

copy 2

Open file - MSHA University

A mining research contract report

JUNE 1983



DEVELOPMENT OF A MINE AIR CONTAMINANT MEASUREMENT PROGRAM—DIESELS AND EXPLOSIVES

U.S. Bureau of Mines
Minneapolis, Minn.

JAN 6 1984

LIBRARY

Contract J0100004
Rocky Mountain Center
for Occupational and
Environmental Health

OFR
84-80

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR



The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the Interior Department's Bureau of Mines or of the U.S. government.

REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	3. Recipient's Accession No.
4. Title and Subtitle Development of a Mine Air Contaminant Measurement Program-- Diesels and Explosives		5. Report Date June 1983	
7. Author(s) WL Wagner, DE Marano, KL White, BF Craft, WJ Kennedy		6.	
9. Performing Organization Name and Address Rocky Mountain Center for Occupational and Environmental Health Building 512 University of Utah Salt Lake City, Utah 84112		8. Performing Organization Rept. No.	
12. Sponsoring Organization Name and Address Office of the Assistant Director--Mining Research Bureau of Mines--Department of the Interior Columbia Plaza, 2401 E Street, N.W. Washington, DC 20241		10. Project/Task/Work Unit No.	
		11. Contract(C) or Grant(G) No. (C) (G)	
		13. Type of Report & Period Covered	
15. Supplementary Notes		14.	
16. Abstract (Limit: 200 words) This report presents a quality control approach to the derivation of strategies for monitoring a work environment; specifically, the environment in underground mines where diesel-powered equipment and blasting agents are used. The approach is presented as a series of 22 steps called the Monitoring Strategy Development Scheme. The scheme is an orderly method for selecting from a number of options a strategy or tactics to cost effectively meet the requirements of a chosen objective related to the monitoring of breathing zone air quality. The scheme provides a format to quantify many of the factors that influence the selection of one strategy or tactic over another, and to ensure that important considerations are not neglected. The premise that breathing zone air in a work environment can be considered to be a manufactured product and that, therefore, conventional quality control approaches are applicable, is introduced. Typical approaches to the quality control of manufactured products and how these approaches can be applied to the selection of monitoring strategies are discussed.			
17. Document Analysis a. Descriptors Diesels, monitoring, quality control, diesel exhaust, industrial hygiene, mine ventilation. b. Identifiers/Open-Ended Terms Air quality, underground mine. c. COSATI Field/Group 06 10 Biological and Medical Sciences/Industrial Medicine.			
18. Availability Statement:		19. Security Class (This Report)	21. No. of Pages
		20. Security Class (This Page)	22. Price

FOREWORD

This report was prepared by the Rocky Mountain Center for Occupational and Environmental Health, Building 512, University of Utah, Salt Lake City, Utah 84112 under USBM Contract number J0100004. The contract was initiated under the Coal Mine Health & Safety Program. It was administered under the technical direction of the Pittsburgh Research Center with George Schnakenberg acting as Technical Project Officer. Bill McCarty and Janice Johnson were the contract administrators for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period January 1980 to June 1983. This report was submitted by the authors on June 30, 1983.

TABLE OF CONTENTS

	<u>Page</u>
Report Documentation Page	3
Foreword	4
List of Figures	6
List of Tables	6
Chapter I. Executive Summary	7
Chapter II. Introduction	11
Introduction	12
Organization of Work Under This Contract	12
Background	13
Approach	16
Summary	17
Chapter III. Industrial Quality Control and Its Application to Air Quality Control in Underground Mines	19
Introduction	20
The Typical Manufacturing System	21
The "Manufacture" of Mine Air	24
Quality Control Procedure Used in Industry	26
Step One	26
Step Two	28
Step Three	28
Step Four	29
Statistical Quality Control	30
Cost	34
Application of Quality Control Approach to Mine Air Quality .	38
Control Techniques	44
Chapter IV. Monitoring Strategy Development Scheme	45
Introduction	46
Monitoring Strategy Development Scheme	46
Discussion of Steps in the Scheme	50
Summary	74

LIST OF FIGURES

Figure III-1. Generalized diagram of a manufacturing system	22
Figure III-2. Generalized diagram of a can manufacturing system	23
Figure III-3. Breathing zone air manufacturing system	25
Figure III-4. Illustration of the theoretical basis for a control chart	31
Figure III-5. Operating characteristic curve for an attributes sampling plan	33
Figure III-6. An example of \bar{x} and R charts	35
Figure III-7. Graph of time-dependent data from table III-2	37
Figure III-8. Theoretical operating characteristic curve for NO ₂ sampling data	41
Figure III-9. Possible CO ₂ concentration data from a load/haul/dump cycle	42
Figure III-10. A control chart for the upper set of values of figure III-9	43
Figure IV-1. System resulting in health effects in underground mine workers: diesel	52
Figure IV-2. Evaluation plan	61

LIST OF TABLES

Table III-1. Quality characteristics of tin cans	27
Table III-2. A sample of time-dependent sales data	36

CHAPTER I
EXECUTIVE SUMMARY

The Rocky Mountain Center for Occupational and Environmental Health, under contract J0100004 to the Bureau of Mines, developed a procedure for methodically developing monitoring strategies to be used in underground mines where diesel-powered equipment and blasting agents are used. The procedure is called the Monitoring Strategy Development Scheme and has been presented to the Bureau of Mines in a document titled Monitoring Strategy Development Scheme Handbook. The handbook details the strategy development procedures, reviews pertinent technical literature, includes an extensive bibliography, and provides examples of how the scheme is used. This report, Development of a Mine Air Contaminant Measurement Program--Diesels and Explosives: Final Report, is a descriptive summary of our efforts in preparing the handbook.

The use of diesel-powered equipment in underground mines in the United States has increased steadily over the past several decades. Diesel mining machinery is more mobile and more convenient to operate than electric-powered machinery, and there is mounting evidence that productivity is increased when diesels are used. However, increased safety potential is perhaps the most important single factor in favor of a dieselized mining system.

On the other hand, diesel engine exhaust contains substances that are potentially harmful to the health of miners. Of greatest concern is the potential for causing cancer and obstructive lung disease.

Blasting residues are included within the scope of this work, along with diesel exhaust. All but one of the primary residues from blasting are found in diesel exhaust, and many mines that use diesels also use blasting agents.

Fortunately, harmful health effects caused by exhaust and blasting residues can be essentially eliminated if the concentrations of these substances are maintained at acceptably low concentrations in the mine air breathed by the miners (commonly referred to as breathing zone air by occupational health professionals). Controls such as maintenance, primary and supplemental ventilation, fuel standards, alteration of exhaust content and location, engine and vehicle modifications, and work practices, including scheduling, are used to maintain low concentrations.

An important component of any control program is a monitoring strategy properly designed and implemented to measure the effectiveness of the controls and to identify malfunctions and maintenance requirements. No engineering control program is truly complete unless it includes such a plan. The crux, then, of the health-related issue of using diesel power or blasting agents underground is effective control of the emissions. We feel that the key to an effective control program is a complementary and effective monitoring strategy.

Unfortunately, much monitoring in the mining industry is performed haphazardly. Therefore, the Bureau of Mines decided to derive a logical, systematic approach for developing monitoring strategies and tactics designed to provide maximum effectiveness in achieving an objective, with a minimum of cost and implementation difficulty. These strategies, so developed, would become integral components of air quality control programs designed to assure that miners in underground mines where diesels and/or blasting agents are used breathe air of acceptable quality.

Since the objective was to derive a logical and systematic approach to monitoring strategy development, we turned to the field of quality control engineering for guidance. Quality control engineering has developed in response to a need for systematic examination of manufacturing systems to ensure that manufactured products meet specified quality standards. For us to use quality control engineering techniques, we only needed to view the breathing zone air in an underground mine as if it were a manufactured product.

A manufacturing system is typically viewed as consisting of three components: 1) raw materials, 2) a manufacturing process, and 3) a product. The "production" of breathing zone air is an analogous system: 1) air, diesel fuel, and blasting agents are the raw materials; 2) the mining processes, including the use of diesel engines and blasting, are the manufacturing process; and 3) breathing zone air is the product. Accordingly, we have implemented a model where air quality is treated as if it were a conventionally manufactured product, so that conventional methods for developing quality control programs could be used.

The classical quality control approach consists of four basic steps. The first step is to identify the quality characteristics desired in the product. In the case of breathing zone air, these quality characteristics may be represented by health standards for airborne substances, indicators of a need for maintenance, or warning levels for certain substances. Step two is to conduct a complete systems analysis to identify the variables of the manufacturing process that either affect or are correlated with the quality characteristics. These process variables, along with product characteristics, are the things that can be monitored or sampled to assure that a process is in control. Step three is to select appropriate measurement options and to determine the best data collection procedures, taking into consideration sources of variability and cost. The fourth and last step is to establish proper data analysis procedures.

The Monitoring Strategy Development Scheme follows, generally, the above procedure. The scheme utilizes 22 steps designed to determine the universe of measurement options and to rank these options according to how well they will satisfy the requirement of the monitoring strategy. In abbreviated form, the scheme is as follows:

- Step 1. The objective of the monitoring strategy is defined.
- Step 2. Critical go/no-go factors are identified.
- Step 3. The mining processes that affect the quality of breathing zone air are identified.
- Steps 4 and 5. Quality characteristics of the breathing zone air that are potentially useful are identified.
- Steps 6 and 7. Variables in the mining process that relate to quantitative correlations with product characteristics are identified.
- Steps 8 and 9. The process variables that substantially affect product quality and that can be used in an engineering control program are identified.

Step 10. Applicable measurement technology for each product characteristic and process variable is identified.

Step 11. Measurans are developed. ("Measuran" is a term coined by us to mean a combination of: 1) a place in the mining system where a measurement could be made, 2) a variable to be measured at that place, and 3) a measurement technique for the variable.)

Steps 12 and 13. Measurans not meeting the requirements of the critical factors from step 2, or for other reasons found to be inferior, are dropped from consideration.

Steps 14 and 15. The number and/or frequency of measurements are determined using statistical analysis.

Steps 16, 17, and 18. Using a worksheet called an evaluation plan, the measurans are given comparative ratings against criteria listed under three major categories: 1) effectiveness, 2) implementation difficulty, and 3) cost. The measurans are ranked according to their overall ratings.

Steps 19, 20, 21, and 22. Strategies are selected that use one or more measurans, according to the overall comparative ratings.

By following the above scheme, the significant factors that influence selection of the most efficacious measurement strategy or tactics from an array of options will have been considered. The scheme, properly utilized, identifies the array of available options and provides a framework for methodically making a selection of strategy or tactics from this array.

CHAPTER II
INTRODUCTION

Introduction

One objective of the Bureau of Mines is to develop technology to ensure that air of acceptable quality is provided to underground miners. The Bureau has long recognized the importance of controlling diesel engine emissions and has made an extensive effort over the years in diesel exhaust control technology development. The Bureau has also made a considerable effort to develop better monitoring and measurement instruments. These instruments are needed to evaluate the effectiveness of engineering controls and to optimally operate control systems. An extensive variety of measurement options is now available. Because of this variety and because monitoring strategies in the past have been generally selected in a rather haphazard manner, the Bureau decided to derive a logical, systematic approach for selecting monitoring strategies and tactics that provide maximum effectiveness at a minimum cost and implementation difficulty. These strategies would be part of an air quality control program designed to assure that workers in underground mines where diesel-powered equipment and/or blasting agents are used receive air of acceptable quality. This report presents an overview of the scheme developed for the Bureau of Mines for methodically deriving monitoring strategies.

Organization of Work Under This Contract

The work performed under this contract is presented in two documents:

1. Development of a Mine Air Contaminant Measurement Program--Diesels and Explosives: Final Report
2. Development of a Mine Air Contaminant Measurement Program--Diesels and Explosives: Monitoring Strategy Development Scheme Handbook.

This document, the Final Report, includes an executive summary (Chapter I), this introduction (Chapter II), and two other chapters.

Chapter III discusses the quality control approach to the operation of manufacturing processes in relationship to product quality. Terms are defined and the background information that evolved into our monitoring strategy development scheme is presented.

Chapter IV presents the scheme and explains each step in detail. Our objective in Chapter IV is to present the information in a format that would permit a technically oriented person such as a health and/or safety specialist to use the scheme to select an effective monitoring strategy for a given objective.

The Handbook includes Chapters II, III, and IV of this Final Report (redesignated as Chapters 01, 11, and 21, respectively) and several additional chapters. The additional chapters (31, 41, and 51) further detail the use of the Monitoring Strategy Development Scheme and provide information and a review of technical literature potentially useful to a user of the scheme.

Chapter 31 consists of subchapters that are specific to the subject of diesel exhaust and blasting in underground mines.

Subchapter 31:1 reviews the variables at the sources that affect the quality of breathing zone air. Variables affecting air quality as combustion and blasting products move from the source to exposed miners are reviewed in subchapter 31:2. These chapters are essentially a review of the mining process (or in quality control terms, the manufacturing process) to determine which variables are important in affecting the quality of breathing zone air.

Subchapter 31:3 reviews commercially available measurement methods and instrumentation in detail sufficient to enable a quantitative comparison. In this chapter, important terminology is introduced in order to categorize various methods and instruments.

Subchapter 31:4 reviews the products of diesel engine combustion and of blasting, summarizes their associated health effects, and estimates ranges of concentrations typically found in today's underground mine in the United States.

Chapter 41 lists a complete bibliography. The bibliography is listed both alphabetically and numerically as referenced in the Handbook.

Chapter 51, which is the appendix to the Handbook, includes a glossary of terms (subchapter 51:1), that may be new to the reader or may be frequently used ambiguously elsewhere. Subchapter 51:2 presents a step-by-step example of how the scheme is used to derive a monitoring strategy. An example objective concerning exposure to CO is used for illustration. Chapter 51:3 is another illustration of the use of the scheme and uses the control of SO₂ as an example.

Background

The worldwide use of diesel-powered equipment in underground mines has increased steadily during the past several decades. In the United States, relatively few diesels are used in coal mines, but the metal and nonmetallic mining industry relies extensively on diesel engines as a power source.

Diesel-powered mining equipment is popular with mine operators because this equipment increases productivity and safety and is more convenient to operate than other types of equipment. Rubber-tired free-moving diesel equipment is considerably more mobile than electric-powered equipment and thus more convenient and productive. However, the potential for a safer operation appears to be the most important single factor in favor of a dieselized mining system. Since a dieselized system has no need for a large number of trolley wires, electrical cables, or batteries, a reduction in electric shocks, fire hazards from electrical equipment malfunction, and methane explosions is expected.

On the other hand, diesel engine exhaust contains toxic substances that could be injurious to miners. Substances commonly considered to pose a hazard to health are carbon monoxide (CO), oxides of nitrogen (NO_x--typically NO and NO₂), sulfur oxides (SO_x), organic compounds, especially the polycyclic aromatic hydrocarbons (PAH), and particulate matter. A more detailed and referenced discussion of health effects is provided in the Handbook.

Generally, health professionals are concerned about the potential for developing cancer or other lung diseases. Cancer may result from exposure to the organic substances in exhaust that are typically associated with the particulate matter. Lung diseases could result from exposure to the other compounds, either individually or in mixtures. These professionals are concerned about the potential for chronic disease resulting from long-term, low-level exposures rather than acute effects. We do not mean to discount the importance of the problems associated with short-term exposure to relatively high concentrations of diesel exhaust components, but only to emphasize that the primary concern and uncertainty among many health professionals in regard to these components is with the potential to cause diseases from chronic, i.e., long-term, exposure.

The concern among health professionals regarding the use of diesel engines in underground mines arises from the potential for disease, rather than from a sweeping and conclusive indictment that miners exposed to any diesel exhaust--no matter how slight--will, in fact, suffer disease. In this regard, there is a differentiation between exposure to a toxic substance and the existence of an actual health hazard. For example, consider the situation where a miner is breathing air contaminated with a very small amount of carbon monoxide. In this situation, the miner is indeed exposed to a toxic substance, but if the amount of carbon monoxide breathed is very small, no adverse effects are observed and, presumably, no health hazard exists. If the concentration of carbon monoxide is increased, the potential for harm to the miner is also increased and, at some higher concentration, a definite toxic effect will be observed. Therefore, there is a threshold below which exposure to a toxic substance does not result in an observable toxic effect. The reasons that health professionals are very conservative in their approach to health standards are that (1) the effects of exposure to low levels of toxic chemicals may not appear for many years--even decades, (2) many health professionals believe that any amount of some chemicals may cause cancer, and (3) for many chemicals the threshold of toxicity is not clearly nor easily determinable and, consequently, a range of exposure usually exists over which the presence of an actual health hazard is debatable.

The difference between exposure to a toxic substance (more appropriately, a potentially toxic substance) and an actual health hazard is important because effective control measures can substantially reduce or eliminate the hazard from exposure to toxic substances. This means that dieselized mining processes can be used to full advantage, in spite of the concern for the potentially toxic exhaust, as long as an effective exhaust control program is also designed into the mining system. The crux of the issue, then, is the effective control of the exhaust components; it is not whether the apparent safety and production advantages of the diesel engine as a power source are outweighed by the potential health hazard.

The most commonly used method to control concentrations of exhaust components in the work areas of mines is ventilation. The objective of a ventilation system is to dilute the tailpipe emissions with fresh air and transport them away from the work areas, thereby maintaining concentrations below "acceptable" levels (usually mandated health standards). Ventilation is expensive, however, so alternative controls are also applied to the engine. These controls can include the specification of fuel characteristics (e.g., sulfur content), engine or vehicle modifications, and treatment (alteration) of exhaust prior to emission from the tailpipe. Several types of controls are in use or under development at the present time; however, all of these controls involve cost and, depending on each particular mining system, provide varying degrees of protection. All control systems also have an inherent requirement that measurements be made in order to acquire information on the effectiveness of the controls and to provide warning if there is a control system malfunction or if maintenance is required. Accordingly, no control system is complete unless accompanied by a plan for determining whether exposures to the exhaust substances are being maintained at or below acceptable levels. This brings us back to the subject of this report--monitoring strategies.

The advantageous use of diesel power in underground mines depends on effective control of exhaust components. We also feel that the key element of an effective diesel exhaust control program is an understanding of its effect on mine air quality. It is also important to know this effect in a timely manner and to identify the processes where control can most effectively be applied. To obtain information on effect, measurements of some type must be made of the control system. The plan for making the required measurements constitutes a monitoring strategy. Measurements may be made of (1) concentrations of toxic components in mine air, (2) other substances that may indicate the presence of toxic components, (3) other mine variables related to engine performance and condition, or (4) ventilation. There are many controls that can be applied to a mining system that uses diesel engines, and there are many measurements and ways of making measurements that can be used to measure the effectiveness of the control systems. All of the different measurements involve cost, utilize someone's time, and provide information of varying degrees of usefulness. The reason for developing a monitoring strategy is to ensure that the measurement techniques selected will optimally provide cogent information at minimum cost and effort.

Unfortunately, most monitoring is performed in a rather haphazard manner, with insufficient planning given to the applicability of the acquired information. For example, measurements of exhaust components are typically made using indicator or stain tubes, also frequently referred to as detector tubes. Although useful for approximating the range of exposures and for similar objectives, detector tubes are relatively inaccurate and generally do not provide information useful for determining the most efficient corrective action to be taken if an undesirable result is obtained. These measurements are made over a relatively short period of time (typically 5 to 15 minutes) but are often used to estimate exposures over an entire workshift. Unfortunately, measurements obtained in the above manner usually provide inaccurate information regarding average exposures, are not truly representative of workplace conditions, and thus, depending on the objective, may be an inefficient use of the time of the personnel involved.

So far, we have discussed only diesel exhaust components and the need for their control. It is logical, however, to also include within the scope of this work the residues from blasting, i.e., shot firing. There are two reasons for this: (1) the primary residues from blasting are CO, CO₂, NO, NO₂, SO₂, and ammonia (NH₃), and, with the exception of NH₃, these same substances also occur in diesel exhaust, and (2) many mines that use diesels also use blasting agents. Although the focus in this report is with monitoring strategies applicable to diesel usage, strategies for mines where blasting agents are used--either alone or in combination with diesel usage--can also be derived using the techniques developed.

Approach

The objective of the contract for the Bureau of Mines was to derive a logical, systematic approach for developing monitoring strategies and tactics to be used in an air quality control program. The key word is "systematic".

The systematic approach to monitoring and controlling the quality of industrial processes is the realm of the systems analyst/quality control engineer. The field of quality control engineering developed in response to a recognized necessity for making a systematic examination of manufacturing systems in order to ensure that manufactured products possess specified characteristics. We chose to apply a quality control approach to our objective.

A manufacturing system typically consists of three components: raw materials, a manufacturing process, and a manufactured product. The breathing zone air of underground miners is somewhat analogous to a manufactured product: the mining process alters raw materials to produce breathing zone air. In the analogy, air, diesel fuel, and blasting agents are the raw materials, the mining of ore, including all control systems and vehicle activities, is the manufacturing process, and breathing zone air is the product. Admittedly, the analogy is imperfect, because the primary function of the mining process is to extract ore, not produce breathable air. However, it is only important to realize that some aspects of the mining process can be considered to be a manufacturing process for breathing zone air and that the other aspect or purpose of the mining process is to efficiently extract ore. We have implemented a model whereby air quality is treated as if it were a conventionally manufactured product, so that a classical method for the development of a quality assurance or a quality control program can be used. The actual controls on the mining process that result in the achievement of acceptable air quality are, of course, limited by economic and practical factors beyond the scope of this work. We are only developing and presenting a scheme for the selection of monitoring strategies that are efficient and effective in assessing or predicting the quality of breathing zone air with a fixed and given set of engineering controls in place. Therefore, the basic premise underlying our approach to this work is that quality control methods can be applied to the goal of achieving acceptable mine air quality, and to apply this concept, it is only necessary to treat the air in the miner's breathing zone as if it were a manufactured product.

The mining processes referred to in this report include the operation of mining equipment, ventilation, mine design, and all other aspects of ore extraction that affect breathing zone air quality. Substances from the ore body itself are excluded from consideration in the process, except to the extent that they interact with the diesel exhaust or blasting residues. Other programs at the Bureau of Mines are addressing the control and monitoring of these ore body-related (methane, dusts, and ionizing radiation) or fire-related (products of combustion) substances.

We have focused our attention in this report on the dieselized mining system rather than the system associated with blasting. We chose this course because we considered the diesel system to be the more complex of the two and, once a scheme had been developed that could be successfully used to select monitoring strategies for diesel-associated objectives, it would not be difficult to apply the scheme to other operations, especially other mining operations such as blasting.

The scheme that we have developed is intended to present a methodical way of making a choice, from a number of options, of the most effective and efficient monitoring strategy for a specified objective. We have purposely attempted to present the scheme in as general a format as possible because it is applicable to other workplace operations and, therefore, other users not concerned with diesels in underground mines may also find it useful.

Summary

- 1) Diesel engines and blasting agents are technologies that are necessary for production and safety in the underground mining industry, but because their use releases contaminants into the mine air, there is a need to control these contaminants to protect the health of exposed miners.
- 2) By the use of engineering controls, mine operators can maintain the toxic substances in diesel exhaust and from blasting to levels below which no short- or long-term threat to the well-being of exposed workers would be expected. The necessary control technology, however, increases the cost of production and can be ineffective if the controls are not properly selected, designed, operated, and maintained.
- 3) Effective operation and maintenance of control technologies for diesel engine exhaust and blasting products requires that appropriate measurements of the mine environment and/or the processes that determine the product levels be made. A program of measurements is a monitoring strategy and is, in our opinion, important to the proper operation of a mine. Just as a roof-bolting plan or a ventilation plan is essential to the implementation of these activities, a monitoring plan is essential to the implementation of measurement activities.

- 4) We have treated breathing zone air as if it were a manufactured product, analogous to a typical industrial product, the characteristics and quality of which can be specified. We have done this in an effort to apply conventional quality control/assurance techniques to those aspects of the mining processes that affect the "production" of breathing zone air, so that we may derive reasonable and logical monitoring strategies, i.e., measurement plans.
- 5) We have derived a scheme for systematically developing monitoring strategies in underground mines where diesel-powered equipment and/or blasting agents are used.

CHAPTER III
INDUSTRIAL OUALITY CONTROL AND ITS APPLICATION
TO AIR OUALITY CONTROL IN UNDERGROUND MINES

Introduction

We have advanced the premise that breathing zone air in an underground mine could be considered to be a manufactured product. The objectives of this chapter are to examine the techniques used to measure and ensure the quality of traditional manufactured products and to show how these techniques can be applied to mine air quality control.

Although the concept of quality control is as old as industry itself, it was about the time of World War II that the application of statistically based quality control procedures became widely accepted in the United States. This acceptance was largely attributable to the emergence of the armed services (and their requirement for very high quality products) as large-volume consumers of American industrial production. Along with the emergence of quality control as an important component of the manufacturing process, the focus of quality control procedure has also changed. The traditional approach to quality control emphasized product acceptance; a recent approach emphasizes process control. This shift of emphasis is a result of technological progress in computer-controlled production. Real-time data collection and analysis, with feedback to the production process, are used to constantly monitor and change the process conditions that affect product quality. Unfortunately, mine air quality control is still predominantly focused on product acceptance, and the product (breathing zone air) is accepted or rejected long after it has been used by the consumer.

Before proceeding into a discussion of quality control, we will clarify certain ambiguities in terminology that have developed. The following definitions, taken from the McGraw-Hill Dictionary of Scientific and Technical Terms, 2nd edition, will be used as the basis for further discussion in this report:

1. Quality Control (QC) is "the inspection, analysis, and action applied to a portion of the product in a manufacturing operation to estimate overall quality of the product and determine what, if any, changes must be made to achieve or maintain the required level of quality."
2. Quality Assurance (QA) is "testing and inspecting all of or a portion of the final product to ensure that the desired quality level of product reaches the consumer."
3. Process Control Engineering is a field of engineering dealing with ways and means by which conditions of continuous processes are automatically kept as close as possible to desired values or within a required range."

Based on these definitions, quality assurance and process control are subsets of the more general field of quality control. Quality control deals with both the quality of the final product and the ways of changing the production process to obtain desired quality. Quality assurance, on the other hand, examines only the quality of the final product and includes the concept of acceptance or rejection of the product by the consumer. A traditional component of quality assurance is the function of acceptance sampling.

Acceptance sampling occurs when a representative sample of a larger group of items is inspected and a decision to accept or reject the entire group is made, based on the results of the sampled group. These activities are contrasted with process control, where the emphasis is placed on measuring and changing interim process conditions that are known to have an effect on the quality of the final product. Also important to this definition of process control is the concept of a continuous process that is automatically kept in control.

This section will 1) examine the traditional quality assurance and process control techniques as they are applied in the field of industrial quality control and 2) will show that such approaches can be used in the systematic development of monitoring strategies for the control of mine air quality. Thus, mine air will be treated as a manufactured product, although in reality it is only a "by-product" of the true manufacturing system, the one that extracts ore from the ground. We will develop the applicability of performing acceptance sampling on the final product (the air quality in the breathing zone of the mine worker), as well as the applicability of using process control techniques to monitor and control those intermediate processes that also affect the final product.

The Typical Manufacturing System

Consider the manufacturing system shown in Figure III-1. In this system, inputs are used in a production process to create outputs for use by consumers. The outputs can be grouped into a unit called a lot. Lot size can either be set arbitrarily or set at some logical size determined by the process, e.g., a "batch" or "run". The needs and desires of the customers define quality characteristics and quality standards for the product, and the quality control process monitors, investigates, and corrects deviations from these standards.

To further illustrate, look at the simplified description of the manufacture of tin cans shown in Figure III-2. Three inputs are labor, tin plate, and solder, which are combined in the manufacturing process to product outputs in the form of products and by-products (in this case, cans, heat, and scrap). The customers are the companies that use the cans as containers for whatever products they are selling. These customers define the required quality characteristics of the cans, i.e., the characteristics the cans must possess in order to be useful. Two of many possible quality characteristics are: 1) holes in the can body and 2) diameter of the can.

The quality standard for holes is simple: a can with a hole is unacceptable since it allows canned material to leak out. The presence or absence of leaks can be determined and the number of such defects counted without measuring the size of any holes. A defect such as a hole is an example of an attribute, a characteristic that is either present or not present and can be counted. A quality standard would have to be set for the number of cans that could have one or more holes, e.g., a strict standard, such as no cans could have a hole or the canner could accept some percentage of cans with holes, knowing that those cans must be discarded.

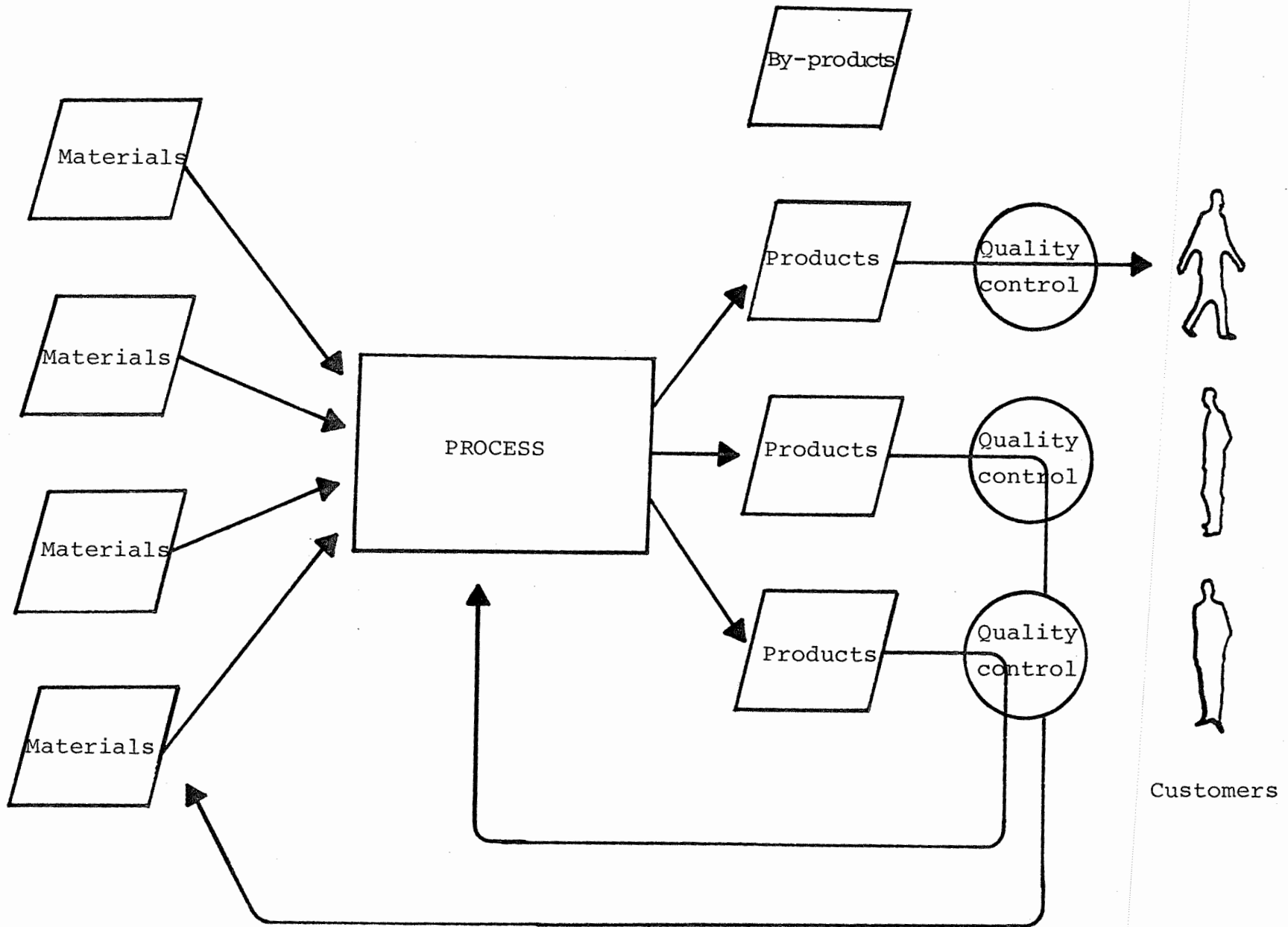


FIGURE III-1. - Generalized diagram of a manufacturing system.

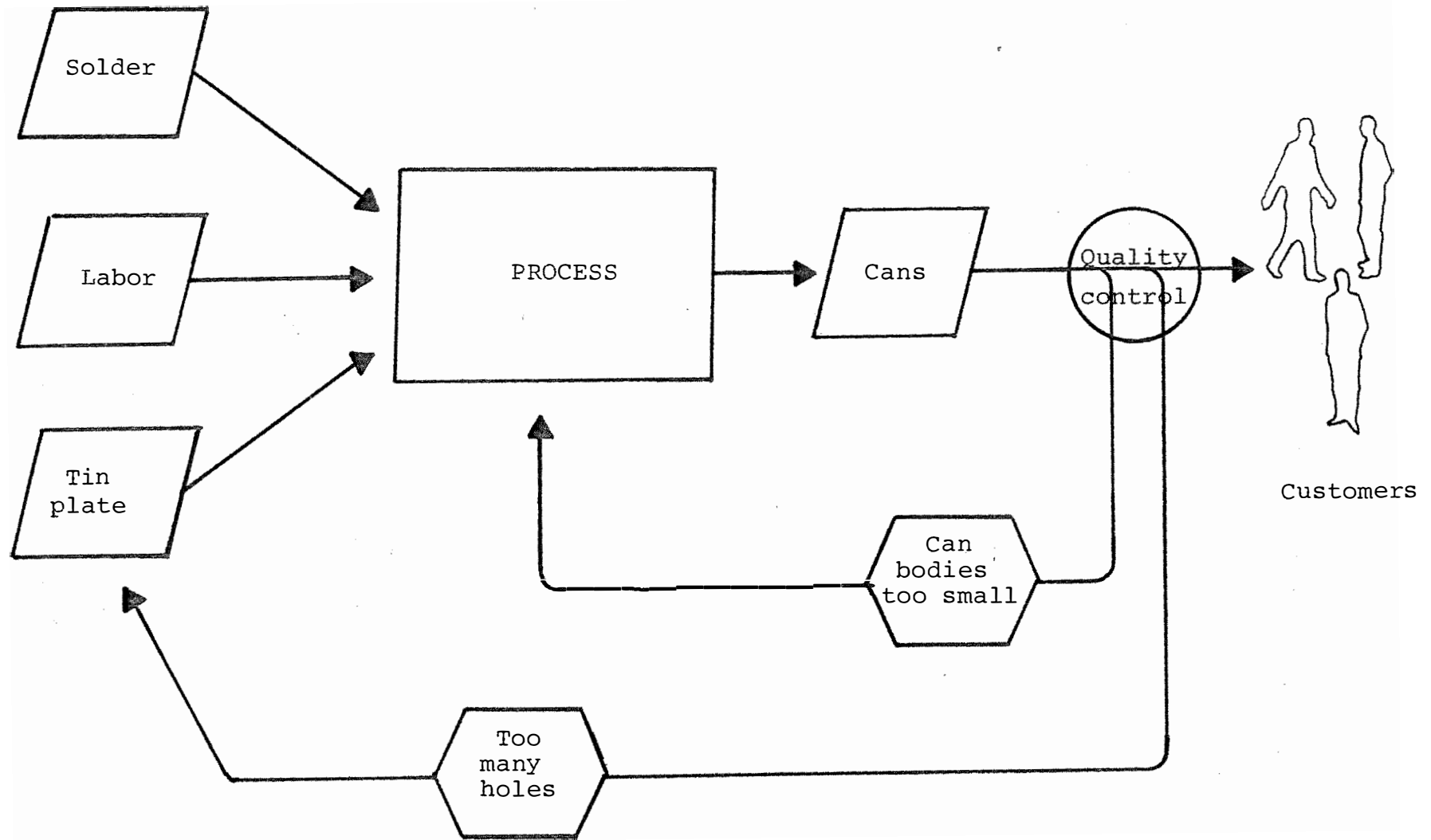


FIGURE III-2. - Generalized diagram of a can manufacturing system.

The diameter of the can is an example of a variable, a characteristic that is measurable on a continuous scale. As an example, the quality standard for this variable might be that a lot of cans is acceptable if 95 percent of the can diameters are between 3.180 and 3.195 inches.

Therefore, quality control can be expressed as the set of procedures used to assure that the product reaching the customer meets the quality standards for the required quality characteristics. These procedures include obtaining samples, counting attributes or measuring variables, investigating the cause of unacceptable quality, and removing the cause of poor quality (whether the cause is in one of the inputs, in the manufacturing process itself, or in unnecessarily stringent quality specifications).

Before an adequate quality control plan can be developed for a given manufacturing system, a complete systems analysis must be undertaken to 1) define the inputs to the system, 2) identify process variables that may ultimately affect product quality, and 3) determine quality characteristics of the final product that are either desired or required by the consumer. This analysis establishes the framework for selecting variables and/or attributes that, when monitored, will provide the most appropriate information required for effective process control or product acceptance.

The "Manufacture" of Mine Air

The "manufacturing" system that produces breathing zone air in an underground mine can be described in the same terms as the system used to produce cans. The raw materials going into this manufacturing process are air and diesel fuel. The manufacturing process consists of 1) transporting the air from outside the mine to the point of use, 2) processing part of the air through a diesel engine where it is mixed with the fuel and burned, 3) mixing the resulting exhaust with mine air and, finally, 4) transporting this mixture to the miners (see Figure III-3). The product is the air-exhaust-blasting residue mixture actually breathed by the miners. The quality characteristics and standards for this air related to health effects are typically defined in the United States by government regulations. However, quality control can also be based on characteristics established by operators for reasons associated with effective mine operation. Quality control in this context includes the control of the contaminants in mine air and the measurement of the contaminants and other variables that relate directly to these contaminants.

Our comparison of the production of breathing zone air with the production of tin cans is not totally appropriate because the cans come off the assembly line in discrete units, whereas the production of breathing zone air is continuous. A more appropriate comparison would be to the manufacture of copper wire by a continuous extrusion process. Quality characteristics for this product might be the number of nicks in the wire per unit length (an example of an attribute, since it is countable) and the diameter of the wire (an example of a variable, since it must be measured on a continuous scale).

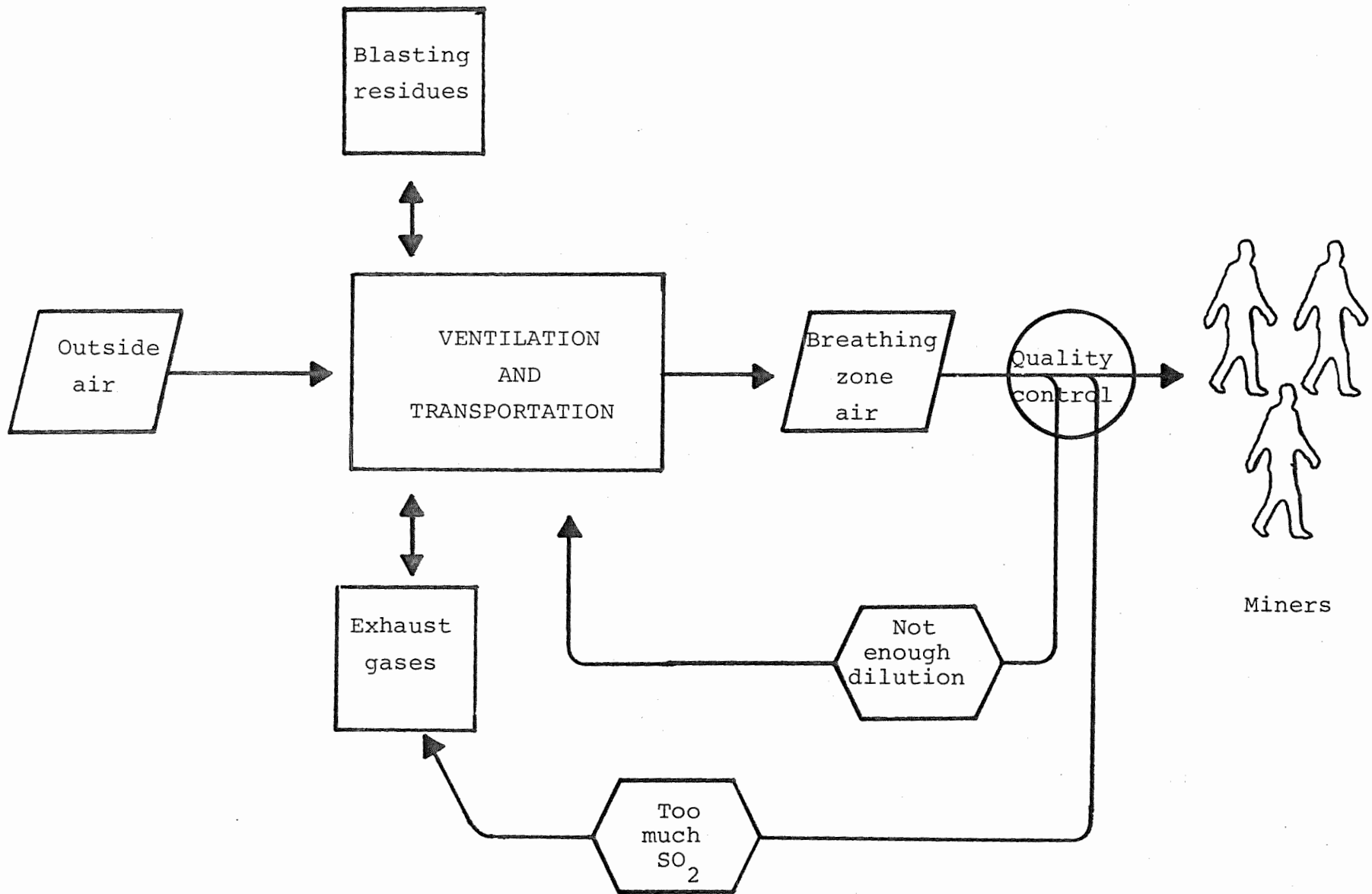


FIGURE III-3. - Breathing zone air manufacturing system.

In the case of the attribute nicks per unit length, it is necessary to select the constant unit of length over which the nicks are counted. It may be a convenient length, such as the amount of wire that fits on a shipping spool, or an arbitrary length, such as 100 feet. On the other hand, if the desired quality characteristic is that the wire diameter never be greater than a given size, the wire could be monitored continuously and no arbitrary wire length would need to be selected.

In the case of the manufacture of mine air, one might conveniently select units of breathing zone air based on time (15-minute or 8-hour periods are commonly used). The desired quality characteristics of those units of air are usually the ceiling and time-weighted average standards established by the Mine Safety and Health Administration. This approach will be developed further in the discussion of application of quality control techniques to mine air quality control later in this chapter.

Quality Control Procedure Used in Industry

The intent of the following discussion is 1) to enable the reader to understand the applicability and limitations of industrial quality control in general, 2) to establish a framework for the discussion of quality control applications to mine air quality, and 3) to present the fundamental steps on which the monitoring strategy development scheme presented in Chapter IV is based. We will review quality control procedure using the manufacture of tin cans as an illustration.

Quality control procedure is best viewed as a series of steps. Step one is to define the desired quality characteristics of the final product. Step two is to conduct a complete systems analysis to identify the variables of the manufacturing process that either affect or are correlated with the quality characteristics. The quality characteristics and the process variables form the universe of items that can be monitored or sampled to assure that the process is in control. Step three involves the selection of appropriate measurement options and determination of the best data collection procedures, taking into consideration sources of variability and cost. Step four is the establishment of proper data analysis procedures. The proper procedure for data collection and analysis depends on whether the objective of the quality control effort is directed toward acceptance of the final product or toward process control (or both).

Step One

The first step, then, is to select and define the desired quality characteristics of the final product. In the case of cans, the choice must be made from a list such as Table III-1. The ultimate choice, however, depends on the customer for the immediate product. If cans are being made for tomatoes, the cans must be capable of withstanding the physical forces imposed by the tomato canning process. The inside of the cans must not create offensive or hazardous chemicals when in contact with the tomato canning liquid. In addition, the can manufacturer may choose to have the outside free from blemishes such as scratches or a mottled appearance.

TABLE III-1. - Quality characteristics of tin cans

Possible characteristics	<u>Used in quality control</u>	
	Variable	Attribute
Diameter	X	
Height	X	
Solder splatter on seam		X
Holes in can body		X
Enamel coverage		X
End book length	X	
Body book length	X	
Enamel thickness	X	
Chrome plate thickness	X	
Tin plate thickness	X	
Seam strength	X	
Seam solder coverage		X

Once the desired or necessary characteristics have been identified, they must be listed in order of importance and made into specifications. These specifications are expressed as either variables (the desired diameter is 3.1875 inches) or attributes (no can should have a hole large enough to allow the escape of air).

Although most attributes cannot be conveniently stated as variables, variables can always be stated in attribute terms. For example, the variable of can diameter can be changed to an attribute by saying that cans with a diameter equal to or less than 3.1875 inches are "O.K." and cans with a diameter greater than 3.1875 inches are not "O.K." Contaminants in mine atmospheres exist in variable concentrations, but quality standards treat them as attributes by considering them to be "O.K." if their concentrations are below certain values and not "O.K." if above certain values.

The major advantage of characteristics expressed as variables is that, generally, more information is gained about the process and, thus, it is easier to assign a cause for an out-of-control situation. With attributes, data collection is generally easier and cheaper, and several qualities can be combined conveniently, making decisions as to acceptance or rejection of items more manageable. Therefore, attributes data are more useful for acceptance sampling, whereas variables data better provide the information necessary for process control.

Step Two

The second step is to define the process variables that ultimately affect the quality of the final product. This step requires a thorough knowledge of the particular manufacturing system in question. To obtain this knowledge, a systems analysis must be performed in which all of the system inputs, process variables, and outputs are clearly delineated. Information must then be collected that establishes a correlation or an association among the identified process variables and the desired quality characteristics. In some cases, no data will be available that link the process variable in question with a desired quality characteristic. In such cases, the process variable will be eliminated as a potential item to be monitored until research is conducted and more information is obtained that links it to the product quality characteristics it affects. What remains is a universe of process variables that have an identifiable effect on the desired quality characteristics of the final product and, thus, represent potential variables to be monitored for process control.

Step Three

After the desired quality characteristics of the final product have been selected and the process variables that affect those characteristics identified, the third step in the quality control process is to select what is to be monitored or sampled. This step is a difficult one because it involves making a trade-off between performing acceptance sampling on the final product and monitoring interim process variables to control the process

for the purpose of achieving the desired product quality. If acceptance sampling is selected, then good information is obtained about the quality of the final product; however, this information is obtained after the product has been produced and, thus, could be costly if a substantial amount of the product is rejected. Also, little information is obtained to aid in changing the process to correct the cause of defects that are found. On the other hand, process control monitoring will generally give less reliable information about the actual quality of the final product but will enhance our knowledge about the cause of an out-of-control situation and will facilitate the correction of such a situation prior to the product being produced.

When making a choice among the many process variables to monitor, keep Pareto's curve in mind. Pareto was an Italian economist who, while studying the wealth of Italy, concluded that the greatest part of the Italian wealth was held by a small fraction of the population. In its application to quality control, Pareto's curve, also known as an 80/20 curve, is a "rule-of-thumb" concept that often 80 percent of defective work comes from only 20 percent of the causes. Thus, it is necessary to conduct a sensitivity analysis on the process variables to determine which ones have the greatest effect on the quality of the product and, therefore, are the more important candidate variables for monitoring.

Step Four

The fourth step is to establish the data requirements that will satisfy all of the requirements imposed by the objective of the quality control program and to determine the data collection and analysis procedures that will meet the data requirements. For instance, if the objective is to correct "out of control" situations (defined later in this chapter) as they occur, then there is imposed a requirement that the process be monitored more or less continuously and that the data be processed relatively rapidly and fed back into the control system. Other objectives might require only infrequent sampling of the product or process with a longer data "turn around" time permissible. The objective determines the data needs, and the data collection and analysis procedures in turn must meet those needs.

An important input into the choice of quality characteristics or process variables to be measured is the availability of sampling instrumentation and methods that are usable, accurate, and commensurate in cost with the importance of the characteristic being measured. The sampling must be capable of being performed by the designated personnel under the conditions of practical use. Procedures must be sufficiently well-defined to preclude the collection of erroneous or misleading data. There must be a calibration procedure by which the accuracy of the equipment can be checked. Additionally, measurement variation caused by operations, sampling procedures, and the production process itself must be specified (either measured, known, or assumed).

Statistical Quality Control

The four steps discussed above are the foundation for the methodical evaluation of an industrial process, and they are the basis of our Monitoring Strategy Development Scheme, which is presented in the next chapter. However, quality control also includes important statistical aspects. These aspects are referred to as statistical quality control. Although statistical aspects are not included in this contract, we feel that it is appropriate to provide a brief discussion of some of the terms and approaches used in statistical quality control. We have not developed this discussion into an application for the derivation of a monitoring strategy, however.

The causes of variation in the quality of manufactured products are categorized as 1) chance causes and 2) assignable causes. Chance causes are random happenings, whereas assignable causes arise from some significant change in the manufacturing process.

Chance variation is the sum of the effects of the whole complex of chance causes. The effect of each cause is slight and no major part of the total variation is traceable to a single cause. The only way to change the chance variation of a process is to revise the process. Chance causes of variation behave in a truly random fashion. They show no cycles or any defined pattern, and no future variations can be predicted other than that future variations will probably fall within certain limits. In other words, chance variations are predictable in accordance with typical statistical theory.

Assignable causes, unlike chance causes, create relatively large variations in product quality and variations attributable to special causes. These variations occur when some part of the manufacturing process changes. Assignable causes include changes in machinery, work practices, materials, or changes in the relationship of combinations of these. Variations from assignable causes cannot be approached using usual statistical theory because these variations do not occur by chance.

A system that is operating within chance-caused variation is said to be under control. If process and product variations conform to a statistical pattern that might reasonably be produced by chance causes, then it is assumed that no assignable causes are present. The process is said to be "under control". If the variations do not conform to a pattern that might reasonably be produced by chance causes, then it is concluded that one or more assignable causes are at work. In this case, the process is said to be "out of control" and an effort should be made to discover the specific cause of the "out of control" situation.

Industrial processes are judged to be under control or out of control through the use of various types of control charts. Quality control specialists use control charts for these purposes: 1) to describe what a state of statistical control is; 2) as devices for attaining control; and 3) as devices for determining whether control has been attained. Knowledge of the behavior of chance variations is the basis for control chart analysis. Control charts are simply another form of expressing statistical distributions. An example of a control chart based on the binomial distribution is shown in Figure III-4.

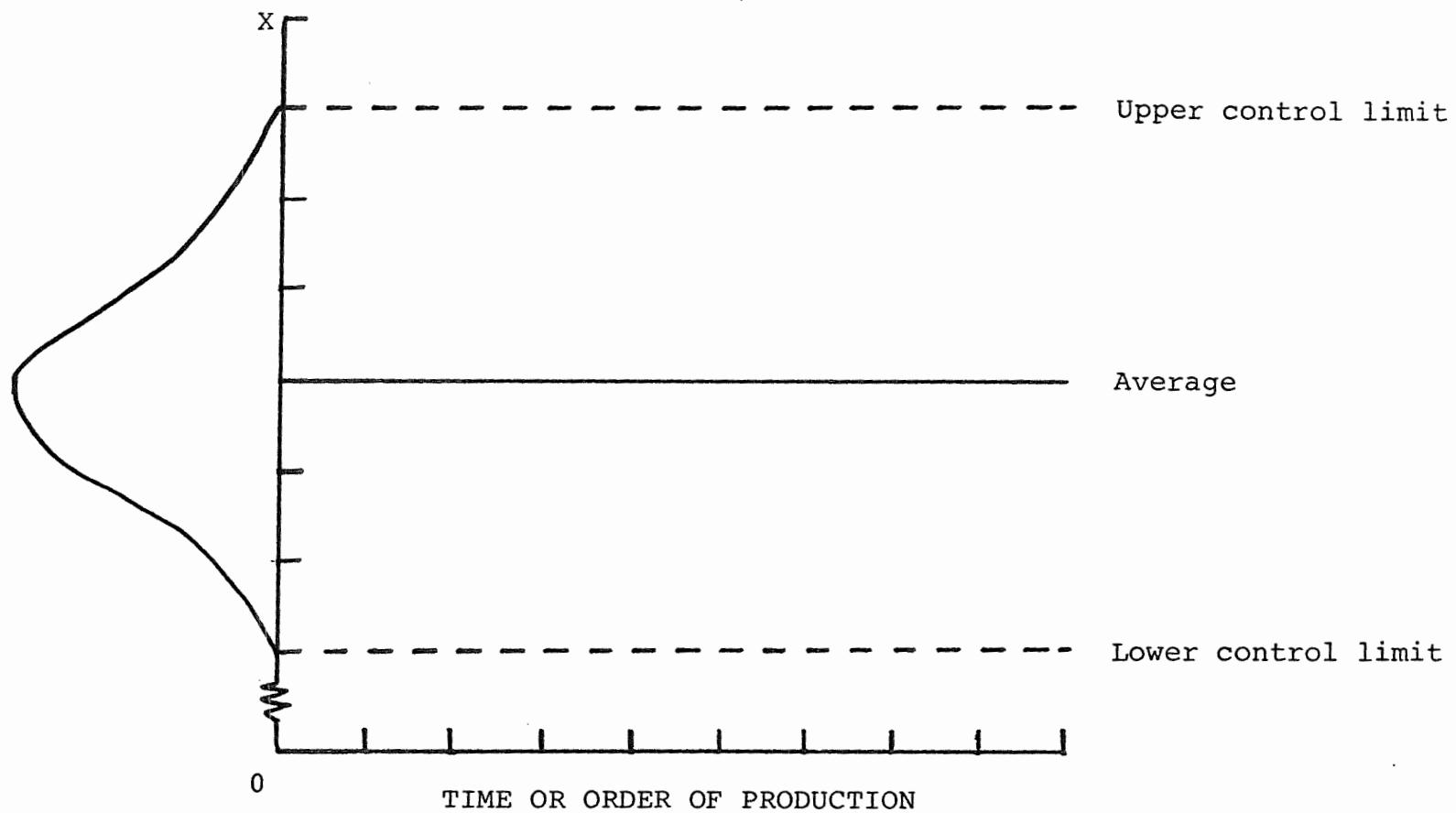


FIGURE III-4. - Illustration of the theoretical basis for a control chart.
(Source: Duncan, A. J. Quality Control and Industrial Statistics. Richard D. Irwin, Inc., Homewood, Illinois, 3d ed., 1965, p. 339.)

The use of control charts can be illustrated by a discussion of attributes and variables sampling. Attributes sampling is often used to decide whether a lot (a homogeneous collection of items produced under approximately the same conditions) is acceptable or not. In the acceptance sampling procedure, a sample with n items, i.e., with sample size n , is selected at random from the lot. If c units or fewer (where c is the acceptance number) are defective, the lot is accepted; if more than c are found, the lot is rejected. The combination of the sample size and acceptance number define a sampling plan uniquely. For each plan, an operating characteristic (OC) curve exists, such as that shown in Figure III-5 (this is one form of a control chart). Since a sample is being examined rather than the entire lot, the possibility always exists for purely statistical errors that cause either a good lot to be rejected or a bad lot accepted. We can determine the probability of either type of error by defining a "good" lot and a "bad" lot. These definitions use the terms Lot Tolerance Percent Defective and the Acceptable Quality Level.

The Lot Tolerance Percent Defective (LTPD) defines a bad lot by stating that the probability of erroneously accepting a lot containing an unacceptably large percent of defective items should be low. Generally, the value of the LTPD for a lot is chosen such that a given sampling plan would detect and, consequently, reject the lot 90 percent of the time. As a result, the customer has a 90 percent probability of detecting the defective condition. It also concurrently defines the consumer's risk as 10 percent (the chance that a given sampling plan will not detect a bad lot).

The Acceptable Quality Level (AQL) defines a good lot by stating that the probability of correctly accepting a lot with a lower percentage of defective items equal to the AQL should be high (generally 90 percent). If the probability that the sampling plan will accept a good lot is 90 percent, then the probability that it will reject a good lot is 10 percent; this is called the producer's risk. The probability distribution that is generally applicable for attributes (the binomial) is often expressed in control curves such as the one shown in Figure III-5. Curves of a similar type are included in many textbooks on probability or statistics.

A major problem in the use of attributes sampling plans is determining the sample size n and the acceptance number c . The method generally used is 1) to define a bad lot by choice of the LTPD and a good lot by the AQL, 2) to choose the probability of accepting a bad lot and of rejecting a good lot, then 3) to use the procedures in statistical quality control textbooks to find values of n and c that give a plan most nearly meeting these criteria. Another way to choose n and c is to assign dollar values to producer's and consumer's risk and to sampling cost, then to choose n and c to minimize the total cost of overcontrol, undercontrol, and sampling. A third way is to use the tables provided in the Military Standard ABC-105. This standard gives a series of plans based on normal, tightened, or reduced inspection, depending on the quality that has been produced in the past and on the degree of protection desired.

While attributes sampling plans deal with information expressed in terms of counts (number of defectives, number of good items, etc.), variables sampling is concerned with measurements on a continuous variable. In its classical application, variables sampling works like this: At a specified

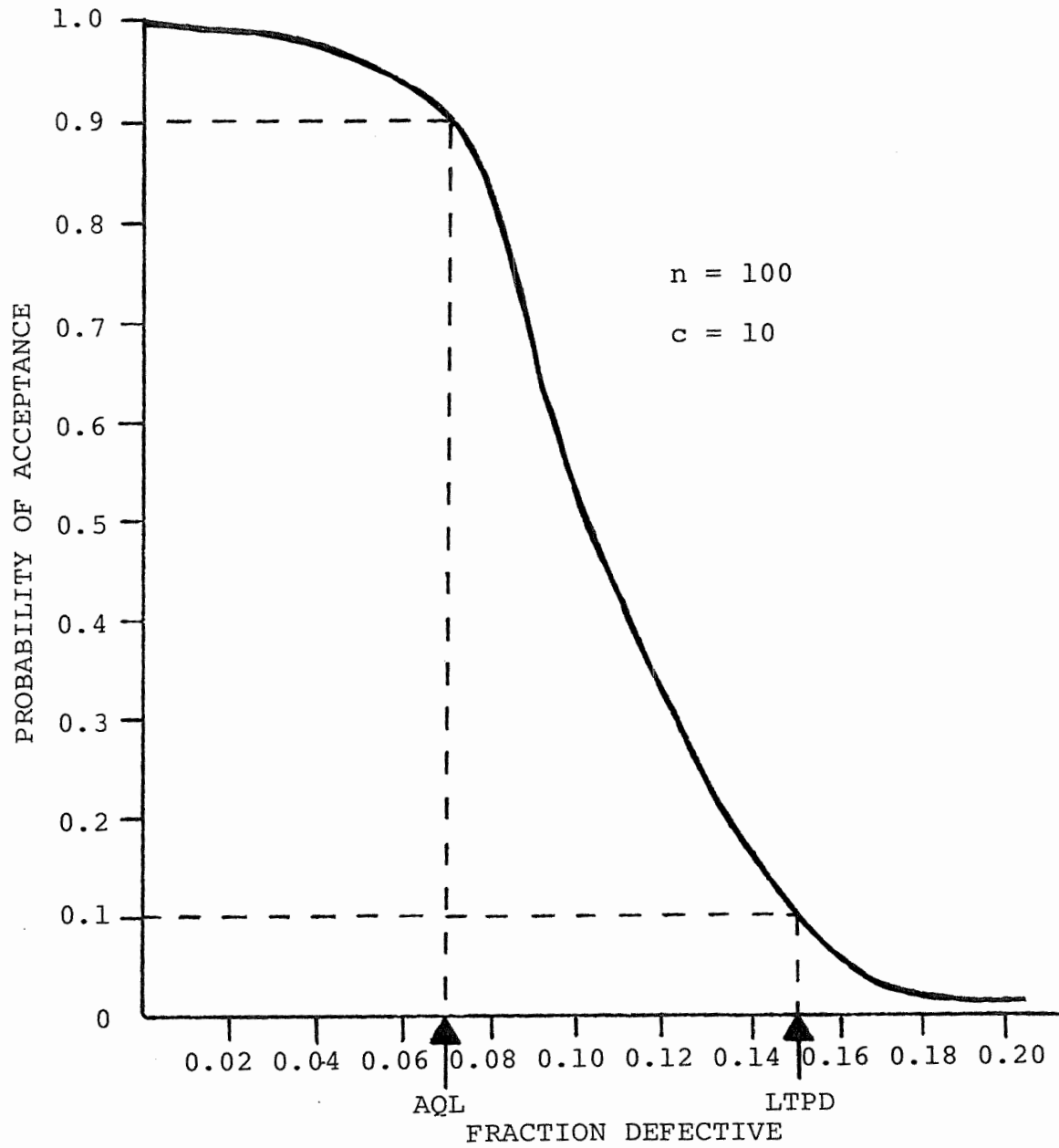


FIGURE III-5. -- Operating characteristic curve for an attributes sampling plan.

time, a random sample of n items is taken from a specified point in the manufacturing process, and a specified quality characteristic (such as the diameter) is measured on each item. The mean of these measurements is then plotted on an \bar{X} (X-bar) chart and the range (highest reading minus lowest reading) plotted on an R-chart. An example of these types of control charts is shown in Figure III-6. Both charts have control limits; if either the mean or the range falls outside of these control limits, some action is initiated to correct the situation. The control limits are usually chosen based on the probability that a point falling outside them by accident is very small--under the assumption that the cost of allowing a small variation to occur is low. Another way to set these limits and the sample size is to calculate the expected cost of a bad product if no remedial action is taken and the cost of sampling, and then to choose the control limits and the sample size to minimize the total expected cost.

Variables data are often analyzed using an assumption that may be wrong. The fundamental assumption in most control charts for the mean is that sample measurements are statistically independent, i.e., a knowledge of one of the measurements in the sample does not provide knowledge of another measurement in the sample. If patterns or trends are present that allow prediction of future measurements, or if a series of measurements are related by time, this assumption is violated and successive measurements are said to be autocorrelated. In this case, time series analysis is used to develop the statistical aspects.

Consider the data relating sales volume to yearly seasons shown in Table III-2 and in Figure III-7. A clear, nonrandom pattern is present, and a knowledge of the sales in Spring 1979 gives a good prediction for the sales in Spring 1980. The standard deviations of sales in Spring, summer, autumn, and winter are, respectively, 3.6, 5.7, 1.5, and 3.6, and it is clearly more representative of the data to use these than it is to use the standard deviation of the entire data set, which is 451.6. Time series analysis, the mathematical technique for time-dependent patterns, takes the time dependence into account, whereas commonly used statistical approaches ignore any correlations in the data. The typical approach can be, depending on the extent of autocorrelation, not only misleading but completely wrong. In such instances, the variability inherent in the data may be overstated and greater sample sizes than are really necessary may be determined.

Cost

In addition to a knowledge of attributes and variables, the design of a quality control plan must consider the associated costs. Costs can generally be divided into costs of sampling and costs of control. Costs of sampling include fixed and variable components: fixed--training, equipment purchase; variable--disposables, labor, downtime for sampling, items destroyed in testing. Sampling cost can often be reduced with less expensive equipment, simpler procedures, smaller sample sizes, or better trained and more versatile inspectors.

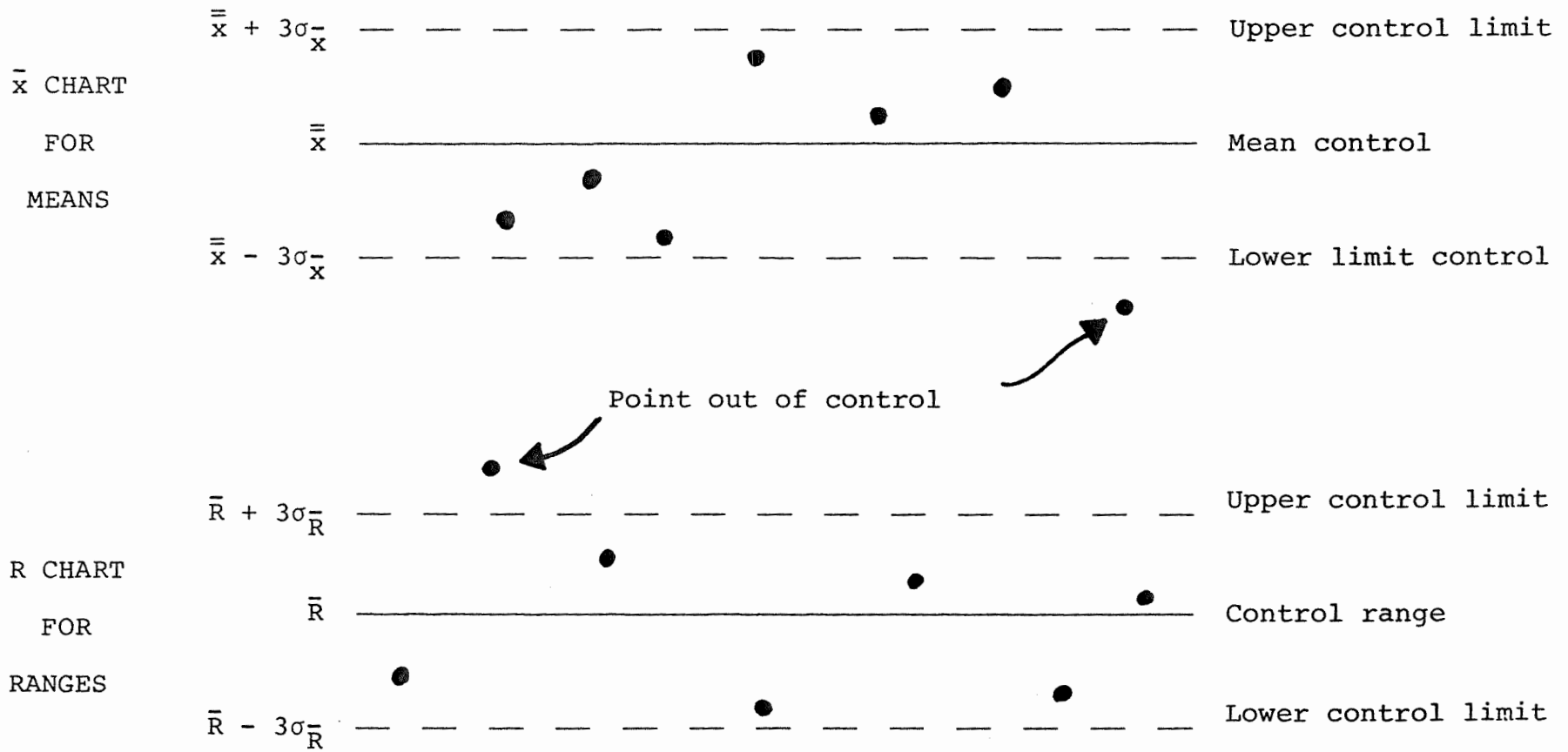


FIGURE III-6. - An example of \bar{x} and R charts.

TABLE III-2. - A sample of time--dependent sales data

	1977	1978	1979	S.D.
Spring	800	805	798	3.6
Summer	1400	1407	1396	5.6
Autumn	600	603	601	1.5
Winter	200	207	202	3.6

Standard deviation (SD) of all data = 451.6

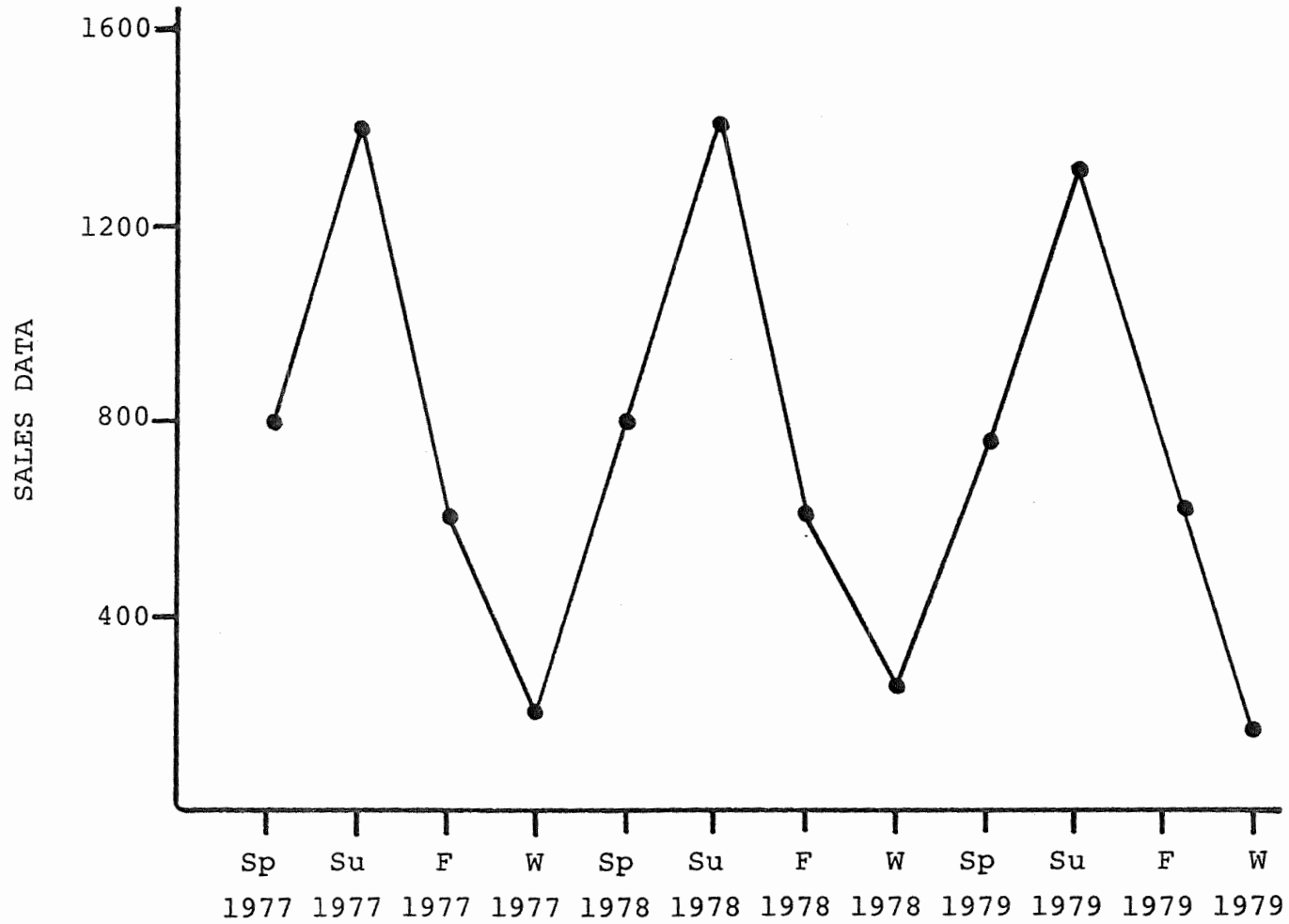


FIGURE III-7. - Graph of time-dependent data from table III-2.

Costs of control can be further divided into the cost of overcontrol and the cost of undercontrol. Cost of overcontrol is generally the cost of looking for a cause of an apparent "out-of-control" situation when the situation is the result of a poor data collection process. This cost can be reduced if 1) the variability introduced by the instruments or the data collection procedure can be reduced or accurately determined, or 2) if a search for the source of the "out-of-control" situation takes place only when the probability of an accidental occurrence of an "out-of-control" measurement is very low. Also included as a cost of overcontrol is the cost of rejecting a good lot of products on the basis of a sample that estimated a larger number of defectives than would have been found by examining the entire lot.

Cost of undercontrol is the cost incurred when the given testing procedure fails to detect a malfunction of the production process. This cost can include the consequences of delivering defective products to the customer, downtime cost incurred if the defective material is delivered elsewhere within the same plant, and other costs associated with a poor quality product. This can occur if the samples are not taken often enough, if the sample size is too small, or if the inspector is looking for the wrong quality characteristic.

Application of Quality Control Approach to Mine Air Quality

The four steps of a quality control approach as discussed above are 1) determine the important product quality characteristics, 2) identify the process variables that affect these product characteristics, 3) select what is to be monitored or measured, and 4) establish data requirements and data collection and analysis procedures. Breathing zone air in an underground mine, like cans or copper wire, can be thought of as a manufactured product, so the same four steps can be applied to the control of underground mine air quality. For underground mine air, however, the details of the quality control steps have not been as well developed, with the result that the data collection and analysis techniques are not as uniform among mines as are the same standard quality control procedures among factories. Nonetheless, the process of developing a quality control system for mine air follows similar steps. A systems analysis must be conducted 1) to clearly define the desired quality characteristics of the final product, 2) to specifically define the "mine air manufacturing system" under consideration, and 3) to identify process variables that either affect or are related to the desired quality characteristics of the breathing zone air. Following the systems analysis, a decision must be made as to which of the quality characteristics or process variables are to be monitored, and the appropriate data needs and collection and analysis procedures must be selected.

In the underground mining environment where diesel-powered equipment and blasting agents are used, a partial list of substances encountered includes nitric oxide (NO), nitrogen dioxide (NO₂), carbon monoxide (CO), carbon dioxide (CO₂), aldehydes, sulfur dioxide (SO₂), polynuclear aromatic hydrocarbons, and respirable dust. In specific mines, other substances such as ammonia may also be present. The concentrations of these and other substances together make up the quality characteristics of mine air.

Choosing which quality characteristics to monitor requires a detailed knowledge of: 1) the mining process, to determine when, where, and how pollutants are generated, 2) measurement technology, to determine what pollutants can be measured directly or whether it is possible to measure other operating variables that are correlated with known pollutant levels, and 3) control methods that can be used to change concentrations of substances that have been found to be too high or too low.

Process variables (if data exist correlating their effect on the level of the desired quality characteristics of breathing zone air) are also potential candidates for monitoring. Process variables usually provide better information for the process control function, since the cause of an out-of-control situation will have been identified. Some examples of process variables found in the mining environment where diesel-powered vehicles are used include: 1) source parameters such as engine type and size, engine condition, fuel composition, exhaust treatment methods, and exhaust direction and outlet location, 2) pollutant transport parameters such as general ventilation rates and patterns, mine geometry, and physical and chemical transformation of pollutants, and 3) parameters in the working area such as local ventilation, the stratification in the air of pollutants, and the use of respiratory protection by the miners.

The next decision is whether an attributes or a variables data collection procedure should be used. This decision is highly dependent on the objective of the quality control program. As was discussed earlier, attributes data are most applicable for acceptance sampling programs. In mining, an analogy can be drawn between accepting a homogeneous lot of material and finding that a particular exposure is in compliance with a given health standard. But the analogy can be misleading. In performing acceptance sampling, the basic assumption is that samples can be drawn randomly from a lot; all of the supporting statistics are based on this assumption. But most data from mines are associated with a time and a particular location, and measurements that are close together in time or location may be highly correlated. Thus, a series of independent samples in a mine may be impossible to obtain for attributes sampling.

It may be worthwhile in some cases, however, to perform attributes sampling by detecting conspicuous nonconformances to standards. Such attribute sampling could be done, for example, by smell (by detecting the characteristic smell when a water-scrubbing unit has quit working on a diesel tram) or by inspection (such as checking whether the air cleaner was replaced as required on a specified shift). If the presence or absence of these data are collected randomly, they may constitute a basis for judgment.

Variables data have the same correlation problems that give rise to problems in attributes data. In addition, there are problems caused by 1) the inherent variability of concentrations of airborne substances over time and distance from source, and 2) the lack of precision and accuracy of the measurement method. Often, these problems can be minimized by investigating the time-related patterns in the data using time series analysis.

Since attributes data are data that are counted, some possible attributes data include the number of complaints about diesel exhaust odors and the number of verified cases of eye, nose, and throat irritation. Another kind of attributes data is the number of times a given ceiling standard is exceeded. These data can be combined in many ways and analyzed to give indications of different problems (multivariate control procedures can be used with varying control limits).

While recognizing that more complicated control procedures are possible, consider how typical quality control procedures could be used to develop an attributes sampling plan for NO_2 . Suppose that all samples are taken at the same time and location in each shift. A sample measurement is declared "high" if it is above 1.2 ppm and "acceptable" otherwise. Suppose that the sampling plan consists of taking eight samples on different days or from different locations within the mine and performing some control action if two or more samples give "high" readings. Under the definitions given before, the sample size is 8 ($n = 8$) and the acceptance number is 1 ($c = 1$). A theoretical operating characteristic curve for this plan is given in Figure III-8. This graph is developed under the assumption that the sample size is small relative to the total number of samples possible. (If this assumption is known to be false, different curves must be developed.) Note that the probability of not acting if 40 percent of the sample are too high is about 20 percent, but that if only 10 percent are too high, the probability of doing nothing is over 90 percent. If either probability is unacceptable, one of the other plans shown may be better. Plans other than those presented are possible; these were chosen for illustrative purposes.

A variables sampling plan is specified by a sample size, detailed sampling procedures, and one or more charts to plot sample data points. The size of the sample taken at any one time can be one or more, depending on the data availability and the purpose of the measurement. The sample procedures should be set up so as to eliminate any known correlation among data points. This generally requires a knowledge of the fundamental behavior of the data under the situation being measured. This point is illustrated in Figure III-9, a hypothetical set of sequential observations of CO_2 concentrations taken in a mine. Note that the data represent a periodic phenomenon with two different sets of readings, one set for the highest concentrations, one for the lowest. These cannot legitimately be incorporated into one probability distribution because there is little that is random about them. It is possible, however, to make up two different probability distributions and to make control charts for each distribution. The control chart for the upper values is given in Figure III-10. Note that it has a much smaller standard deviation (0.011) than would have been attributed to the entire data set treated as a distribution (in this case, 0.112). The use of this control chart thus gives a much better indication of equipment or other malfunctions. The use of a control chart for one set of values (whether the upper or the lower) is justified, because either set, independently, exhibits a random fluctuation about some mean, and a knowledge of one point in this set of values does not give much information about a succeeding point in that range.

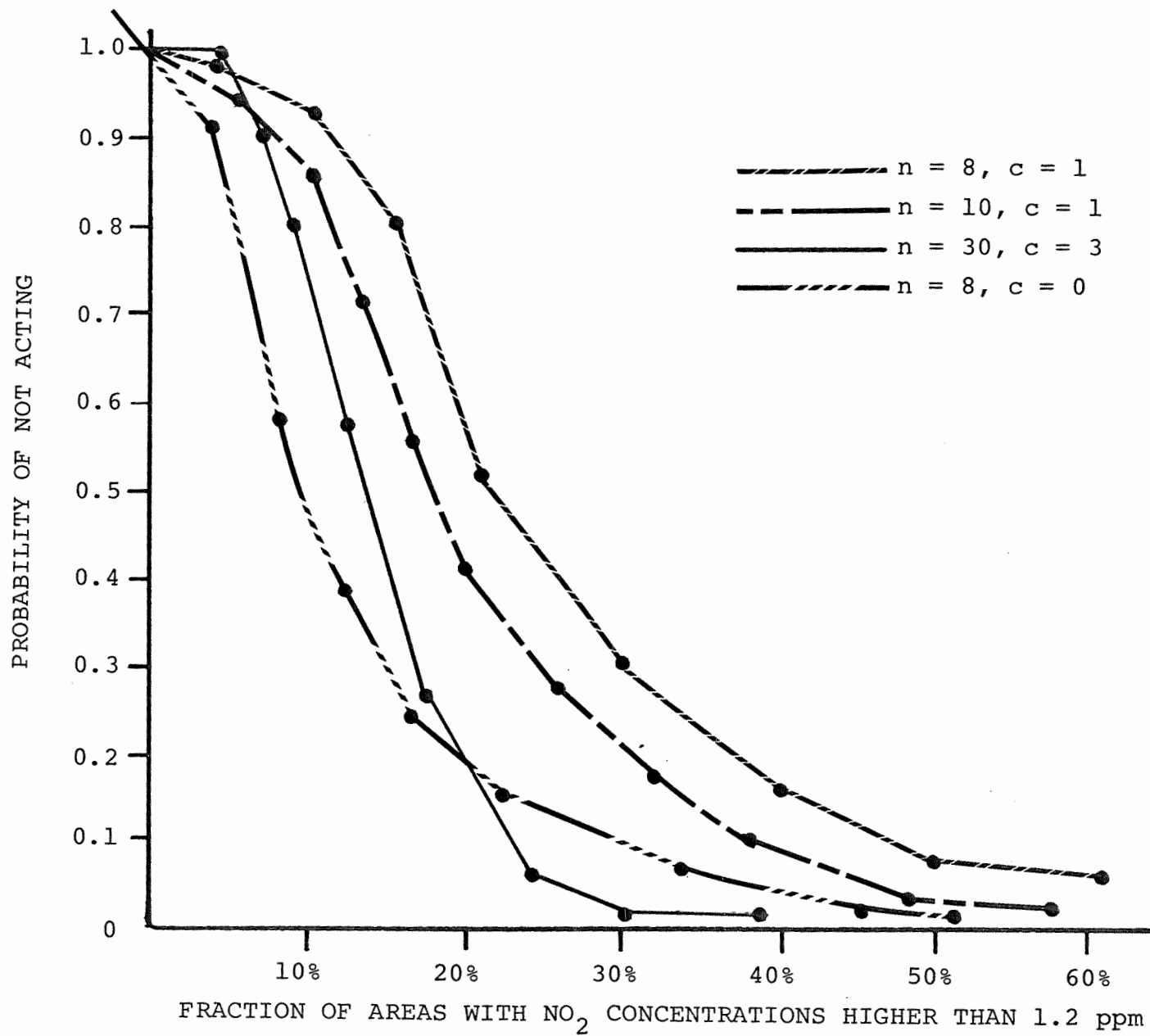


FIGURE III-8. - Theoretical operating characteristic curve for NO₂ sampling data.

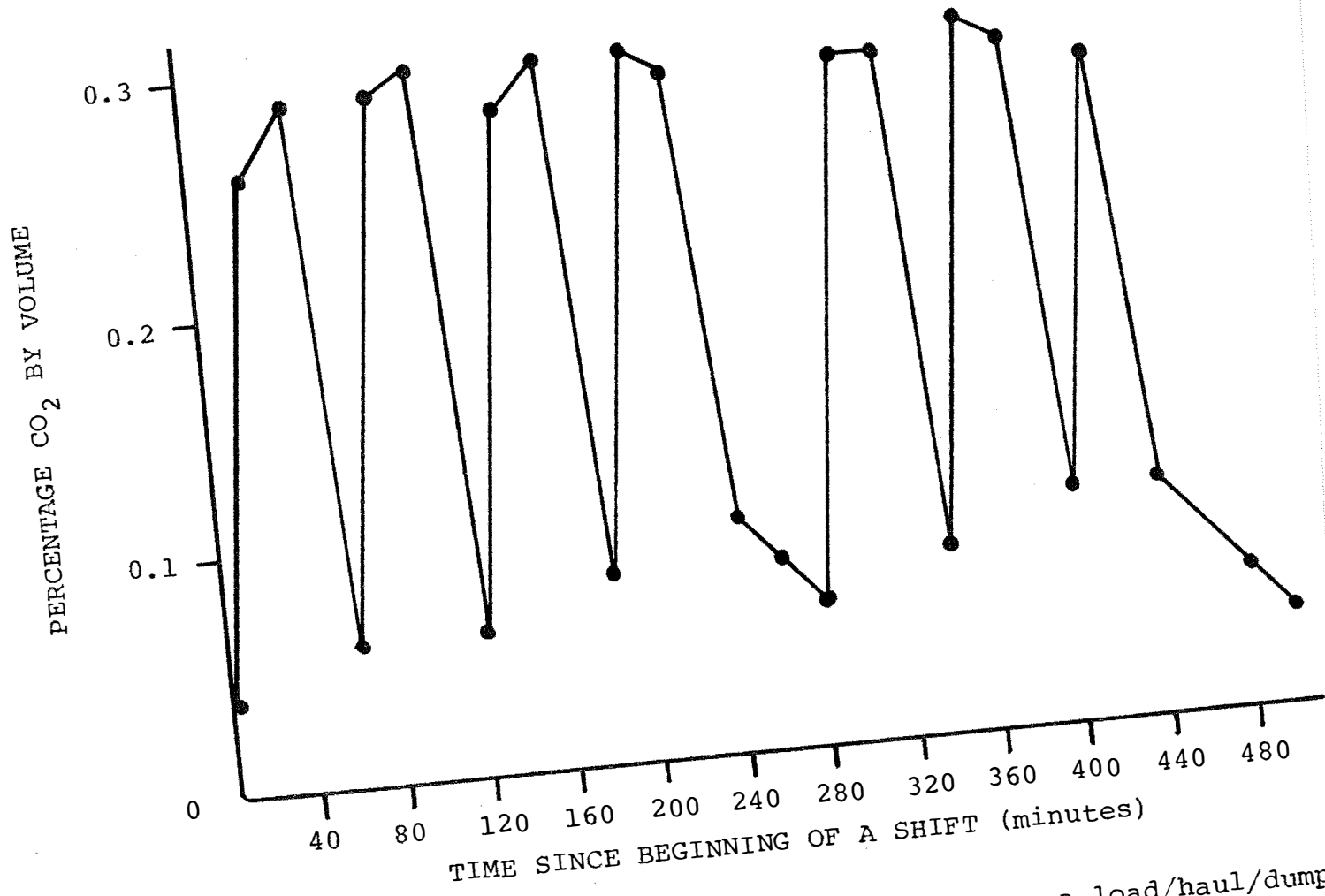


FIGURE III-9. - Possible CO₂ concentration data from a load/haul/dump cycle.

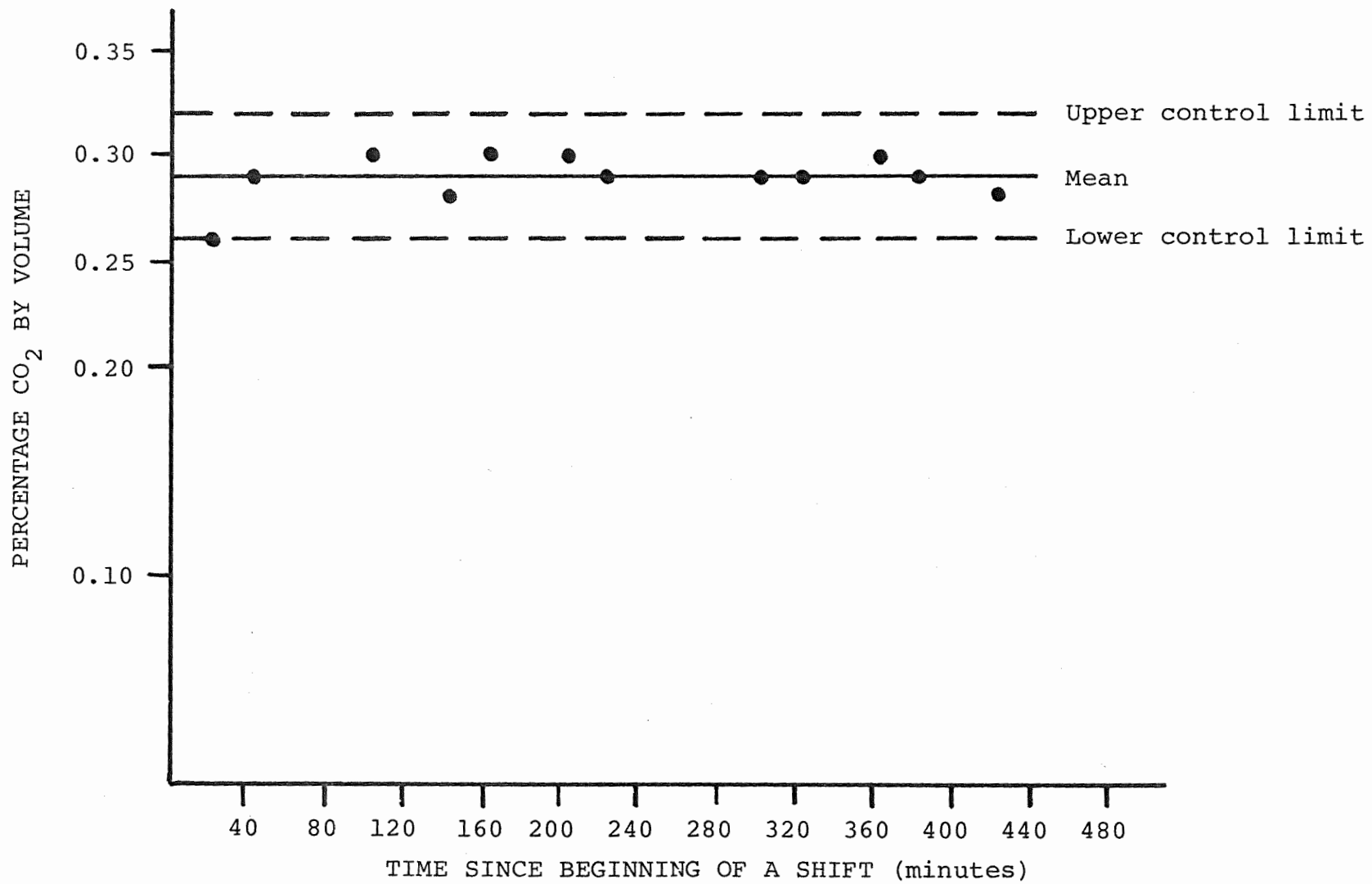


FIGURE III-10.- A control chart for the upper set of values of figure III-9.

In Figure III-10, the control limits used were the mean plus or minus three standard deviations. The mean and standard deviation used to derive the control limits are estimates of the parameter being graphed taken from previous sampling data or, if none are available, from other comparable sources. If individual measurements from one set of environmental circumstances are being graphed, the mean and standard deviation used should be taken as closely as possible from measurements from the same set of circumstances. If the parameter being graphed is the mean of the measurement means, then the standard deviation should be that of the measurement means. The advantages of this system are: 1) it is easy to use, and 2) any point outside the control limit has a higher probability of resulting from an assignable cause rather than from chance. Other values for these control limits could be chosen, particularly if action would only be taken if the readings indicated that CO₂ concentration was too high. In this case, only the upper control limit would be needed. Another possibility is to select control limits on the basis of costs. In general, if the limits are too close to the mean, it may be very expensive to keep adjusting the system to maintain the means within the control limits, but if they are too far away from the mean, the means of the variable may drift far more than is desirable.

Control Techniques

The job of quality control does not stop with monitoring. Recommendations must be made regarding remedial action when it is deemed necessary. In the manufacturing industry, out-of-control conditions are examined to determine the assignable cause of the variation so that the cause can be brought under control. In the mining environment, the relations between possible causes and known effects are still being studied, and the precision with which control actions can be targeted is expected to improve.

Mining control techniques can be categorized into 1) ventilation, 2) equipment maintenance and modification, and 3) administrative measures. Administrative measures are not discussed here. Increasing the amount of ventilation in the immediate vicinity of work usually decreases pollution concentrations. It is also usually helpful to increase the amount of general mine ventilation, although the amount of increase needed to decrease the concentration at a given location by a given amount is generally not clear.

A second major area of control is associated with mining machinery engines. In general, engine control measures can be categorized into design, routine scheduled maintenance, and daily maintenance. The design options include improvement in combustion chambers, addition of exhaust treatment devices, and improvement in feedback-controlled timing mechanisms.

Routine scheduled maintenance of engines includes such items as replacing or cleaning air filters, setting the fuel injection timing, rebuilding and adjusting the fuel injectors, and all the other tasks needed in diesel maintenance. Daily maintenance is also important and includes checking water scrubbers or other anti-pollution equipment to see that they are working properly.

CHAPTER IV
MONITORING STRATEGY DEVELOPMENT SCHEME

Introduction

In this chapter we present a quality control approach to the derivation of monitoring strategies. The approach is organized into a series of steps that we have called the Monitoring Strategy Development Scheme. The steps in the scheme are an elaboration of the four general steps used in quality control, as presented in Chapter III of this report. The scheme constitutes an orderly method for selecting, from a number of measurement options, a monitoring strategy designed to effectively satisfy the requirements of a chosen objective related to breathing zone air quality.

Monitoring Strategy Development Scheme

The scheme consists of a series of steps, each step being an action that produces a result. For convenience of the user, the steps are listed on the left side of each page, and the corresponding results are listed on the right. Each step and result are identically numbered.

The term "manufacturing" system means all of the processes and variables in the mining operation that affect the quality of the air in the miner's breathing zone. The term "product" means, in our case, breathing zone air. Quality characteristics are the concentrations of component substances of diesel engine exhaust and blasting residue that end up in the breathing zone air. These characteristics are the product variables that define quality.

An important term, "measuran", is used extensively in the scheme and was coined by us to provide a word for the combination of three entities: 1) a place in the mining operation where some kind of a measurement could be made, 2) the variable to be measured at the designated place, and 3) the measurement technique available for the variable. Examples of measurans are: 1) CO measured at a miner's breathing zone using an indicator tube; 2) SO₂ measured at the tailpipe of a diesel engine using a gas collection container followed by gas chromatography analysis in a laboratory; and 3) the measurement of engine RPM on a diesel-equipped scoop tram using an electronic tachometer. A measuran, then, is a variable (what) to be measured in a place or at a port of the mining operation (where) using a specific technique (how).

At a certain step in the scheme, quantity and/or frequency requirements (how many and/or how often) are added to the measurans and the use of the term measuran after that step includes the quantity and/or frequency value.

The term "evaluation plan" refers to a work sheet developed to quantitatively evaluate the measurans. In summary, the scheme is designed to identify all possible measurans that could be used to satisfy the objective(s) of a monitoring strategy and then to rank the measurans.

Each step is discussed in this chapter following the presentation of the scheme.

Monitoring Strategy Development Scheme

Step	Result
1. Develop the objective(s) of the monitoring strategy	1. Objective(s)
2. Determine critical factors	2. Critical factors
3. Identify and detail the "manufacturing" system	3. Detailed manufacturing system
4. Identify the "product" quality characteristics directly pertinent to the objective(s) (result 1)	4. Product quality characteristics
5. Identify other "product" characteristics that are potentially useful as substitutes (surrogates) for the directly pertinent characteristics (result 4)	5. Substitute product characteristics
6. Identify variables at places in the manufacturing system (result 3), other than the quality characteristics of the product (results 4 and 5), that could potentially provide measurement alternatives	6. Variables alternative to product characteristics
7. Determine for each variable that is an alternative to product quality characteristics (result 6) whether sufficient data exist to quantify the relationship between the variable and an associated product characteristic(s)	7. System variables suitable for measurement as alternatives to the measurement of quality characteristics (quantifying data exist)
	7A. Variables for which data do not exist. These variables are candidates for research.
8. Determine which system variables (result 7) are especially sensitive or critical in causing changes in product quality (results 4 and 5)	8. Variables that critically affect product quality

Step	Result
9. If the objective(s) (result 1) is (are) directed at control, determine whether the effect on product quality from each critical system variable (result 8) can be adequately controlled using existing technology	9. Potential places in the "manufacturing" system for control technology application (adequate technology exists) 9A. Potential control technology research areas (adequate technology does not exist)
10. Identify the technology (methods and/or instrumentation) that exists to measure each product quality characteristic (results 4 and 5), and each alternative or critical system variable (results 7, 8, and 9) that affect product quality.	10. Measurement technology options (adequate technology exists) 10A. Potential measurement technology research areas does not exist)
11. Combine each product quality characteristic (results 4 and 5) and each alternative system variable (results 7, 8, and 9) with the corresponding measurement technology options (result 10)	11. "Measurans" that are candidates for comparative evaluation, each one consisting of: 1) A place in the system where a measurement could potentially be made; 2) A variable to be measured at the place; and 3) A measurement technique available for the variable.
12. If possible, identify and eliminate any "obviously" inferior measurans.	12. Candidate measurans
13. Eliminate measurans that do not satisfy the requirements imposed by critical factors (result 2)	13. Candidate measurans eligible rating

Step	Result
14. Determine appropriate statistical parameters	14. Statistical parameters: Type I error (α) Type II error (β) Detectable difference (δ)
15. Using the statistical parameters (result 14), determine the required number of measurements and/or frequency of measurement for each measuran	15. Candidate measurans complete with quantity frequency requirements
16. Bias the categories and criteria in the evaluation plan	16. Biased evaluation plan
17. Using the biased evaluation plan (result 16) evaluate the measurans (result 15) and calculate their overall ratings	17. Ranked measurans
18. If additional critical factors have been identified during the evaluation process, eliminate measurans that do not satisfy the imposed requirements	18. Ranked measurans that meet the requirements critical factors
19. If a single measuran appears to satisfy the objective of the monitoring strategy, select a measuran from among the higher ranked measurans (result 18) to be used as the strategy. If this is the case, the scheme is completed with this step.	19. Monitoring strategy composed of a single measuran
20. If the monitoring strategy must satisfy multiple objectives, or if the use of a single measuran does not appear to provide a satisfactory or optimum tactic, compose tactics consisting of multiple measurans	20. Candidate tactics
21. Using the evaluation plan (result 16), evaluate all competing tactics (result 20)	21. Ranked tactics
22. Select a strategy from among the higher ranked tactics	22. Monitoring strategy composed of multiple measurans

Discussion of Steps in the Scheme

1. Develop the objective(s) of the monitoring strategy.

The scheme's initial step is to develop the objective. The objective of a quality control program was not discussed in Chapter III beyond the implicit understanding that a product of specified quality was desired. However, in deriving a monitoring strategy as part of a quality control program, it is absolutely essential to state the objective of the program and to translate this objective into a specific, well-designed objective for the associated monitoring strategy. This step is imperative because the strategy objective influences decisions regarding: use of quality assurance versus process control, measurement of attributes versus variables, selection of instrumentation and methodology, and data processing.

The step of developing the objective is required to force the user to clearly define the objective before attempting to use the scheme to derive the desired monitoring strategy. To perform this action correctly, i.e., to exercise careful and thorough reasoning, is as important, if not more so, as any other step in the scheme. The objective must be stated "completely", i.e., it must be thorough and highly specific, so that it is usable as the preeminent factor to be considered in other steps of the scheme.

The objective should consider the basic goals of the strategy user and the purpose for which information acquired using the strategy will be used. However, there is one underlying and limiting premise that must be considered in developing the objective statement: the objective must be ultimately directed at breathing zone air. Although our purpose here is not limited to the derivation of air monitoring strategies, we are only concerned with strategies that have as their goal the control of, the providing of a measurement of (directly or indirectly), or research related to breathing zone air quality. Consequently, any objective that is not directed at breathing zone air quality is beyond the scope of this work. This does not mean that the general approach presented here cannot be used for other purposes; the approach, in fact, is universal.

The primary users of mine monitoring strategies are operators, inspectors, workers, and researchers. It is important to keep this in mind when developing the objective the different basic goals of these users.

The principal goal of operators relative to breathing zone air quality is to maintain compliance with established health standards. Compliance is typically achieved by applying some type of control within the mining process. Mine operators are, therefore, concerned with air quality control. They need to estimate or measure the personal exposures to airborne contaminants but, additionally, they need to identify the sources and causes of contamination so that they can apply control technology designed to keep the contaminants below established standards.

The principal goal of mine inspectors is to enforce air quality standards and, thus, their primary interest in monitoring strategies leans heavily toward the quality assurance aspect. The demands of an enforcement-oriented

program on a monitoring strategy are that measurements truly represent workplace conditions, that "worst case" situations are identified, and that the measurements meet all legal requirements for accuracy, etc.

Health standards (air quality regulations) are usually expressed as time-weighted averages or ceiling values. Time-weighted averages are concentrations of substances that must not be exceeded on average over some period of time, generally 8 or 10 hours.

Ceiling values are concentrations of substances that must not be exceeded for even very short periods of time, typically 15 minutes. Standards are also normally directed at airborne concentrations in the breathing zone. Hence, the monitoring strategy used by inspectors must provide data commensurate with the type(s) of standard(s) being enforced. Since inspectors must travel to many different mine sites, there is also a greater than usual requirement that the measurement equipment be portable, rugged, electronically or chemically stable, and easily calibrated (or checked for calibration) and operated under typical mine conditions.

Mine workers are also primarily interested in quality assurance related strategies. The miner's greatest concern is whether the breathing zone air contains toxic chemicals at unacceptable levels. Mine workers would generally be particularly interested in strategies that would tend to err toward indicating a worse situation than what actually exists, i.e., they want a safety factor in their favor. They also want assurance that mine management and production considerations will not in any way bias the measurements and, therefore, they want a strategy that has effective checks on the quality of measurements and reporting.

The researcher's goals can be quite varied, since the research may be directed in the areas of control technology, health effects, or measurement technology. Because of the wide variety of research, it is difficult to anticipate what features of a strategy would be desirable. The researcher wants assurance though, as do the other users, that the data collected via a monitoring strategy satisfy the objectives of the research project and are collected at minimum cost and effort.

The goals of each of these users underlie specific objectives, and the value of any monitoring strategy is dependent on how well the strategy supports the objective and the basic goal. A monitoring strategy, then, is very objective-dependent. For example, a mine operator desiring to meet the goal of achieving compliance with established health standards might decide that this goal could be accomplished by limiting carbon monoxide emissions at the tailpipe of all diesel engines to 100 ppm, the idea being that other contaminants will be commensurately low and dilution with mine air will bring the concentrations of all the contaminants down below standards. In this example, a monitoring strategy that only measures carbon monoxide in the mine worker's breathing zone (a strategy that might be appropriate for some other objective) would not be appropriate, since it would provide little information regarding which engines are not within CO emission specifications. A more appropriate strategy for this objective might be to monitor tailpipe CO emissions on each engine in the mine. However, even this activity would not guarantee that CO or the other contaminants would be

at acceptable levels at the worker's breathing zone. The operator also must ensure that dilution takes place, and this requires at least one additional measurement, e.g., ventilation rates per se, or as represented by CO₂ concentrations, at worst case locations.

In developing the objective, it is critical at the outset to ascertain whether the information obtained from the monitoring program is to be used to show compliance or non-compliance with standards, to provide an alert to undesirable long-term trends, to provide warning of immediate danger, to satisfy regulatory dictates, to assist in controlling air contaminant concentrations, or for combinations of these or other purposes. All of these purposes can place different demands on the strategy regarding what is to be measured; where, how, and how frequently measurements are to be made; the information format desired; and the allowable length of time between measurement and data acquisition.

2. Determine critical factors.

A critical factor is defined as any requirement that is to be met by the monitoring strategy for which there exists a go/no-go condition. These factors are identified early in the scheme in order to eliminate measurands that do not meet these requirements so that unnecessary effort will not be expended in considering them. For example, a mining company may have a "Buy American" policy, that is, a policy to purchase and use only goods produced in the United States. If the user is faced with this requirement, there is no sense in identifying and evaluating measurands that use foreign-produced equipment.

Critical factors may sometimes be imposed by the objective. For instance, if a mine operator's objective is to provide warning of a life-threatening level of CO, a critical factor is imposed that the measurement instrument must be an instrument capable of sounding an alarm as soon as some predetermined level is reached. Although critical factors should be identified early in the scheme, some things do not become evident as critical until further along in the use of the scheme and as the user becomes more educated to his/her own requirements. Therefore, critical factors can be identified and applied at any point in the scheme. Particularly in the evaluation phase, additional critical factors may be identified, since each evaluation criterion can have a point at which it becomes critical. For example, although a potential user of a monitoring strategy may recognize the importance of the capital cost of instrumentation as an evaluation criterion, the user may not be aware of a critical amount until it is discovered that the capital cost of one plan under consideration exceeds the allotted budget.

Legal and regulatory requirements could impose a number of critical factors. Sampling instrumentation that is to be used in gassy mines will have to meet permissibility requirements, and the accuracy and adequacy of samples taken for MSHA compliance must be defensible in court. Some other examples of typical critical factors include a requirement that instrumentation be battery powered because of the lack of electricity, a requirement that all sampling be conducted with currently owned equipment, a requirement that the sampling technique be capable of being performed by a non-technical

person, or a requirement that sampling be conducted with a given technique, since that technique is required under law, by company policy, or perhaps by agreement with employees or a labor union.

3. Identify and detail the "manufacturing" system.

We have advanced the concept of considering breathing zone air to be a manufactured product. Under this concept, the mining process to be monitored is treated as if it is a process for manufacturing breathing zone air. The system referred to in this step includes the raw materials and the process that "produces" breathing zone air. The purpose of this step is to identify (for subsequent qualitative and quantitative examination) the variables within the system that could possibly affect the characteristics of breathing zone air. In other words, the system to be identified is the mining process. To detail the system means to identify the variables in the system that potentially determine breathing zone air characteristics.

We feel it is important to reiterate here that the manufacturing system to which we refer is the breathing zone air manufacturing system, regardless of objective. The reason for this is that, although the immediate "product" of interest for a specific objective may be something other than breathing zone air, breathing zone air is the important end point of the system, yet potentially useful measurements can be made for any objective at any place in the system, starting with characteristics of raw materials through characteristics of breathing zone air.

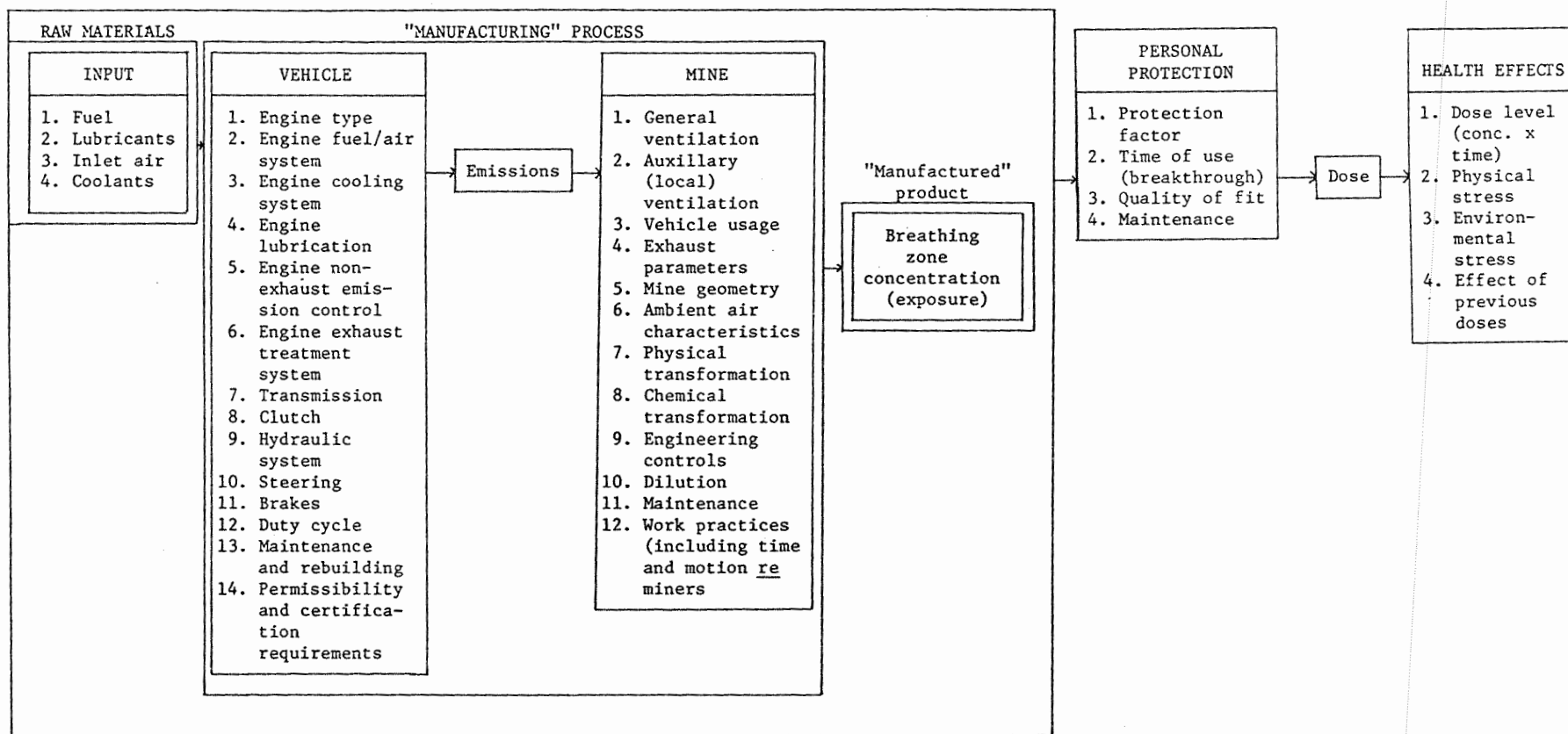
For underground mines using diesel-powered equipment, the "system" is detailed in Figure IV-1. Actually, Figure IV-1 goes beyond the manufacturing of breathing zone air in order to schematically illustrate how health effects are "produced" in the miners. We are not interested in the system beyond breathing zone air because our concern is limited to developing air monitoring strategies or strategies encompassing measurements of characteristics of variables within the manufacturing system. However, if we were including biological monitoring as a possibility in our strategies, e.g., urine analysis, blood analysis, lung function, and so forth, then we would "detail the system" to include all of Figure IV-1. We are, however, only concerned with that part indicated as the "Breathing Zone Air 'Manufacturing' System".

Once the system has been detailed, subsequent steps in the scheme examine each variable within the system to determine which ones are pertinent to the objective.

4. Identify the "product" quality characteristics directly pertinent to the objective(s) (result 1).

This is the first in a series of steps designed to identify the places in the system where measurements are possible and to further identify the characteristics (variables) that could be measured at those places. Specifically, in this series of steps there is an attempt to identify the places in the system where the potential exists to obtain information useful to the objective and to identify the appropriate variables at each place.

BREATHING ZONE AIR "MANUFACTURING" SYSTEM



54

FIGURE IV-1. System resulting in health effects in underground mine workers: diesel.

This step examines the quality characteristics of the product because, for many objectives, measuring some characteristic of the product will be a reasonable option. For example, the group of objectives that deals with compliance to MSHA standards has breathing zone air as the final product and the air contaminants generated by the diesel engine as the quality characteristics. On the other hand, for the objective of determining when catalytic converters are not functioning properly, exhaust gas can be considered to be the product of the manufacturing system and such things as the temperature or the carbon monoxide concentration of the exhaust gas are among the directly pertinent quality characteristics.

In most cases the pertinent characteristics will be clear in the objective statement; however, in some cases, it may be necessary to review the technical literature to identify some of the less obvious pertinent characteristics.

5. Identify other "product" characteristics that are potentially useful as substitutes (surrogates) for the directly pertinent characteristics (result 4).

This step continues to examine characteristics of the product of our manufacturing system; however, now an attempt is made to identify those characteristics that may be indirectly related to the objective. The term surrogate is used to describe these characteristics. These are substitute measurements that may be easier or less costly to make but that will still provide information that will satisfy the objective. Data or some other indication must exist in the technical literature that correlate the potential surrogate with the quality characteristic directly pertinent to the objective. Even if the correlation data are apparently inadequate, it may be desirable to consider the surrogate characteristic at this point so that its usefulness may be evaluated. For example, if the objective pertains to CO in the breathing zone and, although from the literature it can be found that the level of methane in the intake air of a diesel engine correlates well with CO levels in the exhaust gas, there may not be data available that relate these methane levels to CO levels in the breathing zone. However, it could be desirable to consider measuring methane levels for research purposes to establish a correlation, since there may already be a requirement to take methane measurements for another purpose. Similarly, a general correlation between various direct and substitute characteristics may have been demonstrated in other mining situations, but there might not be adequate information relative to the specific mining process under examination and, therefore, it may be desirable to consider some measurements for "research purposes".

6. Identify variables at places in the manufacturing system (result 3) other than the quality characteristics of the product (results 4 and 5) that could potentially provide measurement alternatives.

The preceding two steps examined variables (characteristics) in the product. This step examines variables at places in the system other than the product, the measurement of which may be potentially substituted for measurements of product characteristics. Examination of these system variables is important because: 1) these alternative measurements may be cheaper or

easier to make, 2) they may indicate that a "step"-type of monitoring strategy (a graduated or decision-based strategy that is discussed more fully below) may be more useful than the usual approach of selecting a fixed, less flexible strategy, and 3) they may provide information that is more suitable for a control-related objective than would be information obtained in the breathing zone. Measuring characteristics of the product provide relatively good information about product quality, but do not generally aid in determining the cause of poor quality. By measuring appropriate variables in the process, information useful for control purposes is obtained. If the information can be obtained in a timely manner, the likelihood of producing a product of unacceptable quality is also reduced.

A "step"-type of strategy is one in which measurements are made at a place in the system where measurements are relatively easier or cheap, with the knowledge that as long as a certain critical value is not reached, the concentrations of the pertinent product characteristics are within an acceptable range. If the critical value is reached, then the strategy requires "stepped up" measurements, meaning that either more or different measurements are made or that measurements must now be made of the pertinent characteristics in the product.

As an illustration, consider the case of an objective that concerns exposure to SO_2 . The concentration of SO_2 in mine air is directly dependent on the amount of sulfur in the fuel, assuming that other pertinent variables such as ventilation and the use of exhaust control devices are held constant. If adequate correlating data are obtained (step 7), the strategy would consist of routinely measuring fuel sulfur concentration instead of routinely monitoring breathing zone SO_2 concentrations. If the concentration was below a certain percent, it would be reasonably certain that SO_2 levels in the mine were below the level of concern to the objective, and no SO_2 measurements would be made in the mine. However, if the critical percent was exceeded, then the strategy would require additional measurements, e.g. breathing zone SO_2 , ventilation rate, or CO_2 concentrations, which relates to the amount of fuel burned and ventilation rate.

The detailed system (result 3) provides the universe of variables that are to be examined. This step requires that the system be investigated variable by variable to determine which of the variables have an effect on the quality characteristics directly or indirectly (substitute characteristics) pertinent to the objective. A review of the technical literature is generally required for this step. Chapter 31 of the Handbook provides such a literature review.

7. Determine for each variable that is an alternative to product quality characteristics (result 6) whether sufficient data exist to quantify the relationship between the variable and an associated product characteristic(s).

Often, the general effect of a system variable on a product variable may be known from data collected in one mine, but that the correlating data cannot be used in another mine--especially if the types of mine or mine processes are different. This step is to find quantitative information that

correlates values of alternative system variables with values of associated product characteristics for the mine for which the monitoring strategy is being derived. Using the fuel sulfur/airborne SO₂ illustration, the data required in this step are data that show, for a given percentage of fuel sulfur, the airborne SO₂ concentrations in the mine will be a certain value. In other words, it is not sufficient for the purpose of deriving a monitoring strategy to only know that as fuel sulfur increases, mine atmospheric SO₂ concentrations increase. The quantitative relationship between the two variables must be established for the particular mine, vehicle, and engine in question.

8. Determine which system variables (result 7) are especially sensitive or critical in causing changes in product quality (results 4 and 5).

The purpose of this step is to identify the more important variables pertinent to the objective. This step is called a sensitivity analysis. A product characteristic may be affected by several system variables; however, one of these variables may have significantly greater influence on the product than any of the other variables, or even of all the other variables combined. The variable or variables that have the greater influence are the ones that have the greater potential for being used as measurement alternatives or as places to apply control technology.

9. If the objective(s) (result 1) is(are) directed at process control, determine whether the effect on product quality from each critical system variable (result 8) can be adequately controlled using existing technology.

The purpose of this step is to locate places in the breathing zone air "manufacturing system" that could be integrated into an engineering control program. The quality of the breathing zone air is affected by all of the factors identified when the "manufacturing system" is detailed (result 3). Some of these factors will be especially critical to overall air quality in terms of the contaminants that are created (result 8). Some of the factors may also be easily controlled so that their contribution to decreased air quality can be diminished, thereby raising the quality of the air.

In the previous example, fuel sulfur and its effect on SO₂ in breathing zone air, the important system variable or factor is the sulfur content of the fuel. This step requires a determination to see if the fuel sulfur concentrations can be reduced as part of an effort to control the concentration of SO₂ in breathing zone air. If the objective was to control sulfates in air, then not only would the control of fuel sulfur have to be investigated, but also engine and exhaust-related factors, i.e., the presence of a catalytic converter and its efficiency, that influence SO₂ to sulfate conversion would have to be considered.

Step 9 requires that two results be obtained. The first result is to identify the important or critical variables where control technology potentially could be applied. This result is closely associated with result 8. The second result requires that the user examine existing controls and methods

to determine if the technology available is sufficiently effective and economically feasible. For instance, it must first be determined that lowering fuel sulfur is a critical factor in lowering airborne SO₂. Once this is done (by detailing the system and examining the fuel variables), it must be determined if there is a method of lowering fuel sulfur (or supplying the mine with another fuel source that has a lower sulfur content). Finally, it is necessary to determine whether the available methods can sufficiently reduce the sulfur in the fuel and whether the cost of doing so is prohibitive.

We recognize that many monitoring strategy objectives may not be concerned with control and, therefore, step 9 may not be applicable for all users of the scheme. If this step is inappropriate to the monitoring strategy objective, it can be ignored and the user can move on to the next step.

A desirable byproduct of this step is that if no technology exists, or if the technology available is ineffective or prohibitively costly, then a possibly important area of research and development will have been identified.

10. Identify the technology (methods and/or instrumentation) that exists to measure each product quality characteristic (results 4 and 5) and each alternative or critical system variable (results 7, 8, and 9) that affect product quality.

In this step, determine the data needs for each of the product characteristics or system variables that have been identified as potential measurement options. The data needs are determined by reviewing the objective (result 1), the list of critical factors (result 2), and the technical literature. These needs are then converted into instrumentation or methodology requirements. Subchapter 31:3 of the Handbook can be used for this step. For example, if the objective is to provide a warning of CO exposure in excess of 100 ppm, then the method or instruments used must provide measurement results quickly and an alarm must be provided that indicates CO levels exceed 100 ppm. Similarly, if a review of the literature would indicate that CO₂ measurements made on a moving vehicle are correlatable with NO, NO₂, and CO concentrations in the breathing zone of miners in dead-end drifts, then CO₂ sampling instrumentation is required that is capable of being vehicle mounted and will withstand the accompanying abuse as the vehicle performs its primary function.

To assist in establishing data needs, the user of the scheme may wish to refer to the instrument/method categories detailed in Section 31:3, "Review and Summary Measurement Methods," in the Monitoring Strategy Development Scheme Handbook. After defining data needs, instrument/method categories must be examined to determine if adequate technology exists to make the desired measurements. Therefore, the data needs may most conveniently be expressed in terms of the required physical characteristics of the sampling instrumentation, the time representativeness of the sample collection, the timeliness of the data output, and the time resolution of the data produced. Expressing data needs in these categories requires that the user consider various measurement options in each category. For example, if the data need is for real-time information concerning breathing zone, 8-hour TWA air concentrations, the option of using either personal or portable

methods/devices must be considered. These are called physical characteristics of the measurement instrumentation. Similarly, the option of collecting data on an 8-hour continuous basis or by using intermittent samples coupled with appropriate statistics must be considered. This deals with time representativeness of collection. However, under the categories of timeliness of data output and time resolution, the data needs require the use of methods/devices that are capable of "current", "time-integrated" data output.

Once the data needs for each product characteristic or system variable identified as a potential measurement item are known, the user is in a position to determine whether adequate technology exists to make the measurements. We realize that the identification of data needs is not always a straightforward task, but identifying such needs is an imperative step if a logical strategy is to be developed. To determine if technology is available in the combination of categories that has been specified by the data needs, the user of the scheme is referred to the "Measurement Method/Instrument Summary" sheets found at the end of Section 31:3 in the Handbook. Due to the rapidly changing technology in this field, it may be necessary for these sheets to be updated by the user with current and additional information at the time of use.

11. Combine each product quality characteristic (results 4 and 5) and each alternative system variable (results 7, 8, and 9) with the corresponding measurement technology options (result 10).

By combining each variable option with the appropriate measurement technology options, all of the measurement options for a monitoring strategy will have been identified. Each of these options we call a "measuran" and each one consists of: 1) a place in the manufacturing where a measurement can be made, 2) a variable or variables to be measured at each place, and 3) a measurement technique for each variable. These are the options that must be compared to determine the one or ones most suitable to the monitoring strategy objective.

12. If possible, identify and eliminate any "obviously" inferior measurans.

This step is provided because the user may know without further evaluation that a certain method, piece of equipment, or so forth, will not be satisfactory. If this is the case, it is useless to continue to evaluate that particular measuran. However, this step is fraught with danger and the user should be extremely cautious in determining what is "obvious".

13. Eliminate measurans that do not satisfy the requirements imposed by critical factors (result 2).

The objective of this step is to eliminate measurans for which it would be purposeless to pursue further evaluation, since they can already be shown to be unacceptable options because they do not satisfy a critical factor.

14. Determine appropriate statistical parameters.

At this stage of the scheme, all of the options of where to measure, what to measure, and how to measure have been identified. This step is the

first of two steps to determine for each option how many measurements must be made and/or how frequently measurements must be made. This step requires that a decision be made regarding how much error in the measurements can be tolerated. This error is commonly expressed as consumer's risk, producer's risk, and detectable difference.

Consumer's risk is the probability that a sampling strategy would indicate that a product meets quality standards when, in fact, it does not. Producer's risk is the probability that a sampling strategy will indicate that a product does not meet quality standards when, in fact, it does. Detectable difference is a measure of how great the difference must be between two measurements before it is known that the two measurements are, in fact, different. The values chosen for consumer's risk, producer's risk, and detectable difference establish the values for α error, β error, and δ error that statisticians can use to calculate the number and frequency of samples or observations.

15. Using the statistical parameters (result 14), determine the required number of measurements and/or frequency of measurement for each measuran.

This step is one that for many objectives and situations will be very difficult and we suggest that competent statisticians be consulted to obtain the result.

The result from this step is dependent on the choices of tolerable error chosen in the preceding step and expressed as α , β , and δ values, and the amount of fluctuation of the variable (variance), type of measurement, process, monitoring objectives, and so forth.

When we tried to detail this step, we found that even statisticians experienced difficulty in providing answers. Eventually, it was agreed that a complete description of procedures applicable to all or most objectives was beyond the scope of this work. In subchapters 51:2 and 51:3 in the Handbook, we have provided examples of how we proceeded with this step for two specific example objectives.

We are of the opinion that this subject is an important area that needs to be developed by the Bureau of Mines and other interested agencies and organizations.

16. Bias the categories and criteria in the evaluation plan.

The evaluation of the candidate measurans required by the scheme is more easily accomplished by using a worksheet that we have developed. The worksheet is shown in Figure IV-2. We call the worksheet the Evaluation Plan because the purpose is to make an evaluation and assign a quantitative value for each measuran so that they can be ranked. We, accordingly, refer to this part of the scheme as the Evaluation Plan phase.

The purpose of the evaluation plan phase is to compare measurans to determine which ones have the greater potential to satisfy the objectives of a monitoring strategy. The evaluation plan worksheet can also be used to quantitatively evaluate an entire strategy.

In listing the criteria to be included in a comparative measurement/strategy evaluation, there is an advantage to consolidating the criteria under three major headings. Some criteria such as accuracy, precision, etc., are measures of how well a monitoring strategy would work; others, like process interference and the difficulty of obtaining a measurement, are factors that measure how hard it would be to get the necessary data; other factors are cost-related. These three groups of criteria represent three major areas in which measurements or strategies can be compared: 1) effectiveness, 2) implementation difficulty, and 3) cost. Therefore, the evaluation plan worksheet is divided into these three separate evaluation categories for which separate evaluation ratings are obtained. Furthermore, some of the major criteria within the three categories are broken down into subcriteria, which are considered separately and then averaged to provide a result for the major criteria. For example:

1. Effectiveness (a major evaluation category)
 - 1.1 Site correlation (a major criterion)
 - 1.2 Substance/agent correlation (a major criterion)
 - 1.3 Measurement technique (a major criterion)
 - 1.3.1 Accuracy (a subcriterion)
 - 1.3.2 Precision (a subcriterion)
 - 1.3.3 Sensitivity (a subcriterion)
 - 1.3.4 Interferences (a subcriterion)

The evaluation plan includes a mechanism for weighting individual criteria. The requirement for this provision arises from the fact that cost, for example, might be less of a consideration for some users of monitoring strategies than others--for some, cost might be paramount--and, therefore, the evaluation plan needs a mechanism to include this preference or bias. Another example is that, when comparing monitoring equipment, a certain type of equipment might have enhanced value to a user because that equipment was already available. This preference also needs to be built into the evaluation. It is also evident that the importance of any one category or criterion depends on the objective of the monitoring strategy. The value of using highly accurate technology, for instance, is very objective-dependent. While accuracy appears to be a desirable factor, how important are measurements of ± 1 percent to an industrial hygienist trying to reconstruct occupational exposures over the past thirty years? The answer, of course, is that the industrial hygienist does not need data this accurate, since there are other large error-inducing factors involved. For the preceding reasons, the evaluation plan includes a provision for weighting or biasing the evaluation factors.

There is, then, the opportunity to apply a weighting factor to each of the criterion in the plan. The weighting is placed in column 1, "Bias Weighting". The lower end of this weighting was chosen as zero, so that criteria judged to be not applicable could be removed from the evaluation. The other possible choices available to a user are 1/2, 1, and 2. Normally, it is intended that a value of 1 would be the assigned bias weighting value. A user could also choose 1/2 or 2 if the criterion was to be given less or more weight, respectively.

17. Using the biased evaluation plan (result 16) evaluate the measurans (result 15) and calculate their overall ratings.

In this step each measuran is given a rating for each of the criteria in the evaluation plan and an overall rating for each measuran is obtained. The measurans are then ranked according to their ratings.

The range chosen for rating the criteria (column 3 in the plan) is 0-5. A range of 1-100 was considered to provide a "test score" of typical magnitude, but it seemed inappropriate to ask a user to give a rating over such a wide range; in fact, we felt that to score criteria from 0-10 would be difficult. A smaller range such as 0-3 seemed more suitable. This range provides the option of essentially judging that a measuran had no value (0), little value (1), average value (2), or high value (3) for a given criterion. This is a much more practical rating range than 0-100 or 0-10. We decided to give the user a little more flexibility by providing an additional rating on each side of average and chose a rating range of 0-5.

The product of the rating and the bias weighting provides a biased rating for each criterion. The sum of the biased ratings in each of the three categories divided by the sum of the corresponding bias weightings results in an evaluation rating (which will also fall in the range of 0-5) for the category.

The category scores are combined according to the formula on the final page of the evaluation plan worksheet to give an overall evaluation rating, which is the final score for the measuran or strategy and is the quantity used to determine comparative value, i.e., ranking. Provision is also made for weighting of each of the three categories, but a range for the weighting has not been specified and weighting is left entirely to the judgment of the user.

EVALUATION PLAN

Measuran: Substance _____ Location _____
 Type _____ Instrument _____
 No. of Samples/Frequency _____

(col. 1) Bias Weighting (0, 1/2, 1, 2) (a) (b)		Evaluation Criteria	(col. 3) Rating (0-5) (a) (b)		(col. 4) Biased Rating (col. 1a x col. 3b) (a) (b)	
		1. Effectiveness				
		1.1 Site correlation				
		1.2 Substance/agent correlation				
		1.3 Measurement validity				
		1.3.1 Bias - nonrandom error				
		1.3.2 Bias - random error				
		1.3.3 Minimum/maximum detectable levels				
		1.3.4 Interferences				
	Σ				Σ	
		1.4 Output				
		1.4.1 Time representativeness				
		1.4.2 Output delay				
		1.4.3 Time resolution				
		1.4.4 Type of record (alarm/display/hard copy)				
		1.4.5 Interface with controls				
	Σ				Σ	
		1.5 Psychological factors				
		1.5.1 Confidence in the plan				
		1.5.2 Confidence in the mine air quality				
	Σ				Σ	
		1.6 Statistical adequacy				
col. 1a		Effectiveness Evaluation Rating = $\frac{\sum \text{col. 4b}}{\sum \text{col. 1a}} = 0 < \text{EER} < 5$				Σ

FIGURE IV-2. - Evaluation plan.

EVALUATION PLAN

Measuran: Substance _____ Location _____
 Type _____ Instrument _____
 No. of Samples/Frequency _____

(col. 1) Bias Weighting (0, 1/2, 1, 2) (a) (b)		Evaluation Criteria	(col. 3) Rating (0-5) (a) (b)		(col. 4) Biased Rating (col. 1a x col. 3b) (a) (b)	
			2. Implementation Difficulty			
		2.1 Mine worker burden (effort)				
		2.2 Machine operation burden (effort)				
		2.3 Process interference				
		2.4 Quality assurance (measurement or sample tampering)				
		2.5 Ease of measurement				
		2.5.1 Skill required (sampling/field instruments/lab instruments)				
		2.5.2 Effort required (time and complexity)				
		2.5.3 Frequency and complexity of calibration				
		2.5.4 Stability of instrumentation and/or sample				
	Σ			Σ		
		2.6 Level of cooperation required				
		2.6.1 Production management				
		2.6.2 Mine worker				
		2.6.3 Organized labor				
		2.6.4 H & S management				
		2.6.5 Government				
	Σ			Σ		

FIGURE IV-2. - Evaluation plan (continued).

EVALUATION PLAN

Measuran: Substance _____ Location _____
 Type _____ Instrument _____
 No. of Samples/Frequency _____

(col. 1) Bias Weighting (0, 1/2, 1, 2) (a) (b)		Evaluation Criteria	(col. 3) Rating (0-5) (a) (b)		(col. 4) Biased Rating (col. 1a x col. 3b) (a) (b)	
			2.7 Ruggedness			
		2.7.1 Mechanical/electrical				
		2.7.2 Ambient conditions (RH & temperature)				
	Σ				Σ	
		2.8 Portability				
		2.8.1 Size/weight				
		2.8.2 Power requirements				
	Σ				Σ	
		2.9 Safety				
		2.9.1 Workers (including intrinsic safety of measuring/sampling devices introduced into the mine environment)				
		2.9.2 Sample taker				
	Σ				Σ	
		2.10 Statistical burden				
Σ col. 1a		Implementation Difficulty Evaluation Rating = $\frac{\Sigma \text{ col. 4b}}{\Sigma \text{ col. 1a}} \equiv 0 < \text{IDER} < 5$				Σ col. 4b

FIGURE IV-2. - Evaluation plan (continued).

OVERALL EVALUATION RATING

$$\underline{\text{Overall Evaluation Rating}} = \underline{\text{OER}} = \frac{(X)\underline{\text{EER}} + (Y)\underline{\text{IDER}} + (Z)\underline{\text{CER}}}{X + Y + Z}$$

$$0 < \underline{\text{OER}} \leq 5$$

X, Y, Z weighting biases for effectiveness, implementation difficulty, and cost, respectively.

FIGURE IV-2. - Evaluation plan (continued).

As mentioned previously, the evaluation criteria have been identified and organized under the three major categories of Effectiveness, Implementation Difficulty, and Cost. Although the worksheet presents the criteria we feel are most appropriately used in the selection of monitoring strategies, it should not be considered exhaustive. If, for example, a particular objective has associated with it some unusual characteristics, it may be necessary to add one or more criteria to any of the three categories to adequately evaluate the possible measurans.

The following discussion is provided to briefly explain the meaning and reference of each of the criteria on the evaluation plan worksheet:

1. Effectiveness--All of the criteria listed under this general category evaluate how well the objective is addressed by the monitoring strategy being tested.
 - 1.1 Site correlation--How well does the site where samples are taken correlate with the site specified in the objective? For example, if the objective calls for information about workers' breathing zone concentrations and breathing zone samples are taken, then the correlation is high. On the other hand, if area samples are taken for the same objective, then the correlation may not be very good, as determined by available data in the literature.
 - 1.2 Substance/agent correlation--How well does the substance/ agent sampled correlate to the substance/agent identified in the objective? For example, if the objective requires the determination of CO concentrations and CO is measured, then the correlation is very good. However, if CO₂ is measured for the same objective, the correlation may not be as good. Again, the degree of correlation will be determined by the available literature or data.
 - 1.3 Measurement technique--How good is the measurement technique in terms of accuracy, i.e., bias (How well does it measure the true concentration?), precision (How well does it repeat the same measurement?), sensitivity (How well does it detect small changes in the concentration?), and interferences (What substances interfere with the measurement and to what extent is the measurement accuracy, precision, and sensitivity affected by various concentrations of the interfering substances?).
 - 1.4 Output--How well does the form of the output meet the requirements of the objective?
 - 1.4.1 Maintenance of records--If the objective requires that the records be maintained for some period of time, how well does the form of the output lend itself to maintenance for the required period?
 - 1.4.2 Integrated vs. discreet--Is the output already integrated over time (time-weighted average), or is it presented as individual data points that need to be manually integrated?

- 1.4.3 Current display--Is the output information available immediately, or is there a time delay in obtaining the output?
 - 1.5 Psychological factors--For some objectives the psychological aspects of the proposed monitoring plan may be more important than the actual technical aspects. A monitoring plan that may be technically very effective could be useless if the workers and/or the management believe it to be a poor approach.
 - 1.5.1 Confidence in the plan--How do labor and management feel about the proposed plan? Is it something they believe will work, or does it need to be forced on them?
 - 1.5.2 Confidence in the mine air quality--Do labor and management believe that the results of the monitoring strategy adequately reflect the mine air quality? This could be enhanced by such things as labor participation in the sampling or by providing results to individual workers.
 - 1.6 Statistical adequacy--To what degree have compromising assumptions been made to develop the statistical parameters? For example, were calculations based on gross estimates of variance? Was it assumed that the air samples are normally and independently distributed when it is known that they most likely are not?
2. Implementation difficulty--The criteria under this general category are designed to determine how difficult it will be to carry out the specific monitoring strategy. This level of difficulty is evaluated in more subjective terms, such as the burden on the worker and the sample taker, and the level of cooperation required from various involved parties. It is also evaluated in more objective terms, such as size, weight, portability, and ruggedness of the sampling equipment.
 - 2.1 Mine worker burden--How much of a burden is placed on the mine worker during the sample collection? For example, requiring the mine worker to wear impinger lapel samplers and personal sampling pumps is a significantly greater imposition than is some type of stationary area sampling device.
 - 2.2 Machine operation burden--How much of a burden is imposed on the operation of mining machinery? For example, will there be equipment mounted on a scooptram that will interfere with the operation of the vehicle?
 - 2.3 Process interference--To what degree will the proposed monitoring strategy interfere with the mining process? For example, must the mucking operation be halted so that samples can be taken in a dead-end drift?
 - 2.4 Quality assurance--How much of a burden is imposed by the proposed method of assuring that the measurements or samples have not been altered or spiked, if this is a requirement of the objective?

This will become particularly important in the objectives dealing with compliance, since the chain of custody of samples and data is important to ensure honest results.

- 2.5 Ease of measurement--How difficult is it to make the required measurements in the field? This is evaluated by the following four criteria:
 - 2.5.1 Skill required--How much skill/knowledge in relation to the measurement method is required of the individual taking the measurements or in the analysis of any samples taken? A measurement method that requires highly trained individuals will rate low here in comparison to methods that can satisfactorily be accomplished by untrained individuals.
 - 2.5.2 Effort required--How much effort is required on the part of the individuals making the measurement or analyzing the sample, and how complex is the measurement procedure? A method that is simple to execute and requires relatively little effort to take and analyze will rate high here.
 - 2.5.3 Frequency and complexity of calibration--How complex are the measurement equipment calibration procedures, and how often does calibration need to be performed? Complex procedures that must be done often will rate low here.
 - 2.5.4 Stability of instrumentation and/or sample--if an instrument is being used to make the measurements, how stable is it? Does it need to be zeroed or the span checked often? If so, it will rate low in this category. Similarly, if a sample is taken, how stable is it? Are there special handling procedures to assure sample stability? If so, this method will rate low for this criteria.
- 2.6 Level of cooperation required--How much cooperation is required of the various "concerned" parties (production management, mine workers, organized labor, health and safety management, and the government) to assure the success of the monitoring strategy under consideration? A plan that requires a great deal of cooperation from all "concerned" parties will rate low for this criteria.
- 2.7 Ruggedness--How rugged is the measurement equipment--both from a mechanical viewpoint and from an electrical viewpoint?
- 2.8 Portability--How portable is the measurement equipment? This criteria will carry varying degrees of importance, depending on how much portability is required by the objective. It is assumed that all equipment will need to be moved sometime, therefore, more portable equipment will always be more desirable, no matter how slight.

- 2.9 Size (dimensions)--What is the physical size of the sampling equipment? It is assumed that smaller equipment will generally be more desirable than larger equipment.
 - 2.10 Weight--How much does the sampling equipment weigh? Again, it is assumed that generally lighter equipment is more desirable than heavier equipment.
 - 2.11 Safety--How safe is the proposed method of taking measurements, both to the worker and to the individual taking the samples? In this case an automated piece of equipment will rate much higher than a method requiring an individual to be on a moving piece of mining machinery to obtain a sample.
 - 2.12 Statistical burden--How much of an effort is required to perform the statistical computations necessitated by the monitoring strategy under consideration?
3. Cost--All of the criteria listed under this category are designed to determine the costs (both initial and per sample) for the monitoring strategy under consideration. Although there is a more objective way of rating these criteria-dollars, we decided to translate dollars into the more subjective rating scale of 0 through 5, so that a bias weighting could be factored in, as was done for the previous criteria. The ability to bias weight-cost considerations is important because lower initial costs and higher disposable costs may be more desirable because there is little money now but more is expected in the future. Or, the situation might be that there is ample money for instruments but personnel costs must be kept down. This approach to evaluating the cost criteria allows such factors to be taken into consideration.
 - 3.1 Capital costs for devices--What is the level of the initial outlay required to purchase the measurement equipment?
 - 3.2 Cost of disposables--What is the level of the per sample cost or cost of disposables? These will be the costs of items that will be used up and, therefore, not capitalized as an asset.
 - 3.3 Replacement frequency--What is the level of cost associated with the replacement of capital cost items? This could also be thought of in terms of the depreciable life of a capital cost item. For example, although the initial cost of a specific sampling pump is low, if it must be replaced annually, then it may not be a highly desirable option.
 - 3.4 Maintenance--What is the estimated cost of maintenance of the measurement equipment? Although it is unlikely that there will be good data on maintenance costs for a specific piece of equipment, estimates can be made of the relative degree of maintenance required for the options under consideration.
 - 3.5 Personnel costs--These are the costs related to the number of people required to take samples, calibrate equipment, perform quality control checks, and provide administrative support. For example, if a particular mine has extra people around during slack

periods, it is possible that personnel costs would not be as important as other out-of-the-pocket expenses.

- 3.6 Analytical costs--These are the costs of having samples analyzed either in-house or at a contract laboratory.
- 3.7 Record keeping--These are the costs associated with keeping records of measurements that are made. Since administrative costs are included under personnel costs, record keeping costs generally only include such things as computer time or copying costs.
- 3.8 Lost productivity--If the proposed monitoring program causes a major disruption of production, the costs of the lost production will be included under this category.

The evaluation plan is used by completing the following steps:

1. Assign bias weightings to subcriteria and put in column 1(b).
2. Assign bias weightings to major criteria and put in column 1(a).
3. Sum the bias weightings in column 1(b) for each criterion.
4. Choose a rating for each subcriterion and place in column 3(a).
5. Multiply the weighting in column 1(b) by the corresponding rating in column 3(a) to get the biased rating to be inserted in column 4(a) for each subcriterion.
6. Sum the biased rating values in column 4(a) for each subcriterion.
7. Divide each of the summations in column 4(a) by the corresponding summation in column 1(b) to obtain the criterion rating and insert the value into column 3(b).
8. For each criterion, multiply the weighting in column 1(a) by the rating in column 3(b) to obtain the biased rating, which is placed in column 4(b).
9. After the above steps have been completed for all of the criteria in each of the three major categories (Effectiveness, Implementation Difficulty, and Cost), sum the values in column 1(a) for each category.
10. Sum the values in column 4(b) for each category.
11. For each category divide the sum of column 4(b) by the sum of column 1(a) to get the evaluation rating for each category. The rating will be a value between 0 and 5.
12. Assign a bias weighting to each of the three major categories.

13. Multiply each category's evaluation rating by the corresponding bias weighting and add the values.
14. Divide the answer obtained in step 13 by the sum of the category's biased weightings (chosen in step 12). The answer is a number between 0 and 5 and is the overall evaluation rating (ranking) for the measuran or strategy.

Upon completion of the Evaluation Plan worksheets, step 18 is the next step in the scheme.

18. If additional critical factors have been identified during the evaluation process, eliminate measurans that do not satisfy the imposed requirements.

We anticipated that during the evaluation of measurans other critical factors might become evident and, if so, that some measurans could be excluded at this step from the list of ranked measurans.

19. If a single measuran appears to satisfy the objective of the monitoring strategy, select a measuran from among the higher ranked measurans (result 18) to be used as the strategy.

A monitoring strategy can include the use of one or more measurans. The use of a single measuran in lieu of several may not be adequately effective and may not always be the cheapest or easiest strategy to implement. However, if one or more of the higher ranked measurans appears to satisfy all aspects of the monitoring strategy objective, the user can make a selection at this step and the use of the scheme is completed. The decision at this point is left totally to the discretion of the user.

It would be nice if only one measuran were clearly rated superior to the others, but this may not be the case. Hopefully, there will be a small group of measurans clearly superior and the selection of the measuran should be made from this group according to preference. If there is no clear grouping, all of the measurans would probably have to be considered equivalent regardless of rating, unless the significantly different spread of the ratings was well established (such as is done by Consumers Union in rating consumer products).

20. If the monitoring strategy must satisfy multiple objectives, or if the use of a single measuran does not appear to provide a satisfactory or optimum strategy, compose strategies consisting of multiple measurans.

Identifying measurans that have higher ratings does not necessarily provide the user with a monitoring strategy. The strategy may consist of a single measuran, several measurans, or measurans utilized in a step-type of strategy explained previously. It is, therefore, desirable that the user examine the ranked measurans and determine if some combinations of measurans appear to have value as monitoring strategies.

21. Using the evaluation plan (result 16), evaluate all candidate strategies (result 20).

These strategies are compared and evaluated the same way as were the measurans. The same Evaluation Plan worksheet is used.

22. Select a strategy from among the higher ranked strategies.

The strategy to be used is selected in the same manner as was the single measuran. This step completes the use of the scheme.

Summary

In Chapter II we presented the argument that an effective monitoring strategy should be an integral component of the operation of underground mines where diesel-powered equipment and blasting agents are used. We also introduced the premise that breathing zone air could be considered to be a manufactured product. We advanced this premise so that we could approach the monitoring and control of breathing zone air in mines in a way similar to that used by quality control engineers for industrial processes that produce consumer goods.

In Chapter III we discussed typical approaches to quality control and how they could be applied to the selection of appropriate monitoring strategies. The approach to quality control was presented in distinct steps: 1) define the desired quality characteristics of the final product and conduct an exhaustive systems analysis to identify the variables of the manufacturing process that affect, or are correlated with, these characteristics; 2) conduct a sensitivity analysis on the process variables to determine which have the most effect on the product characteristics of concern; 3) select monitoring options commensurate with the objective of either acceptance of the final product or process control to assure the quality of the final product; and 4) establish proper data analysis procedures.

In this chapter we presented a 22-step scheme, developed from the four steps above, designed to identify the universe of measurement options for a chosen objective, and to evaluate and rank those options. The scheme itself is not limited to our subject of interest, but is presented in a very general format because it has the potential for application to other industrial operations. Its practical utility arises from the fact that an attempt has been made to quantify many of the factors that influence the selection of one strategy or tactic over another, and that it provides a step-by-step approach to ensure that important considerations are not inadvertently neglected in the process. One could say that it documents the obvious and, therefore, assures that the "obvious" is not overlooked.

There is one particularly important aspect of the scheme that should be emphasized. The scheme is focused on the quality of breathing zone air. This focus does not mean that only breathing zone air is monitored (there are other "places" in the system where monitoring could be performed), but only that the purpose of the monitoring strategy is to satisfy an objective that is related to breathing zone air quality. In this regard, the industrial "system" with which we are concerned is the system that "produces" breathing zone air. This emphasis goes back to our original premise that breathing zone air can be treated as a manufactured product. Breathing zone air is our subject of interest (our "product"), and the "manufacturing system" that produces this air is the only system to be considered when applying this scheme.