee will suffer diminished health, functional capacity, or life expectancy as a result of his work experience, with emphasis on ways to discover latent disease, establishing causal relationship between diseases and work conditions; (4) serves as a principal focus for training programs to increase the number and competence of persons engaged in the practice of occupational safety and health; (5) develops and coordinates the appropriate reporting procedures which assist in accurately describing the nature of the national occupational safety and health problems; and (6) consults with the U.S. Depart-

ment of Labor, other federal agencies, state and local government agencies, industry and employee organizations, and other appropriate individuals, institutes and organizations with regard to promotion of occupational safety and health."

Program activities are carried out through the Offices of the Director, Extramural Activities, Administrative Management, Planning and Resource Management, Research and Standards Development, Manpower Development and Health Surveillance and Biometrics. These offices are located in Rockville, Md. and Cincinnati with staffs including Associate Directors for the specific areas.

Operating programs are carried out primarily in Cincinnati by the Divisions of Laboratories and Criteria Development, Field Studies and Clinical Investigations, Technical Services, Occupational Health Programs, Training and (at Morgantown, West Virginia) by the Appalachian Laboratory for Occupational Respiratory Diseases.

Staffs are diversified and include physicians, nurse consultants, hygienists, engineers, chemists, toxicologists, statisticians, physicists, physiologists and psychologists as well as other specialized personnel.

Prior to the passage of the Occupational Safety and Health Act of 1970, NIOSH was engaged in a broad program encompassing research and field investigations on occupational diseases, technical and consultative services, and short term training. Specific functions and activities include: environmental studies of uranium mines and medical studies of uranium miners to clarify the relationship to lung cancer of occupational exposure to radioactive ore; prevalence study of chronic chest disease problems in soft coal miners; long-term study to determine the occurrence of asbestosis and lung cancer in workers in the asbestos products industry; toxicologic and pathologic research on materials anticipated or encountered in the occupational environment, including determination of acute, subacute and chronic toxicity, safe limits of exposure, modes of action and tests for hypersensitivity; development of improved analytical and field sampling methods; studies of effect of heat on well being or work performance; national noise study; engineering, medical and nursing assistance and consultative services to states, federal agencies, and other groups; survey of employee health services in 7,000 general hospitals; a research grants program; and a technical information service.

The following additional activities as authorized by the Occupational Safety and Health Act of 1970 are being carried out: conduct of research for developing criteria for recommendations of new occupational safety and health standards for submission to the U.S. Department of Labor for promulgation; conduct of a grant program for support of demonstrations and training as well as of research at universities, state and local agencies, and other public and non-profit institutions; hazard evaluations in work places upon receipt of written requests from employers and representatives of employee groups; conduct, directly or by grants or contracts, of research, experiments

or demonstrations relevant to occupational safety and health, including studies of behavioral and motivational factors involved; conduct, directly or by grants, education programs to provide an adequate supply of qualified personnel to carry out the purposes of the Act; maintenance of an analytical and instrument calibration service for the Department of Labor; publication of an annual listing of all known toxic substances and the concentration levels at which such toxicity is known to occur; with the U.S. Department of Labor, review of state plans and grants; and consultation to the Secretary of Labor on various other provisions of the Act including the collection and compilation of national health and safety statistics.

Implementation of the Coal Mine Safety and Health Act of 1969. (See also under Bureau of Mines.) NIOSH responsibilities under the Act include: (a) operation of the medical examination program in which over 60,000 underground coal miners have been provided chest X rays through contracts with coal operators or directly by NIOSH. The Morgantown facility serves as the X-ray receiving station and processes the X rays: (b) development of mandatory health standards for the protection of life and the prevention of occupational diseases of miners, including standards on noise, which are then transmitted to the Department of Interior for publication and enforcement; and (c) the conduct of studies, research, experiments, and demonstrations to prevent or control occupational diseases originating in the coal mining industry. For example, the National Study of Coal Workers' Pneumoconiosis was conducted to provide basic research information for epidemiologic purposes. Approximately 10,000 miners in 31 selected mines in 10 states were given medical examinations. A considerable amount of research is underway on the development of techniques for prevention and control including identification of hypersusceptibles and the determination of relationship between the coal mine environment and occupational diseases. Interim standards for respirable dust exposure have been published. The Morgantown facility, which conducts much of the research, has also been designated the certification laboratory for safety equipment and sampling instruments.

As authorized by the Act, the Secretary of HEW appointed a Coal Mine Health Research Advisory Council which meets periodically to advise on research priorities.

Payment of Black Lung benefits authorized by the Act is the responsibility of the Social Security Administration. By June 1971, the SSA had received 297,162 claims, processed 267,042, and approved benefits for 126,396 miners or their widows, totalling more than \$313 million.

U.S. DEPARTMENT OF LABOR

Occupational Safety and Health Administration

The Occupational Safety and Health Administration (OSHA) was formed in April, 1971 to carry out the functions assigned to the Secretary of Labor in the Occupational Safety and Health Act of 1970. It is headed by the Assistant Sec-

retary for Occupational Safety and Health, an Office established by the Act. By order of the Secretary of Labor (Federal Register, May 12, 1971), all safety and health responsibilities, personnel, and facilities assigned to the Employment Standards Administration (formerly called the Wage and Hour Administration) were transferred to the Assistant Secretary for OSHA. The former Bureau of Labor Standards was absorbed by the newly created Administration.

Responsibilities of OSHA are carried out through 1) the Federal and State Operations, 2) Office of Standards, and 3) Office of Training and Education. Field operations are conducted on a decentralized basis under 10 Regional Administrators who report directly to the Assistant Secretary for Occupational Safety and Health. They will supervise 50 area offices. Field staffs include safety engineers, safety officers and industrial hygienists who serve as safety and health compliance officers.

The Act also established the Occupational Safety and Health Review Commission, consisting of three members appointed by the President, to adjudicate disputes arising from the enforcement of the Act. This Commission is an independent agency and is not in the Department of Labor.

Major Responsibilities of OSHA under the Occupational Safety and Health Act of 1970 include the promulgation, modification and enforcement of occupational safety and health standards; inspections and investigations of premises of industrial establishments; issuance of citations and proposing penalties for job safety or health violations; conduct of programs (with HEW) for the education and training of employees and employers in recognition and prevention of unsafe or unhealthful working conditions in covered employments; operation of the grants program to states to assist in identifying their needs and for developing plans, and to assist in the enforcement of federal safety and health standards or equally effective state standards; formulation of regulations requiring employers to keep and make available to the Secretary of Labor and the Secretary of HEW records on certain employer activities, employee exposures to potentially toxic substances or harmful physical agents, and records and reports of work-related deaths, injuries and illnesses. Interim standards with which all employers subject to the Act must comply, entitled "Occupational Safety and Health Standards" and consisting of certain National Consensus Standards and Established Federal Standards have been promulgated (Federal Register, May 29, 1971, Part II).

Other Functions and Responsibilities. OSHA is also delegated responsibility for implementing and enforcing the safety and health aspects of other Acts including the following:

The Walsh-Healy Public Contracts Act was passed in 1936, and applies to contracts for materials and supplies exceeding \$10,000. It conferred on the Department of Labor responsibility for protecting safety and health of workers, and authority to promulgate safety and health standards with which employers must comply. Safety inspectors in-

spect the establishments of contractors, and those who do not comply with rules and regulations are not permitted to bid upon future government contracts.

McNamara-O'Hara Service Contract Act applies to contracts for service to the federal government exceeding \$2,500.

Federal Construction Act was passed in 1969, and applies to federal and federally assisted or financed construction contracts exceeding \$2,000. *The Longshoremen's Act* enacted in 1959, empowered the Department of Labor to establish safety and health standards for longshoremen and shipyard workers.

Other functions of OSHA include supervision and direction of a federal employees safety program through the Federal Safety Council; conduct of safety training courses for governmental personnel, industry, and unions; and assistance to states and others in the development of safety codes and improvement of employment standards through better administration and legislation.

Bureau of Labor Statistics

The Bureau of Labor Statistics is the fact-finding agency of the Department in the field of labor economics and statistics. The collection and compilation of work-injury statistics is the immediate responsibility of the Division of Industrial Safety. Annual mail surveys of work injuries which provided the basis for frequency and severity rates per 1,000,000 hours worked have been conducted for many years on a voluntary basis in a sample of industries. Rates have been published for industry groups and by states. In 1970, 17 states participated in the collection and tabulation of the annual reports.

Under the Occupational Safety and Health Act of 1970, the Secretary of Labor, in consultation with the Secretary of Health, Education and Welfare, is authorized to develop and maintain a program of collection, compilation and analysis of statistics on work-related injuries and illnesses, other than minor injuries requiring only first-aid treatment. The Bureau of Labor Statistics was delegated the responsibility of carrying out this program (Secretary of Labor's Order 12-71; Federal Register, Wednesday, May 12, 1971), as well as the provision regarding grants to states to assist them in developing and administering programs dealing with occupational safety and health statistics. With the passage of these provisions, the federal government was authorized for the first time to collect and compile statistics on work-related injuries and illnesses on a national basis. Regulations of the Secretary of Labor entitled "Recordkeeping Requirements under the Williams-Steiger Occupational Safety and Health Act of 1970" have been published and disseminated to employers subject to the Act.

The regulations require employers to keep records on reportable injuries and illnesses as defined, and to file an annual report as prescribed with the Secretary of Labor, upon request. Because of emphasis on lack of statistics on occupational illnesses during the hearings prior to the enactment of the Act, the system designed specifies seven categories of reportable work-related illnesses.

Bureau of Employees' Compensation

The Bureau administers the Federal Employees' Compensation Act applicable to Federal civilian employees; the Longshoremen's and Harbor Workers' Compensation Act which covers private maritime employment on navigable waters in the United States, and also applies to employment in the District of Columbia; and several other Acts covering military and other personnel.

DEPARTMENT OF THE INTERIOR

Bureau of Mines

The Bureau of Mines has responsibility for protecting the safety and health of workers employed in the coal, metal and non-metallic mining industries. The Bureau has been in operation since 1910 when, as a result of a series of coal mine disasters, it was established in the Department of the Interior. Its major functions then were limited to the study of safe methods and appliances best adapted to prevent mine accidents and disasters. Subsequent legislation provided authority for coal mine inspection (1941) and in 1952, enforcement of the Mine Safety Code, including the closing of mines if imminent danger existed. The Bureau also carries out functions dealing with inspections and enforcement of health and safety standards, delegated to the Secretary of Interior, in the Federal Metal and Nonmetallic Mine Safety Act of 1966, and the Federal Coal Mine Health and Safety Act of 1969. The Bureau is composed of a headquarters in Washington, D.C., and a field organization of district offices, technical support centers and field health groups.

The Bureau through its Health and Safety Activity conducts programs of mine research and development, approval and testing of mining equipment and protective devices, certification of respirators, mine inspections and field investigations, safety education and training, and mine accident statistics analysis. It is responsible for the formulation and enforcement of health and safety standards. The Bureau has worked closely with NIOSH, HEW, in research and studies of dust diseases over the years.

Responsibilities of the Bureau under the Federal Coal Mine Health and Safety Act of 1969 include annual inspections and investigations in coal mines; development, promulgation and revision, as necessary, of improved mandatory safety standards (in consultation with HEW, and others) and the promulgation of mandatory health standards transmitted by NIOSH, HEW; enforcement of the Act's interim mandatory safety and health standards together with the Interim Compliance Panel, established by the Act to hold hearings and review permit requests from Coal operators for temporary periods of noncompliance with interim respirable dust standards; establishment of specifications for personal sampling equipment; evaluation of dust measuring instruments and those approved for usage under the Act; and expansion of education and training programs in recognition and prevention of accidents or unsafe working conditions. The Secretary of the Interior in coordination with the Secretary of HEW and of

Labor is authorized to make grants to states to assist in developing and enforcing effective coal mine health and safety laws, among other functions.

Under the Act, operators are required to carry out respirable dust sampling programs in coal mine atmospheres by devices and in a manner approved by the Secretary of the Interior and the Secretary of HEW. The samples are transmitted to the Bureau's Pittsburgh Dust Laboratory where they are weighed automatically. Some 30,000 samples are processed monthly. Data are computerized out of the Denver Office and results sent to the Districts and coal mine operators. A periodic sampling scheme has been developed which permits the Bureau to maintain control on exposures in working sections of mines, and at the same time, provide environmental data for epidemiologic purposes.

The Act also provides that operators make arrangements in advance for obtaining emergency medical assistance and transportation of miners requiring such assistance; selected agents of the operator be trained in first aid; and coal mines to have adequate supplies of first-aid equipment at strategic locations at and near working places. The Secretary of the Interior may also require operators to provide potable water and sanitation facilities.

Mandatory safety standards are being proposed for the prevention of explosions from inflammable gases that may be found in underground coal mines. These include methane, carbon monoxide, hydrogen sulfide and others.

Other Federal Agencies

A number of other federal agencies have vested authority in some aspect of occupational safety and health. For example, *the Department of Transportation*, through its assistant Secretary for Systems Development and Technology, has responsibility for the regulation of the transportation of hazardous materials in interstate and foreign commerce and the conditions under which hazardous chemicals may be shipped by carriers. Through the Hazardous Materials Regulations, it also controls the transportation and packaging of radioactive materials.

The Department of Commerce, through the Bureau of Standards, contributes greatly to the evaluation of the industrial environment through its research and central national services in broad program areas, covering basic, material, and technological measurements and standards.

The Department of Defense was established by the National Security Act Amendments of 1949, which also provided that the Departments of the Army, Navy and Air Force be military departments within it. Each of the three departments have in operation extensive occupational medicine, safety, industrial hygiene and environmental health programs conducted for the protection of the safety and health of their own employees in the various installations, bases, repair shops and shipyards in the United States.

In the Department of the Army, occupational safety and health activities are responsibilities of

the Army Environmental Hygiene Agency; in the Department of Navy, of the Industrial Hygiene and Safety Branch; and in the Department of the Air Force, of the Bio-environmental Engineering Program. Activities also cover radiological health aspects, air pollution, hearing conservation programs, disaster preparedness, acoustics and research into allied areas.

The Atomic Energy Act, amended in 1959, provides for the establishment of the Federal Radiation Council to advise the president on radiation matters affecting health, the formulation of standards, and the establishment of cooperative programs with the states.

The Food and Drug Administration, HEW, has enforced the 1960 Federal Hazardous Substances Labeling Act designed to protect consumers from the misbranding of hazardous substances used in industry and in the home.

Federal Employee Health Services

The Occupational Safety and Health Act of 1970 requires each federal agency to establish and maintain a comprehensive safety and health program for its employees, consistent with the Department of Labor's safety and health standards required of industry.

Most federal agencies have established such programs. However, depending upon appropriations, activities and number of employees, extent of services provided varies widely. Agencies may operate their own programs, or they may contract for care with the Division of Federal Employee Health, Public Health Service, or with private medical sources. The Civil Service Commission, through its Bureau of Retirement, Insurance and Occupational Health, also promotes government-wide occupational health and safety programs for federal employees in those establishments that have not as yet arranged for such services.

STATE AND LOCAL AGENCIES

Occupational Health Programs

Until the passage of the Federal Occupational Safety and Health Act of 1970, direct legal responsibility for the health and safety of employed workers rested with state governments. The first state industrial hygiene programs were established in 1913 in the New York Department of Labor and Ohio Department of Health. Growth in initiation of additional programs lagged until 1936 when Social Security funds were made available for expansion of public health programs including industrial hygiene. The mounting silicosis problems of the 1930's also influenced the creation of several programs. Other major events that precipitated their development were World War II and the designation of federal grants-in-aid from 1947 to 1950. During these three years, state and local programs reached an all-time high. The withdrawal of these funds and decreases in state appropriations resulted in retrogression of occupational health activities reflected in a loss of personnel and discontinuance of some programs. However, not all programs were affected to the same degree. Because of the basic expertise of industrial hygiene staffs, many units were given

additional responsibilities in areas of air pollution control and radiological health which helped to stabilize financial situations.

State occupational health programs are at crossroads once more. The implementation of the Occupational Safety and Health Act of 1970 may well alter the operating patterns of both state health and labor agencies.

Administration. Primary objectives of a state governmental program in occupational health are the provision of direct services in the recognition, evaluation and control of occupational health hazards and the promotion of basic preventive health services for workers in all places of employment.

The design and operation of programs will necessarily vary widely from state to state, depending upon extent of industrialization, size and type of industrial establishments, administrative support, program resources, and legislative and political mandates, among other factors. Most state and local occupational health units operate as subdivision of environmental health bureaus in departments of health. A few are independent units. The establishment of the Environmental Protection Agency as a separate federal agency may well influence state counterparts to break away from the health department. Should this be the case, as in Pennsylvania, the Occupational Health activity is likely to be transferred also. When in a state labor agency, the industrial hygiene activity functions either as a separate administrative entity, or in a division of industrial safety. Regardless of where the program operates, provision should be made for adequate financing, staffs, facilities and equipment.

Personnel. A broadly-based program requires many disciplines including industrial hygienists, engineers, physicists, chemists, physicians, nurses and supporting auxiliary staff. For an effective minimum environmental program, staff should include at least one administrator, well-trained in industrial hygiene, one full-time field industrial hygienist, one specially trained chemist, and at least one secretary-stenographer. An approximate rule-of-thumb for field industrial hygienists is one per every 35,000 workers in areas with heavy industries; and in less industrialized areas, the recommended ratio is one per every 50,000 workers.

In view of the perennial shortage of qualified and trained personnel, consideration should be given to the use of technicians and industrial health aides who could, under proper supervision, perform many of the routine tasks necessary in work environment control. Recruitment of personnel could come from qualified junior college or high school graduates. In addition to on-the-job training, these individuals should be given an opportunity to attend short-term training courses, and if indicated, time to attend and work towards a degree at some local college.

Budgets. Budget allocations should be provided for: salaries of personnel (which should be adequate in order to recruit and retain qualified personnel); travel; field and laboratory instruments, both for new and replacements; allowances for

manuals, books and professional journals, printing, postage and communications; and allowances for special consultation services in areas for which the occupational health agency lacks personnel and/or capabilities.

Legislation and Regulations. For effective operation of a program, specific statutory authority regarding investigations of occupational health hazards is generally desirable. Such legislation should include right of entry, inspections, investigations, rule making and promulgation, and enforcement powers. In actual practice, a diversity of situations exist. In some states, the authority is derived from broad powers of state health departments and labor authorities; in other states, it is specific, but may vary in extent of vested responsibilities. In others, authorities overlap or are divided between two or more departments.

The situation regarding state rules and regulations governing health and safety at work places is generally described as "chaotic." In some states, regulations may be general in scope, in others specific for industry or processes or segments of the workforce, and in others absent altogether. Separate regulations dealing specifically with prevention and control of occupational health hazards exist in a few states or may be combined with accident prevention. "Occupational Safety and Health Standards," which were promulgated by the U.S. Department of Labor in 1971, take precedence over the existing, inadequate state laws and regulations, and may well bring order and uniformity in regulations governing safety and health of workers.

Functions and Activities. The operation of state occupational health programs is based on the philosophy that corrective measures in industry for the protection and improvement of the health of workmen are accomplished largely by private efforts and funds. The important task for the state or local occupational health agency is to point out to industry how to solve its own health problems. The types of services which the occupational health agency can provide alone or in cooperation with other groups are extensive and will depend upon the agency's resources and occupational health problems in the area.

As a rule, in inaugurating a program, the first step is the development of an occupational profile of the area. This includes obtaining information on the characteristics of the labor force, types and locations of industries, prevalence of occupational diseases and injuries, availability of community resources, and functions of other agencies with responsibility for health and safety of workers.

Associated with the profile is the "preliminary" or "walk-thru" survey of a well-designed sample of industrial establishments. By this means, information is collected on potential health hazards and their control, availability of preventive health services to workers, extent of safety activities, adequacy of sanitation facilities, house-keeping practices, general ventilation and illumination. Frequently, advice on control of obvious hazards can be offered on the spot. Such surveys

also offer the program administrator an opportunity to become acquainted with the industries in the area under his jurisdiction.

A well-balanced program includes both environmental, including industrial hygiene, and medical and nursing components. Following are examples of functions comprising the *environmental* component:

1. Routine inspections, surveys and technical studies of work places for identification of hazards and their control. Surveys and studies usually require the collection of air samples for contaminant evaluation and materials for laboratory analysis, field measurements of noise, vibration, ionizing and non-ionizing radiations, heat, extremes of pressures, illumination and ventilation.

2. Supportive laboratory services including the calibration of instruments.

3. Follow-up on compliance with recommendations made for improvement or control of health hazards.

4. Professional investigation of reported or suspected occupational diseases with recommendations for elimination or control of causative agents to prevent their recurrence.

5. Consultation services on industrial hygiene matters at request of management, labor, physicians, nurses and others.

6. Review and examination of engineering plans for plant alterations and installation of environmental control equipment.

7. Development and distribution of occupational health materials such as periodic bulletins, information sheets, etc., to employers, employee groups and others concerned.

8. Maintenance of adequate records and reports including lists of new industries coming into the area.

9. Maintenance of cooperative working relationships with other official agencies such as state departments of labor, mine inspectors, state fire marshalls and industrial commissions on matters relating to health and safety at the work place.

10. Writing of needed or improved and updated regulations governing health and safety at the work place or providing assistance to the agency authorized to promulgate such rules and regulations.

Examples of medical and nursing services that can be offered to industry include:

1. Medical consultation to management, labor and private physicians on recognition and diagnosis of occupational diseases.

2. Cooperation with medical societies and individual physicians in the stimulation of proper replacement examinations in industry.

3. Medical consultation in industry regarding health services for in-plant medical departments.

4. Promotion of nursing services in industry and nursing consultation to plant nurses in improvement of health services or to first-aid workers regarding emergency first-aid procedures.

5. Promotion of and assistance with establishing cooperative preventive health services for workers in small plants.

6. Assistance with establishment of employee health services for workers in governmental state or municipal jurisdictions.

7. Consultation to community health agencies regarding extension of public health services to the working population and assistance with their implementation.

8. Participation in joint medical and environmental studies of workers exposed to specific health hazards.

Status of Currently Operating Programs. In actual practice, occupational health programs ranging from token to relatively sophisticated activities operate in practically all the states. Administration is as diversified as the scope of the programs. Ten units are located in state departments of labor, 42 in state departments of health, one in a Department of Environmental Resources (Pa.) and some 40 in local health departments. In several states, programs operate in both health and labor agencies. The smallest units usually consist of part-time or at most, one full-time industrial hygienist working alone, with reliance on others for laboratory support. Larger units may also be staffed by chemists, physicians, consultant nurses, health educators, statisticians and supporting auxiliary staff. Where air pollution and/or radiological health is part of the unit, staffs include various specialists in these areas.

Best developed phases of programs deal with engineering services. Because of continuous loss of personnel, medical and nursing activities are responsibilities of only a small number of units. On the other hand, about one-half of the state units continue to have responsibilities in areas of radiological health and air pollution control. Activities range from provision of laboratory services, monitoring of air and fall-out materials, studies of community air pollution in collaboration with other agencies, to full direction of both community and occupational aspects. In a number of instances such responsibilities have constituted a drain on the occupational health activities, whereas in others they have given the program more visibility.

Major Constraints. As is typical of many governmental agencies, problems of most currently operating units center on inadequate budgets, manpower shortages, inadequate legislative authority, inadequate salaries, poor leadership and lack of administrative support. The lack of quantitative data on prevalence of occupational diseases is also frequently mentioned as a handicap in obtaining funds, but as a rule this is not a deterrent to many of the more effective programs. Considerable knowledge exists on the kinds of occupational diseases and potential health hazards that are associated with specific occupations and industries, and this can be used as a guideline in setting up priorities.

Factors Contributing to Effectiveness of Operating Programs. These include strong leadership; sup-

port of the department and legislature; good budget justification and program planning; periodic self-appraisals of goals, accomplishments and needs; professionally competent and dedicated staffs; adequate salaries, retirement and health benefits; opportunity for graduate training, self-advancement, and self-expression as in writing articles for publication; participation of staff in activities of professional organizations; good public relations, and rapport with industry and labor; mutual inter-change of problem referrals between the occupational health unit and the labor authority; foresight and resources to tackle new problems; prompt response to requests for service; and high caliber of technical services provided.

Impact of Occupational Safety and Health Act of 1970. It is too soon to determine the impact of the Occupational Safety and Health Act of 1970 on the existing state and local occupational health units. Governors in most of the states have designated the agency or agencies to receive grants for planning and conducting occupational safety and health programs. According to the "Directory of Governmental Occupational Safety and Health Personnel, January 1972" (available from NIOSH), labor authorities were so designated in 32 states and Puerto Rico; state health departments in 4 states (Kentucky, Massachusetts, Oklahoma and South Dakota) and both state labor authority and the health department in 8 states (Connecticut, Hawaii, Louisiana, Michigan, New Hampshire, New Mexico, Tennessee and Virginia). In 5 other states, designated agencies vary. For example, in West Virginia, 4 different agencies were named, including the State Health Department. In Texas, the Occupational Safety Division (counterpart of a state department of labor) of the State Department of Health was so designated.

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CHAPTER 50

AN INDUSTRIAL HYGIENE SURVEY CHECKLIST

Robert D. Soule

Previous chapters have discussed in detail both the theoretical and practical aspects of the various interrelated considerations of which the industrial hygiene profession is comprised. In conducting any given industrial hygiene survey, the investigator must follow a prescribed set of procedures incorporating the "scientific method" of problem solving. In its simplest form, this method can be described as consisting of five distinct phases: recognition and definition of the problem, design of studies, quantification of the problem (i.e., data acquisition), evaluation of data, solution of the problem. The experienced industrial hygienist uses this approach, often without full awareness of its being used; a person relatively inexperienced in the practice of industrial hygiene requires some means of identifying and using the sequence of steps of the method.

It is the purpose of this chapter, therefore, to present in simple checklist format, the various steps required in conducting an industrial hygiene survey. Although designed primarily for the "neophyte" in industrial hygiene, such a procedural outline has value to the experienced industrial hygienist as well, since it minimizes the possibility of overlooking various aspects of a study and maximizes the overall efficiency of the survey.

Chapters in this Syllabus which discuss in detail the various points presented in this checklist are indicated by the numbers in parentheses following the specific items.

AN INDUSTRIAL HYGIENE SURVEY CHECKLIST

- Determine purpose and scope of study (2, 8, 9, 10).
 - Comprehensive industrial hygiene survey?
 - Evaluation of exposures of limited group of workers to specific agent(s)?
 - Determination of compliance with specific recognized standards?
 - Evaluation of effectiveness of engineering controls?
 - Response to specific complaint?
- Discuss purpose of study with appropriate representatives of management and labor.
- Familiarize yourself with plant operations (2, 10).
 - Obtain and study process flow sheets and plant layout.
 - Compile an inventory of raw materials, intermediates, by-products and products (2, 4, 10).
- Review relevant toxicological information (7, 8, 17, 48).
- Obtain a list of job classifications and the environmental stresses to which workers are potentially exposed.
- Observe the activities associated with job classifications (32).
- Review the status of workers' health with medical personnel (17, 48).
- Observe and review administrative and engineering control measures used (35, 36).
- Review reports of previous studies.
- Determine subjectively the potential health hazards associated with plant operations (7-10, 17, 24, 26-34).
- Prepare for field study.
 - Determine which chemical and physical agents are to be evaluated (7, 23, 25, 26-34).
 - Estimate, if possible, range of contaminant concentrations.
 - Review, or develop if necessary, sampling and analytical methods, paying particular attention to the limitations of the methods (e.g., sensitivity, specificity, (11-16, 18-21, 25-29, 31, 40).
 - Calibrate field equipment as necessary (11, 12).
 - Assemble all field equipment.
 - Obtain personal protective equipment as required (hard hat, safety glasses, goggles, hearing protection, respiratory protection, safety shoes, coveralls, gloves, etc.) (36).
 - Prepare a tentative sampling schedule.
- Conduct field study (9, 10, 13, 15, 16, 25, 26, 27, 28, 29, 31, 32).
 - Confirm process operating schedule with supervisory personnel.
 - Advise representatives of management and labor of your presence in the area.
 - Deploy personal monitoring or general area sampling units.
 - For each sample, record the following data:
 1. Sample identification number.
 2. Description of sample (as detailed as possible).
 3. Time sampling began.
 4. Flowrate of sampled air (check frequently).
 5. Time sampling ended.
 6. Any other information or observa-

- tion which might be significant (e.g., process upsets, ventilation system not operating).
 - Dismantle sampling units.
 - Seal and label adequately all samples (filters, liquid solutions, charcoal or silica gel tubes, etc.) which require subsequent laboratory analyses.
- Interpret results of sampling program.
 - Obtain results of all analyses (14, 18, 19, 20, 21, 22).
 - Determine time-weighted average exposures of job classifications evaluated (8, 9, 10).
 - Determine peak exposures of workers (8, 9, 10).
 - Determine statistical reliability of data, e.g., estimate probable error in determination of average exposures.
 - Compare sampling results with applicable industrial hygiene standards.
- Discuss survey results with appropriate representatives of management and labor.
- Implement corrective action comprised of, as appropriate:
 - Engineering controls (isolation, ventilation, etc.) (35-46, 52).
 - Administrative controls (job rotation, reduced work time, etc.)
 - Personal protection (36).
 - Biological sampling program (17, 48).
 - Medical surveillance (17, 48).
- Determine whether other occupational safety and health considerations warrant further evaluation:
 - Air pollution? (43)
 - Water pollution? (44)
 - Solid waste disposal? (45)
 - Safety? (47)

CONVERSION FACTORS AND EQUIVALENTS

(Arranged Alphabetically)

<p>1 acre = 4047 m² 1 atmosphere = 14.7 lb/in² = 29.92 in Hg = 760 mm Hg = 1.013 × 10⁶ $\frac{\text{dynes}}{\text{cm}^2}$</p> <p>1 bar = 10⁶ dynes/cm² 1 B.t.u. = 0.252 kilocalories = 778 foot-pounds (ft-lb) 1 B.t.u./min = 12.96 ft-lb/sec. 1 B.t.u./hr-ft² = 0.0003154 watts/cm²</p> <p>1 calorie = 4.186 Joules 1 calorie/sec-cm² = 13.272 B.t.u./hr-ft² = 4.186 watts/cm² 1 candela = Footcandles × D² (Distance in feet from source to illuminated object) = lumens = $\frac{12.57 \text{ ft.}^2 \text{ (area of a sphere of 1 ft radius)}}{12.57 \text{ ft.}^2 \text{ (area of a sphere of 1 ft radius)}}$</p> <p>°C (Centigrade) = [°F (Fahrenheit) - 32] ÷ 1.8 1 centimeter/second (cm/sec) = 1.97 ft/min = 0.0224 mile/hr = 1.9685 ft/min</p> <p>1 cubic centimeter (cm³) = 0.0610 cubic inch (in³) 1 cubic foot (ft³) = 28.32 liter = 7.481 gallons (gal) 1 cubic foot (ft³) of air at 70°F and 1 atmosphere weighs 0.075 lb 1 cubic foot (ft³) of water (H₂O) at 62°F weighs 62.32 lb 1 cubic meter (m³) = 35.315 cubic feet (ft³) = 1000 liters (l)</p> <p>1 dyne/cm² = 0.0021 lb/ft²</p> <p>1 electron Volt (eV) = 1.6 × 10⁻¹² ergs</p> <p>°F (Fahrenheit) = 1.8 × °C (Centigrade) + 32 1 foot (ft) = 30.48 cm 1 ft of water (H₂O) = 0.4335 lb/in² 1 footcandle = 1 lumen incident/ft² = 10.764 lumen incidents/m² = $\frac{1 \text{ lumen}}{1 \text{ lumen/ft}^2}$ = 10.76 LUX (surface area in sq. meters) 1 foot lambert = $\frac{1 \text{ lumen (reflected or emitted)}}{\text{ft.}^2}$ = 1 foot candle (reflected or emitted) 1 gallon (gal) = 3.785 liter 1 gal (U.S.) of H₂O at 62°F weighs 8.33 lb. 1 gram = 15.43 grains = 10³ milligrams (mg) 1 gram-calorie = 0.00397 B.t.u.</p>	<p>1 gram/cm³ = 62.43 lb/ft³ = 8.345 lb/gal</p> <p>1 Hertz = 1 cycle/sec 1 horsepower (hp) = 0.707 B.t.u./sec = 550 ft-lb/sec = 0.75 kilowatt = 2545 B.t.u./hr</p> <p>1 inch (in) = 2.540 cm 1 in. of mercury (Hg) = 0.4912 lb/in² = 13.57 in H₂O</p> <p>1 Joule = 10⁷ ergs = 0.239 calories</p> <p>°K (Kelvin) = 273 + °C 1 kilogram (kg) = 2.205 pounds (lb) 1 kilometer (km) = 1000 m = 0.6214 mile</p> <p>1 liter = 1.057 quarts (U.S., liquid) = 0.03531 ft³ = 1000 cubic centimeters (cm³ or cc) Lumen = Footcandles × Area (sq. ft.) = candela × 12.57 ft² = Foot lamberts × sq. ft. area reflecting or emitting light flux.</p> <p>1 meter (m) = 3.281 feet (ft) = 39.37 inches (in) = 10⁶ microns (μ) = 10³ millimeters (mm) = 10² centimeters (cm)</p> <p>1 milligram (mg) = 10³ micrograms (μg) 1 mg/m³ = 0.000437 grains/ft³ 1 millimeter (mm) Hg = 1.36 cm of H₂O</p> <p>1 ounce (oz) = 28.35 grams</p> <p>Pi (π) = 3.1416 1 pound (lb) = 453.6 grams = 16 ounce (oz)</p> <p>1 pound/square inch (lb/in²) = 2.31 ft. H₂O</p> <p>°R (Rankine) = 460 + °F</p> <p>1 square foot (ft²) = 0.0929 square meter (m²) 1 square inch (in²) = 6.452 square centimeters (cm²)</p> <p>1 square kilometer (km²) = 0.3861 square mile (mile²) (U.S.)</p> <p>1 Volt = 1 Joule/coulomb 1 Watt = 1 Joule/sec</p>
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