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A RECOMMENDED APPROACH TO RECIRCULATION OF EXHAUST AIR

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An attempt to provide an efficient and toxic free method of recirculating industrial exhaust air is discussed. An overview is made of the overall design process, the feasibility of recirculating industrial exhaust air, physical and chemical contaminant characteristics, exhaust cleaning, surveillance and response strategies, design of a system and validation of its performance, and maintenance and operation of the system.

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ABSTRACT

The recirculation of industrial exhaust air can provide for substantial reductions in consumption of energy for tempering make-up air. However, since industrial exhaust air often contains toxic contaminants, there is an attendent potential for such systems to create adverse health impacts in a variety of situations.

The goal of this report is to provide a methodology by which the design, installation, and operation of recirculating systems can be undertaken and completed in a manner which ensures the health of employees within the work place. This goal is achieved by systematic review and discussion of the various factors which bear upon the successful implementation of a recirculation system. Topics addressed include an initial feasibility assessment; contaminant characteristics; air cleaning; designing and recirculation system; surveillance and response strategies; system performance validation; and system maintenance and inspection. Included in discussions are both qualitative and quantitative design approaches.

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1. INTRODUCTION

1.1 Objectives of this Report

The recirculation of industrial exhaust air is one of a number of available engineering approaches toward energy conservation in industry. The primary goal of this report is to provide guidelines to help ensure that the design, installation and operation of recirculating systems is undertaken and completed in a manner which will assure the health of employees within the work place.

The report does not take a stand on the pros and cons of recirculating exhaust systems. Instead, the report concentrates on developing general system specifications and design procedures which, if adhered to, should ensure that no adverse impacts on employees' health are experienced. The procedures provided are such that the economic advantages of recirculating systems can be simultaneously estimated and maximized; however, no attempt is made to guide the detailed design or specification of hardware for such a system.

1.2 What are Recirculating Exhaust Systems?

The term "recirculating exhaust system" applies to any industrial ventilation system in which contaminated exhaust air is removed from one location within the work environment, cleaned, and reintroduced to either the same or nearby locations. The system consists of several basic components including a collection device, the necessary duct work to convey air streams to desired locations, an appropriate air cleaning device, equipment or techniques to detect reduced system performance, hardware needed to respond to system failures (e.g., by-pass dampers), a primary air mover, some supply of fresh make-up air, and a return air system with the appropriate hardware to reintroduce and distribute recirculated air throughout the work place.

1.3 Why Recirculate?

Any amount of air removed from a work place by a conventional ventilation system must be replaced by an equivalent amount of outdoor air, either by the introduction of make-up air or the allowance of infiltration. When such replacement air is excessively hot, cold, dry or wet, it becomes necessary to provide a means for tempering it for the purposes of maintaining a comfortable working environment and/or of controlling process conditions. The practice of tempering large amounts of air requires considerable energy consumption in many industries. Thus, energy savings may be realized when large volumes of exhaust air can be cleaned and recirculated while maintaining a safe and healthful work place.

1.4 Where are Recirculating Exhausts Appropriate?

Recirculating exhaust systems can be applied to existing facilities or new plant designs. The recirculation concept is extremely flexible, and may be incorporated into some part or all of ventilation systems comprised solely of local exhausts, solely general exhausts or combinations of the two. Additionally, the concept may be applicable for both single and multiple contaminant systems having emissions from a single point source or from a variety of spatially distributed locations.

1.5 Who Can Design These Systems?

The design and implementation of a recirculation system requires complete a priori knowledge of existing conditions within the work place. Additionally, it requires that the system be carefully designed with respect to hardware and general system specifications, and that it be installed, tested, and operated in a manner which ensures worker comfort and health. In direct consequence, the implementation of a recirculating exhaust system will generally require a team effort involving personnel experienced in the areas of ventilation system design, industrial hygiene, analytical chemistry, and air pollution control.

1.6 The Potential Hazards of Recirculating Exhaust Systems

Since this report is primarily concerned with the health issues involved in the use of recirculating exhaust systems, it is pertinent to briefly discuss these issues at the outset.

Airborne contaminants generated by industrial processes are often toxic. Consequently, it is common practice to collect undesirable emissions and to discharge them to the outside atmosphere. Depending upon the nature of these contaminants, and pertinent air quality regulations, it is also common practice to reduce contaminant levels in exhaust streams through utilization of air cleaning devices.

Recirculation implies that cleaned air would be returned to the work place. It follows, therefore, that this air must be sufficiently clean to maintain a healthful working environment, and that adequate precautions must be taken to ensure a continued, satisfactory level of cleanliness. The goal of this report is to provide information which helps define the precautionary measures appropriate for any specific situation.

1.7 Future Refinement of Recirculation Criteria

This report represents an initial effort to develop practical guidelines for exhaust air recirculation. It is recognized that, as recirculating exhaust installations become more common and as these recirculation criteria are applied, modification and refinement may be appropriate.

One effort to validate these criteria is planned by NIOSH during 1977-78, and the results of NIOSH-sponsored field validation efforts will provide important input to the revision of this report. As various industrial facilities evaluate and implement exhaust air recirculation, it is hoped that their experiences will be shared in the technical literature.

Of interest to some readers will be the fact that this report was revised somewhat based upon the comments of participants at a NIOSH-sponsored symposium on the recirculation of industrial air (in October 1977). To those who attended and actively participated in the proceedings, the authors must extend their gratitude. Their collective and individual wisdom resulted in a number of significant insights concerning what this document should say, and how it should go about saying it.

2. THE OVERALL DESIGN PROCESS

2.1 The Steps Involved

The design, installation and operation of a recirculating exhaust system requires the sequential and/or simultaneous performance of a number of tasks. These involve, with some overlaps:

- an initial feasibility assessment;
- determination of work place contaminant characteristics;
- determination of work place, process, and ventilation system characteristics;
- selection of appropriate air cleaning equipment for further consideration;
- selection of appropriate equipment or methods of detecting reduced system performance for further consideration;
- determination of feasible system configurations;
- design optimization for feasible configurations;
- a system failure analysis for each feasible configuration;
- selection of the "best" overall configuration;
- final selection of equipment or methods for air cleaning, detecting reduced system performance, and responding to system failures;
- detailed system design and installation;
- system performance validation; and
- planned maintenance and inspection.

2.2 The Initial Feasibility Assessment

Chapter 3 describes a general procedure for assessing the feasibility of recirculating exhaust air from a specific operation or process. The purpose of the outlined procedure is to provide an initial indication of whether recirculation is worthwhile or possible before proceeding with detailed and expensive design efforts.

2.3 Contaminant Characteristics

Knowledge of which contaminants are present in a work place, and at what levels they are present, is an important prerequisite for proper performance of virtually any task associated with the implementation of recirculation. In consequence, many sections of this report are concerned with what specific data are needed, how the data are obtained, and how data are utilized in the design process. More specifically, sub-chapter 3.4 discusses such issues in the context of an initial feasibility assessment, Chapter 4 discusses what must be known about individual contaminants, and parts of Chapter 7 and Appendix A describe how the data is used for determining general system specifications. Such data are also required for selection of adequate air cleaning equipment, and equipment or methods for detecting reduced system performance.

2.4 Work Place, Process, and Ventilation System Characteristics

In addition to knowledge of contaminant characteristics, it is necessary to characterize existing or proposed work places, processes, or ventilation systems in terms of air volumes handled, locations of air inlet and outlet locations, work station locations, air flow patterns, and other factors. A section in Appendix A entitled, "A Close Look at Design Parameters" lists and discusses the specific information needed. Sections of Chapter 7 and other parts of Appendix A describe how the data is utilized.

2.5 Selection of Air Cleaning Equipment for Further Consideration

A recirculating exhaust system will usually contain one or more air cleaning devices for reducing contaminant concentrations in exhaust air. Knowledge of the availability, efficiency, economics, maintainability, and general reliability of such equipment is, therefore, necessary before general system design parameters can be specified. Chapter 5 discusses various issues of concern in selecting such equipment in the context of recirculation. To be noted is that this step involves the identification and information gathering for all equipment pertinent to the task of cleaning contaminated streams characterized above. Final selection of equipment for use is accomplished in a subsequent task.

2.6 Selection of Surveillance Equipment for Further Consideration

One or more failure modes for a recirculation system may lead to undesirable contaminant concentrations in employee work stations. In consequence, one must determine what equipment is available and/or appropriate for detecting conditions leading to adverse health effects before such conditions manifest themselves. Chapter 6 provides guidance for this effort. As above, the task involves identification and information gathering on all feasible methods for implementation, not the final selection of one.

2.7 Determination of Feasible System Configurations

Generally speaking, there is more than one recirculation system configuration applicable to a work place which will provide a healthful working environment and a reduction in energy consumption. Each of these configurations, however, will provide a different balance of overall safety (relating to health issues) and cost savings, depending upon the specific exhaust volumes recirculated and the design options specified. Thus, one must identify those configurations feasible for implementation in a specific work place before attempting to optimize and select the one which is most appropriate. Chapter 7 and the examples of Appendices A, D, and E provide insights concerning how the task may be accomplished.

2.8 Design Optimization for Feasible Configurations

Chapter 7 and Appendices A and B provide the methodology by which each feasible system configuration can be optimized in terms of the relative costs of cleaning versus tempering air volumes. Basic constraints on the optimization procedure are, of course, the necessity to maintain acceptable contaminant concentrations in all work stations.

2.9 Failure Analysis for Feasible Configurations

Chapter 7 and Appendix F provide the basis for determining the consequences of reduced system performance and the time frame within which detection and/or response methodologies must react. This type of analysis is necessary for each system configuration still considered feasible after the preceding optimization task.

2.10 Selection of the "Best" Configuration

At this point, one has complete information required to choose which optimized system configuration provides the best balance of health safety and cost savings. The selection process requires an awareness of all issues involved and the application of some degree of professional judgment. Examples in Appendix A provide insights to how the selection process may proceed.

2.11 Final Equipment Selection

Given the parameters which describe the most appropriate system configuration for installation, and the results of the failure analysis for this configuration, it remains to finalize the selection of the specific types of equipment or methods to be utilized for air cleaning and system performance surveillance. A degree of professional judgment is required, based upon the information available from previous efforts described above.

2.12 Detailed System Design and Installation

At this stage, the design process has provided the user with all data necessary for specifying flow volumes, inlet and outlet locations, air cleaner efficiencies, etc. Detailed system design and installation of the system can, therefore, be accomplished by personnel skilled in this field.

2.13 System Performance Validation

Once the system is installed, it must be inspected and tested to insure it will operate as intended. Chapter 8 provides guidance for this task.

2.14 Planned Maintenance and Inspection

It is imperative that components of recirculating exhaust systems be maintained and inspected as necessary to insure continued, satisfactory performance. This is the subject of Chapter 9.

3. ASSESSING THE FEASIBILITY OF RECIRCULATING INDUSTRIAL EXHAUST AIR

3.1 Decision Criteria

This chapter describes a general, preliminary screening procedure which may be employed to identify the relative ease, and probability of success, of designing and installing a recirculation system. Since the actual design of a recirculation system is a time-consuming and costly undertaking, the screening procedure is a useful tool which can help avoid unnecessary efforts and expenses (such as field sampling programs, hardware evaluation, and design optimization). The assessment process is not always comprised of "yes or no" decisions. Rather, the impact of various process or facility parameters upon recirculation design is considered and subjectively evaluated.

The factors considered in this screening process can be sequentially ordered to provide a logical assessment procedure. The ordering is not based upon relative importance (all factors are important), but rather upon the ease with which the factors can be analyzed.

In order, these factors concern:

Legal Issues - Do state and/or local regulations prohibit recirculation?

Energy Consumption - How much energy is currently expended to temper make-up air, and what is the future outlook in this area?

Contaminant Classification - What type and quantity of contaminants are released into the work place?

Air Quality Regulations - Does the exhaust have to be cleaned for air pollution purposes?

Air Cleaner Availability - Can the contaminant levels in the exhaust air be substantially reduced?

Surveillance - Can reduced performance of the system be detected?

Process Emission Profile - Is the process under evaluation representative of a steady-state condition or must an alternative condition be assumed?

Ventilation System Design - Can the conventional ventilation system be modified for use with a recirculation system?

3.2 Legal Issues

Prior to undertaking detailed recirculation system design, one should determine whether Federal, state, or local regulations govern such installations. Where a state (such as Michigan) has specific regulations governing exhaust air recirculation, authorities should be consulted to ensure that any contemplated system will be acceptable. If recirculation is prohibited, and regulatory agencies will not reconsider the prohibition, then the question of whether or not to recirculate is a moot issue.

3.3 Energy Consumption

It is important to determine, with reasonable accuracy, the expenses involved with tempering make-up air. If the expense is substantial, and/or energy is not available for this purpose, then recirculation may be an attractive approach to reducing energy consumption. If energy requirements for this purpose are insignificant relative to those of other uses, then recirculation is probably not worthwhile.

In many industrial plants, the costs of tempering make-up air are not separately accounted for. In these cases, the ACGIH Industrial Ventilation Manual and the ASHRAE handbooks provide useful techniques for estimating these costs. In general, the cost of tempering make-up air is proportional to (i) the quantity of make-up air being treated; (ii) the number of degree days at the plant location; (iii) the number of hours worked per year; and (iv) the cost of energy. Other influential factors are whether air-conditioning is used in the summer time, and the efficiency of heating (or cooling) units.

3.4 Contaminant Classification

The types and quantities of contaminants released from a particular process have a major influence on the feasibility of recirculating the exhaust from that process. These contaminant characteristics will determine whether recirculation is desirable, whether cleaning of the exhaust is practical (and whether it is economical), and whether surveillance of system operating performance is feasible.

An important fact is that the recirculation system design process requires that all contaminants in exhausts to be recirculated be identified, and their concentration levels quantified. Where there is reason to believe that a process generates large numbers of unknown contaminants, this may constitute a prima facie case against recirculation.

Assuming that all contaminants can be identified, it is necessary to determine whether any substances designated by OSHA as human carcinogens are present. These substances are the one group of contaminants that NIOSH recommends should not be recirculated regardless of other factors (since there is no demonstrated safe exposure level for carcinogens).

Beyond this point, the types and quantities of contaminants also play major roles in assessing the technical feasibility and economics of cleaning air streams. Important factors to consider are:

(a) whether the exhaust contains one contaminant or many;

(b) in the case of two or more contaminants, whether they are all in the same phase (particulate or gaseous) or in different phases;

(c) in the case of particulates, the size distribution of the particulates;

(d) in the case of multi-contaminant exhausts, whether the relative proportion of the contaminants is constant or varies significantly over time.

Factors such as these determine whether or not the exhaust can be adequately cleaned, and whether a surveillance method is available for tracking the performance of the system in operation. Obviously, the more "complicated" an exhaust stream is in terms of numbers of contaminants and phases present, the size distribution of particulate matter, and any fluctuations, the more expensive and difficult it will be to develop effective cleaning and surveillance methodologies.

The toxicity of contaminants must also be considered on a case-by-case basis. Although the recirculation of any contaminant, except a carcinogen, is not expressly discouraged, one has the obligation to realize that recirculation of lowly toxic substances is preferable to recirculation of highly toxic substances. This is especially true where acute exposure effects are possible. Significant uncertainties in assessing toxicity may arise when a substance has not been addressed by NIOSH, OSHA, or the ACGIH TLV Committee. This fact may make it difficult to estimate the possible effects of recirculation upon worker health.

Finally, special attention should be drawn to the fact that, under certain processing conditions, a known contaminant may be broken down or converted to a more toxic form. Therefore, processes involving application or generation of heat, pressure, or reactivity will require careful study to insure that the contaminants present do not undergo changes to other, possibly more toxic, forms.

In summary, it can only be stated that the characteristics of contaminants present in exhaust streams, and/or the difficulties and expenses involved with determining these characteristics, must be assessed and considered in any decision to recirculate.

3.5 Air Quality Regulations

The abatement of fugitive and point sources of pollutant emissions is the mission of numerous local, state and Federal regulatory agencies. Thus, many industrial plants must now provide for the cleaning of contaminated exhaust streams, regardless of whether or not recirculation is contemplated. Consideration of recirculating exhaust air in such circumstances has particular advantages not otherwise available.

Regulatory agencies do not require air cleaning measures until such time that adequate equipment for air cleaning and surveillance activities are generally available. Thus, one is more apt to find the efforts required for designing a recirculation system facilitated, if the contaminants involved are of concern to these agencies. Additionally, it becomes more likely that any recirculation system will be cost-effective when costs are attributed not only to the needs of recirculation, but to compliance activities for air quality regulations. Indeed, the additional costs for recirculation even overlap, to some extent, the expenses associated with current and proposed OSHA regulations for airborne toxic substances.

Another aspect worthy of note is that reductions in the amount of fuel used by a plant may result in lower pollution control costs for exhausts from energy or heat generation equipment. This may especially be true if a plant is considering or using coal instead of gas as a fuel.

3.6 Air Cleaner Availability

It is essential that any contaminated air stream be cleaned or sufficiently diluted to lower the concentration of toxic materials to acceptable levels prior to re-introduction to the work place. Therefore, one of the basic components of most recirculating ventilation systems is the air cleaner, which may be either an existing cleaner in an exhaust system, a new device specifically selected for the recirculation system, or a combination of both. In any situation, it will be important to establish the availability of an air cleaning equipment train for the contaminants in the exhaust air stream before an affirmative decision regarding recirculation is finalized.

For an initial feasibility assessment concerning recirculation, it is sufficient that one determine that the applied technologies for air cleaning have provided reliable and durable equipment pertinent to the task at hand. Generally, it will be found that numerous types of units are commercially available for particulate contaminants, that a limited but effective range of equipment types is available for some gases and vapors, and that no currently available equipment makes sense for application to other gases and vapors. To be additionally noted is that one must consider the effect of cleaning exhaust air upon the desirable qualities of the air.

Finally, it must be noted that the attractiveness of recirculation may be reduced whenever it becomes necessary to employ two vastly dissimilar air cleaners in series (e.g., a bag filter followed by a carbon adsorption unit). This situation is not, in itself, a basis for exclusion, but can in general weigh against adopting a recirculation design. In the particular example cited, a bag break may lead to clogging of the adsorbent and a need for its replacement. Depending upon the circumstances, this may be an expensive proposition in terms of system downtime and maintenance costs.

3.7 Monitor Availability

Provision for detecting reduced performance of a recirculating exhaust system is essential. The failure of a system may expose employees to contaminant levels above those considered safe and permitted by OSHA. Therefore, it is mandatory that a surveillance system become an integral part of the overall recirculation system design. It is also important to recognize that such a system must be designed, installed, and operated in such a manner that it can either automatically or manually trigger the appropriate response mechanism, be it by-pass of exhaust air, process shutdown, or plant evacuation. In consequence, one must make a preliminary assessment of the contaminants present and the air cleaner types available in the context of determining whether methodologies exist for tracking the performance of the operational recirculation system.

3.8 Process Emission Profile

It is important to properly consider the perceived emission profile of each process being controlled to ascertain the nature of contaminant release. The most desirable situation for recirculation is the presence of a single, steady source, or several sources with the same emission profile which are collected in a common exhaust system. The steady release of contaminants simplifies the selection of air cleaning and monitoring equipment, while extreme fluctuations in process emissions increase the difficulty of sizing air cleaning equipment and specifying an appropriate surveillance procedure.

It is patently possible to address the situation where fluctuating processes are operating. However, under these situations, more conservative design approaches must be adopted to insure that workers are not exposed to contaminants above permissible levels. These approaches tend to reduce the economic benefits of recirculation, but are necessary because of the attending uncertainties.

3.9 Ventilation System Design

The design of the current or proposed ventilation system for a plant can have a marked effect upon the feasibility of recirculating exhaust air. In some cases, the conversion from a conventional to a recirculating exhaust system may be trivial, while in other instances this may require extensive retrofitting and redesign of equipment. One must consider, therefore, what difficulties, if any, may be involved in the conversion.

In evaluating the present system within a plant, it is also important to insure that the existing system is operating at, or near, maximum efficiency. Only under these conditions will it be possible to extract the maximum benefit from a recirculating exhaust design. If there are a large number of uncontrolled or poorly controlled sources within the work place, the benefits associated with cleaning and recirculating air can be measurably decreased. In this situation it may be economical to first expand, improve, or implement engineering controls, and then to install the recirculating system.

4. CONTAMINANT CHARACTERISTICS

4.1 Introduction

A principle objective of industrial ventilation systems is the control of process emissions so as to avoid employee exposures to hazardous materials. When designing a ventilation system (recirculating or not), it is important to define as design parameters the identities and characteristics of contaminants as well as the airborne levels that are "acceptable" in employee breathing zones and in system components. Levels of acceptability may be based upon consideration of health effects, aesthetics (e.g., odor), and/or chemical and physical properties (e.g., corrosivity, flammability, reactivity).

4.2 Physical and Chemical Description

The basic classification of contaminants as particulates and gases/vapors provides some immediate insight into the complexity of the cleaning and system performance surveillance devices that will be needed. Where both particulate and gaseous/vapor contaminants are present, it will frequently be necessary to address the physical states separately; however, the presence of particulate contaminants alone may indicate that a fairly simple particulate filter fitted with a pressure-drop sensor can adequately satisfy recirculation system needs.

For particulate contaminants, the information commonly needed for the selection and/or design of air cleaning equipment trains or sub-systems to detect reduced system performance includes:

- identity of contaminants;
- particle size distribution;
- particle density;
- particle shape and airborne agglomeration;
- bulk density of collected material;
- solubility;
- corrosivity;
- reactivity;
- abrasiveness;
- stickiness;
- tendency to pack when lying undisturbed;

- tendency to absorb water from atmosphere;
- flammability or explosivity;
- wettability
- dielectric properties (if electrostatic precipitation may be used);
- value (e.g., for recovery of material);
- toxicity;
- loading and mass rate.

The toxicity of each contaminant present must also be known to define the airborne levels which are acceptable in employee breathing zones. The loading and mass rate of contaminants are usually those for an existing or proposed conventional ventilation system, but may be modified within the framework of the recirculation system design process.

Corresponding data are commonly required for gas/vapor contaminant streams and/or air streams. These data include:

- identity of contaminants;
- volume rate;
- temperature;
- dewpoint;
- pressure;
- density;
- viscosity;
- solubility;
- specific heat;
- flammability or explosivity;
- corrosivity;
- reactivity;
- specific heat;
- thermodynamic properties;

- toxicity;

- ability to be absorbed or adsorbed.

As above, the volume rates and contaminant concentrations in streams may be modified during the recirculation system design process.

Finally, one must give some consideration as to whether recirculation of exhaust air will unacceptably increase odor levels perceived by employees. If this possibility exists, one may desire to choose an acceptable airborne level in breathing zones based upon odor characteristics of the offending contaminant. Otherwise, one may simply design the system such that existing contaminant levels are maintained (i.e., such that there is no degradation of the working environment).

4.3 Health Effects

4.3.1 Exclusion of Contaminants

As a general rule, exhaust air containing any contaminant may be recirculated if suitable equipment for air cleaning and detecting reduced system performance exists. However, where a contaminant has been designated as a human carcinogen by OSHA, it is recommended that recirculation not be undertaken, since no safe threshold level of exposure for carcinogenesis has been documented. (Permissible exposure limits for carcinogens are typically based upon factors such as limits of detection, not upon documented safe exposure levels.) For substances which are suspected of being carcinogens, individual judgments relative to specific situations must be made by qualified personnel on a case-by-case basis.

4.3.2 Allowable Levels

There are several sets of established guidelines for the definition of allowable exposure levels to toxic substances. These include:

- OSHA Regulations: Within the Code of Federal Regulations (Title 29, Part 1910), OSHA has established a "permissible exposure level" for each of approximately 400 toxic substances. These levels represent legal limits which are enforced by OSHA compliance officers. OSHA permissible exposure levels are expressed as 8-hour time-weighted-averages (TWA's) and/or ceiling levels. These latter values represent concentrations that should not be exceeded, and are usually measured as 15-minute TWA's.

- NIOSH Criteria Documents: An on-going NIOSH program has been established to review available technical data and make recommendations for the establishment or revision of occupational health standards. For each individual substance (or family of substances) studied, a "Criteria Document" is published to document the NIOSH-recommended standard.

- Threshold Limit Values: The ACGIH Threshold Limit Value (TLV) Committee publishes a revised TLV list annually. Within this list, allowable exposure levels are recommended for approximately 650 substances (including all of those regulated by OSHA). Since this list is revised annually, it reflects up-to-date judgments on industrial toxicology. The exposure limits are expressed as 8-hour TWA's and/or ceiling levels.

Where established guidelines for an allowable exposure level do not exist for one or more of the contaminants present at a candidate recirculation site, available toxicological literature should be reviewed by a qualified health professional (e.g., an industrial hygienist and/or an industrial toxicologist) to select a "pseudo-TLV." The absence of established exposure guidelines may suggest that a contaminant causes no adverse health effects, but is equally likely to mean that the contaminant's presence is not sufficiently widespread to have prompted specific consideration by OSHA, NIOSH, or the ACGIH. It is important to recognize that the employer is responsible for providing a safe and healthful work place, even where specific OSHA regulations do not exist.

In selecting breathing zone exposure levels for use as recirculation design criteria, consideration should be given to the reduction of toxicologically-suggested levels by a safety factor. Since the design of any new process or control system entails some degree of uncertainty, the design of a recirculation system to provide marginally acceptable exposure levels may result in inadequate control upon actual system operation. Applying a safety factor to the desired breathing zone concentration (designated by C_{BZ}^{D}) prior to recirculation system design will alleviate the possible adverse effects of uncertainties.

4.3.3 Multiple Contaminants

If more than one contaminant is present in work-place air, the toxicity of the mixture must be evaluated in addition to that of the individual contaminants. The ACGIH recommends that the effects of mixture components be considered as additive in the absence of contrary information, and that an "additive mixture TLV" be evaluated using the expression:

$$\frac{C_1}{T_1} + \frac{C_2}{T_2} \; . \; . \; . \; \frac{C_n}{T_n} \leq 1$$

where C_n indicates the observed concentration of a contaminant and T_n the corresponding TLV. Where the sum of these fractions exceeds 1, the "additive mixture TLV" is considered exceeded.

If a qualified health professional concludes that the components of a mixture exhibit independent effects, the established TLV of each component may be compared to its observed level without consideration of other factors.

Additionally, one must be concerned about potential "synergistic effects" among mixture components. Such consideration should always be given prior to recirculation of air from processes and worksites where multiple contaminants are present, and this evaluation must also be performed by a qualified health professional.

5. CLEANING THE EXHAUST

5.1 Introduction

The air cleaning equipment train is the heart of a recirculating exhaust system. Hence, the specific choice of air cleaning devices will generally have a major impact on the economic and health aspects of recirculation.

Extensive literature is devoted to discussions of cleaner mechanisms, their effectiveness for specific contaminants, and techniques for their selection. This report does not, therefore, attempt to provide detailed assistance for the selection or design of an air cleaning section for use in any particular situation. Instead, an overview is presented of important factors that a designer should consider.

5.2 Air Cleaner Mechanisms

There are several air cleaning mechanisms in common use, including the following major ones:

(a) filtration (cloth, felt, paper, etc.);

(b) absorption (scrubbers);

(c) adsorption (primarily activated charcoal);

(d) centrifuging (cyclones);

(e) electrostatic precipitation;

(f) incineration/combustion.

These mechanisms of cleaning differ from one another in several important characteristics, and these variations will guide decisions involving the appropriateness of various cleaner types for a particular exhaust stream.

5.3 Air Cleaner Characteristics

The important characteristics of air cleaners that must be taken into account in selecting one or more for a recirculating exhaust system are:

(a) the overall efficiency of the unit for cleaning contaminants present (see section 5.4);

(b) the ratings available, defined as the volume of air each unit is capable of cleaning;

(c) space requirements;

(d) specificity of cleaning ability: whether the cleaner is specific to a single contaminant or a group of contaminants. Groups might include particulates, organic vapors, etc.;

(e) failure modes: the ways in which cleaner performance can degenerate (see section 5.5);

(f) ease of detection of failure modes;

(g) reliability;

(h) ease of maintenance;

(i) pressure drop, and its variation (if any) with the extent of loading;

(j) method of disposal of the collected contaminant, and its possible impact on plant personnel, water pollution, etc.;

(k) modifications to air stream characteristics such as humidity, temperature and ozone content, as well as the possible chemical transformation of contaminants due to reaction; and

(l) cost, both capital and operating.

It is recommended that these factors be carefully reviewed with expert help before one or more air cleaners are selected for use. Factors relating to failure modes, reliability, ease of maintenance and air stream modification are of particular importance to the development of a recirculating system with satisfactory performance characteristics.

5.4 Air Cleaner Efficiency

Many definitions of air cleaner efficiency are in use. The only definition that is pertinent to the design of a recirculating exhaust system is what is commonly termed the weight efficiency, where:

$$\eta = 1 - \frac{\text{contaminant weight per unit air volume at outlet}}{\text{contaminant weight per unit air volume at inlet}} .$$

The user should be aware of two possible pitfalls in selecting air cleaners based on efficiency data provided by equipment manufacturers:

(a) efficiency data published by the manufacturer may not be expressed on a weight efficiency basis;

(b) data may need interpretation should particulates of interest vary in particle size distribution from those used to generate published efficiencies. In some instances, "fractional efficiencies" are available, describing weight efficiency as a function of particle size, and such data can be invaluable.

For the cleaning of particulates, it is worth noting that the efficiency of a cleaner depends strongly on the particle size distribution and the air flow velocity. The effect of particle size distribution is of particular significance when the exhaust contains very fine, respirable, toxic dusts. These may not be adequately cleaned, even though the overall efficiency is extremely high. An example of this effect is discussed in Appendix D.

When dealing with the cleaning of gases and vapors, the situation may be more complex. Few data are available on cleaner efficiency, and each gas or vapor generally has to be examined as a special case. At present, it appears that the only widely applicable technique which does not adversely affect the characteristics of the exhaust stream is adsorption on activated charcoal. The degree of adsorption, however, depends in a complex way on the molecular structure of the contaminant, and collection efficiencies cannot always be predicted in advance for unusual contaminants. In multi-contaminant situations, different rates of adsorption will be obtained for different contaminants. Also, it is possible for molecules of one contaminant to dislodge those of another from the adsorbent, leading to significant variations in efficiency over time.

Variations in air cleaner efficiency over time are extremely important in the design of recirculating systems. Such variations are well documented for cloth collectors, Figure 5.1 being an example. When data on efficiency variations are unavailable, it is recommended that a reduced efficiency be used in design calculations, and that the extent of reduction be determined by discussions with the manufacturer.

5.5 Cleaner Failure Modes

The design procedures outlined in this report require the identification of the failure modes of an air cleaner. A failure mode is any change in air cleaner function which results in an unacceptable level of one or more contaminants in the breathing zone of any employee.

For baghouses, for example, two important failure modes exist:

(a) excessive loading, leading to reduced air flow and thus to degeneration of exhaust hood performance; and

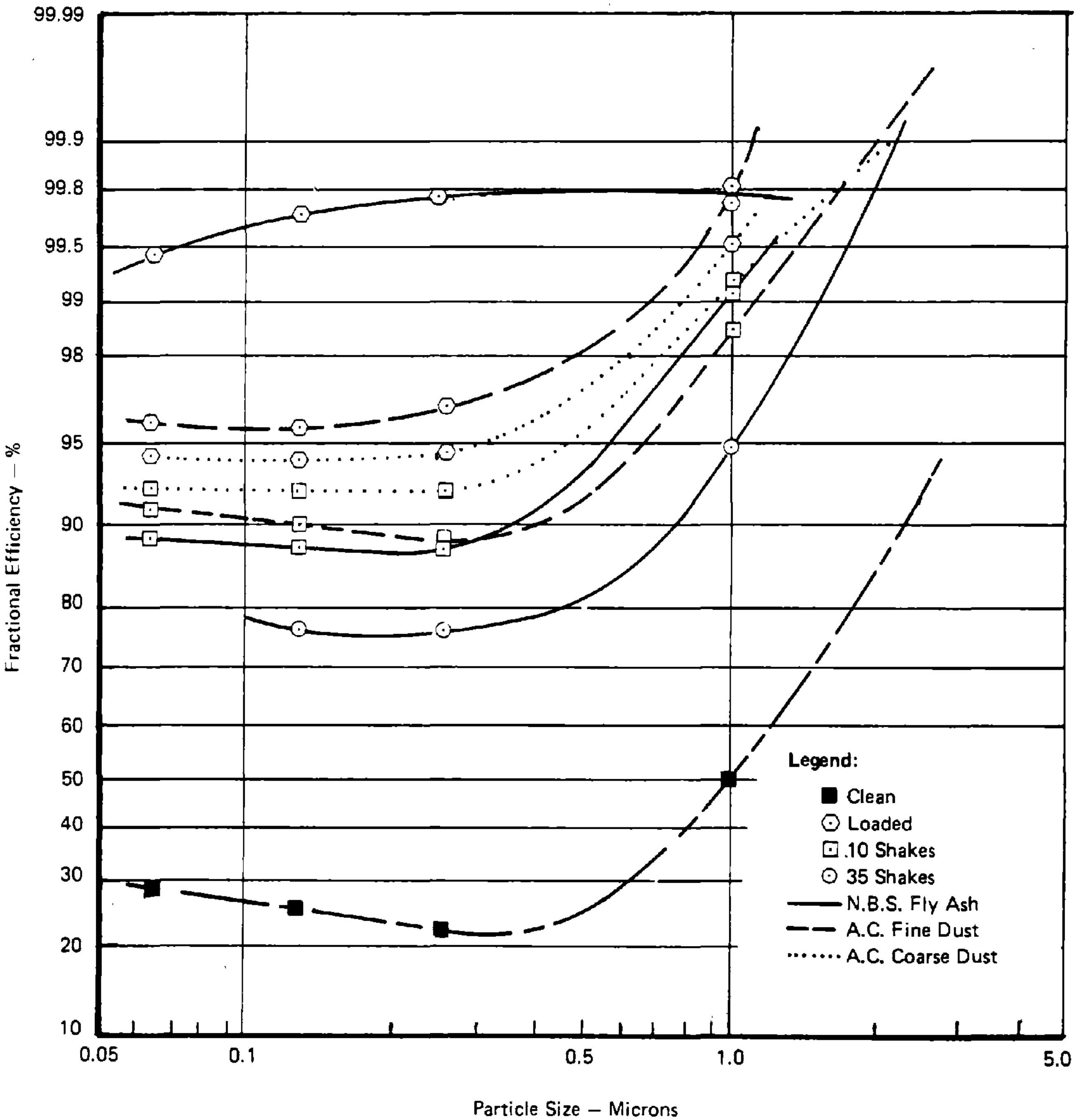
(b) bag rupture, leading to a reduced collection efficiency.

For electrostatic precipitators, the following major failure modes have been identified ("Electrostatic Precipitator Maintenance Survey," Journal of the Air Pollution Control Association, November 1976):

(a) discharge electrode failures;

(b) rapper or vibrator failure;

(c) collecting plate failure;



Source: C. M. Peterson and K.T. Whitby, "Fractional Efficiency Characteristics of Unit Type Collectors," ASHRAE Journal, May 1965

FIGURE 5.1 FRACTIONAL EFFICIENCY CURVES FOR STANDARD UNIT TYPE CLOTH COLLECTOR USING FINE, COARSE, AND NBS FLY ASH LOADING DUSTS

(d) dust removal system failure; and

(e) insulator failure.

For cyclones, failures are usually associated with plugging of the collection tubes, or with components such as fans, motors, bearings, and V-belts.

From the viewpoint of recirculating system design, it is of primary importance that the decrease in air cleaner efficiency with each failure mode be quantified. In the absence of such information, it is the recommendation of this report that the efficiency be taken to fall to zero for pertinent failure modes. Analyses presented in this report concerning the effects of air cleaner failure on breathing zone concentrations are based on such an assumption.

5.6 Cleaner Combinations

In some cases the designer must deal with the possibility of combining one or more air cleaners, of the same type or of different types, in series or in parallel. The pros and cons of the various possible combinations are the subject of continuing debate, and it is not believed that general recommendations are possible. The following observations may, however, be useful.

1. When several exhausts are to be cleaned and recirculated, significant safety benefits can be obtained by cleaning them in parallel, and then mixing the cleaned exhausts before reintroduction into the work space. If downtime of processes due to air cleaner malfunction, maintenance, and/or cycling characteristics is expensive, it may be economically feasible to utilize cleaners in parallel which are each capable of handling the entire loading. These would alternately be put into service.

2. When particulate and gaseous contaminants coexist in an exhaust, the use of series cleaners of different types is almost inevitable. An important issue is which phase should be cleaned first, since the first cleaner in the series will see both phases. This may or may not impair its performance.

3. Redundant identical cleaners in series help improve safety but may make little economic sense. More useful (with particulates) is pre-filtering to increase the life of the main filter, and the use of an absolute or other air filter after the main filter. The final filter can act both as a safeguard and as a monitoring device.

6. SURVEILLANCE AND RESPONSE STRATEGIES

6.1 Introduction

In a recirculating exhaust system, failure of the air cleaning device can result in buildup of the contaminant concentrations to which workers are exposed. This potential of exposing employees to hazardous levels of airborne contaminants mandates the inclusion of a surveillance sub-system as a key component of any recirculation system. The surveillance device to detect reduced ventilation system performance should be provided for from the initial stages of recirculation system design through its installation and operation.

Surveillance can follow two basic approaches: either the recirculation system itself may be monitored to detect significant changes in system performance (for example, a large increase in contaminant concentration within return air), or the work place environment may be monitored to detect changes in overall contaminant concentration levels. Following the detection of a recirculation system malfunction, corrective measures must be instituted. Failure responses may include the manual or automatic activation of by-pass dampers, shut down of a process, or evacuation of affected plant areas.

6.2 Surveillance Strategies

6.2.1 Definition of Alternatives

Surveillance sub-systems for use with an air recirculation system may be classified in several ways. This classification, and the subsequent selection of appropriate approaches for any specific situation, may be based upon the sub-system's location, principle of operation and/or degree of automation.

- Automatic vs. Manual

Recirculation surveillance sub-systems can be automatic or manual. An automatic surveillance sub-system operates without operator intervention, sampling or detecting continuously or on a continuous-batch cycle, and provides a "real-time" warning of potential system failure. By contrast, a manual system requires some degree of action by an operator, either in taking a sample, conducting an analysis, or reading and interpreting results. Because the characterization of a surveillance sub-system as automatic or manual is based upon the overall mode of action of detection, analysis, interpretation and alarm, it is possible to have an expensive, technologically sophisticated system such as an automated sampler-fed gas chromatograph classified as a manual system if (for example) the chromatograph output is so complex as to require periodic review and interpretation by an operator.

- Area vs. Duct

As previously noted, the recirculation surveillance sub-system can be designed as an area monitor, sensing the quality of work place air, or as a "duct-based" system, monitoring air near or far downstream of the air cleaner.

Area monitoring, while providing direct information on work place air quality, has several disadvantages. First, normal process fluctuations may cause variations in work place contaminant levels, and design of an area monitoring sub-system must consider this in specifying an alarm level. Second, detection of recirculation system failure by an area system may be slower than a duct system, since return air contaminant concentrations are diluted throughout the work place. Finally, installation of an area system can be expected to be more costly than a duct system, since numerous sample locations might be necessary.

The duct system offers the opportunity to measure an environment in which process fluctuations are dampened by the air cleaner, and only a single area location need be monitored to receive rapid detection of system failure. In considering duct systems, however, care must be exercised to evaluate the various ways in which air cleaner failure may be manifested. While such failure often results in a substantial increase in return air contaminant concentration, air cleaner failure may also cause reduced air flow without contamination of returned air (i.e., when the pressure drop builds up across a particulate filter). Thus, duct systems for recirculation monitoring must be designed to detect failure manifested by both return air contamination and reduced air flow rates in the return stream.

- Specific vs. Non-specific

Surveillance sub-systems may be designed to detect the specific contaminant(s) of interest within the work place, or may be designed to react to any change (beyond predetermined limits) in the composition of work place air.

The latter (non-specific) type of system will generally be less sophisticated than a chemical-specific detection system. Typical non-specific detection approaches might involve the measurement of changes in the electrical properties of the air, its thermal conductivity, total oxidizable hydrocarbon content, degree of light obscuration, or the pressure drop across a filter. Chemical-specific monitoring systems provide a greater amount of information to the user (and can help to diagnose the cause of failure), but may require sophisticated interpretation of results (particularly where more than one contaminant is present).

6.3 Selection of Appropriate Strategies

6.3.1 Compilation of Information

In order to select those monitoring strategies that are appropriate for any specific work place, several data items must be compiled. These are:

1. The identities of the contaminants present in the work place,
2. The acceptable level of each; and
3. Based upon the transient analysis methodology, the "critical response time" for the planned recirculation system (see Chapter 7 and Appendix F).

6.3.2 Strategy Selection

In each of the following paragraphs, a series of conditions will be described. The applicability of various surveillance strategies can be determined by evaluating the ability of a contemplated recirculation system to satisfy the listed conditions. One exception to these selection criteria should be noted: If the only contaminant present is a non-respriable, non-toxic (nuisance) dust, the only surveillance necessary may be visual checking of the return air for contamination.

- Automatic Systems

Automatic monitoring is always desirable since it reduces the possibility that human error or neglect may lead to unacceptable working conditions. However, automatic monitoring can entail large capital costs, may be prone to mechanical or electrical failure in industrial environments, and will not be available for all contaminants and mixtures of contaminants. Additionally, an automatic surveillance subsystem must satisfy the following operational requirement:

- The sum of the time interval between samples and the time needed to implement emergency response activities must be less than the critical response time (see Figure 6.1).

- Manual Systems

Because manual surveillance is prone to failure through human error, this strategy is recommended only where the following conditions are satisfied:

- The critical response time is greater than 4 hours; and

- The sum of the time interval between samples and the time needed to implement emergency response activities is less than the critical response time; or

- The only contaminants present are nuisance (non-toxic) materials; and

- If gases or vapors which are simple asphixiants are involved, a continuous combustible gas detector (if appropriate) and an oxygen deficiency monitor are employed.

If one of the above sets of conditions is satisfied and a manual surveillance system is to be utilized, the following minimum procedural steps should be planned:

1. A written surveillance protocol should be prepared and the responsibility for surveillance assigned to a specific employee.

2. All employees should be instructed regarding the impact of recirculation system failure and the planned responses to such failure (which may range from verifying the operation of an automatic bypass damper to plant evacuation).

3. Surveillance observations should be recorded in a log, and the log should be regularly checked by plant management and/or safety personnel.

- <u>Area Systems</u>

For an area surveillance system to be appropriate, the following conditions should be satisfied:

- Contaminant level fluctuations based upon normal process operations should be well characterized quantitatively; and

- Anticipated process-related contaminant level peaks should be below the level (defined in the transient analysis) that is reached at the critical detection time (see Figure 6.1); and

- The area sensor should include those points that (based upon smoke-tube or tracer-gas air-flow studies) are expected to be affected first when the recirculation system fails; or

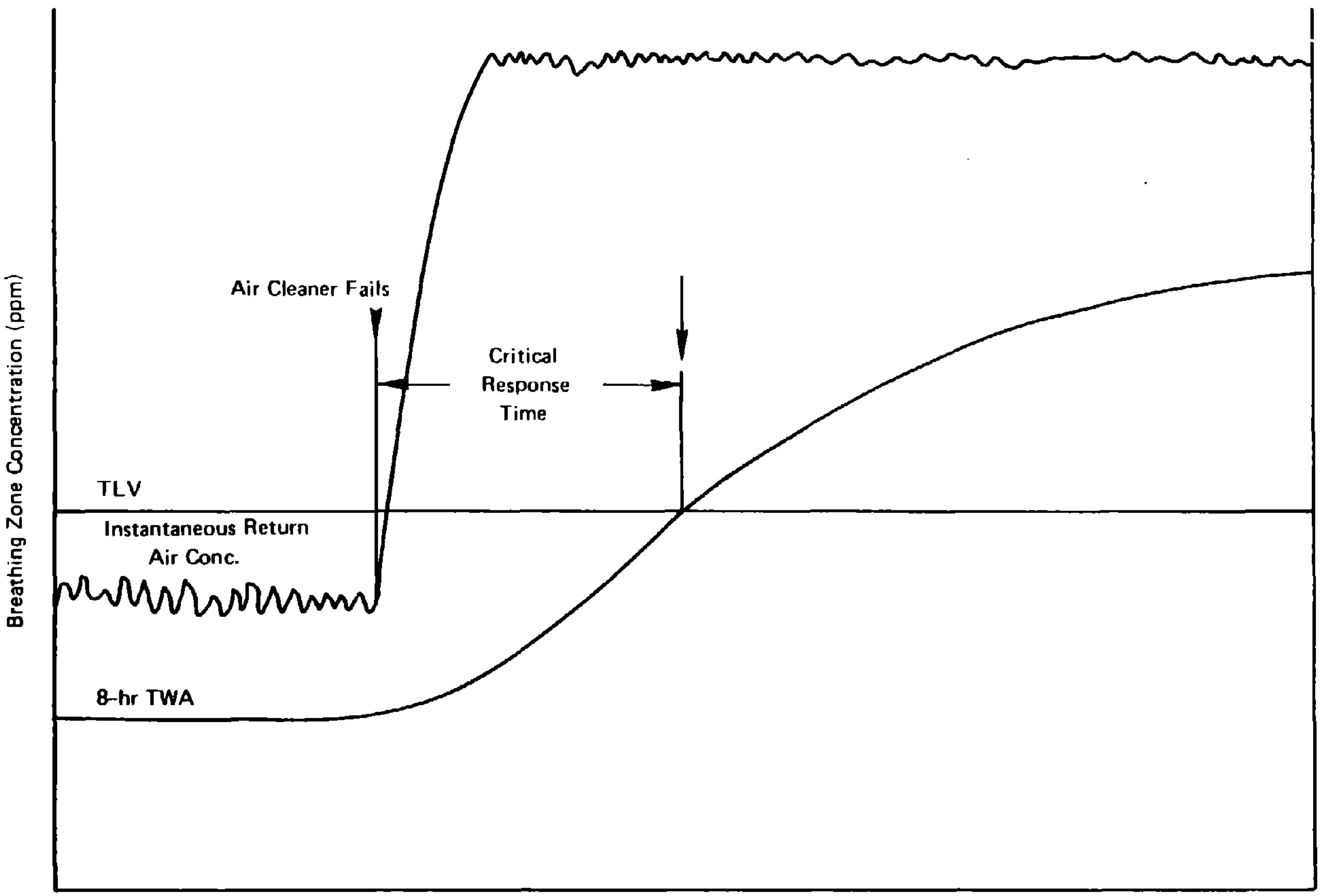


FIGURE 6.1 SAMPLE RESULTS OF TRANSIENT ANALYSIS

- The only contaminants present are nuisance (non-toxic) substances.

- Duct Systems

A duct surveillance system is recommended when:

- All types of air cleaner failure can be detected, i.e., reduced air flow as well as increased contamination of return air.

- Contaminant-Specific Systems

Contaminant-specific surveillance sub-systems may be employed in an installation where:

- The identities of all contaminants are known; and

- Each contaminant whose acceptable level may be exceeded is monitored; and

- The violation of any contaminant's acceptable level, or the acceptable level of the mixture present, triggers an alarm.

- Non-Specific Systems

The following conditions should be satisfied by any non-specific surveillance system:

- The air characteristic measured must be known to change with an increase in the concentration of any contaminant, and combination of contaminants, present; and

- The trigger level selected should be tested to ensure that recirculation system failures rapidly trigger an alarm.

- Summary of Surveillance Strategy Selection

Each potential surveillance system, when classified according to its automation, location, and principle of operation, can be placed into one of eight categories. Based upon the guidelines presented, the applicability of each category to any contemplated recirculation system can be judged:

Automation	Location	Priciple of Operation	Acceptable	Not Acceptable
Automatic	Duct	Specific	________	________
		Non-Specific	________	________
	Area	Specific	________	________
		Non-Specific	________	________
Manual	Duct	Specific	________	________
		Non-Specific	________	________
	Area	Specific	________	________
		Non-Specific	________	________

For any contemplated recirculation system, the choice among acceptable surveillance strategies may be made based upon convenience, equipment availability, and cost.

6.4 Selecting a Surveillance Sub-System

The evaluation of failure response consequences and surveillance guidelines presented in Appendix F and above provide a basic set of performance requirements for a recirculation surveillance sub-system. In designing a recirculation system, it may be necessary to apply these requirements to the selection of specific devices.

The first step in selecting surveillance sub-system hardware is to consider the physical state of the contaminants present, i.e, are there particulates, gases and vapors, or a mixture of both. The presence of a multiple-state contaminant mixture will generally require that at least two detection devices are provided in series. Where a single phase mixture is present, it will sometimes be possible to utilize a single detector for all components of the mixture.

Next, candidate surveillance hardware must be identified and the technical capabilities of each device defined. In gathering this information, sources that may be explored include monitor equipment manufacturers' literature and industrial hygiene and air pollution engineering technical literature. It should be recognized that monitoring hardware applicable to recirculation systems will often be designed for applications such as stack sampling, analytical chemistry, area sampling, leak detection, etc. Thus, the adaptation of monitoring hardware will sometimes be necessary. Table 6.1 lists examples of the various approaches that may be applied to recirculation monitoring.

TABLE 6.1

EXAMPLES OF MONITORING APPROACHES

Gases & Vapors

Approach	Characteristics
Gas Chromatography	Chemical specific; highly sensitive; relatively costly; interpretation of output complex for multi-contaminant systems; batch analytical technique with slight lag in output
Photo-ionization	Non-specific; fairly sensitive; moderately costly; continuous sampling with rapid output
Catalytic oxidation	Non-specific; employed in many combustible gas indicators; continuous or batch sampling with rapid output; not highly sensitive
Photometry (infrared, ultraviolet or visible light)	Chemical-specific; good sensitivity; use for continuous monitoring of multi-contaminant stream is difficult; rapid response
Metal Oxide Semiconductor	Non-specific; fairly sensitive; inexpensive; continuous sampling with rapid output

Particulates

Pressure Drop Across Filter	Non-specific; oblivious to particles that are small enough to pass through filter; continuous sampling with immediate output
Light Scattering	Non-specific; fairly sensitive; continuous sampling with rapid output

Approach	
Atomic Absorption Spectrophotometry	Chemical specific; batch system of analysis; high sensitivity; interpretation of output complex; generally utilized for manual analyses in a laboratory setting

When data on candidate surveillance systems has been compiled, each system should be classified vis a vis the procedure described in Section 6.3. Those systems which fall into categories considered unsuitable for the specific recirculation site of interest should be eliminated from further consideration. The remaining candidate surveillance systems should be evaluated to ascertain their desireability for the application envisioned.

Three factors which should be considered in selecting among candidate surveillance systems are reliability, ease of maintenance, and system cost. Since the surveillance sub-system is an integral part of a recirculation program, monitoring equipment down-time will necessitate a halt in recirculation; thus, monitor reliability and maintainability are extremely important. Data on monitor reliability in an industrial recirculation environment is not readily available at this time, and judgments based upon previous experience with monitoring equipment and relative system complexity will be required. The ease with which monitoring systems can be maintained depends upon both the hardware design and the technical capabilities of the user.

Surveillance system cost should be examined on an overall life-cycle basis, whereby the capital and operating costs of a system are projected over the expected life of the system. Some surveillance systems may require large capital investment but entail low operating costs (for utilities, maintenance and repair labor, replacement parts, etc.), while other surveillance systems may be inexpensive initially but require higher recurring costs.

In selecting a surveillance sub-system from among acceptable candidates, the final decision will rest upon the user's perception of the value of system features versus their costs.

6.5 Response to System Failures

Any recirculation system should be designed with consideration given to the time when failure may occur. Through the design and installation of system hardware as well as the preparation of work procedures and the training of employees, a definite failure response plan should be considered.

As Figure 6.1 indicates, the speed with which failure responses can be implemented will partially specify the performance requirements of the monitoring system, and the inverse is also true. Thus, an emergency response plan should be prepared during the design of a recirculation system. Several alternatives for emergency response are discussed below.

6.5.1 Exhaust Air By-Pass

The failure of a recirculation system air cleaner can be temporarily circumvented by utilizing a by-pass damper to exhaust contaminated air out of the work place. (Limitations on this response posed by local environmental regulations should be considered.)

By-pass dampers can be either automatic (operated upon detection of failure by an automated surveillance sub-system) or manual (operated by employees when an alarm sounds). Automatic by-pass dampers have two major advantages: dependence upon human response is eliminated, and response time is essentially zero (maximizing the acceptable sampling interval in the surveillance sub-system). The use of by-pass dampers permits continued process operation during recirculation system failures; however, by-passing air from an area that has a pressure balanced recirculation system will result in a negative pressure within the area.

6.5.2 Process Shut-Down and Evacuation

Should by-pass dampers not be employed, recirculation system failure will force the shut-down of operations and/or (depending upon the severity of existing exposure hazards) evacuation of work places. The implications of these actions upon specific processes should be carefully considered during recirculation system design.

7. DESIGNING A RECIRCULATION SYSTEM

7.1 Introduction

Chapter 2 of this report listed and briefly discussed the various steps involved in the implementation of a recirculating exhaust system. Chapters 3, 4, 5 and 6 then discussed an initial feasibility assessment, the characteristics of contaminants which must be known, the selection of air cleaning devices, and the selection of methods or equipment for detecting reduced system performance. Application of the information provided in these chapters allows completion of a number of the initial steps listed in Chapter 2.

The objective of this chapter is to provide qualitative and quantitative guidance in performing the remaining tasks enumerated in Chapter 2. For completeness, however, the chapter covers all steps beyond the initial feasibility assessment.

7.2 Contaminant Characteristics

Knowledge of the existing or expected contaminant concentrations in breathing zone air, in air intended to be recirculated, and even in fresh make-up air, is one prerequisite to understanding the effect of recirculation upon the working environment. Besides concentration levels for each contaminant, one must also have details of the toxic effects of each substance, their permissible exposure limits, and their physical and chemical properties which might affect the design and selection of the overall system configuration.

Chapter 3 of the report, as noted above, is devoted to a discussion of the various important characteristics of individual contaminants. Section 2 of Appendix A discusses the locations in a plant at which concentration levels and contaminant characteristics must be evaluated. The need for specific data will become apparent as this chapter delves into quantitative design techniques.

7.3 Work Place, Process, and Ventilation System Characteristics

The procedures presented in this report for the design of recirculation systems involve a prediction of the incremental effects of recirculation compared to a conventional ventilation system. (Such a procedure is necessary because of the inadequacy of practical experience with the behavior of recirculation systems.) Consequently, the characteristics of the work place, process and ventilation system prior to recirculation are essential inputs to the design of a recirculation system. When recirculation is not being retrofitted, there is no existing conventional system prior to recirculation. It is then appropriate to substitute the expected characteristics of a commonly used conventional system that would be used in such a situation.

A specific chapter of the report is not devoted to the determination of these data, but their definition, and the methodology for their evaluation will emerge from the following paragraphs and the information presented in Appendix A.

Essentially, the information requirements consist of the volume rates of all inflow and outflow air streams, definition of the locations of all exhaust hoods in relation to work stations, definition of the seasonal and other factors which might affect the performance of the recirculation system after it is operating, and an understanding of how the return airflow from the recirculation may interact with or modify existing airflow patterns.

7.4 Air Cleaning Equipment

Knowledge of contaminant concentrations and characteristics, together with flow volume data for streams intended to be recirculated, allows one to define the basic types of air cleaning equipment that may be used. Chapter 5 discusses various issues involved in cleaner selection, while Chapter 2 notes that an awareness of all available types of equipment and their associated costs and operating characteristics is necessary to the overall design procedure.

7.5 Surveillance Equipment or Methods

One must identify the methods and equipment available for detecting any variation in system performance which may result in an unhealthy working environment. The topic is addressed by Chapter 6, and requires an understanding of the costs and operating characteristics of the various alternatives.

7.6 Feasible System Configurations

7.6.1 Need for Definition

The quantitative techniques for specifying system performance allow one to assess the operating characteristics and costs associated with specific combinations of equipment and specific recirculating system configurations. In consequence, one must define which configurations are feasible for implementation before these techniques are applied. This requires the recognition that there may be more than one set of flow volumes, system configurations, or combinations of equipment which can provide an acceptable working environment. The differences between these various possible solutions will lie in costs and margins of safety.

7.6.2 Options

Given some quantitative indication of the flow volumes, temperatures, humidities, and contaminants in the various exhaust volumes leaving the plant area of interest, one can choose which streams are of interest for recirculation simply on a judgmental basis. Factors to be given consideration will be the volume rates of the streams, the perceived ease with which the streams can be cleaned, the number of contaminants and their phases, the availability of equipment for detecting reduced system performance, and several other factors discussed in this report. This should not be an overly difficult task, since it is usually the presence of one or more seemingly ideal streams for recirculation which leads to the decision to investigate the matter further.

Having identified these streams, one must now consider how various streams may be conbined before being put through the air cleaning equipment train. The number of options can be large; usually, however, the decision process will reduce to the questions:

- Should only certain general exhaust volumes be recirculated?
- Should only certain local exhaust volumes be recirculated?
- Should certain general and local exhaust streams be combined before entrance to a single air cleaning equipment train?
- Should general and local streams both be recirculated, but with separate air cleaning equipment trains?

Given a choice of exhaust air streams to be recirculated, the design of an air cleaning equipment train will need to be investigated. Such a train may contain one air cleaning device, or more than one device with units placed in series or parallel. The specific configurations for investigation must be chosen by the designer based upon the expected loading on the cleaners, the economics involved, and the relative safety aspects. Section 5.5 provides some guidance on the matter, but the pros and cons of the various possible combinations are the subject of continuing debate.

At this point, an important design option must be considered. Air leaving the cleaners may be returned directly to the work place, or first be mixed, in a duct, with any available amounts of fresh, make-up air entering the plant area. The practice of pre-mixing recirculated air with fresh air has certain advantages in that the contaminant levels in air from the cleaners are further diluted. The practicality of this design option, however, is dependent upon the physical layout of existing ducting and make-up air supply units.

The distribution of return air within the work place determines its influence upon breathing zone concentrations of contaminants. Available options include distribution to a number of separate locations throughout the plant area, to one specific location, or to a plant area physically separated from the area where the recirculated air originated. Additionally, one may consider use of return air in well-designed push-pull systems.

7.7 Design Optimization

7.7.1 The General Approach

Based upon knowledge of the identities and characteristics of contaminants, one first specifies for each contaminant some level of concentration which should not be exceeded in the breathing zone of any employee. These levels are designated by the symbol C^D_{BZ} (desired breathing zone concentration). Mandatory limits and other guidelines are discussed in Chapter 4, and a further discussion of issues involved is provided in Section 2 of Appendix A. However, a summary of certain factors to be considered is also presented in this chapter.

Given the desired breathing zone concentration for each contaminant, knowledge of various concentrations and flow volumes in the plant area, one or more overall air cleaning equipment train efficiencies, and one or more feasible system configurations, one may now apply the equations for the various system design models presented in this report. Application of these models, when all parameters are specified, provides estimates of the concentration levels of contaminants directly after the air cleaning equipment train (parameter C_D), returning to the working environment (parameter C_R), and in specific employee work locations (parameter C_{BZ}). Additionally, given a user-specified cost function, an estimate of overall system cost is provided (parameter $\$_T$) on an annualized basis.

The individual sets of applicable equations, called "models" in this report, mostly include parameters for which values can be supplied from consideration of existing or expected plant conditions when air is not being recirculated. Some parameters, however, and these are typically flow volumes, are independent design variables; in the sense that their values can be "adjusted" until the models indicate that the system will provide desired breathing zone concentrations at minimum cost. Hence, the design procedure for each feasible system configuration is a constrained, usually iterative, optimization process. The primary constraints are that desired breathing zone concentrations should not be exceeded and that various flow balances must be maintained.

Once the optimization of each feasible system configuration has been accomplished, the designer will have knowledge of all flow volumes and concentration levels to be expected after the implementation of recirculation. Also known will be the associated cost of implementation. With this information, he can then proceed with the remaining steps outlined in Chapter 2.

7.7.2 The Desired Breathing Zone Concentration

One of the most important parameters in the design of a recirculating exhaust system is the desired breathing zone concentration, C^D_{BZ}. The choice of a value for this parameter is complex, and must always be made by a qualified health professional. The report makes no recommendations regarding this choice, but the following is a brief summary of some of the considerations that should be recognized.

Time-weighted average limits based on toxicological considerations constitute an absolute limit for C_{BZ}^{D}. Setting C_{BZ}^{D} equal to a permissible exposure limit, however, is generally unwise with recirculation systems, since unexpected process fluctuations or a small decrease in air cleaner efficiency can cause the permissible exposure limit to be violated. In general, a safety margin between the permissible limit and C_{BZ}^{D} is desirable, and this margin should increase as system performance uncertainties increase, or when dealing with contaminants that have acute toxic effects.

Another important consideration in choosing a value for C_{BZ}^{D} is the response time available after an air cleaner failure before hazardous conditions arise. If C_{BZ}^{D} is set equal to a permissible limit, for example, the response time will be zero, and continuous monitoring as well as an automated bypass will be indicated. Subsequent sections of this report discuss these issues.

In multi-contaminant situations, a value of C_{BZ}^{D} must be chosen for each contaminant. The several values will depend on whether the toxic effects of the contaminants are independent, additive or synergistic.

7.7.3 General Description of Models

The models presented in this report are based on the assumption of steady-state conditions. That is, it is assumed that all parameters can be represented by constant values or by values which represent time-weighted-average conditions. The effects of this assumption and others on results are fully discussed in Section 5 of Appendix A.

Each model consists of four basic equations. These define: (i) the concentration in air leaving the air cleaning equipment train (parameter C_D); (ii) the return air concentration (parameter C_R); (iii) the expected breathing zone concentration (parameter C_{BZ}); and (iv) the estimated annualized cost for the system (parameter $\$_T$). Associated equations define flow balances and the individual volume rates of all air streams.

7.7.4 Model Illustration

To illustrate the concepts upon which all models are based, the equations for a simple case will be developed. The specific models discussed in Appendices A, B and C are considerably more flexible for application.

Figure 7.1 illustrates a plant area before recirculation. The area contains a local exhaust system, and a general mechanical exhaust system. The various C's on the diagram represent time-weighted-average concentrations and are differentiated by various sub-and super-scripts. Flow volumes are similarly designated by Q's. For this example, any air flows due to natural ventilation or infiltration are disregarded, and it is presumed that values for all parameters shown on the figure are available.

Figure 7.2 shows two alternative configurations for the recirculation of the local exhaust stream, using a unit collector of overall efficiency η for the single contaminant generated by the process. The upper diagram represents the design option of allowing the recirculated air stream to directly enter the room after cleaning. The lower one demonstrates the option of combining the recirculated air with the fresh make-up air supply. In both cases, the amount of tempered make-up air required for the room is reduced by the quantity Q_L^o by implementing recirculation.

The first step in model development is the definition of the concentration and volume for the stream entering the unit collector. The volume, assuming the hood had been properly designed, can be taken to be the same before and after recirculation. It is important to note that this volume represents the flow through one hood in this example, but could also represent the combined flow volume for a number of hoods entering a main duct to the air cleaner.

The average concentration in the local exhaust duct after recirculation may not be the same as the average concentration before recirculation. Thus, it is designated in Figure 7.2 by C_E. Like the local exhaust volume, it can represent the concentration for a single exhaust stream, or the average for a number of combined streams.

The contaminant concentration in the air leaving the air cleaner (whose efficiency is η) will obviously be:

$$C_D = (1 - \eta)\ C_E.$$

For the configuration without pre-mixing, this concentration will equal the return air concentration C_R. For the configuration with pre-mixing, it is necessary to appropriately combine the two streams and:

$$C_R = \frac{C_D Q_L^o + C_{MU} Q_G^o}{Q_L^o + Q_G^o}$$

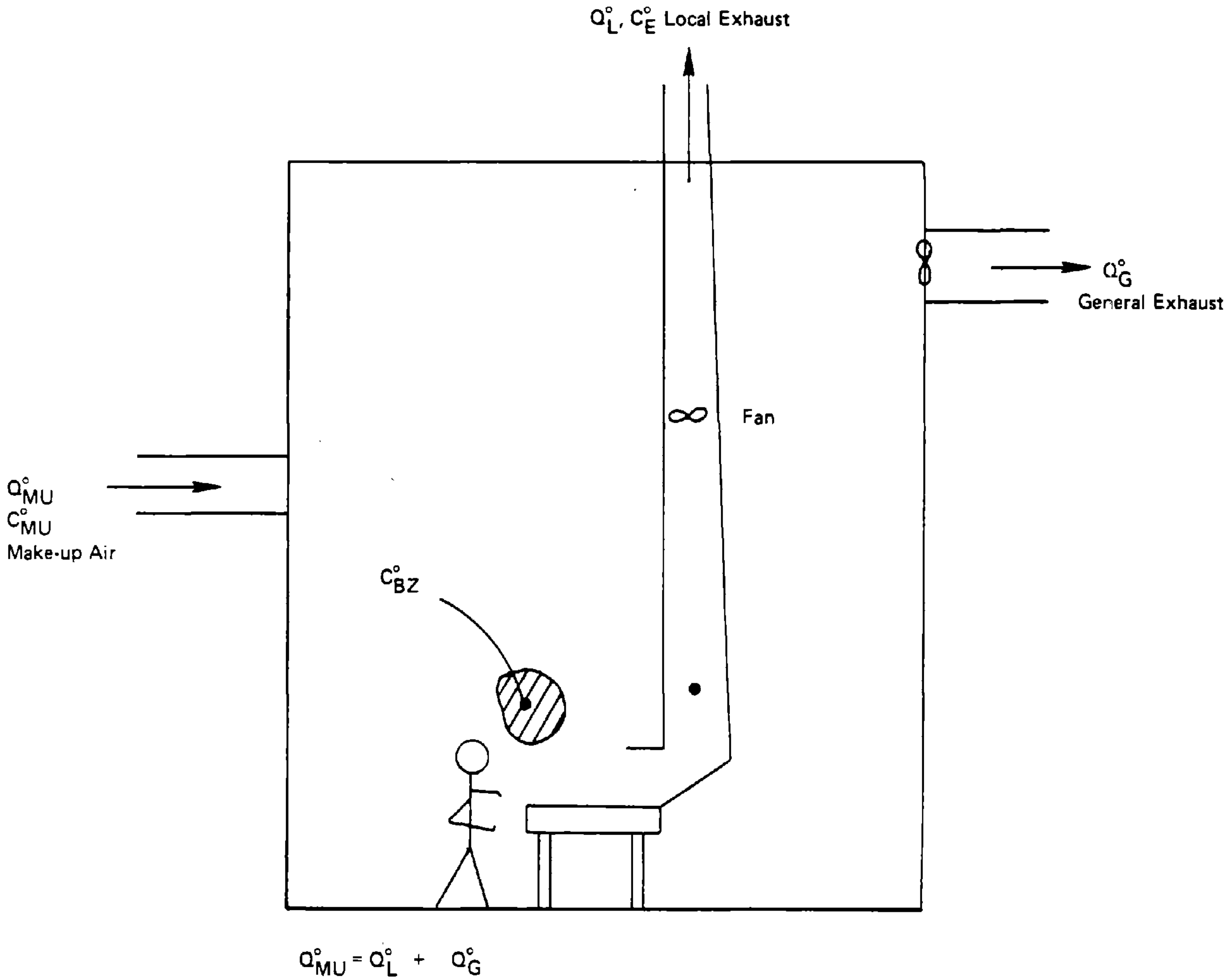
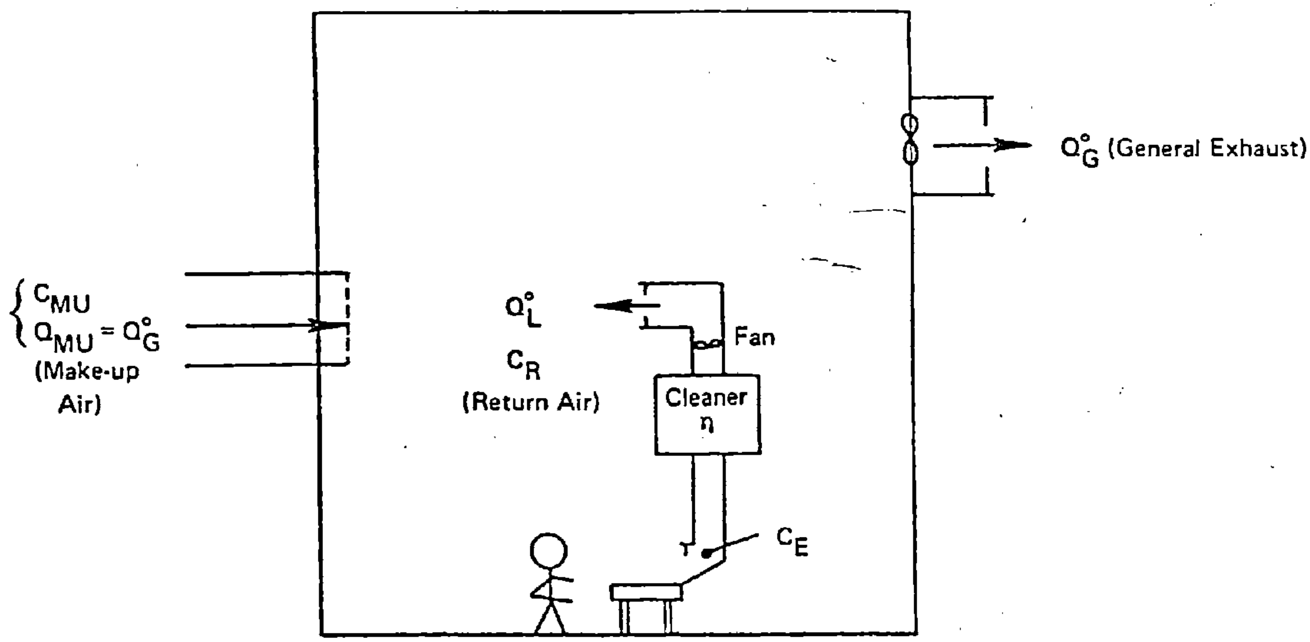
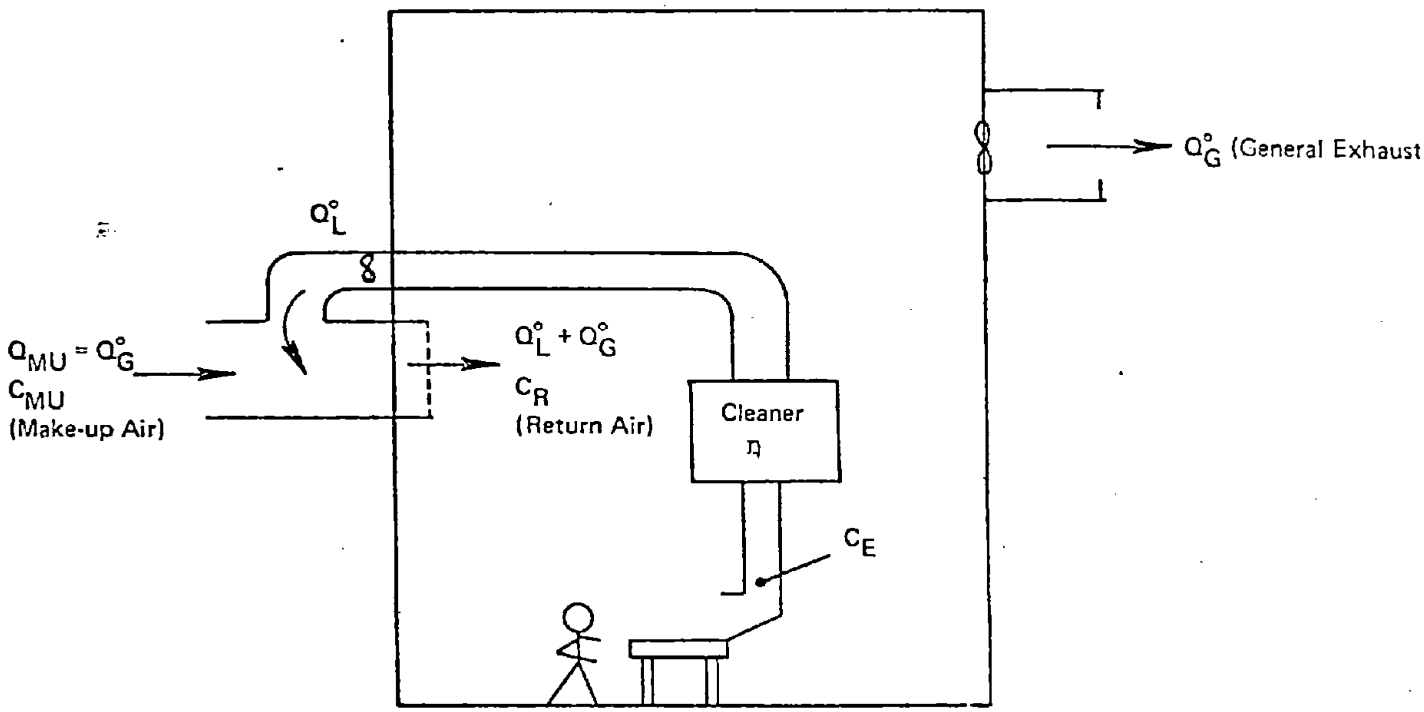


FIGURE 7.1 PROCESS BEFORE RECIRCULATION OF LOCAL EXHAUST



(a) Recirculation Without Pre-mixing



(b) Recirculation With Pre-mixing

FIGURE 7.2 TWO ALTERNATIVE CONFIGURATIONS FOR RECIRCULATION OF THE LOCAL EXHAUST FOR THE PROCESS SHOWN IN FIGURE 7.1.

An obvious unknown at this point is the value for C_E. Although one may assume that C_E equals the concentration C_E^o before recirculation, the assumption may not be valid. The air entering the local exhaust hood after recirculation is at least in part comprised of return air, which may or not be more contaminated than the make-up air that originally supplied the hood.

The introduction of a return air "contribution factor" for the local exhaust hood allows estimation of the value for C_E based on the value of C_E^o and the contaminant concentrations in the return air stream and the make-up air (if any). This factor, designated by k_R, is defined as the physical fraction of the local exhaust volume which originates in the return air stream. A detailed discussion of the significance of the parameter k_R, and of techniques for estimating its value, is presented in Appendix A. It can be estimated from consideration of the relative volumes of fresh air and return air entering the plant area, and its use results in the expression:

$$C_E = C_E^o + k_R (C_R - C_{MU}).$$

Insertion of this expression into the relationship for C_D, and some algebraic manipulation, results in the following expression for the system configuration without pre-mixing.

$$C_D = C_R = \frac{(1 - \eta) [C_E^o - k_R C_{MU}]}{1 - k_R (1 - \eta)}$$

For the case with pre-mixing, the appropriate expression for C_R is:

$$C_R = \frac{(1 - \eta) \frac{Q_L^o}{Q_{MU}^o} [C_E^o - k_R C_{MU}] + C_{MU} \frac{Q_G^o}{Q_{MU}^o}}{1 - (1 - \eta) \frac{Q_L^o}{Q^o_{MU}} k_R}$$

These equations are similar to those obtained for all models described in this report. Perceived differences are only due to the addition of various streams to the basic system configurations being considered. Each parameter used by the models is fully discussed in Section 3 of Appendix A.

7.7.5 The Breathing Zone Equations

Knowledge of contaminant concentrations in return air streams is insufficient by itself for overall design purposes. Methods for assessing the effect of the return air stream upon breathing zone concentrations are also needed. This need has led to the development of two equations named "The Breathing Zone Equations". One of these is utilized to relate return air concentrations to breathing zone levels for employees not stationed in strong flow fields induced by local exhaust hoods (such as a walk-in booth). The other is for employees who may be stationed in such fields.

The breathing zone equations incorporate a number of novel features and assumptions which provide the key to their understanding. Basic among these are the concepts that:

- Return air (at concentration C_R) will physically replace some known amount of fresh make-up air (at concentration C_{MU}) that entered the plant area before recirculation; that

- Increases in the total ventilation rate due to the implementation of recirculation will proportionately lower breathing zone concentrations in general plant areas due to the dilution effect; that

- Some areas in a plant, such as a work station in a large walk-in booth, will not directly experience the dilutory effect of modified total ventilation rates (due to changes in the general mechanical ventilation rate); and that

- The physical fraction of breathing zone air which originates in the return air stream, can be measured with a tracer gas technique or conservatively estimated.

The equations themselves are:

For employees <u>not in</u> strong flow fields:

$$C_{BZ} = \frac{Q_T^o}{Q_T}\left(C_{BZG}^o - C_{MU}\right) + k_{BZ}C_R + \left(1 - k_{BZ}\right) C_{MU}$$

For employees <u>in</u> strong flow fields:

$$C_{BZ} = C^{o}_{BZL} + k_{BZ}\left(C_R - C_{MU}\right)$$

where:

C_{BZ} is the TWA breathing zone concentration for some particular employee in the plant;

Q^{o}_{T} is the pre-recirculation total ventilation rate in the plant;

Q_T is the post-recirculation total ventilation rate in the plant;

C^{o}_{BZG} is the TWA breathing zone concentration in general plant areas not under the direct influence of strong flow fields induced by local exhaust hoods;

C_{MU} is the TWA contaminant concentration, if any, in fresh make-up air;

C^{o}_{BZL} is the TWA contaminant concentration in plant areas which <u>are under</u> the direct influence of strong flow fields induced by local exhaust hoods;

C_R is the contaminant concentration in return air streams, and

k_{BZ} is the actual physical fraction of breathing zone air which comes directly from the return air stream.

A detailed discussion of the rationale underlying each of these concepts, and the manner in which the equations were formulated, is presented in Section 4 of Appendix A. Nevertheless, a few words concerning the newly introduced parameter k_{BZ} are in order.

The parameter k_{BZ} is a contribution factor similar to the factor k_R previously discussed. It represents the physical fraction of breathing zone air that originates in the return air stream. Introduction of this type of factor was considered to provide certain advantages which the commonly utilized mixing factor did not. These advantages are that k_{BZ} can only have a value ranging from zero to one, that it can be determined or estimated from simple tracer gas studies in many existing plants, and that it may be adequately estimated in many plants through an examination of the volume rates of fresh make-up air and return air entering the plant, and the locations of employees in relation to inlet points.

7.7.6 Cost Functions

The last type of relationship which must be defined for system design and optimization purposes is one which relates the cost of the recirculation system to the volumes of air handled and other parameters of interest. It is beyond the scope of this report to address this question of economics in any great detail, but a simple cost function was developed for use in the various examples shown in Appendix A, D and E. In practice, the factors which must be included in a complete economic analysis are:

Energy Costs

(i) reduction in make-up air volume

(ii) degree-days for the plant location

(iii) type of heating system (oil, gas/direct, gas/indirect, etc.)

(iv) cost of fuel

(v) availability of fuel

Capital Costs

(i) cost of new air cleaner (if any; an adequate air cleaner may already be installed to meet air quality regulations)

(ii) cost of additional ductwork

(iii) cost of a monitoring subsystem

(iv) cost of a by-pass

(v) design costs

(vi) installation and performance testing costs

Operating Costs

(i) air cleaner upkeep (bag replacement, etc.)

(ii) air cleaner power requirements

(iii) inspection and maintenance of the system

Intangible Costs or Benefits

(i) lost time; on the one hand due to non-availability of energy and, on the other, due to recirculating system failure.

(ii) air cleaner space requirements, if any.

7.8 System Failure Analyses for Feasible Configurations

7.8.1 The Necessity of System Performance Monitoring

The central safety issue in the use of recirculated exhausts is: what are the consequences of failure of the recirculating system, and how can these consequences be kept within acceptable limits?

It is the basic premise of this study that regardless of how reliable a recirculating system is designed to be, it may eventually fail, and the consequences of failure may be unacceptable from an occupational health standpoint. Therefore, it is imperative that a surveillance subsystem be installed that detects system failures and allows the consequences of failure to be mitigated before concentrations become excessive.

In this perspective, the question of how reliable the air cleaner should be is fundamentally a question of economics. The only reliabilities that are important from a safety standpoint are those of the failure monitoring system and the response to failure. These reliabilities can be kept at a high level as much by proper training, inspection and maintenance as by design sophistication and redundancy. If the reliabilities of the monitoring system and the response to failure are kept high (by whatever means), then the likelihood of a failure of the overall system to protect employees' health is extremely small. The techniques presented here for determining the characteristics required in a monitoring system and a response strategy are based on conducting a failure analysis for each of the chosen feasible system configurations. These techniques are outlined in what follows:

7.8.2 System Failure Modess

A recirculating system has three principal modes of failure:

a. air flow is reduced, either due to a fan failure, or an increase in back-pressure due to cleaner or duct loading, or leaks in the system;

b. air cleaner efficiency is reduced or becomes zero, due to a partial or complete failure of the air cleaner.

c. uncleaned exhaust is discharged, due to a leak in a duct where the pressure is positive and the exhaust uncleaned.

The third failure mode can be avoided by following the simple rule that the fan is always placed after the air cleaner. This ensures that those portions of the ductwork that carry uncleaned exhaust are always at a negative pressure relative to the work space.

The effect of reduced air flow is to decrease the control velocity at the hood, possibly to the point where contaminant capture is reduced and the contaminant concentration level in the area around the process dangerously increases. Failure modes leading to reduced exhaust flows are no different for a recirculating system, however, than for a conventional, non-recirculating system. The consequences are also identical. This report presumes that adequate monitoring techniques (e.g., periodic velocity and pressure checks) and response strategies already exist for this class of failures, and that they are equally applicable after exhaust recirculation is instituted. For this reason, only air cleaner failures will be considered in the following discussion.

The effect of a failure of the air cleaner or degeneration of its performance is to introduce uncleaned or inadequately cleaned air into the work space, eventually leading to unacceptable breathing zone concentrations.

7.8.3 Air Cleaner Failures

A failure of the air cleaner is an event that results in its cleaning efficiency being significantly reduced from the nominal value.

For most air cleaner types, failure will result in virtually zero efficiency within a short period of time. These failures may be termed "complete breakthrough." For some types of air cleaner, however, partial breakthrough is possible. An example is the rupture of one bag in a baghouse. Such a failure may result in a substantial decrease in cleaner efficiency, but not necessarily in zero efficiency.

Despite the possibility of partial breakthrough, however, it is recommended that surveillance and response strategies be based on the assumption of complete breakthrough, i.e., an instantaneous reduction of the efficiency of the air cleaner to zero. Even in cases where partial breakthrough is the dominant failure mode, it is overly optimistic to assume that complete breakthrough may never occur.

7.8.4 Transients in the Breathing Zone Due to Air Cleaner

After an air cleaner failure, breathing zone concentrations will begin to increase, since the return air concentration has increased. Important considerations are the extent to which breathing zone concentrations increase, and the rate at which they increase. The procedures for analyzing these transients are illustrated by a simple example in what follows. Generalizations required by more complex configurations follow relatively easily.

With the air cleaner operating normally, the analyses of sections 7.7 suggest, for the system of Figure 7.2(a), that the breathing zone concentration will be:

$$C_{BZ} = C^{\circ}_{BZ} + k_{BZ}(C_R - C_{MU})$$

$$= C^{\circ}_{BZ} + k_{BZ} \left\{ \frac{C^{\circ}_E (1-\eta) - C_{MU}}{1 - k_R(1-\eta)} \right\}$$

for an employee in the vicinity of a local exhaust hood.

To simplify the following discussion, it is assumed that $C_{MU} = 0$ (no contamination of fresh make-up air), leading to:

$$C_{BZ} = C^{\circ}_{BZ} + C^{\circ}_E \frac{k_{BZ}(1-\eta)}{1 - k_R(1-\eta)} .$$

Now assume that at some instant (designated as t = 0) the air cleaner fails in the complete breakthrough mode. Thus, for $t > 0$, the air cleaner efficiency is $\eta = 0$. If nothing is done about the cleaner failure, the breathing zone concentration will eventually reach a new, and higher, steady-state value than that shown in the expression above. The new steady-state value is, in fact, obtained by setting $\eta = 0$ in the preceding expression:

$$C^{FS}_{BZ} = C^{\circ}_{BZ} + C^{\circ}_E \frac{k_{BZ}}{1-k_R}$$

The superscript F on C_{BZ} denotes its value after cleaner failures. The superscript S indicates that this is the steady-state concentration after failure.

This equation is illuminating. It suggests (for the ventilation system of Figure 7.2(a)) that if $k_R = 1.0$, (i.e., the local exhaust is supplied entirely by return air), then the post-failure breathing zone concentration will rise indefinitely, unless $k_{BZ} = 0$. It is unlikely that $k_{BZ} = 0$, since this requires that no employee's breathing zone ever contains any return air.

The more pressing question, however, is how quickly does the breathing zone concentration increase from the value C_{BZ} to an undesirable level?

Unfortunately, there is no general answer to this question. What can be stated, at best, is that the breathing zone concentration at time t will be given by an expression of the form:

$$C^F_{BZ}(t) = C_{BZ} + (C^{FS}_{BZ} - C_{BZ})\ [1-e^{-(\frac{t}{t_o})}]$$

where t_o is an unknown "rise time". The value of t_o depends on many factors, including the location of the breathing zone of interest with respect to the return air duct.

For example, if an employee were to stand in front of the return air duct, then $t_o \simeq 0$, and he would experience the high concentration almost immediately. (In point of fact, the immediate concentration seen by such an employee for the simple configuration being analyzed is the initial exhaust duct concentration C_E. From then on, he would experience a more gradual rise to the steady-state value C^{FS}_{BZ}. Since, in most instances, an exposure to the concentration C_E will be inadvisable, this refinement matters little.)

For an employee some distance away from the return air duct, the rise time "t_o" may be large. In this case, the rate of increase in the breathing zone concentration to its final value is more gradual.

It is important to note that for different employees, not only is the rise time "t_o" different, but also the final breathing zone concentration C^{FS}_{BZ}. For different employees, both C^o_{BZ} and k_{BZ} are different. Thus various employees may experience one or another of the various breathing zone concentration transients sketched in Figure 7.3

Some important recommendations follow from the preceding discussion:

- It is preferable not to have a recirculated exhaust volume supplied entirely by return air, if the contaminant is flammable and C^{FS}_{BZ} approached or exceeds the lower flammable limit of the substance. This is not an absolute prescription, since safe operation with such a system is still possible, given a monitoring system and a response strategy that are adequate.

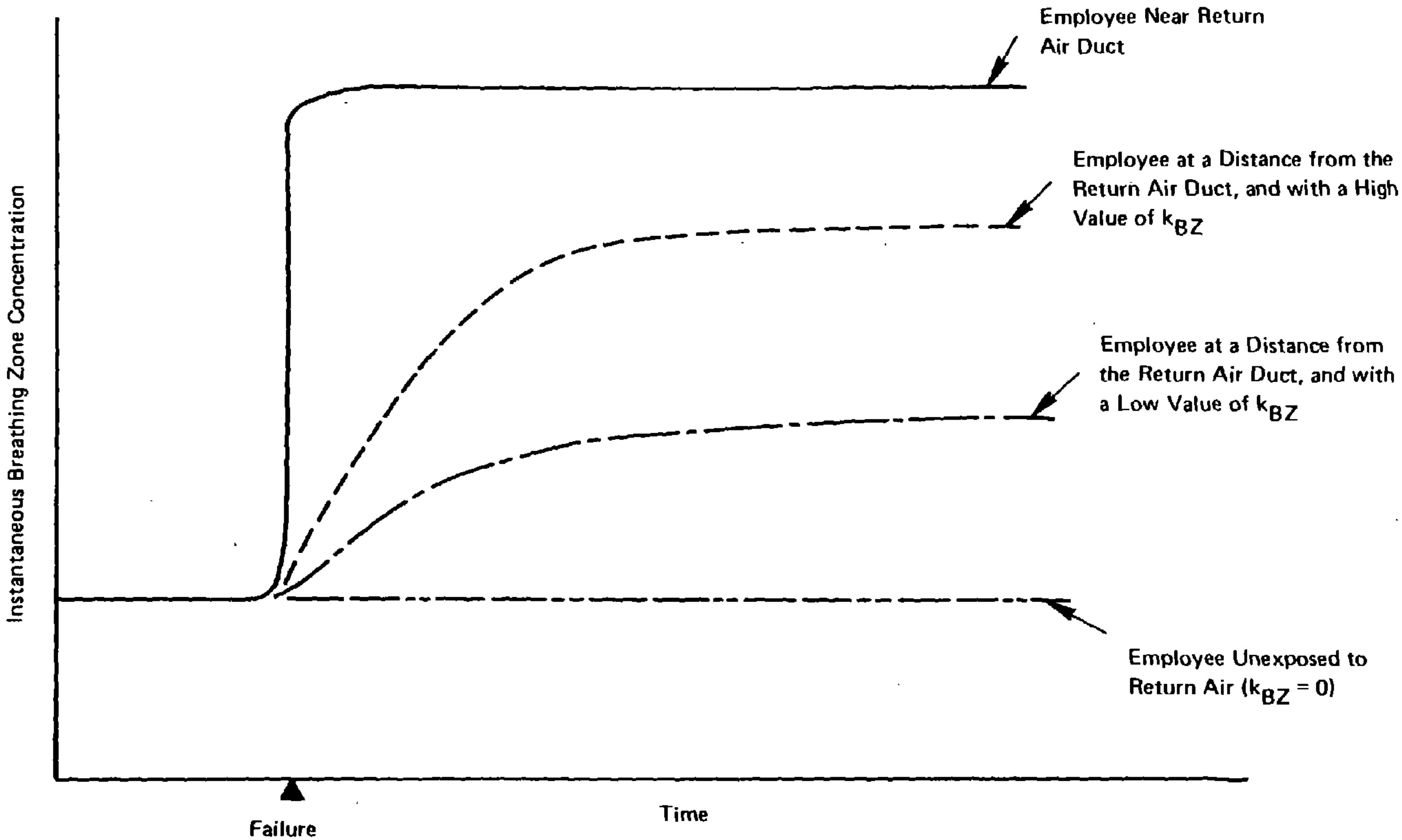


Figure 7.3 **VARIOUS POSSIBLE BREATHING ZONE TRANSIENTS AFTER AN AIR CLEANER FAILURE**

- A return air duct should never be so placed that an employee could experience an almost instantaneous rise to a high value in his breathing zone concentration. This is equivalent to suggesting that the rise time "t_o" should, at a minimum, be a few minutes for any employee. This, in turn, is equivalent to requiring that the return air be directed in such a way that it undergoes a substantial amount of mixing before it reaches any employee.

- The rise time "t_o" should be measured whenever possible. It is an essential input to the selection of monitoring systems as well as strategies for responding to air cleaner failure. Judgment will need to be exercised in selecting an appropriate area for measuring t_o since, as has been pointed out above, there will always be points within a room with very small or very large values of t_o. Techniques for estimating t_o are discussed in Appendix F.

The generalization of the preceding procedure for more complex configurations involves the following steps:

(a) Write down the expression for the return air concentration C_R; in this expression, set the efficiency of the failed air cleaners equal to zero, and determine the post-failure return air concentration.

(b) Introduce the post-failure return air concentration into the equation for the breathing zone concentration, to obtain the post-failure steady-state breathing zone concentration C_{BZ}^{FS}.

(c) Experimentally determine the rise time t_o for areas of interest.

(d) Write down the post-failure <u>transient</u> breathing zone concentration $C_{BZ}^{F}(t)$ in terms of the pre-failure steady-state breathing zone concentration C_{BZ}, and in terms of C_{BZ}^{FS} and t_o. The expression will be similar to that presented above for the simple configuration.

7.8.5 Critical Response Time After Failure

After an air cleaner failure, an employee's instantaneous breathing zone concentration will resemble one of the curves shown in Figure 7.3. Each curve is characterized by only three values:

a. the breathing zone concentration before failure, C_{BZ}, shown in Figure 7.3 (for simplicity) as the same for the four employees considered there;

b. the steady-state breathing zone concentration after failure C_{BZ}^{FS}; and

c. the rise time "t_o".

Assuming that these parameters are known for any employee, it is desired to determine the shortest time in which any employee is exposed to unacceptable concentration levels. This is termed the "critical response time." If response strategies to counter the effects of failure are not initiated within this period, a hazardous situation will prevail.

In this context, a hazardous situation is defined to be one in which either of two scenarios occurs:

a. the time-weighted average (TWA) breathing zone concentration level exceeds the desired level; or

b. the instantaneous breathing zone concentration for any employee exceeds the permissible ceiling level for the contaminant of concern, if such a ceiling exists.

As outlined above, the instantaneous breathing zone concentration level after failure is given by:

$$C_{BZ}^{F}(t) = C_{BZ} + (C_{BZ}^{FS} - C_{BZ}) \, [1-e^{-(\frac{t}{t_o})}].$$

From this equation, it is possible to compute the running TWA at time t. The procedure is outlined in Appendix F. Assuming such a computation has been made, it is then necessary to develop a sketch such as that shown in Figure 7.4. In this case, the critical response time T_c is determined by the ceiling level limit. This procedure must be repeated for several breathing zones. The lowest of the resulting set of critical response time estimates is the true critical response time.

If a response strategy is instituted at or before time T_c, the worst-case breathing zone concentration will be as shown in Figure 7.5. This figure demonstrates that hazardous levels will not be reached.

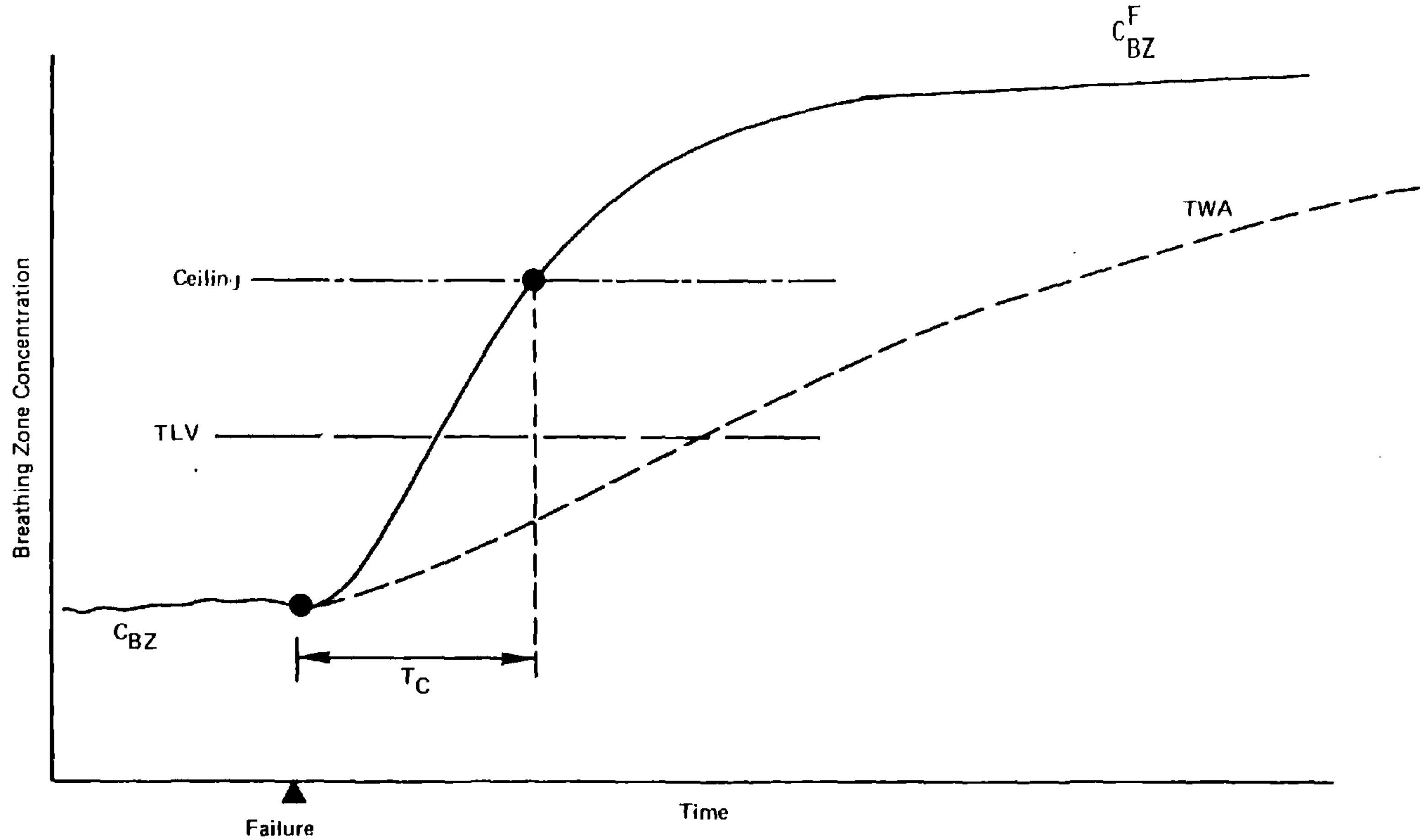


FIGURE 7.4 DETERMINATION OF THE CRITICAL RESPONSE TIME T_C FOR AN EMPLOYEE

Figure 7.5 illustrates the effects of the most delayed response allowable. In practice, it is recommended that the estimated value of the critical response time be reduced by at least 10% for planning monitoring and response strategies.

One interesting fact illustrated in Figure 7.5 is that the TWA continues to rise even after the response strategy is instituted. This is better illustrated in Figure 7.6, which illustrates a situation in which no ceiling level exists for the contaminant of concern. If a response is instituted at the moment that the TWA equals the TLV, this will, in fact, be too late. The TWA will continue to rise for some time, violating the TLV limit. A more detailed analysis would compute the TWA using the instantaneous breathing zone concentration after the response strategy is instituted, as illustrated in Figure 7.7. This procedure is extremely complex, however. A more reasonable approach is to allow a safety margin when estimating the critical response time.

7.8.6 Monitoring Frequency for Intermittent Monitoring

When system monitoring is to be intermittent (i.e., not continuous), a minimum monitoring frequency must be maintained. This frequency depends on:

a. the critical response time T_C, as determined from the analyses summarized above; and

b. the time required to implement a response strategy, T_R. Response strategies include exhaust by-pass, use of personal protective equipment, use of a stand-by ventilation system, process shut-down and plant evacuation.

The maximum permissible monitoring interval T_M is then given by:

$$T_M = T_C - T_R.$$

If $T_M + T_R$ is not less than T_C, then it is possible for hazardous situations to arise when a failure occurs immediately after a monitoring measurement has been made. To determine the maximum permissible sampling interval it is thus imperative that good estimates be available of the response time required.

7.8.7 Trigger Levels for the Monitor

- Air Cleaner Monitoring

A system of monitoring the performance of a air cleaner must be assigned a trigger level. This is the concentration or other pertinent level at which the monitor will trigger an alarm and set in motion the subsequent responses to failure.

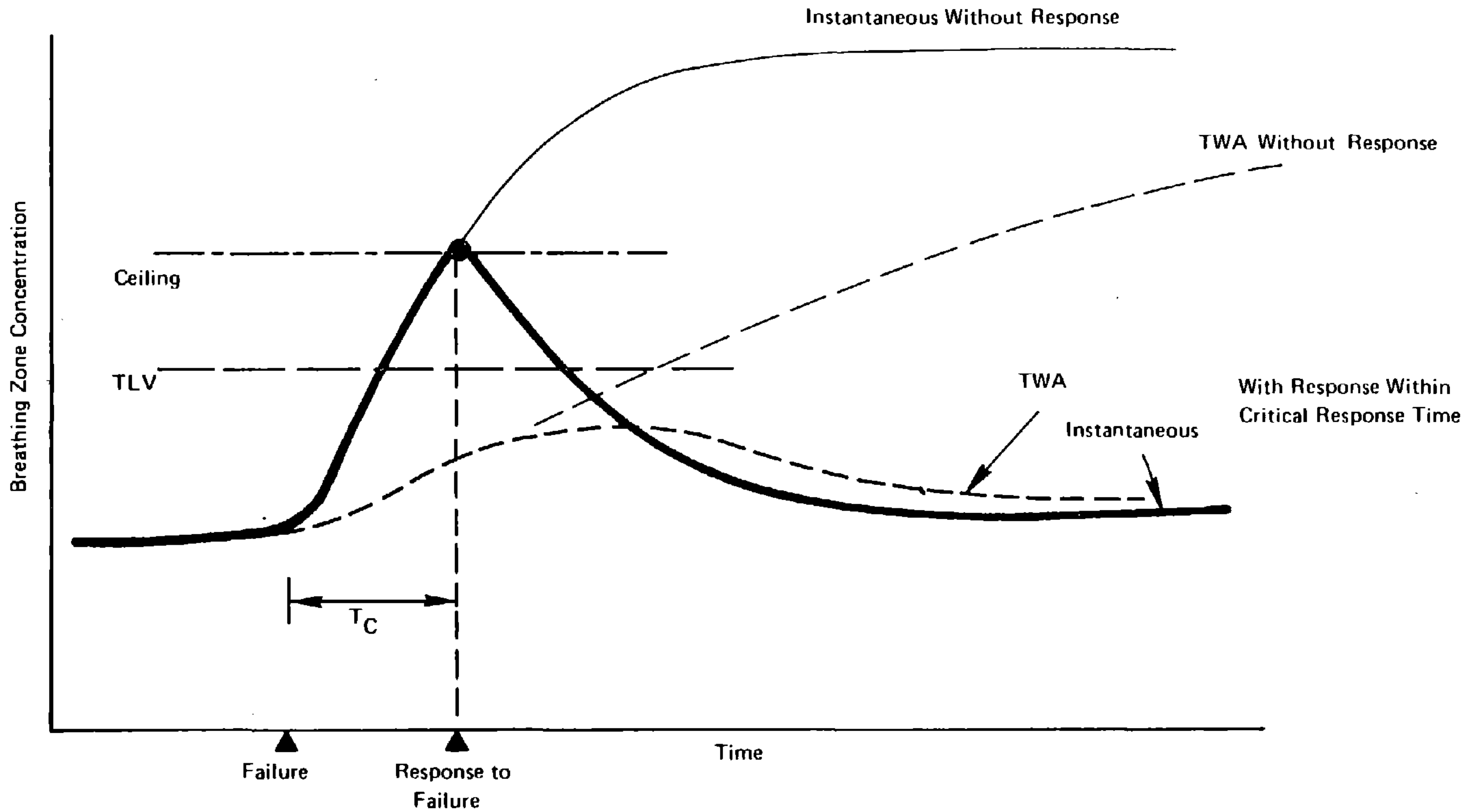


FIGURE 7.5 EFFECTS OF RESPONSE TO FAILURE WITHIN THE CRITICAL RESPONSE TIME T_C

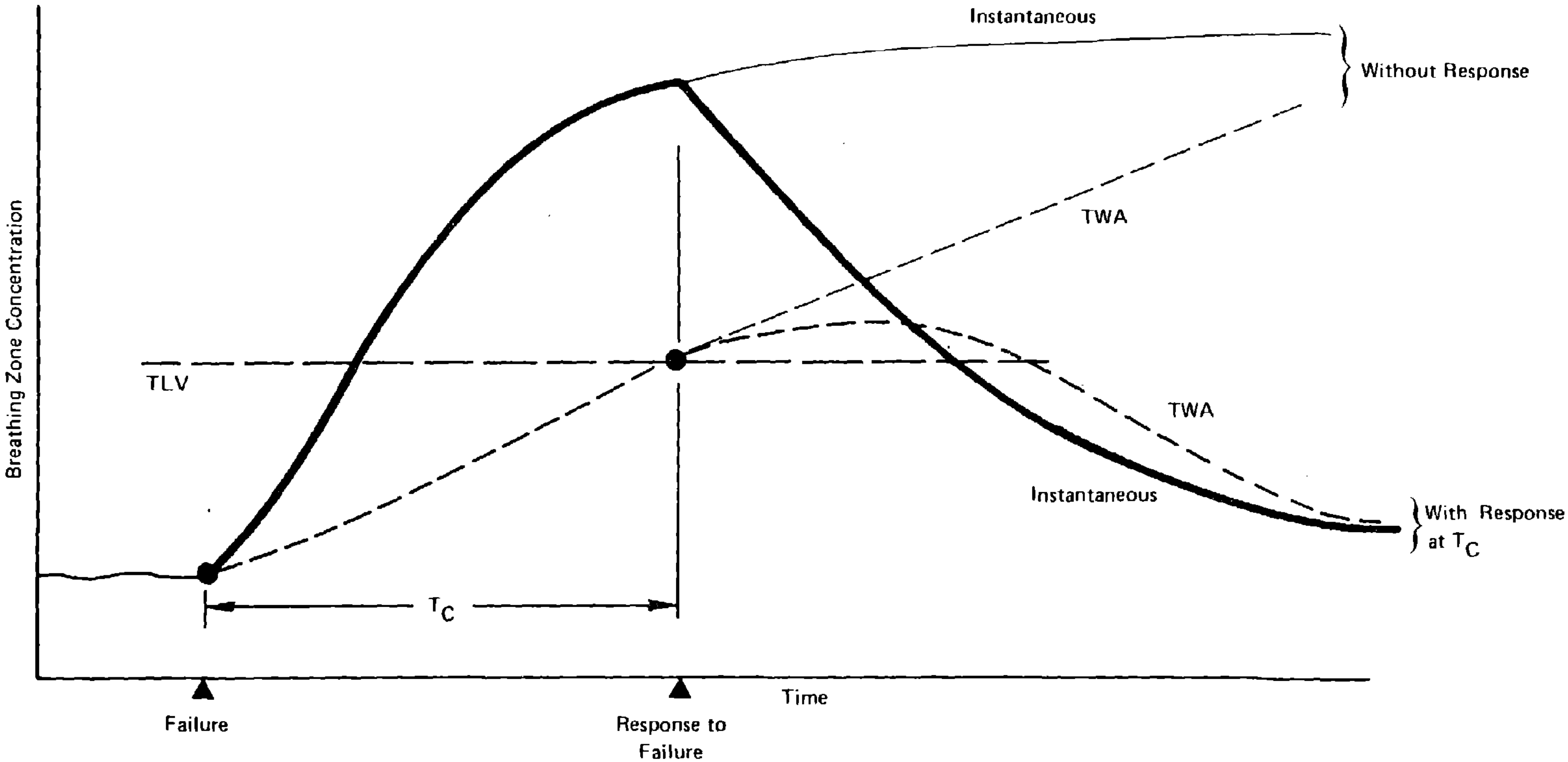


FIGURE 7.6 RESPONSE TO T_C BASED ON TWA MAY NOT BE ADEQUATE. NOTE VIOLATION OF TLV.

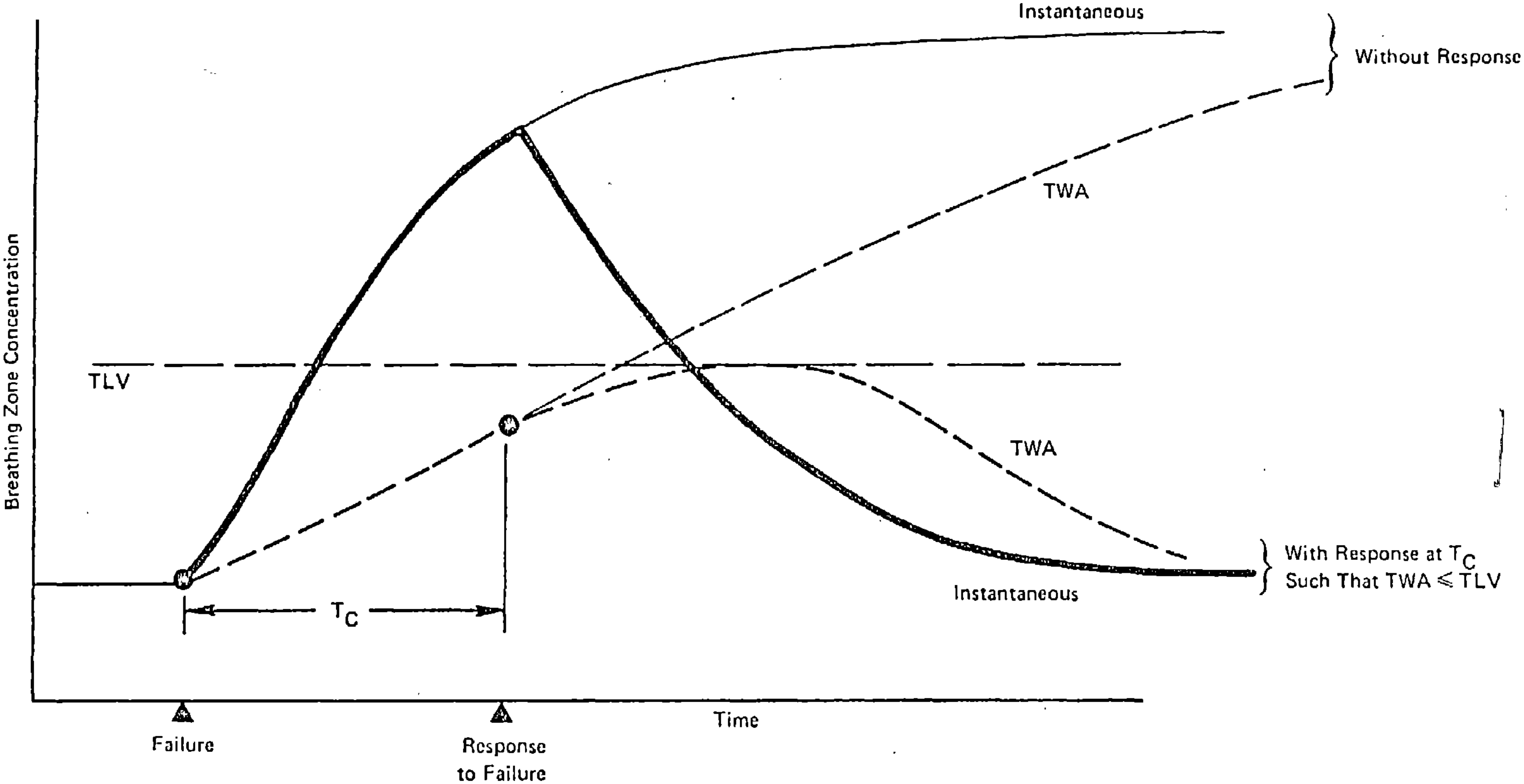


FIGURE 7.7 SHORTENING OF THE CRITICAL RESPONSE TIME SHOWN IN FIGURE 7.5 LEADS TO A SAFE SITUATION. COMPUTATION OF THE C VALUE OF T_C SHOWN HERE IS VERY COMPLEX, HOWEVER. IT IS RECOMMENDED THAT THE T_C VALUE OF FIGURE 7.5 BE REDUCED 10% TO 20% TO ACHIEVE THE DESIRED EFFECT

The effects of setting too low a trigger level may be to trigger the alarm too frequently, i.e., even without a cleaner failure. A typical cause may be process fluctuations, leading to occasional peaks which are not hazardous.

The effects of setting too high a level may be to allow hazardous levels of contaminant concentration in employees' breathing zones.

- Duct Monitoring

For duct monitoring, the trigger level is bounded on the low side by the exhaust concentration fluctuations which are typical of the process. Periodic exhaust duct sampling may indicate, for example, that the exhaust concentration has a mean value of 5000 ppm and never exceeds 5500 ppm. Then 5500 ppm - or a slightly higher number, to allow a margin - multiplied by $(1 - \eta)$, where η is the air cleaner efficiency, is the minimum desirable trigger level.

The trigger level is bounded on the high side by the requirement that return air concentrations below the trigger level not be hazardous. Thus the maximum permissible trigger level is that which would lead to a breathing zone concentration equal to the TLV for the "worst case" employee. As an example, consider this employee to be in the vicinity of the local exhaust hood in the system of Figure 7.2(a). For this employee, the breathing zone concentration was estimated to be:

$$C_{BZ} = C^{\circ}_{BZ} + k_{BZ}(C_R - C_{MU}).$$

Setting C_{BZ} = TLV, one obtains a maximum permissible trigger level for the return air concentration:

$$C_R = \frac{TLV - C^{\circ}_{BZ}}{k_{BZ}} + C_{MU}.$$

In some instances, a situation may arise in which normal process fluctuations give rise to return air concentrations which are larger than the preceding maximum permissible trigger level. The only permissible solution here is to use two trigger levels, one being as defined above, the other being a permissible 15-minute ceiling. This 15-minute ceiling limit can be based on the contaminant's permissible ceiling level, if one exists:

If the primary trigger level based on the TWA is crossed, the alarm need not be sounded for 15 minutes, as long as the return air concentration C_R stays below the trigger level based on the ceiling. A fluctuation of C_R beyond the ceiling-based trigger should be considered an indication of cleaner failure.

If a ceiling level does not exist, fluctuations of C_R beyond the TWA-based trigger level may also be allowed, up to a secondary trigger level. This secondary level should be such that, should air cleaner failure have occurred, the critical response time remaining would still be adequate. As before, however, fluctuations of more than 15 minutes beyond the primary trigger level should always be taken to indicate failure.

In the case of intermittent monitoring, if the TWA-based trigger level be exceeded in a given measurement, it is recommended that this be considered a failure when the contaminants have a ceiling level. When no ceiling exists, it is recommended that a second measurement be made within 5 minutes. If the return air concentration should still exceed the trigger level, failure response strategies should be initiated.

- Area Monitoring

Where area monitoring is the preferred course, the trigger level is directly based on the 8-hour TWA and the ceiling. The monitor should be designed to trigger whenever either limit is exceeded.

7.8.8 Parameters Required for Failure Analysis

The only parameter required for the failure analysis of a recirculating exhaust system (in addition to those required for the steady-state analysis) is the rise time "t_o", defined in section 7.8.4. Techniques for estimating t_o are discussed in Appendix F.

It must be stressed that whereas the parameters C^o_{BZ} and k_{BZ} require estimation for only one employee (the "worst case") for the steady-state analysis, these parameters, along with t_o, may need to be estimated for several employees for the failure analysis. This further requirement arises from the need to accurately estimate the critical response time T_C. It is possible, for example, that the breathing zone with the highest value of C_{BZ} during normal operations also has a long rise time t_o, and may not, therefore, be the worst case in the event of system failure.

7.9 Selection of the Best Overall Configuration

At this point, several alternative feasible recirculation system configurations will be available, each capable of attaining the desired values set for breathing zone concentrations. These alternatives will differ from one another in respect of initial and operating costs, and in terms of their behavior after a system failure. One is now in a position to choose one of the alternatives for further development. Factors that must be considered in making this choice are:

(a) Differences in cost, both initial and operating;

(b) Monitoring equipment and response strategies required; and

(c) Ease of installation and maintenance.

The examples in Appendix A provide further information on how the selection proceeds.

7.10 Final Selection of Equipment

For the one system configuration chosen above, equipment that meets system performance specifications can now be chosen. Factors that will need to be considered include air cleaner sizes and efficiencies, fan ratings, monitoring equipment capabilities and costs. Obviously no general guidelines are available for this selection process. Assistance must be sought from equipment manufacturers and from a designer of industrial ventilation systems. The pros and cons of various alternative pieces of equipment will need to be weighed. A checklist of such issues for air cleaners is presented in Chapter 5.

7.11 Detailed System Design and Installation

The designer will now have to proceed to the detailed design of the recirculation system, and then to its installation. Detailed design encompasses such issues as duct sizing and routing; fan installation; techniques for pre-mixing air; locations for monitoring; the design of by-pass systems, if any, and so forth. These techniques are well understood and are not addressed in this report.

During installation, care will have to be taken that the system as installed is free of defects or errors, so that the performance validation procedure outlined in the next Chapter does not lead to false results. Here, too, no major problems are to be anticipated; it is merely suggested that close supervision is useful.

8. SYSTEM PERFORMANCE VALIDATION

Once a recirculating exhaust system has been designed and installed, a program to prove that its performance meets design specifications must be undertaken, before production operations are started.

The most important elements of such a validation program are concerned with the performance of the air cleaner, the surveillance system, the alarm and the emergency response strategy.

8.1 Checking Air Cleaner Performance

Since system design is likely to be based on relatively imprecise estimates of air cleaner efficiency, it is essential to demonstrate that the return air concentration is no higher than the value planned on. The planned or "required" value must satisfy the following constraint:

$$C_R \leq \frac{1}{k_{BZ}} \left(C^D_{BZG} - C^o_{BZ} \frac{Q^o_T}{Q_T} \right) + C_{MU}$$

if it has been determined that an employee in a generally ventilated area suffers the worst exposure to the contaminant. The various symbols are defined in Chapter 7.

If it has been determined that the worst exposure is suffered by an employee near a local exhaust hood, the constraint on the desired value of C_R is:

$$C_R \leq \frac{1}{k_{BZ}} \left(C^D_{BZL} - C^o_{BZ} \right) + C_{MU}.$$

These two equations are obtained by requiring that the actual breathing zone concentration C_{BZ} never exceed the desired value, C^D_{BZ}.

Measurements of C_R must be made according to a plan which ensures that process fluctuations are adequately taken into account. A further factor that should be taken into account is the possible variation in air cleaner efficiency.

Similar measurements should be made of typical breathing zone concentrations, to determine whether they are within the desired value. Either area or personal sampling may be used, as appropriate. Important factors which should guide the design of a plan for these measurements are process fluctuations, cleaner efficiency variations, and the location of the return air duct relative to the employees.

8.2 Testing the Surveillance System and the Alarm

The ability of the monitoring system to detect a system failure and activate an alarm must be established. Since it is undesirable to create failure conditions for such a test (with the possibility of hazardous exposure for the testing personnel), the trigger levels on the monitor should be reduced until the alarm is activated. A comparison should then be made of the presumed trigger level and the actual contaminant concentration that the monitor has been exposed to, as a demonstration of the accuracy of calibration of the monitor. Where several trigger levels exist (in some multi-contaminant situations, for example), the performance of each trigger must be established.

In cases, where two trigger levels are being used for the same contaminant (where occasional large process fluctuations are expected) and the monitor therefore contains a delay circuit, a test must be conducted to demonstrate the proper functioning of both trigger levels as well as the delay circuit.

With the pressure-differential monitors, a test procedure must be designed which will create a pressure differential equal to the trigger level. For a monitor across an absolute filter, an increased pressure differential is called for; for a monitor across a baghouse, a reduced pressure differential. All tests of monitoring equipment and alarms must be conducted with the equipment fully in place, to avoid the possibility of errors during installation going undetected.

8.3 Testing the Failure Response Strategy

Failure Response strategies will probably include one or more of the following:

(a) automatic by-pass

(b) manual by-pass

(c) use of personnel protective equipment

(d) use of redundant cleaners

(e) use of emergency ventilation systems

(f) process shut-down

(g) plant evacuation.

Whichever strategy is chosen, it must be demonstrated that the time T_R it requires for implementation meets the criterion

$$T_R \leq T_c - T_M,$$

where T_c is the critical response time (Chapter 7) and T_M is the time interval between monitoring samples. (T_M is zero with continuous monitoring.) Such a demonstration may involve a drill in the case of strategies (c) and (g) above. When the strategy involves the activation of some piece of equipment (e.g., a by-pass damper), it must be demonstrated that the equipment works, and can be operated within the available time.

8.4 Recording Performance Data

The results of the tests described above should be recorded in a log, with particular emphasis on any observations on potential problems that the system might suffer from. This log should be reviewed by plant management. The adequacy of system performance should be certified by a qualified health professional.

9. MAINTAINING AND OPERATING A RECIRCULATING SYSTEM

9.1 The Importance of Scheduled Inspection, Periodic Maintenance and Failure Response Planning

The equipment and man-hours required for the installation of a recirculation system represent a significant investment. Protection of the value of this investment, minimization of operating costs, and the absolute necessity of ensuring the continued safety of the working environment require detailed consideration of the particular maintenance and inspection needs of all equipment during the life of the system. To do otherwise can ultimately lead to employee health problems, lost production, conflict with health authorities, expensive repairs, and a host of other problems.

It is equally important to develop procedures to continually establish the adequacy of failure response strategy, be it exhaust by-pass, use of personal protective equipment, process shut-down or evacuation.

In this chapter, guidelines are presented in the following areas: inspection and maintenance of ventilation system equipment, air cleaners and monitoring and alarm equipment; failure response planning; record-keeping; and air quality checks.

9.2 Maintenance and Inspection of Ventilation System Components

With the exception of an air cleaning device, a ventilation system essentially consists of hoods, ductwork, dampers, blast gates, and a fan. Each of these components is subject to wear and tear, misuse and eventual obsolescence. In consequence, such equipment requires the same degree of attention as process equipment. Table 9.1 provides a general listing of the types of problems to be anticipated.

9.3 Maintenance and Inspection of Air Cleaners

The manufacturer of the air cleaner is in the best position to provide instructions concerning the maintenance of his product. In consequence, the buyer should insist that the manufacturer provide written in-depth instructions on operation and maintenance (including maintenance trouble-shooting). This information should be thoroughly studied and utilized in developing a preventive maintenance schedule, and stored in a safe location accessible to personnel responsible for equipment maintenance. In addition, maintenance personnel must be impressed with the fact that schedules must be adhered to not only to protect the company investment in the unit, but more importantly, to ensure the health of employees.

9.4 Inspection and Maintenance of Monitoring and Alarm Equipment

Devices which measure pressure differentials across an air cleaner are usually familiar to plant personnel and easy to maintain. More sophis-

TABLE 9.1

Check List for Periodic Inspection and Maintenance of Ventilation Equipment

Fans - Check for:

- Tightness of all bolts
- Bearing vibration or signs of wear
- Wear and dirt accumulations on housing and wheels
- Worn blades, flanges, etc.
- Worn belt sheaves
- Improper lubrication and possible binding of bearings
- Proper belt tension

Duct Work - Check for:

- Accumulations in branch or main ducts
- Corrosion (frequent in elbows)
- Loose or leaking clean-out doors
- Broken joints
- Poor connections
- Loose supports

Hoods - Check for:

- Damaged or missing parts
- Obstacles to airflow
- Improperly utilized dampers
- Unauthorized modifications
- Wear, direct accumulations and corrosion

Others - Check:

- Dampers for synchronization and operation
- Blast gates for improper adjustment
- Proper exhaust air velocities and/or volumes at hood locations

ticated devices which measure actual or perceived contaminant concentrations, however, may require specialized knowledge for maintenance and calibration. The situation is thus analogous to that for air cleaners. The user must insist that the manufacturer provide detailed written instructions, ensure the information is studied and understood by responsible personnel, and provide for safe but accessible storage of the information.

In cases where the monitoring equipment is required to activate visual or audible alarms, or automatic by-pass systems, it is particularly important that the operation of the entire warning system be periodically tested. The frequency of this procedure can be determined from a consideration of the severity of service experienced by the equipment and the recommended time period between equipment calibrations.

9.5 Air Sampling Studies

During the time period immediately following start-up of a recirculation system, it is necessary to measure breathing zone contaminant concentrations frequently. Such efforts will allow preliminary assessment of the adequacy of the overall system design and definition of the actual operating characteristics of all subsystems. Adjustments can then be made, if necessary, to ensure the overall system satisfies design specifications.

As experience is obtained with operation of the system, and as confidence is gained that the system functions as intended, the frequency of sampling can be reduced, with certain exceptions, to more common levels.

Exceptions to the above involve periods of time following events which may influence the performance of the system. Examples include process changes, hood alterations, revision of materials handling procedures, changes of season (as they might affect the degree of fresh air infiltration), changes in production rates, and introduction of new contaminants. Because of the nature of recirculation systems, these and other significant changes in the working environment will call for unscheduled checks that breathing zone contaminant concentrations are within acceptable limits. If there is any doubt whether any particular event is significant, qualified health personnel should be consulted.

9.6 Record-Keeping

The practice of keeping detailed records of inspections, repairs and performance characteristics of the system is quite useful. Based upon periodic reviews of records, maintenance and testing schedules can be optimized, and the effect of proposed changes in the working environment can be predetermined. Over the longer term, such records can also provide the framework for more accurate initial design of other recirculation systems.

Furthermore, record-keeping spurs adherence to maintenance and inspection schedules.

9.7 Failure Response Planning

Virtually any system which treats harmful toxic or physical agents has the potential to malfunction due to unexpected causes. In consequence, it has become common practice in many industries to prepare detailed plans which describe the tasks which must be performed during an emergency situation and which provide for assignment of specific responsibilities to personnel present in the plant. The process of developing such plans usually leads to the identification of training requirements, of requirements for posting appropriate signs, of needs for protective equipment for emergency use, etc.

In the case of recirculation system malfunction, topics which should be addressed for planning purposes include, but are not limited to:

- activation and verification that by-pass systems have operated;
- evacuation procedures;
- providing necessary make-up air;
- identifying and repairing the cause of system failure;
- assignment of specific responsibilities;
- training requirements;
- posting of information;
- decision regarding the cessation of production activities;
- availability of properly functioning personal protective equipment, if required; and
- medical resources.

10. CONCLUSIONS

This chapter summarizes the various qualitative recommendations and conclusions developed in preceding chapters and in Appendices to this report. Several quantitative recommendations also appear in the report, but are subject to misinterpretation when taken out of context. Hence, these are not included here.

The recommendations and conclusions of interest are:

1. An initial assessment of the feasibility of recirculation, as described in Chapter 3, is necessary, if only to ensure that all important factors are taken into consideration in the design phase.

2. In an existing plant, the effectiveness of all local and general exhaust systems should be optimized before design of a recirculating system is undertaken.

3. All contaminants in the exhaust air to be recirculated must be identified, and their concentration levels quantified by application of accurate sampling and analysis techniques. Similar information must be obtained for employee breathing zones which may be affected by the advent of recirculation.

4. Contaminants designated as human carcinogens by OSHA should not be recirculated. The decision to recirculate should be given careful evaluation by qualified health professionals when substances suspected of being carcinogenic are present in work place air. (See Chapter 4).

5. A qualified health professional should establish acceptable concentrations for the airborne contaminants present, based upon an examination of the pertinent regulations or, when regulations do not exist, on available toxicological information. (See Chapter 4). These desired levels should be reduced to some degree to account for the vagaries of the overall system design process.

6. The magnitude of all make-up and exhaust air volumes in the plant area must be determined or estimated. Additionally, an awareness of how various air volumes interact with airflow patterns in the plant must be developed.

7. Possible variations in breathing zone and exhaust air contaminant levels due to temporal variations in processes and trends or sequences in work practices must be given consideration. Similarly, consideration must be given to the effects of seasonal changes in natural ventilation or infiltration rates, and usual changes in production rates, product types, etc.

8. Individual air cleaning devices selected for use should be reliable, should not adversely affect the quality of the air being cleaned, and should provide a substantial degree of cleaning. The overall efficiency of the air cleaning equipment train for each of the various contaminants present must be known and must be adequate.

9. Health and economic issues require consideration of using a number of air cleaning devices in parallel and/or in series. Such decisions must be made on a case-by-case basis.

10. The recirculation system designer has many options concerning how various air volumes can be combined in ductwork and in the work place air. All such options should be evaluated in the context of providing a healthful work environment.

11. Designers should fully evaluate the possibility of lowering existing airborne contaminant levels in breathing zones by increasing appropriate general or local exhaust volumes. With recirculation, this may be feasible at little or no additional cost.

12. A recirculation system should never be designed and installed haphazardly by "seat-of-the-pants" methods. In all cases, it is necessary to rigorously apply state-of-the-art technology during the design phase. This report provides various computational techniques which may be utilized.

13. All major modes of failure of the recirculating system which result in health hazards must be identified. (See Chapter 7.)

14. Equipment or methodologies must be implemented which allow detection of reduced system performance and activation of an alarm mechanism. (See Chapter 6.)

15. In most circumstances, provision must be made to by-pass contaminated exhaust air to the outdoors in the event of air cleaner or other recirculation system component failure.

16. Return air, generally speaking, should not be directed directly at an employee, since this leaves no margin of safety in the event of system failure. Instead, it should be well-distributed throughout the same or a different plant area. This is equivalent to requiring a reasonably slow transient breathing zone concentration increase after failure.

17. A failure response strategy should be chosen and implemented. Adequate training must be provided to all concerned personnel to ensure satisfactory execution of the strategy.

18. The monitoring frequency and response strategy should be based on an analysis of post-failure breathing zone concentration levels to ensure that adequate time is available for successful implementation of the response strategy. (See Chapter 7.)

19. Trigger levels for devices to detect reduced system performance should be selected such that no employee is exposed to concentrations violating pertinent exposure limits. (See Chapter 6.)

20. A performance validation program must be undertaken after installation of the recirculating system. Specific items requiring attention are: the air cleaner, devices or methods for detecting reduced system performance, the alarm, and the failure response strategy. (See Chapter 8.)

21. A maintenance and inspection plan should be implemented in accordance with the recommendations of Chapter 9.

22. Any proposed subsequent changes to the ventilation or recirculation systems, the processes conducted in the plant, the number of work shifts, the materials handled, production rates, etc., must be evaluated to ensure that the recirculation system will continue to provide a healthful working environment.

APPENDIX A

MODELING OF INDUSTRIAL VENTILATION SYSTEMS WITH RECIRCULATED EXHAUST AIR

1. THE NECESSITY OF MODELING RECIRCULATING EXHAUST SYSTEMS

In designing a ventilation system incorporating the recirculation of cleaned exhaust air, a number of questions arise:

- What will be the concentration of any toxic substances in the breathing zones of employees?
- What is a desirable maximum concentration of these contaminants in the air being returned to the workplace?
- What air cleaner efficiency is required in order to obtain the desired contaminant concentration in the return air?
- How does one make the trade-off between the cost of make-up air and the cost of cleaning the recirculated air? What are the cost-optimum values for the flow rates of the various air streams in the ventilation system?
- Which local exhaust and/or general exhaust volumes should or can feasibly be recirculated?
- Where should the recirculated air be brought back into the work space?
- How does one make the trade-off between safety margins (from an occupational health standpoint) and cost savings?
- If any design parameters vary over time, or if errors have been made in estimating various parameters, how much will this affect the safety margin available to the employees?
- Are there any clearly preferable approaches to designing recirculating systems - approaches that markedly improve safety without necessarily adding to cost?
- What are the occupational health consequences of a failure of some part of the recirculating system? How can these consequences be kept within safe limits?

Many of these questions arise equally in the design of conventional ventilation systems not using recirculated air. In these situations, however, the designer has access to a great deal of previous experience - his own or that of others - upon which to base his decisions. With recirculating systems this backdrop of experience is absent and other tools or aids are required to develop answers to the type of questions posed above. Such tools are presented here: three "models" of industrial ventilation systems, each of which represents one or more feasible recirculation system design configurations.

These calculation algorithms or procedures are based on practical representations of the physical processes that occur in a ventilation system. The two fundamental physical processes of interest are how the air in a room flows and mixes, and how toxic contaminants are captured or dispersed. The models are sufficiently practical to yield tractable solutions, while at the same time, are sufficiently detailed so as to yield reasonably accurate answers. This goal has been achieved during model development efforts by a continuous, critical examination of the effects that various parameters have on the solutions generated by the models. The parameters of primary importance are included while those having second-order effects are ignored. This is not to suggest that second-order effects are irrelevant; rather, that since their inclusion contributes a minor improvement in the overall accuracy of solutions while creating additional complications, consideration of these effects is believed unwarranted.

Some details that are not addressed in a quantitative manner by the models include: detailed system design considerations such as duct sizing, hood design, choice of fans, etc.; the effect that by-passing normally recirculated air to the outside after an air cleaner failure may have on the air pressures within the building; the effects that recirculation may have on the quality and quantity of dilution ventilation in neighboring areas, due to the change in air flow patterns; and the effect that recirculation may have on the contaminant concentrations, if any, in fresh make-up air supplied. However, qualitative recommendations are offered on many of these issues in various sections of this Appendix.

Major design parameters that are included in the models are the locations of the intake and exhaust air streams, the volumes of the various air flows, the location of the employees with respect to these air flows, the quality of mixing of the air within the room, and the extent of dispersion of contaminants from various sources through the room.

The models presented below must be viewed as being capable of and requiring continuous improvement. Some of the parameters required are difficult to estimate - though not unreasonably so. Removing these difficulties will require a considerable amount of pragmatic research, particularly in the areas of air flows, room air turbulence, and local exhaust hood design. However, the models are based on sound physical principles, are comprehensive, are capable of field validation (which many past models have not been), and incorporate the most important design variables entering into a cost/benefit analysis.

The most important input to be provided by the user of a model is a "desired breathing zone concentration." This is the time-weighted average contaminant concentration which is selected as a target for design purposes. This input forces attention to the most important issue: To what toxic substances are the employees going to be exposed, and what is an acceptable exposure level for each of these substances? If safety margins are desired to account for possible inaccuracies in the system design procedure, these must be reflected in the selection of desired breathing zone concentrations that are below permissible or desirable exposure limits for the contaminants being evaluated. Once such a desired breathing zone concentration has been selected for each contaminant, each model attempts to accurately quantify system design parameters so that the desired level is achieved. It is possible to vary this desired level and examine the consequences on system design and cost, providing a mechanism to develop a clear awareness of the trade-offs between costs and safety margins in a recirculation system.

2. THE CONTENTS OF THIS APPENDIX

Each model presented in this appendix contains a number of parameters which describe flow volumes, concentrations, and other features of a plant area of concern. Most of these parameters are straightforward in definition. Some, however, are novel in concept and require discussion before the equations comprising any model can be inspected and understood. In consequence, the next section of this appendix, entitled "A Close Look at the Design Parameters in Recirculation System Models," discusses in detail the definition of each parameter required by the models.

"The Breathing Zone Equation" employs a question and answer format to derive, in a step-by-step fashion, an important equation which is present in all recirculation models. The importance of this equation results from its use of estimated contaminant concentrations in return air streams to predict the breathing zone concentrations that will be present after recirculation is implemented.

Given this background, the reader is next introduced to assumptions inherent in the models, then to the equations for one model (Model #1), and an example of how the model may be applied in a variety of situations. These sections are followed, in order, by descriptions of Models #2 and #3, and sections addressing:

- Application of the Models for Multi-Contaminant Work Places;
- Ceiling Limit Checks Required; and
- Estimating Design Parameters for New Facilities.

3. A CLOSE LOOK AT THE DESIGN PARAMETERS IN RECIRCULATING SYSTEM MODELS

C_{BZ}^{D} - The Desired Breathing Zone Concentration

Recirculation of industrial exhaust air in many, but not all, cases will increase the rate at which airborne contaminants enter the workplace. This is a direct consequence of the fact that the air being returned to the work area, although cleaned to a large extent, will usually have a greater contaminant concentration than the relatively clean make-up air it has replaced.* An exception to this occurs when the outdoor air is contaminated to the extent that the air cleaner chosen for use discharges air less contaminated than outdoor air. As a consequence, the contaminant level chosen as the desired breathing zone concentration, C_{BZ}^{D}, can have a significant effect upon the final design of an acceptable recirculation system, and this concentration must be considered as one of the most important parameters in the computation procedure.

In many circumstances, it may be decided that the breathing zone concentration with a recirculation system should be equivalent to those obtained with the conventional ventilation system. If these original breathing zone concentrations were acceptable to employees, management, and health officials, then maintenance of these levels may be the most desirable course of action. However, depending upon the economics of the situation, it may be prudent to design for lower concentrations at modest additional expense. Alternatively, raising the exposure levels may be acceptable in some situations.

Some properly controlled processes and operations expose employees to contaminant concentrations which are well below any level considered either hazardous to health or causing primary irritation. This is often due to either overdesign of the engineering controls or to the very nature of the contaminant and the manner in which it is utilized. In these situations, the designer may be justified in deciding to allow some increase in breathing zone contaminant concentrations when recirculation is implemented. The specific level which is chosen must then be carefully evaluated to ensure that it is safe and acceptable to all concerned (see Chapter 4).

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*Although the recirculated return air may be more highly contaminated than fresh make-up air, the use of recirculation reduces the "energy penalty" normally associated with increasing minimum local exhaust volumes. Recirculation may permit increased local exhaust rates, providing improved contaminant capture at hoods, while providing an overall decrease or constant level of energy consumption.

Where more than one contaminant is present in the recirculated air stream, the designer must recognize the responsibility to identify each and every substance, and to select desired breathing zone concentrations for each. Close attention must be given to the evaluation of whether the health effects of two or more constituents are synergistic. This procedure should include a thorough review of all decisions by fully qualified industrial health personnel.

Finally, it is necessary to address the application of an appropriate safety factor for the overall recirculation system design process. Since all models presented are fairly rigorously derived, it is necessary for the designer to include the safety factor inherently in the input parameters. It is suggested that this be accomplished by utilizing a value for C_{BZ}^{D} which is somewhat lower in magnitude than that actually desired. The lower bound upon the chosen value depends upon the complexity of the selected system configuration and the accuracy of available design data.

C_{BZ} - - The Predicted Breathing Zone Concentration

Given a specific and complete set of input parameters, the models allow estimation of resulting breathing zone concentrations for each contaminant being recirculated. The overall procedure for use of the models calls for adjustment of independent design parameters until such time as these concentrations, designated by C_{BZ}, are equal to or slightly less than the desired breathing zone concentrations, designated by C_{BZ}^{D}.

C_{BZG}° and C_{BZL}° -- Initial Breathing Zone Concentrations

The parameters C_{BZG}° and C_{BZL}° represent breathing zone concentrations experienced by workers prior to implementation of recirculation. C_{BZG}° is designated to be the time-weighted average (TWA) concentration originally experienced in open plant areas. By "open," it is meant that the workers present are in a region affected by the total ventilation rate through the plant area, and are not in a region affected only by induced flows from large volume exhaust systems. The following discussion concerning the parameter f defines differences between these two types of regions. C_{BZL}° represents original TWA concentrations in those plant areas which are influenced by the presence of large volume local exhaust hoods.

A number of pertinent questions need to be addressed about how, when, and where these concentrations are to be obtained. Among these are:

1. For which areas in the plant are these concentrations necessary?

2. What airborne substances in the workplace are of concern?

3. What is used for C_{BZL}° if the plant does not have local exhaust systems.

4. Should general area or personal sampling techniques be utilized to obtain these concentrations?

5. How accurate must the data be?

6. Are seasonal variations important?

7. Are there any differences in procedure for one, two, or three shift operations?

8. How are these concentrations to be determined for new plants, before they are built and put into operation?

The answer to the first question is that the C°_{BZG} values used for initial system design purposes should include the "open" area of the plant which contains the highest original concentration(s) of contaminant(s) of interest, and the area expected to be most influenced by the return air stream. Such concentrations are also necessary for major plant regions with differing concentrations, but only for the purposes of verifying that all breathing zone concentrations will be less than or equal to the maximum desired value C^{D}_{BZ}. Circumstances may arise with recirculation whereby a previously high contamination area becomes less contaminated than adjoining, previously lesser contaminated areas. In a similar fashion, values used for C°_{BZL} should represent breathing zone locations near local exhaust hoods which contain the highest original concentration(s) of contaminant(s), and for the location most influenced by the return air stream. Values for differing locations should be determined, again, for verification purposes.

In answer to the second question, it can only be stated that all substances are of concern. Recirculation, by definition, involves reintroduction into the room of partially cleaned air which previously was exhausted to the atmosphere. Therefore, to insure maximum safety of operation all contaminants must undergo exhaustive qualitative and quantitative analysis.

The third question addresses the issue of evaluating C°_{BZL} if local exhaust systems are not present. Obviously this parameter is set to zero for these conditions. Values of C°_{BZL} are also not required if the plant area has local exhaust systems, but these systems do not negate the influence of the total ventilation rate through the plant on breathing zone concentrations. In this case, breathing zone concentrations would be designated by C°_{BZG}, even if they were associated with locations near local exhaust hoods.

The issue as to whether general area sampling or personal sampling techniques are appropriate is simply answered by stating that both types are necessary and appropriate. Accurate determination of parameters affecting recirculation system design requires that:

a. A general area sampling program be conducted for all locations where exposed employees work;

b. A personal sampling program be performed for selected employees; and

c. That the results from both programs be compared by observing the amount of time spent by employees at each location during the course of a typical workday.

This two-pronged approach is necessary to identify abnormalities in data caused by the work practices of specific employees. Also, it is much less expensive to halt such practices than to design a recirculation system which accounts for their results.

The fifth question asks how accurate the data should be. The proper answer is that analytical methods utilized should be the best available for the contaminant(s) being addressed. Any errors in data utilized for system design purposes will have a direct bearing on the final values for every independent design variable contained in the recirculation system models. In other words, if the designer does not give the model the right numbers, the model will reciprocate. Incidentally, it is better to utilize concentrations which are too high, than to provide values too low. High values will only serve to better protect workers from the effects of a poorly designed recirculation system. However, the use of overly high values will limit the cost/effectiveness of recirculation designs. More specific guidance concerning how to determine airborne concentration levels can be found in the NIOSH Manual of Sampling Data Sheets (1), the NIOSH Manual of Analytical Methods (2), and a set of publications describing analytical methods developed during the NIOSH/OSHA Standards Completion Program.

Seasonal variations in breathing zone concentrations may be caused by differences in natural ventilation rates with concommitant variations due to changes in production rates, product types, etc. To account for these variations, the designer must give full consideration to all factors which can influence breathing zone concentrations. This is a difficult but necessary task, especially when desired breathing zone concentrations are equal to or only slightly less than permissible exposure limits. Similar consideration must also be given to all other concentration data required by the recirculation system design models.

The number of work shifts per day can be important if steady-state concentration levels are not quickly achieved during the first shift of each day. For one shift operations, it will usually be sufficient to utilize eight-hour TWA concentrations monitored during typical shifts. For longer workdays, experienced industrial hygienists should be consulted for aid in developing a monitoring program. These personnel should give full consideration to temporal variations in processes and trends or sequences in work practices which can affect breathing zone concentrations.

Determination of concentration parameters for new plants involves a methodology which is applicable to several additional input variables for the model. Therefore, direction regarding this issue is reserved for discussion in Section 9 of this Appendix.

C_G° and Q_G° -- The Initial Concentration and Volume of General Exhaust Air

In situations where the plant area of concern has a general mechanical ventilation system intended for recirculation, it is necessary to determine or estimate for each contaminant the time-weighted-average concentration, C_G°, in the general exhaust air stream of the conventional ventilation system. These concentrations, along with their associated exhaust volume, Q_G°, are utilized to define the mass rate of each contaminant leaving the plant area of concern before recirculation is implemented. Hence, for mass balance and safety purposes, it is important that these parameters be determined precisely or estimated conservatively, i.e., C_G°'s should be high and/or Q_G° should be low.

If C_G° is experimentally determined in an existing plant, the designer must ensure that the concentration used in models properly accounts for seasonal or other variations. These parameters need not be determined if the plant area of concern does not initially contain a general mechanical ventilation system. They can simply be defined as zero values in this case.

C_E° and Q_L -- The Initial Concentration and Volume of Local Exhaust Streams

For purposes of mass balance, certain of the design models require accurate information regarding the average concentration(s) of contaminant(s) in the local exhaust system streams intended for recirculation. These concentrations are designated by C_E°, and the total local exhaust volume intended for recirculation by Q_L. Depending upon the physical layout of the local exhaust ducts, these parameters may be determined by either of two methods.

When all local exhaust streams intended for recirculation enter a main duct leading to the atmosphere or to an air cleaner, the contaminant concentrations and flow volume are measured in the main duct. If such a measurement location is unavailable or inaccessible, the concentrations and flow volume in each branch duct must be separately determined and appropriately averaged or summed as illustrated in the following.

Given two or more branch ducts with specific contaminant concentration C_{E1}, C_{E2}, C_{E3}, . . . etc., and exhaust volumes Q_{L1}, Q_{L2}, Q_{L3}, . . . etc., it can be simply shown that:

$$C_E^\circ = \frac{C_{E1}Q_{L1} + C_{E2}Q_{L2} + C_{E3}Q_{L3} + \cdots}{Q_{L1} + Q_{L2} + Q_{L3} \cdots} \qquad \text{(for one specific contaminant only)}$$

$$Q_L = Q_{L1} + Q_{L2} + Q_{L3} + \cdots$$

The values utilized for C_E° will have a significant effect upon results of the system design process. As for other inputs required by the models, it is, therefore, necessary to ensure that C_E° and Q_L are accurately measured or conservatively estimated, i.e., C_E° should be on the high side and/or Q_L on the low side. If C_E° can fluctuate widely for various reasons, it is particularly important that the value used reflects the average for time periods during which C_E° is higher than usual. This action will ensure that the recirculation system maintains acceptable breathing zone concentrations during worst case operating conditions.

Note: Techniques for arriving at reasonable estimates of C_E° and C_G° in situations where they cannot be measured (when designing a new plant, for example) are discussed in Section 9 of this Appendix.

C_{MU} -- The Concentration in Make-up Air

Air exhausted from a plant area is generally replenished by an equivalent amount of make-up air. Any contaminant present in the make-up air provides a "background" level of contaminant concentration, C_{MU}, in workers' breathing zones. Knowledge of an average value for this concentration, for all contaminants and inlet air streams, allows the recirculation system model to differentiate between such background levels and those levels generated by operations being conducted in the area of concern. This differentiation, in turn, allows the model to partially or completely "replace" background levels caused by contaminants in make-up air streams with a background level caused by contaminants entering the room due to recirculation.

Measured or estimated values for C_{MU} should err on the low side for conservatism, since the lower the rate of contaminant entering with make-up air, the more stringent becomes the upper limit constraint on the concentration(s) of contaminant(s) in the recirculated air.

Q_G' -- General Exhaust Volume Not Recirculated

For one reason or another, it may not be advantageous to modify or consider for recirculation a general mechanical ventilation system which is separate from local or general exhaust systems intended for recirculation. In this case the parameter Q_G' is utilized to represent the flow volume of such a general exhaust system.

Q_{MU}' -- Fixed Make-up Air Supply Rate

In some plants, the energy available for tempering make-up air might be partially available, at little or no cost, from waste heat sources such as low quality steam and hot waste-water. Optimum use of such energy can be made by utilizing it either for making-up energy losses in the return air stream or for tempering a certain amount of fresh make-up air. In the latter case, the volume of such a stream could be accounted for in the model by specifying Q'_{MU}.

Q°_{MU} -- Make-up Rate for Conventional System

The parameter Q°_{MU} is simply the volume of make-up air necessary for all conventional ventilation systems in the plant area of interest before recirculation is implemented. In all cases, the models assume that Q°_{MU} equals the total volume of all exhaust volumes mechanically extracted from the area. If the existing system is not so balanced, then one must assume the system is balanced, and appropriately decrease the value specified for Q_N.

Q_N -- The Natural Ventilation Rate

Temperature differences and wind forces can cause infiltration, exfiltration, and natural ventilation of air to or from virtually any type of building. Depending upon the environment of the structure and its design, this natural ventilation rate may have a significant effect upon concentrations experienced in breathing zones. To facilitate estimation of the magnitude of such phenomena for any particular structure, the reader is directed to the following publications:

- ASHRAE Handbook of Fundamentals -- Chapter 19; (3)
- Plant and Process Ventilation by W.C.L. Hemeon -- Chapter 15;(4) and
- Fundamentals of Industrial Ventilation by V.V. Baturin -- Chapter 13(5)

ASHRAE is particularly useful for estimating air leakage through windows, doors, and walls. Hemeon and Baturin more fully treat ventilation caused by large heat sources within typical industrial buildings.

Designers are forewarned that the recirculation system design models presented in this report contain the assumption that all air mechanically extracted from a workplace will be mechanically made-up. In consequence, natural ventilation rates are not utilized in equations as a source of any amount of necessary make-up air.

A final note is that a specific value for this parameter is not required for model use when the parameter f has a value of 1.0, and/or the total ventilation rate through the plant area will be the same after recirculation as it was before recirculation ($Q_T = Q^{\circ}_T$). This occurs for the situation when only local exhaust is recirculated, the general mechanical ventilation rate remains unchanged, and the total rate of local exhaust is constant prior to and following recirculation.

Q_G -- Total General Mechanical Ventilation Rate Intended

For Recirculation

Normally treated as an independent design variable in computations, Q_G represents the total rate at which generally exhausted air, heading towards the air cleaning equipment train, is extracted from the plant area of concern. It need not be the actual volume which reaches this equipment if some amount of this air is by-passed to the outdoors.

Q_{LT} -- Total Local Exhaust Volume from Plant Area

Q_{LT} is the total exhaust volume rate for all local exhaust systems in the plant area of concern.

Q_{GB}, Q_{GB1}, Q_{LB}, and Q_{LB1} -- "Dirty" Exhaust Volume By-pass Rates

Some plants contemplating recirculation may be forced by local, state or Federal air quality standards to clean any exhaust volume emitted outdoors. In such situations, designers must specify cleaning of exhaust volumes before by-pass of some portion. This can be accomplished in Model #1 by using by-pass rate Q_{CB} instead of Q_{GB} and/or Q_{LB}. In Model #2, Q_{GB2} and/or Q_{LB2} would be used instead of Q_{GB1} and Q_{LB1}. All of these parameters are independent design variables.

Q_{MU1} -- Make-up Air Supply Rate for Air Mixed with Recirculated Air

In some specific situations it may be expedient to dilute contaminant concentrations in air exiting air cleaners by mixing this air with fresh make-up air. The rate at which fresh make-up air is introduced for this purpose is designated by Q_{MU1}. Q_{MU1} will usually be a dependent design variable in computations, its magnitude depending upon those of other exhaust volumes and make-up air supply rates.

Q_{MU2} -- Make-up Air Supply Rate for Air Not Mixed with Recirculated Air

When it is not practical to dilute recirculated air volumes with fresh air, Q_{MU1} should be set to zero and Q_{MU2} utilized to represent the necessary make-up air supply rate. Similar to Q_{MU1} in concept but differing in the manner in which it is brought into the plant, Q_{MU2} will also normally be a dependent design variable.

Q_D -- Air Volume Rate After "Clean" Air By-Pass

Q_D is simply the volume rate of air passing through the air cleaning equipment train, minus any volume rate of cleaned air by-passed to the outdoors after the train.

Q_R -- Return Air Volume Rate

Q_R is the volume rate of air entering a plant area from a recirculation system. It is simply the sum of Q_D and Q_{MU1}.

η -- The Air Cleaner Efficiency

The efficiency of an air cleaning device is related to the loading on the cleaner and exhaust concentration by the relationship:

$$\text{System efficiency } (\eta) = \frac{\text{Concentration in - concentration out}}{\text{Concentration in}}$$

Hence, an air cleaning device which can reduce a 10 mg/m^3 inlet concentration to 1 mg/m^3 has an efficiency of 0.90 for the specific contaminant in question. Obviously, then, the higher the efficiency of a particular device, the lower the outlet concentration delivered by the device.

When more than one air cleaning device is placed in series, the overall air cleaning efficiency of the equipment train can be estimated from:

$$\text{Overall Efficiency} = [1 - (1 - \eta_1)(1 - \eta_2)(1 - \eta_3)]$$

where η_1, η_2, η_3 . . . are the efficiencies of the individual air cleaning devices for a particular contaminant being addressed. When air cleaning devices are placed in parallel, the appropriate overall efficiency for use is that for the equipment in any branch; assuming, of course, that each branch contains identical equipment.

The efficiency of air cleaning devices sometimes depends upon the contaminant concentration at the inlet to the cleaner. For particulate contaminants, the particulate size distribution of the contaminant entering the device is also important. Consequently, where cleaners are placed in series, the designer must estimate the efficiency of each device based upon the characteristics of the air stream which actually enters that device. Where particulates are being treated, careful attention must be given to the efficiency of the overall equipment train in regards to the respirable dust fraction as well as the total dust count. When the efficiency of a unit, such as a bag filter, changes during its operating cycle, the designer must ensure that periods of time when cleaner efficiencies are low do not result in breathing zone concentrations in excess of ceiling limits.

k_R -- Contribution Factor of Return Air to Local Exhaust Systems

To aid in defining the amount of contaminant which re-enters the recirculation system after leaving the air cleaner, the "contribution factor" k_R has been introduced. By definition, this factor represents the actual physical fraction of locally exhausted air which comes directly from the return air stream. In consequence, valid values for the factor can only range between zero and one, inclusive, and often will be even more restricted in range.

To illustrate the concept of k_R, refer to Figure A1. Figure A1a illustrates examples of plant areas which have recirculation rates equivalent to the volume of air exhausted from the workplace. Since no other air volumes leave or enter these areas, the value for k_R can only be 1.0 (disregarding natural infiltration).

Figure A1b illustrates a case where part of the air volume being exhausted must come from the 50,000 cfm fresh make-up supply. Without reservation, 0.75 is the only correct value for k_R (disregarding infiltration). Figure A1c represents the other extreme possible. Here, because there are no local exhaust systems present in the plant area, k_R can only have a value of zero.

Figure A1d shows plant areas in which the value for k_R can range from a computable minimum to a computable maximum value.

To compute the actual limits within which k_R can range for any particular system design, we perform the following computations:

a. Compute the volume of fresh air which enters the work area and call it Q_f.

$$Q_f = Q_{MU2} + Q'_{MU} + Q_N$$

b. Compute the volume of return air from the recirculation system and call it Q_R.

$$Q_R = Q_G - Q_{GB} + Q_L - Q_{LB} - Q_{CB} + Q_{MU1}$$

c. The minimum value for k_R is then the <u>greater</u> of:

$$0.0 \ \underline{\text{or}} \ \frac{Q_L - Q_f}{Q_L}$$

d. The maximum value for k_R is the <u>lesser</u> of:

$$1.0 \ \underline{\text{or}} \ \frac{Q_R}{Q_L}$$

In actual practice, it will often, but not always, be found that the specific value for k_R does not have a significant effect upon final design parameter values selected. This will be especially true when the overall efficiency of the air cleaner equipment train is high for each contaminant of interest, and the concentration(s) of contaminant(s) in fresh make-up air supplies are low. Since both of these conditions are typical, it is

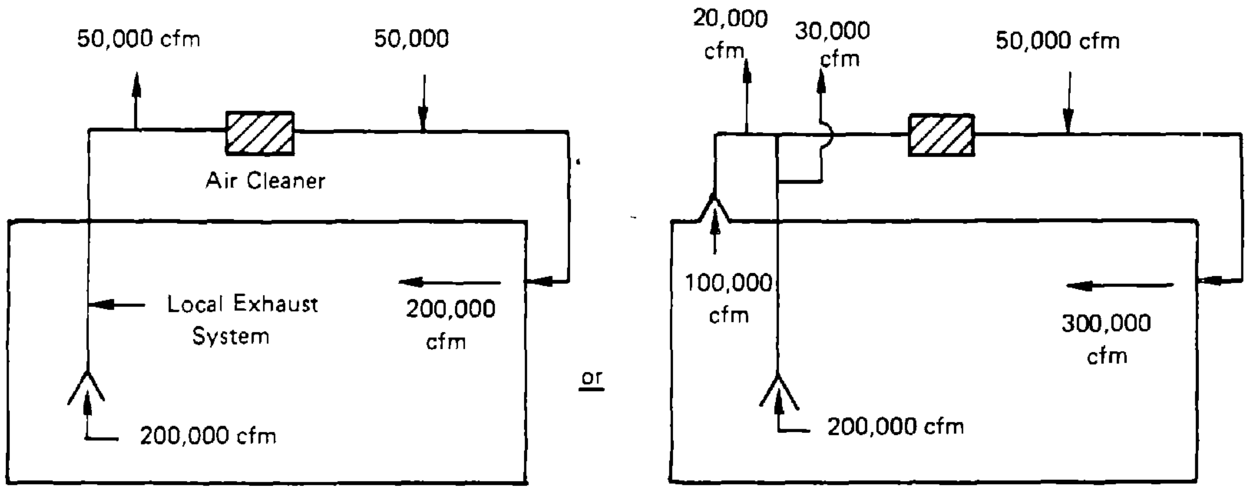


Figure A.1a (k_R = 1.0 Only, Disregarding Natural Infiltration)

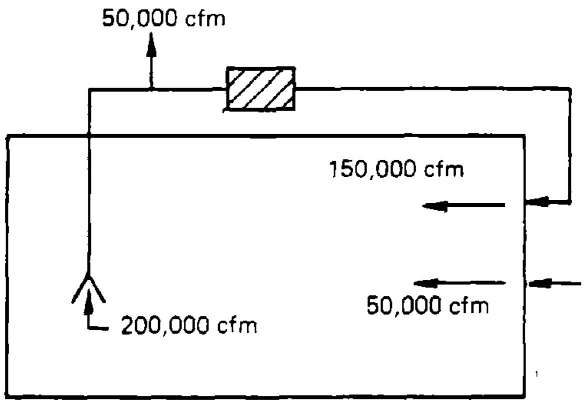


Figure A.1b

$$k_R = \frac{200{,}000 - 50{,}000}{200{,}000} = 0.75 \text{ Only}$$

(Disregarding Infiltration)

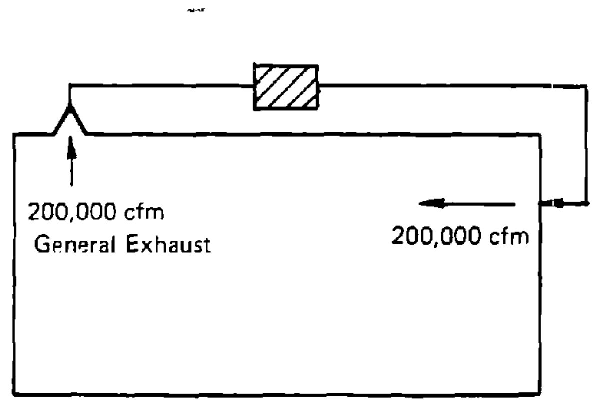
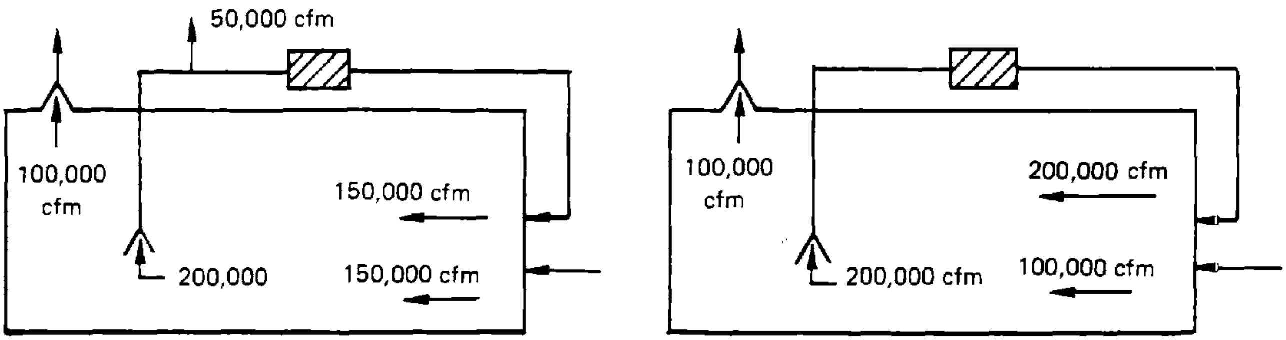


Figure A.1c

k_R = 0.0; No Local Exhausts



$0.25 \leqslant k_R \leqslant 0.75$ (Disregarding Infiltration)

Figure A.1d

$0.5 \leqslant k_R \leqslant 1.0$ (Disregarding Infiltration)

FIGURE A1 . ILLUSTRATION OF k_R CONCEPT unnecessary to become overly concerned with precisely defining a value for k_R. A reasonable estimate, on the high side of the possible range for conservatism, should suffice.

k_{BZ} -- Contribution Factor of Return Air to Breathing Zones

A second contribution factor introduced is k_{BZ}. Similar to k_R in definition, it represents the actual physical fraction of breathing zone air which comes from the return air stream. It also can only range in value in the closed interval zero to one. Unlike k_R, however, particular limits for k_{BZ} within the range 0 - 1 cannot be directly computed, except in very special circumstances.

Figure A2 illustrates that the physical configuration of the work environment must be carefully assessed to arrive at a reasonable value for k_{BZ}. In Figure A2a, a worker stands directly in an inflow stream of fresh make-up air. Obviously, this worker will not experience significantly increased breathing zone concentrations due to the implementation of recirculation. Consequently, one is justified in choosing a fairly low value for k_{BZ} for this case. Other circumstances under which such a choice would be justifiable include:

a. When all return air is being utilized for "push-pull" systems and the worker is well away from the stream between the air outlet and inlet;

b. When, regardless of system configuration, employee breathing zones are continually and solely flushed with fresh make-up air; and

c. When the return air stream is introduced by means of an air distribution system with a number of widely separated outlets, and/or the return air volume is a small fraction of the total ventilation rate through the plant area of interest.

In Figure A2b the opposite case occurs as the exposed worker is between the return air inlet and the points in the plant where air is extracted. Here it is reasonable to expect a relatively high value for k_{BZ} to be appropriate. As a special case, note that k_{BZ} can have a value of one and only one if there were no fresh make-up air supply to the plant area shown.

Figure A2c represents the situation which requires careful attention. Although a k_{BZ} of 0.5 appears reasonable as a first approximation, any of a number of factors could produce a k_{BZ} value of zero, or one or anything in between. To be conservative, one can make the worst case assumption that k_{BZ} is one.

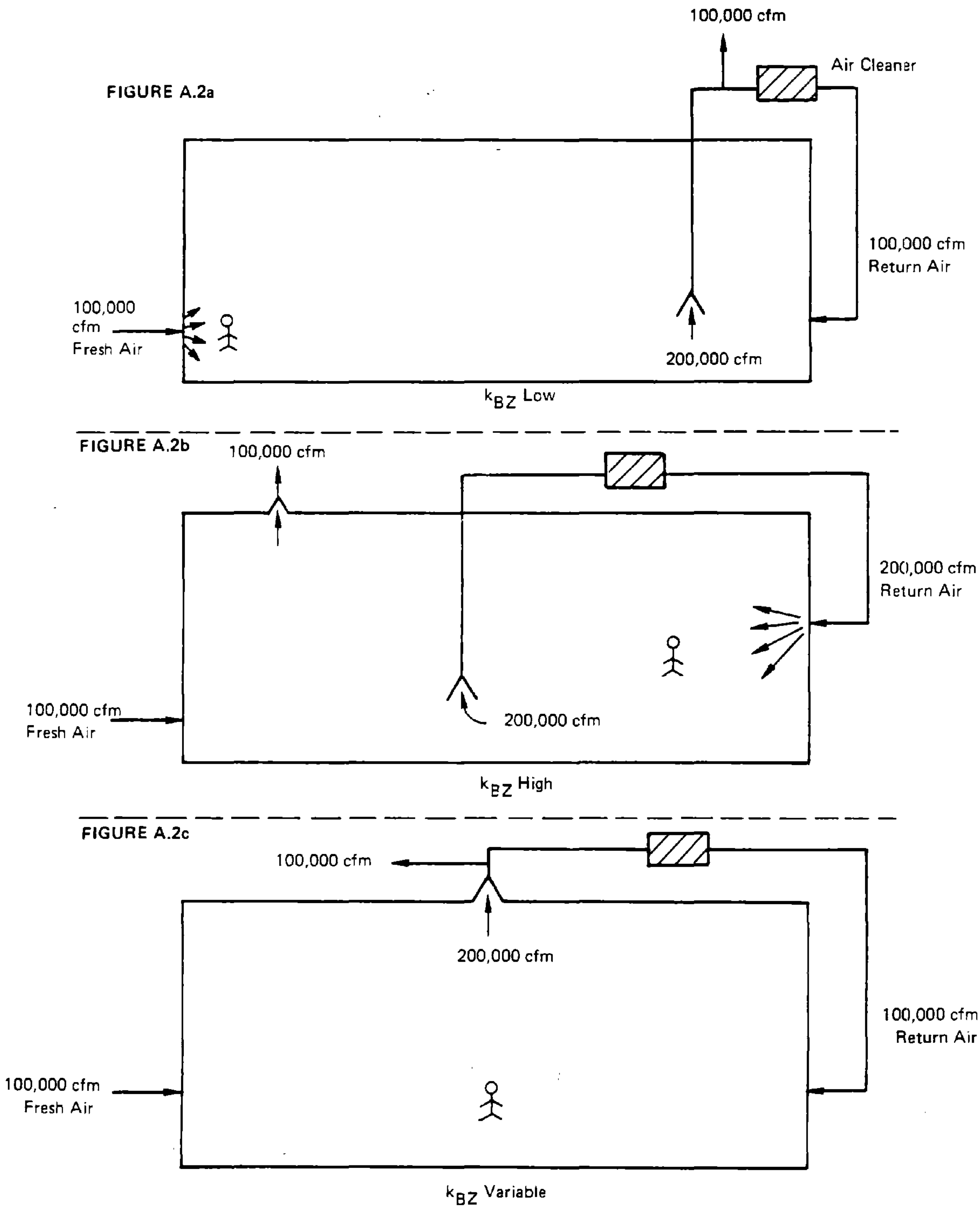


FIGURE A2 ILLUSTRATION OF k_{BZ} CONCEPT

Inspection of the breathing zone concentration equation will indicate that predicted concentrations are directly proportional to the value chosen for k_{BZ}. Figure A3 illustrates the effect upon predicted breathing zone concentrations for a range of k_{BZ} values and a variety of C_R concentrations (the concentration of contaminant(s) in the return air stream). The example leads to a number of interesting observations concerning the sensitivity of breathing zone concentrations to design parameters. Among these are:

a. The value for k_{BZ} has no effect upon predicted concentrations if the contaminant concentration in return air is the same as the concentration in fresh make-up air; and

b. The sensitivity of predicted breathing zone concentrations to k_{BZ} values increases with increases in the value of the ratio C_R/C_{MU} and values for k_{BZ}.

These observations, in turn, lead to some important qualitative guidelines to be followed in designing recirculation systems. These are:

a. The undesirable effects of utilizing too low a value for k_{BZ} in computations can be reduced by minimizing C_R. It is, therefore, advisable to reduce C_R by mixing fresh or other relatively clean air with the air released from the air cleaner, or to utilize conservatively estimated k_{BZ} values in computations, i.e., use higher than probable values); and

b. The sensitivity of C_{BZ} to k_{BZ} decreases with lower k_{BZ} values. Thus, return air distribution systems should be designed to minimize actual k_{BZ} values. (Other important reasons for this action are discussed in a section concerning system failures).

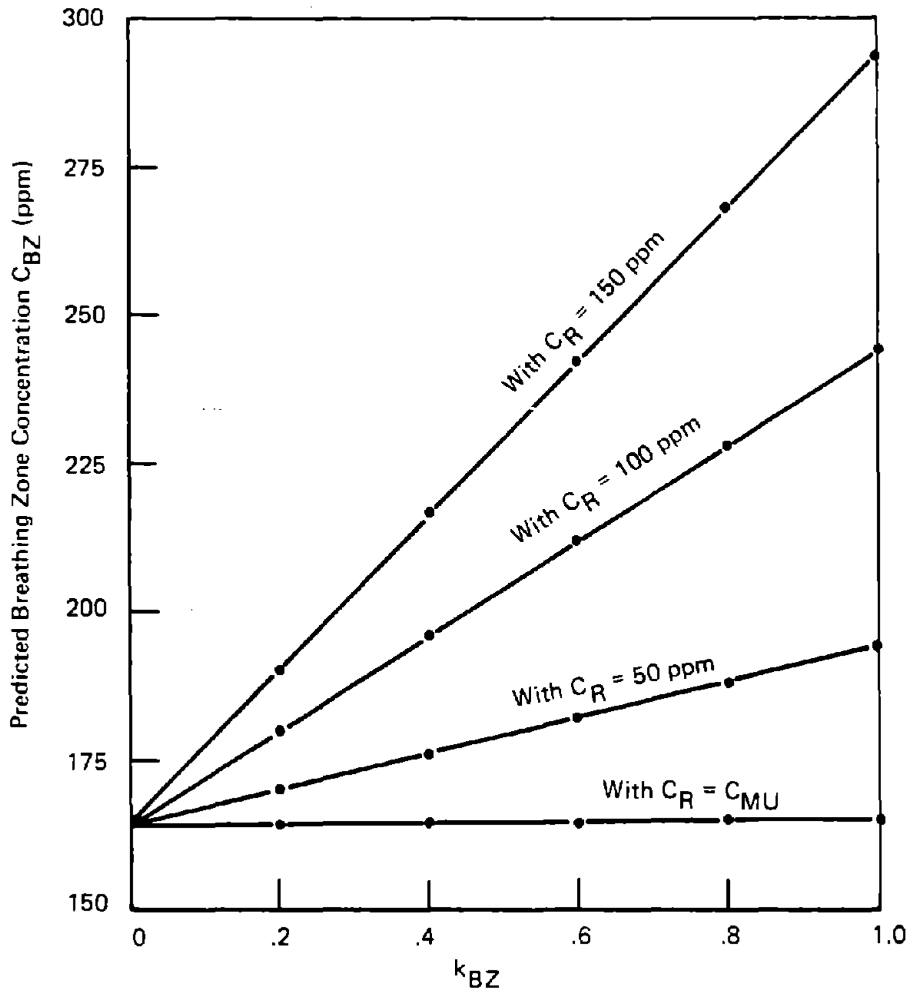
In existing plants already containing the ductwork and fans intended for use with the recirculation system, one may attempt to determine k_{BZ} experimentally. This can be done by continuously releasing a tracer-gas into the main air supply duct which is intended to be used for the return air stream, and then measuring tracer-gas concentrations in breathing zones of interest and at inlet points. An indication of the appropriate value for k_{BZ} would then be given by:

$$k_{BZ} \cong \frac{C_P}{C_R}$$

where:

C_P is the peak tracer-gas concentration(s) measured in breathing zones; and

C_R is the tracer-gas concentration in air out of the air supply duct.



Design Parameters For Example:

$f = 0.0$

$Q_T = 1.25\, Q_T^o$

$C_{BZG}^o = 200$ ppm

$C_{MU} = 20$ ppm

$$C_{BZ} = \frac{1}{1.25}(200-20) + 0.0 + k_{BZ}\, C_R + (1-k_{BZ})\,(20)$$

FIGURE A3 SENSITIVITY OF C_{BZ} TO k_{BZ} AND C_R

It is interesting to note that, although the definition for k_{BZ} previously given is valid, k_{BZ} can also be defined as a ratio of contaminant concentrations in breathing zones to concentrations in return air streams. This is in contrast to a definition for the currently used mixing factor K which indicates:

$$K = \frac{C_P}{\overline{C}}$$

where:

- K is the traditional mixing factor (not including an arbitrary safety factor);
- C_P is the breathing zone concentration experienced; and
- $\overline{C}$ is the average contaminant concentration in a plant area as would occur if perfect mixing immediately took place between all air volumes.

The primary advantage of using k_{BZ}, and indeed, the reason for its introduction, is that it is a ratio of real concentrations with measurable, and understandable, physical significance. A more complete expression for k_{BZ} in terms of concentrations, as actually used in design computations, is:

$$k_{BZ} = \frac{(\Delta C_P - C_{MU})}{C_R - C_{MU}}$$

where

- ΔC_P is the increase of contaminant concentration in breathing zones when recirculation is initiated.

The previous equation given for k_{BZ} is a special case which assumes the tracer gas is not normally present in fresh make-up air or in breathing zones.

Another topic to be discussed involves one of the assumptions upon which the breathing zone concentration equation is based. This assumption concludes that contaminant concentrations entering breathing zones from different sources are additive. It requires that the air distribution system is designed to insure return air streams are properly mixed with any air present in the workplace. If this did not occur, the breathing zone concentration experienced would be C_{MU} or C_R and not the value predicted by the equation.

Design of a post-recirculation air distribution system which forces fresh air, and only fresh air, through breathing zones is a feasible approach, and is not in any way discouraged. What is generally discouraged is the practice of directing return air streams directly into worker breathing zones. The reason for this is that breathing zone concentrations might immediately increase to harmful levels if an air cleaning device malfunctions. Therefore, it is recommend that return air streams be distributed throughout plant areas in a manner which minimizes the actual value for k_{BZ}, allows the breathing zone equation to be valid, and provides sufficient time for response if an air cleaner fails. These latter topics are more fully discussed in a section concerning system failures.

A final comment about k_{BZ} concerns the fact that this parameter may or may not be treated as a constant in computations, depending upon the manner in which fresh make-up air is brought into the plant. Each of the recirculation models presented provides the designer with the option of premixing make-up air with recirculated air (using parameter Q_{MU1}) or of bringing the fresh air in separately (using parameter Q_{MU2}).

With premixing, the designer need only estimate a single, accurate value for k_{BZ} which is used as a constant in the computations. This is a direct consequence of the fact that all air volumes entering the plant will remain as constants, and only concentrations in inlet streams will be affected by parameter adjustments during the optimization procedures. In the alternate case, concentrations will remain constant, but volumes will change. Since changes in volumes can affect the actual value for k_{BZ}, it will be necessary to assign a different k_{BZ} value to each breathing zone location of interest for each different make-up air volume (Q_{MU2}) utilized in the iterative procedure. This will obviously require considerably more effort because one air volume may be highly contaminated (Q_R), the other may be slightly contaminated (Q_{MU2}), and mixing is attempted in the workplace rather than in the return air duct.

f -- Local Exhaust System Influence Factor

It is well understood that air movement in the work environment is directed towards openings under negative pressure, i.e., towards any typical local exhaust hood. Consequently, "flow contours" exist in front of hoods where these contours, in two-dimensional representations, are described as "lines" of equal velocity. Normally, for round hoods, and for rectangular hoods which are essentially square, there is a rapid velocity decrease experienced with increasing distances from the hood, varying almost inversely with the square of the distance, up to a distance about 1.5 times the diameter of round hoods or the side length of essentially square hoods. Beyond this distance, velocity decreases somewhat less rapidly with distance. At relatively far distances from the hood, moderate or high cross draft velocities can disrupt this air velocity profile, while the effect of cross drafts is negated upon close proximity to the hood.

While developing the breathing zone concentration equation discussed in "The Breathing Zone Equation" section of this appendix and elsewhere, it was realized that the air flow patterns experienced by workers near large local exhaust hoods will significantly differ from those experienced by workers distant from such hoods. Upon examining the situation closely, it was concluded that these differences must be considered when assessing the effects of recirculation upon individual breathing zone concentrations.

If a worker stands in an open area of a plant with a conventional ventilation system, and the general ventilation rate is increased, the contaminant exposure will decrease somewhat proportionally to the ratio of the before and after total ventilation rates. This is understandable and is a basic assumption of commonly accepted general dilution equations. However, if the same worker enters a large local exhaust hood (e.g., a walk-in spray booth) and the general mechanical ventilation rate is increased, the worker's breathing zone concentration will change only due to changes in the background level of contaminant in air flowing past the worker. The air flow volume through the breathing zone, at small distances from the hood, will be the same before and after the increase.

To allow the breathing zone equation to account for the possible effects of such local exhaust hood induced flow fields, a local exhaust system influence factor f has been introduced. This factor is defined as being the fraction of the workday that a worker normally spends within a local exhaust flow field: For example, f equals one for a situation where the entire workday is spend in the flow field. If six hours are spent in a flow field and two hours in open plant areas, the f value would be 6/8 or 0.75. When the worker never approaches local exhaust hoods, or such hoods are not present in his work area, the proper value for f is zero.

Figure A4 further illustrates the concept of f. Here, in Figure A4a a worker is shown at the face of a large, locally exhausted booth. Obviously, if there is a typical face velocity of 100 fpm or greater at the hood face, the breathing zone concentration experienced by the worker will not be significantly influenced by changes in the general mechanical ventilation rate. Figure A4b represents the other extreme, with the worker shown in an open area well away from the booth. Hence, changes in the rate of general ventilation will directly influence breathing zone concentrations.

In actual practice, it will often be difficult to define a value for f which will be valid for all times following installation of the recirculation system. Individual work practices and changes in plant production rates and product lines can at any time cause significant variations in the actual value. To fully account for such changes with time, it is suggested that designs be completed on the basis that a worker spends all or most of the day in the local exhaust flow field (f = 1.0), or on the basis that the worker only occasionally enters such a flow field (f = 0.0). Indeed, for complete characterization of contaminant concentrations in workroom air, the designer should strive to provide fully acceptable working environments in both types of locations, i.e., so

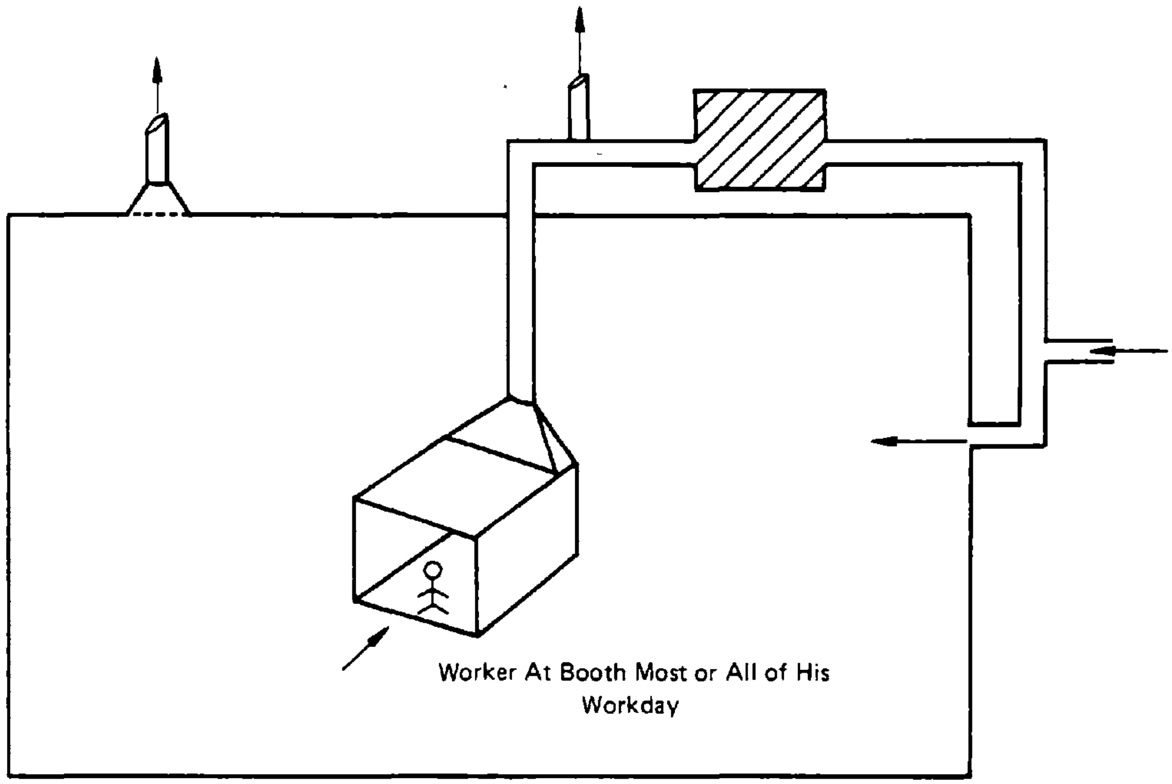


Figure A.4a (f = 1.0)

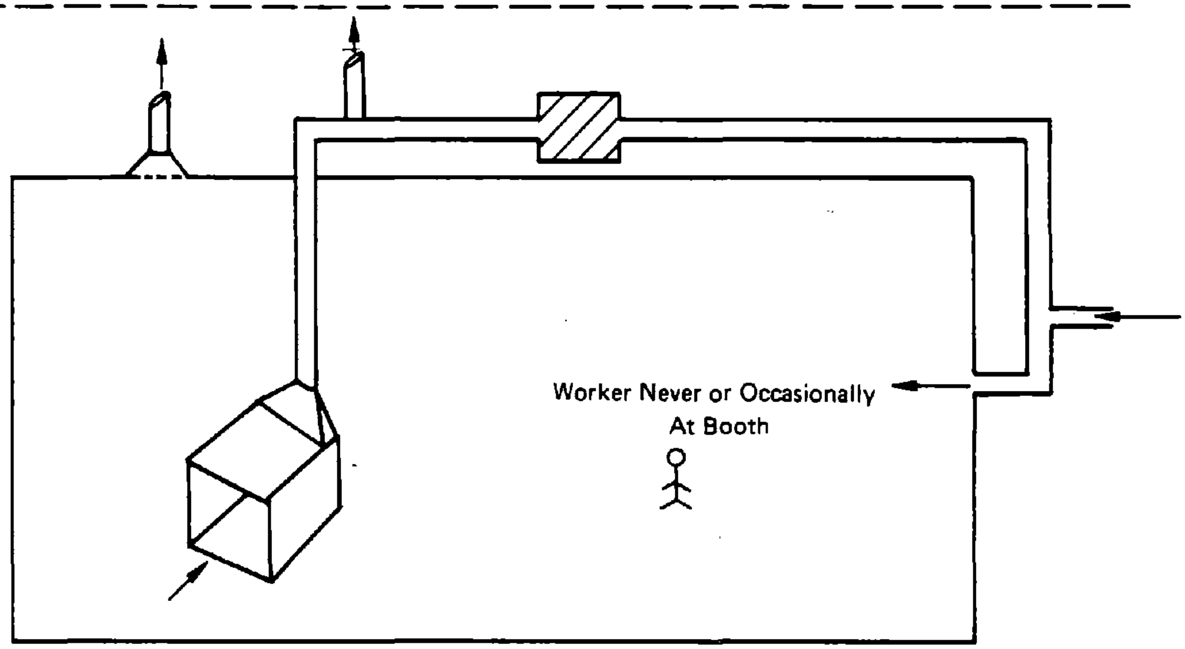


Figure A.4b (f = 0.0)

FIGURE A4 **ILLUSTRATION OF f CONCEPT**

that 8-hour TWA breathing zone concentrations are always at or below desired levels (C^D_{BZ}) both in front of large, local exhaust hoods and in the general plant area. This is accomplished by ensuring that the final computed value for C_{BZ}, the predicted breathing zone concentration, is less than or equal to C^D_{BZ} regardless of whether f equals zero or one.

In the example above, a large walk-in type booth was utilized for illustrative purposes because it clearly represents a hood which influences air velocities through breathing zones. When other types of large volume hoods are involved, it is not quite as simple a task to identify whether or not the hood will produce the kind of flow field being addressed, but a great deal can be said in the way of qualitative guidelines. These are:

a. The air velocity at any point in front of a hood can be estimated from equations presented in Chapters 4 and 5 of the ACGIH Industrial Ventilation Manual[4] and in numerous other reference materials. If the velocity computed (or measured) for breathing zone locations is greater than cross draft velocities and is in the direction of the hood (as estimated, measured with instruments, or determined from smoke tube studies), the flow field will influence the breathing zone air velocities.

b. Low volume-high velocity hoods near contaminant sources are unlikely to influence breathing zone air velocities.

c. Flanged open hoods are somewhat more likely to be of influence than unflanged hoods.

d. Walk-in booths used for various purposes are likely to produce the types of flow fields of concern.

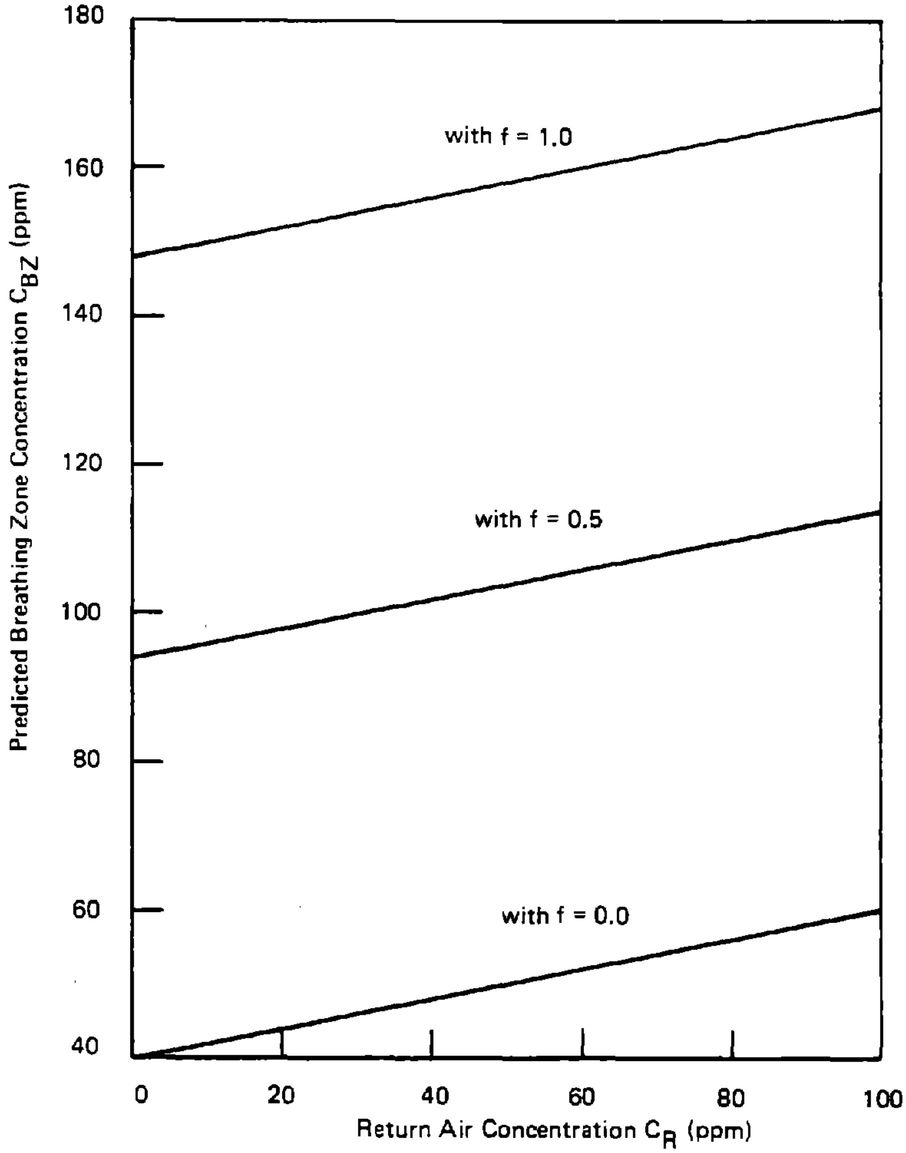
Finally, it is necessary to illustrate the effect of f upon predicted breathing zone concentrations. This is done if Figure A5 for a representative set of design parameters. Inspection of the figure reveals the following features of interest.

a. The value of f has no effect on the sensitivity of C_{BZ} to C_R.

b. Predicted C_{BZ}'s are proportional to f values; and

c. The degree of C_{BZ} sensitivity to f is strongly influenced by the difference between the expressions;

$$\frac{Q^\circ_T}{Q_T}\ (C^\circ_{BZG} - C_{MU}) \text{ and } (C^\circ_{BZL} - C_{MU}).$$



Design Parameters for Example:

$Q_T = 1.25\, Q_T^o$

$C_{BZG}^o = 50$ ppm

$C_{BZL}^o = 150$ ppm

$C_{MU} = 20$ ppm

$k_{BZ} = 0.20$

$$C_{BZ} = (1-f)\,\frac{Q_T^o}{Q_T}\,(C_{BZG}^o - C_{MU}) + f\,(C_{BZL}^o - C_{MU}) + k_{BZ}\,C_R + (1-k_{BZ})\,C_{MU}$$

FIGURE A5 **SENSITIVITY OF C_{BZ} TO f AND C_R**

The first observation serves to confirm the previous conclusions regarding the sensitivity of C_{BZ} to variations in k_{BZ} and C_R. It is arrived at by noting that the slopes of the three straight lines on Figure A5 are identical.

The second and third features noted are interrelated. These indicate that the values for f strongly influence predicted C_{BZ}'s, and that the degree of influence is determined by the difference in breathing zone concentrations experienced near local exhaust hoods and in open plant areas. It is because these differences will typically be considerable in plants containing local exhaust systems, and because it is difficult to precisely determine values for f, that it was recommended above that designers ensure safe working environments when f is either 0.0 or 1.0. If breathing zone concentrations are acceptable at these extremes, they will also be acceptable for all intermediate f values.

4. THE BREATHING ZONE EQUATION

As previously noted, an equation has been developed which attempts to utilize estimated contaminant concentrations in return air streams to predict breathing zone concentrations after recirculation is implemented. Since the calculation of the post-recirculation breathing zone concentration is a critical requirement for the successful development of any recirculation system, the importance of the breathing zone equation cannot be overstated. Underlying the analysis are the following questions and their attendant answers. These show how the breathing zone equation was developed in a step-by-step and straightforward manner.

Question: There is an employee in an open plant area with general mechanical ventilation. This employee never approaches locally exhausted operations. What is the concentration level in the breathing zone of this worker with the conventional ventilation system operating?

Answer: The TWA breathing zone concentration for this employee can be designated by C^o_{BZG}. It is a measurable quantity in any existing plant, an estimable quantity for new plant operations.

Question: At present, the total ventilation rate through the plant area can be designated by the parameter Q^o_T. It is known that increasing this rate will decrease the contaminant concentration in the worker's breathing zone. What will the concentration (C_{BZ}) be if the total rate is changed from Q^o_T to Q_T?

Answer: It is generally accepted that breathing zone concentrations are proportional to the ratio of total ventilation rate through the plant area of concern before and after recirculation. Thus, doubling the ventilation rate, with the same air distribution pattern, will essentially halve the breathing zone concentration experienced. The relationship of these parameters is therefore:

$$C_{BZ} = \frac{Q^o_T}{Q_T} \quad (C^o_{BZG})$$

Question: There are solvents in this plant area. Won't increased air velocities cause more of these solvents to evaporate?

Answer: In this analysis, it is assumed that an increased ventilation rate does not cause significantly increase contaminant generation. If it will in your plant, then you must use considerable caution in attempting to reduce concentrations by increasing the total ventilation rate.

Question: Will increased ventilation rates effect the performance of local exhaust hoods?

Answer: There are no problems if a moderate ventilation rate is used with properly designed exhaust hoods which are currently free from excessive cross drafts.

Question: Will return air streams cause the breathing zone concentrations to change if I initiate recirculation?

Answer: Currently, the employee is exposed to a concentration of C^o_{BZG}. Most of the contaminants in his breathing zone come from sources all around him. A small part of them may come from concentrations found in the make-up air supply. For the moment, assume that the recirculated air passes directly through the worker's breathing zone, and that this air will replace the fresh make-up air that used to pass his location. The new breathing zone concentration will be:

$$C_{BZ} = \frac{Q^o_T}{Q_T} \quad (C^o_{BZG} - C_{MU}) + C_R$$

where: C_{MU} is the original concentration of contaminant in your make-up air; and

C_R is the concentration in the return air stream

Question: If I increase the total ventilation rate somewhat, and make sure that C_R isn't very much greater than C_{MU}, can I keep the breathing zone concentration the same?

Answer: Yes, but the positioning of the return air stream in the employee's face severely limits what C_R can reasonably be and causes other problems in the event of system failure. Thus, this practice is not generally recommended.

Question: What should be done?

Answer: The return air stream can be introduced at several locations within the plant. This may result in dilution of the return air by other air streams before return air reaches the worker, and thus a new parameter must be introduced to quantify the portion of the worker's breathing zone air which comes from the return air stream. This parameter, k_{BZ}, is defined as being the physical fraction of breathing zone air originating in the return air stream. We can make a good guess at k_{BZ}'s value or, for an existing plant, we can utilize tracer gas studies to measure it.

Question: What does this factor physically represent?

Answer: It represents a real quantity of air that started out at concentration C_R and has become diluted as it moves through the plant. If return air were going past the worker's location at full strength, then k_{BZ} would have a value of 1.0. If none of this air reached the worker, k_{BZ} would be 0.0. If half the air breathed by the worker came from the return air stream, k_{BZ} would be 0.5. Thus, it can only vary from zero to one, inclusive.

Question: How is k_{BZ} used in the equation?

Answer: Previously, C_R represented the new background level when the return air stream flowed past the worker intact. For this case k_{BZ} had a value of 1.0. Inserting k_{BZ} into the equation yields:

$$C_{BZ} = \frac{Q_T^o}{Q_T}(C_{BZG}^o - C_{MU}) + k_{BZ}C_R + (1-k_{BZ})C_{MU}$$

Question: What is the last term?

Answer: The last two terms together define what the new background mixture concentration will be for the air passing through the worker's breathing zone.

Question: How are work locations such as large spray booths addressed?

Answer: These can result in exposure to higher concentrations than found in normal plant locations. Also, increases or decreases in the general mechanical ventilation rate through the room do not greatly affect the contaminant concentrations in these booths.

Question: Why won't these workers benefit from an increased general ventilation rate?

Answer: Spray booths which have an average face velocity of approximately 100 to 150 feet per minute under good operating conditions will be unaffected by the external workplace environment. Therefore, this represents a special case situation.

Question: What is the functional form of the equation for this special case?

Answer: First, designate the TWA concentration in one of these booths, or near one of the other systems, by C^o_{BZL}. This quantity can be estimated or carefully measured. Using an analysis analogous to that above, it can then be shown that:

$$C_{BZ} = (C^o_{BZL} - C_{MU}) + k_{BZ}C_R + (1-k_{BZ})C_{MU}$$

Question: This is similar to the previous equation except that the Q^o_T over Q_T multiplier is missing from the first term and a different initial concentration is used. Is k_{BZ} going to have the same value for workers in booths as for workers in the general plant area?

Answer: The value for k_{BZ} is going to be different for each work location. A high value can be selected to cover all workers, or actual values can be determined for work locations near return air supply inlets and for locations which had the highest initial exposures.

Question: Can the two equations be combined?

Answer: To do so, a factor called the local exhaust hood influence factor (f) must be defined.

Question: What is the influence factor?

Answer: This is the fraction of the workday that a worker spends in a booth and/or in the flow field of a large volume local exhaust hood. Like our other factors, it theoretically ranges from zero to one: 0.0 when the worker never approaches local exhaust hoods, 1.0 when the entire workday is spent in the flow field, and something intermediate when the worker only spends part of the day in a flow field. For workers who spend half the shift in an operating spray booth and half out, f would be 0.5. The complete equation now becomes:

$$C_{BZ} = (1-f)\,\frac{Q_T^o}{Q_T}\,(C_{BZG}^o - C_{MU})$$

$$+ \; f(C_{BZL}^o - C_{MU})$$

$$+ \; k_{BZ}\, C_R$$

$$+ \; (1 - k_{BZ})\, C_{MU}$$

Question: When f is 0.0, we have the first equation, and when it's 1.0, we have the second equation. When it's between the two limits a hybrid results. What does C_{BZ} mean when f is not 0.0 or 1.0?

Answer: If C_{BZG}^o is the TWA concentration in your general plant area, and C_{BZL}^o is the TWA concentration for a worker in a booth, C_{BZ} is the overall TWA breathing zone concentration for a worker who spends fraction f of his time in the booth.

Question: How can a single value of k_{BZ} be used for a worker who is mobile within the plant?

Answer: The problem arises from the fact that it is difficult to determine an accurate value for f. A value observed on one day could be completely different on the next day, even when the same worker is studied. Furthermore, the value might vary with changes in production rates, products manufactured, etc. To resolve the problem, it is recommended that only values of 0.0 and 1.0 be considered for f. If workers do not enter local exhaust system flow fields, a value of 0.0 should be selected for f, an appropriate value for k_{BZ} determined, and computations performed. If workers do spend considerable time in local flow fields, a similar procedure should be undertaken with f equal to 1.0. To be safe, calculations should be carried out for both conditions if both types of these conditions exist in the plant.

Question: Why do both?

Answer: If the design insures that 8-hour TWA concentrations are acceptable both within the flow fields and in the general plant area, then there is no possibility of selecting a design which is safe only when the worker spends a specific (f) fraction of him time in the flow field.

Question: What would the complete equation be if a more rigorous treatment were given to k_{BZ}. This equation may be useful for redesigning conventional ventilation systems.

Answer: The complete equation is:

$$C_{BZ} = (1-f)\frac{Q_T^\circ}{Q_T}(C_{BZG}^\circ - C_{MU}) + f(C_{BZL}^\circ - C_{MU}) + k_{BZG}C_R + (1-k_{BZG})C_{MU} + k_{BZL}C_R + (1-k_{BZL})C_{MU}$$

where:

k_{BZG} is the return air contribution factor for breathing zones in open plant areas; and

k_{BZL} is the factor for zones in local exhaust system induced flow fields.

Question: What about background contaminants in the make-up air?

Answer: The concentration of contaminant in make-up air, if any is there to begin with, will probably drop upon recirculating. This will be especially true when the current make-up air system re-entrains some of your exhaust air. After all, recirculation systems usually contain air cleaners which reduce the amount of contaminants released to the atmosphere. An even more rigorous derivation of these equations requires that a different value of C_{MU} be applied to original breathing zone concentrations than to other parameters in the equation.

Question: Is this important?

Answer: The procedure to estimate the new level of C_{MU} is very complicated and full of uncertainties. By assuming that the level stays constant, a slight amount of conservatism is added to the equations and improves the ease of application. The contaminant concentrations involved are much less than those in the breathing zone and are often negligible.

5. INHERENT ASSUMPTIONS OF THE MODELS

The models which will be presented contain a number of inherent assumptions requiring identification. In the following section, the most important of these assumptions are stated and discussed.

Steady-State Assumptions

In plants which do not conduct operations on a 24-hour basis, there will be some period of time each day when process equipment and/or ventilation systems are turned off. During such periods of time, natural and other ventilation processes will tend to significantly reduce contaminant concentrations existing throughout the plant at the end of the previous shift. Following reactivation of equipment and ventilation systems, contaminant concentrations will again increase to their previous "steady-state" levels.

A major assumption of all models presented is that a steady-state representation of all concentrations is adequate for design purposes. This presumes that all contaminant-producing activities within any plant area of concern will continue for a sufficient length of time that all concentrations will approach, and stabilize at, fairly constant values. Figure A6 serves to illustrate how these concentrations would increase with increasing time. C^o is the concentration experienced at time equals zero, and C' is the final steady state concentrations achieved at approximately time T'.

To assess the overall effect of the steady-state assumption upon system design procedures, it is necessary to discuss a number of topics separately. Among these are:

a. Breathing zone concentrations near locally exhausted operations;

b. Breathing zone or other concentrations in general plant areas; and

c. Concentrations in local exhaust ducts.

Contaminant concentrations near locally exhausted operations are usually higher than "background" concentrations in general plant areas. This is generally due to the fact that certain volumes of contaminated air can escape from hoods due to a variety of factors, and this causes more severe exposures near hoods than would be experienced at locations distant from the hoods. Taking into account the reasons for these higher concentrations, it is concluded that breathing zone concentrations near hoods will increase very rapidly when the operation is started-up, and that the concentration after a matter of minutes will be much closer to C' than to C^o. The remaining increment to bring the concentration up to C' will disappear somewhat more slowly as background contaminant levels increase. In direct consequence, the time period from T^o to T' will be relatively short, for all practical purposes, and the steady-

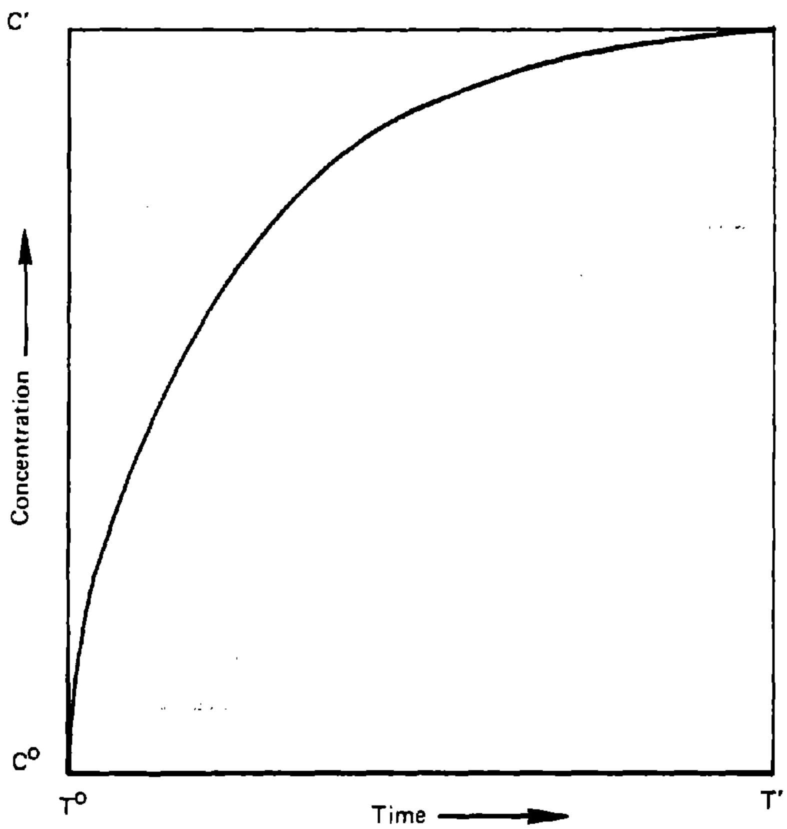


FIGURE A6 ILLUSTRATION FOR STEADY-STATE ASSUMPTION state assumption can generally be accepted as not having a significant effect upon predicted versus actual concentrations present in these locations.

Contaminant concentrations in general plant areas (i.e., those somewhat distant from operations requiring local exhaust) are more likely to increase at a rate sufficiently low that the difference between T^o and T' can be measured in hours. Indeed, under some circumstances, concentrations may not reach steady-state levels by the end of the workday. If recirculation system designs were based upon final concentrations achievable, it would be found that the system was somewhat over-designed. Since the recirculation system would provide desired breathing zone concentrations when all concentrations were at maximum levels, and such levels would never be reached, actual breathing zone concentrations would be lower than desired. Although this situation presents no health hazard, it is economically disadvantageous.

To account for the possibility of such situations, and to limit their effects upon the economics of recirculation, all models specifically require breathing zone and other general area concentrations which are time-weighted averages (TWA's). Thus, if the difference between T^o and T' is small, the initial concentrations required by the model would essentially represent final achievable concentrations. If the difference were large, the design would be based upon lower than final achievable values and would provide considerably more accurate answers.

Contaminant concentrations in local exhaust ducts will be considerably higher than any breathing zone or other general area concentrations. These will rise almost instantaneously from their C^o concentration to near their steady-state level. The reasons for this behavior are self-evident and do not require further elaboration.

In summary, therefore, it can be concluded that the steady-state assumption for the models should not result in significant overdesign of recirculation systems except under extraordinary circumstances. The basic conservatism of the approach has been given full consideration and tempered as necessary.

<u>Assumption of Constant Make-up Air Contamination</u>

The models assume that any contaminant concentration (C_{MU}) in fresh make-up air is the same before and after recirculation. However, since recirculation systems will usually contain highly efficient air cleaning devices, and less contaminant will generally be emitted from the plant after recirculation is initiated, this assumption is not completely valid. Unless contaminants in make-up air originate in nearby plants and not in the plant of interest, one can usually expect that make-up air concentrations will be reduced.

To properly estimate the post-recirculation make-up air contaminant concentration requires determination of the total rates at which contaminants are normally released outdoors before and after recirculation. It then requires full consideration of the orientation of all air outlets and inlets, knowledge of the normal ambient concentration(s) of the contaminant(s), a number of simplifying assumptions, and finally, the solution of a set of non-linear equations at each step of the system design optimization procedure.

It is realized that any reduction in "background" contaminant levels allows related increases in the concentration of return air streams. Therefore, an estimation procedure was developed to account for most of the factors mentioned above. This effort led to the conclusion that the benefits to be gained from having an accurate value for a post-recirculation C_{MU} were far outweighed by the uncertainties and complexities of the feasible calculation procedures. In consequence, C_{MU} is treated as a constant in models described in this report. For those plants which experience relatively low make-up air contamination, the assumption is irrelevant. For those which do have significant contamination, it is suggested that the locations of air supply inlets be reviewed and modified as necessary, an action which would not only negate the influence of the assumption but would conform with good ventilation design practice.

Perfect Mixing in Ducts

The models are essentially based upon simple mass and flow balances. Whenever two air streams are joined in the system, it is assumed that perfect mixing takes place within the turbulent flow patterns of exhaust ducts.

Balanced Systems

Models assume that the volume of air mechanically extracted from the plant is equal to the volume mechanically introduced into the plant. Maintenance of positive or negative pressures in certain plant areas requires appropriate modification of the flow balance. In doing so, care should be exercised to insure that no reduction is made in the air volumes which provide an essential dilution effect on breathing zone concentrations. This is best accomplished by supplying more fresh make-up air than necessary to insure positive pressures and, conversely, removing (to the outdoors) more contaminated air than is replaced when negative pressures are desired.

General Ventilation Effects

The equation for predicting breathing zone concentrations contains two assumptions involving the effect of decreasing or increasing the total ventilation rate through the plant area. The first is that part of the concentration experienced will vary proportionately with the ratio of "before" and "after" total ventilation rates. The second assumption is that the rate at which contaminants enter the air of working environments due to processes and operations in the area will not change with changes in the total ventilation rate. Both assumptions presume that changes in this ventilation rate would only be accomplished by varying the general mechanical ventilation rate, and not local exhaust volume rates.

The first assumption is valid if the air velocity past any point in the room changes linearly with changes in the total ventilation rate. In essence, it is saying that the mixing factor K is not influenced by changes in air velocities for a similar air distribution pattern. This, in turn, signifies that a ratio of before and after "effective" total ventilation rates is equal to a ratio of actual rates.

To investigate the validity of this assumption, the authors refered to a doctoral dissertation from the University of Minnesota[7]. Having conducted numerous well-controlled experiments in a large chamber, and having statistically analyzed the resulting data, the researcher concluded "The mixing factor was found to be inversely related to ventilation rate, but the differences observed for a wide range of ventilation rates (5 to 20 air changes per hour) -- while statistically significant -- are small and have no practical significance." Further support was obtained from examination and manipulation of mean concentration data obtained in tests with 5, 10 and 20 air changes per hour[7]. Regardless of the specific sample point location and source location, a doubling of the ventilation rate was shown to cause a 37 to 53 percent reduction in concentrations measured. The average for all tests indicated that a 100% increase in ventilation rate causes a 45% decrease in contaminant concentration.

The assumption involving contaminant generation rates from process equipment is valid if increased air velocities do not cause normally settled dust to become entrained and do not cause solvents to enter breathing zones at an appreciably greater rate than usual. The first possibility is entirely feasible when local exhaust systems allow some amount of fine particulate matter to completely escape the influence of hoods, and this matter normally settles on the floor or equipment after some airborne residence time. It is also feasible if the general ventilation rate is increased to the degree that cross-drafts adversely affect the performance of local exhaust hoods. However, since general mechanical ventilation is seldom successfully applied for controlling fumes and dusts, the issue is deprived of practical significance.

Increased solvent escape rates would be of significance when the performance of local exhaust hoods for solvent vapors is adversely affected. Otherwise, where solvent-based coatings are allowed to air dry or similar operations are conducted, the drying time for each item would decrease, but the average evaporation rate (lbs solvent/cfm) would remain constant, if the production rate remained constant.

The presumption that increases or decreases in total ventilation rates would only be accomplished by changes in the general mechanical ventilation rate is based on the fact that it is difficult to account for changes in local exhaust volumes which influence breathing zone concentrations. Hence, as noted elsewhere, it is suggested that the total local exhaust volume Q_L be treated as a constant during the system design optimization procedure and/or that experimentation with changing

Q_L be conducted during the period of time that data are being gathered for use in the recirculation system design process.

Overall, the validity of these assumptions when ventilation rates are drastically increased or decreased is unknown. For moderate changes, however, it is concluded these are of adequate acceptability for design purposes.

Air Displacement Effects

The equation for predicting breathing zone concentrations is based on the assumption that return air streams will be distributed throughout the workplace in a manner which precludes a significant change in original air-flow patterns. In other words, the equation is only valid when the return air stream provides a "background" level of contamination which is additive to concentrations produced by normal plant activities. It is not valid when return air volumes are directed to breathing zones with such force that workers will only experience the concentration level of the return air stream. In such cases, C_{BZ} would equal C_R, and not the concentration predicted by the equation.

The practice of discharging return air streams directly into breathing zones is discouraged. The reason for this stems not from the fact that the breathing zone equation would require modification, but because of the consequences of air cleaner failure. For example, imagine that a dust of severe and acute toxicity is being removed from recirculated air by a bag filter. If a bag burst, and the return air stream was directed to breathing zones, employees might immediately be subjected to harmful concentrations, regardless of the fact that a monitoring device sounds an alarm. Alternatively, consider the situation where the return air stream enters the plant at a number of widely separated locations, none of which are near breathing zones. In this latter case, there would be a slower build-up of concentration in breathing zones, and sufficient time would be available to respond to warnings from monitoring devices.

6. STEADY-STATE RECIRCULATION MODELS FOR SINGLE CONTAMINANTS

Introduction

In the following, three recirculation system models referred to as Models #1, #2 and #3 are presented. Each of these represents a number of recirculation system design configurations, and is similar in format to the simple "model" developed in Chapter 7. Together, they cover most design configurations likely to be used in industry. The principal difference among the three models is the manner in which air streams are recirculated, and how they are cleaned. Model #1 allows recirculation of general and local exhaust, but with the proviso that a single air cleaning equipment train is used for both streams. Model #2 allows different air cleaning equipment trains to be used for the local and general exhausts. Model #3 envisages recirculating general exhaust air without cleaning.

To illustrate these models, the equations for Model #1 are presented directly below and followed by an example of their use when only one contaminant is involved. Next, Models #2 and #3 are presented. (Note: A detailed derivation of Model #1, illustrating the methodology utilized to develop all models, can be found in Appendix C. Appendix B contains variations of the three models which might be of interest in particular situations.)

Models #1 and #2 are considerably generalized. A first glance at the diagrams describing them may give the impression that the systems shown are excessively complicated, and contain numerous branches or sub-systems which would never be present in an actual plant. However, each of these models was formulated to fully represent a number of different system design configurations, and each may be simplified by setting various concentrations and exhaust volumes to zero during the computation procedure.

For example, in Figure A7, the diagram for Model #1, the recirculated air streams contain three exhaust volumes by-passed to the outdoors. One of these is the uncleaned general exhaust air stream (Q_{GB}), one is the uncleaned local exhaust air stream (Q_{LB}), and one is at a point after the remaining air volumes have been cleaned (Q_{CB}). Obviously, no system design would have all three of these by-pass systems; however, if a contemplated design has too high a contaminant concentration in the cleaned return air stream, the contaminant level may be reduced by utilizing by-pass volumes Q_{LB} and/or Q_{GB} (if this can be done without violating Federal, state or local air quality standards). If there is concern for violation of air quality standards, it is possible to utilize by-pass volume Q_{CB} in computations. Once the desired by-pass locations are selected, the air flow volumes for the other by-pass locations are set to zero and the streams are assumed to have disappeared from the diagram. Similar manipulations are possible with every other branch duct or subsystem shown in the diagrams.

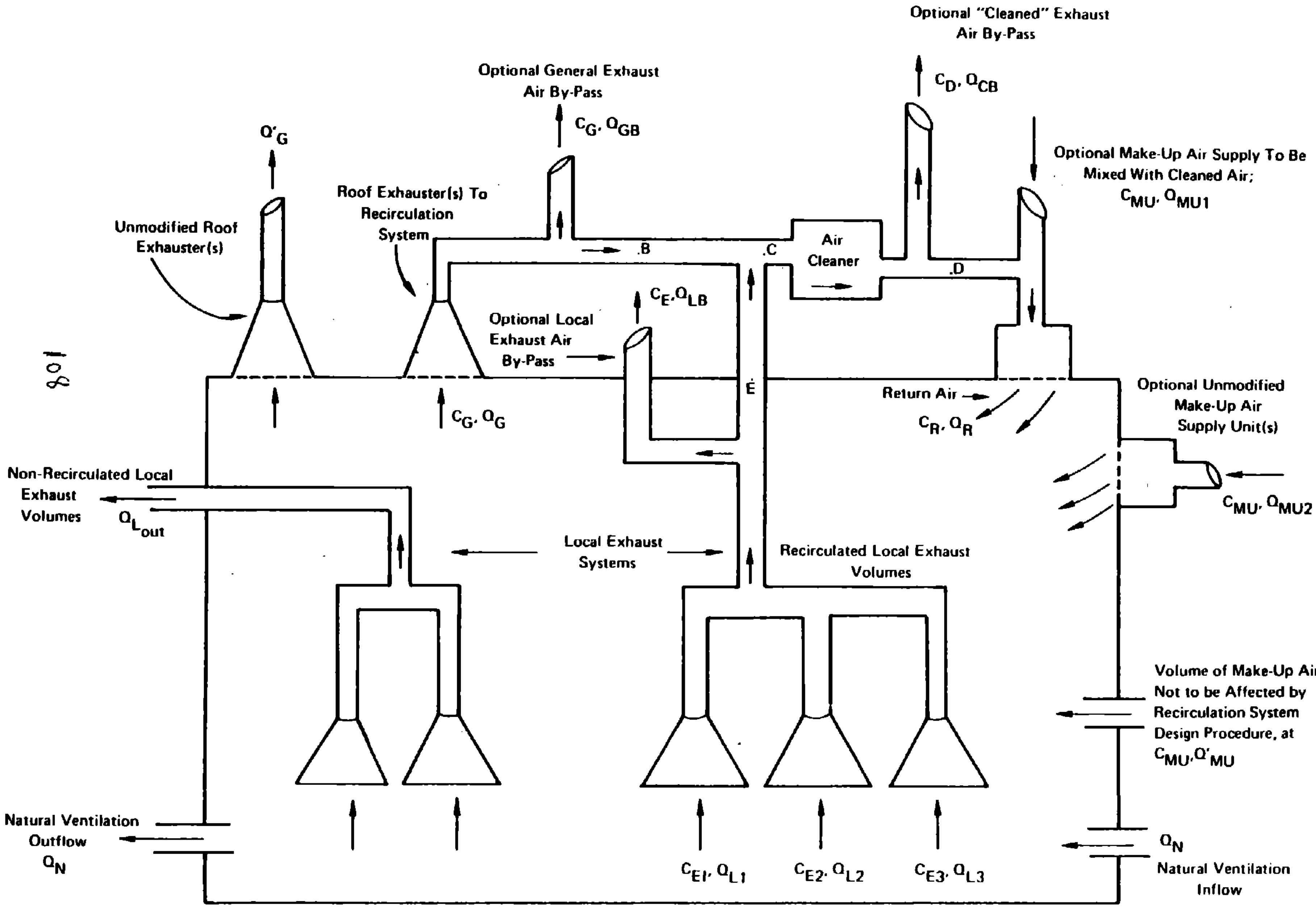


FIGURE A7 PLANT AREA WITH RECIRCULATION – MODEL #1

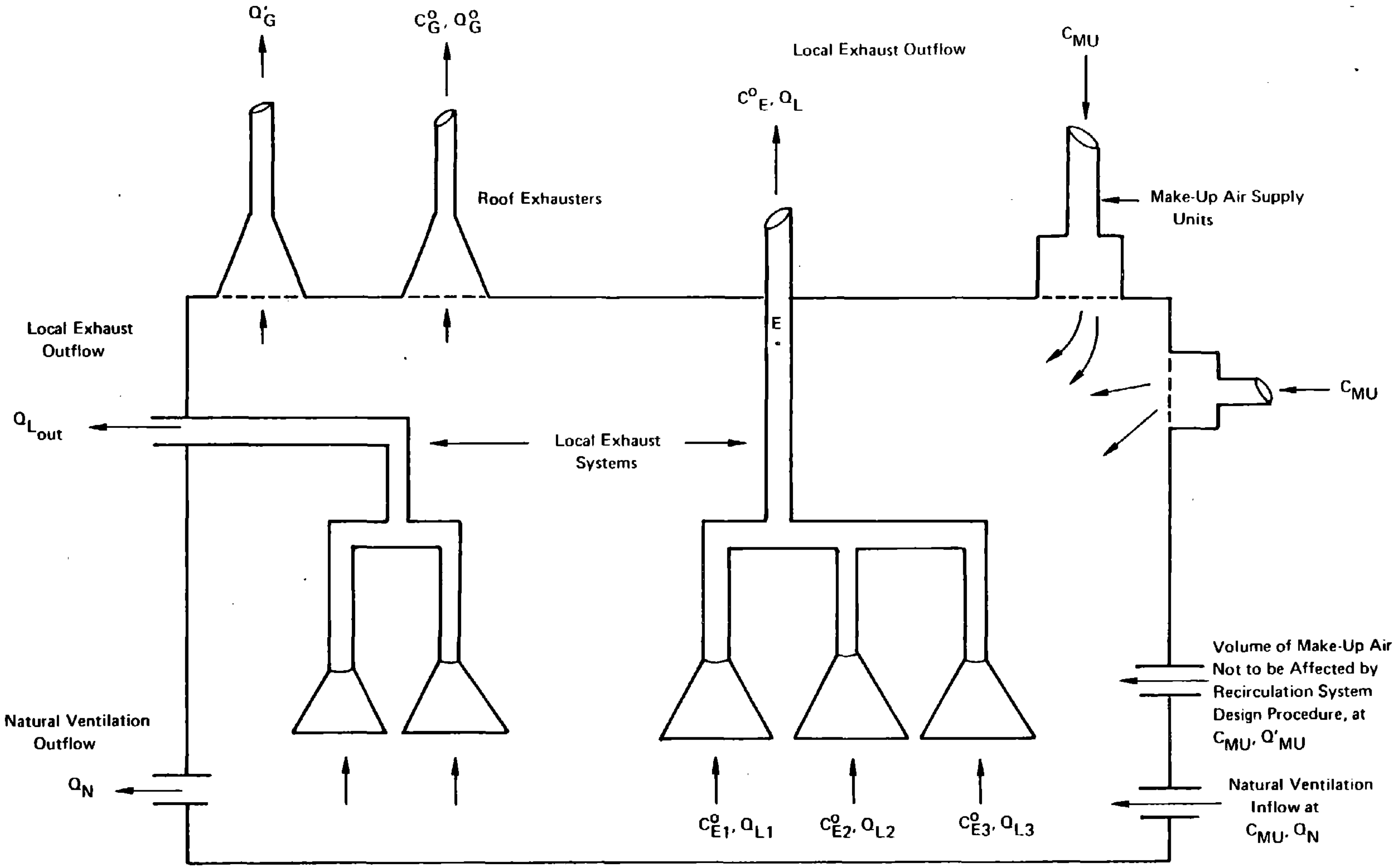


Figure A8 **PLANT AREA BEFORE RECIRCULATION**

The Equation for Model #1

Figure A7 schematically represents a plant area having general and local exhaust air streams being recirculated, and similar streams not being recirculated. It shows a natural ventilation rate through the plant (Q_N), a "fixed", or constant make-up air supply (Q'_{MU}), and two other make-up air streams. One of these (Q_{MU1}) is mixed with air leaving the air cleaning section. The other (Q_{MU2}) is separately introduced into the work room. Figure A8 shows the configuration of the conventional ventilation system in the plant as it may have appeared before recirculation. In both of these figures, and in all succeeding diagrams, pertinent contaminant concentrations are denoted by the letter "C" with appropriate subscripts. Air flow volumes are similarly denoted by the letter "Q".

The detailed derviation for Model #1 which is presented in Appendix C (along with the derivation of the breathing zone equation presented previously) leads to the following set of equations representing the model. All parameters were previously defined in the section entitled "A Close Look at the Design Parameters in Recirculation System Models." The model itself is actually an elaborate version of the simple one developed in Chapter 7*.

$$C_D = \frac{(1-\eta)[U(A+B) + T(D+E)]}{1.0 - (1-\eta)\left(\frac{Q_D}{Q_R}\right)(UF + Tk_R)} \quad (1)$$

$$C_R = \frac{C_D Q_D + C_{MU} Q_{MU1}}{Q_D + QMU1} \quad (2)$$

$$C_{BZ} = \frac{Q^{\circ}_T}{Q_T}(C^{\circ}_{BZG} - C_{MU})(1-f) + (C^{\circ}_{BZL} - C_{MU})f$$
$$+ k_{BZ}C_R + (1 - k_{BZ})\,C_{MU} \quad (3)$$

where:

$$U = \frac{Q_G - Q_{GB}}{Q_G(Q_D + Q_{CB})} \qquad \text{if } Q_G = 0, \text{ then } Q_{GB} = 0, \text{ and } U = 0$$

$$A = C^{\circ}_G Q^{\circ}_G + C_{MU}(Q_{MU2} + Q'_{MU} + k_R Q_L - Q^{\circ}_{MU})$$

$$B = \frac{C_{MU}Q_{MU1}(Q_R - k_R Q_L)}{Q_R} \quad \text{if } Q_R = 0, \text{ then } Q_{MU1} = 0, \text{ and } B = 0$$

---

*Readers wishing a basic introduction to the conceptual approach underlying this and other models should refer to Chapter 7.

$$T = \frac{Q_L - Q_{LB}}{Q_D + Q_{CB}} \qquad \text{if } Q_D + Q_{CB} = 0\text{, then } Q_L \text{ equals } Q_{LB}\text{, and } T = 0$$

$$D = C_E^\circ - k_R C_{MU}$$

$$E = \frac{k_R C_{MU} Q_{MU1}}{Q_R} \qquad \text{if } Q_R = 0\text{, then } Q_{MU1} = 0\text{, and } E = 0$$

$$F = Q_R - k_R Q_L$$

$$Q_D = Q_G - Q_{GB} + Q_L - Q_{LB} - Q_{CB}$$

$$Q_{MU1} + Q_{MU2} = Q_{GB} + Q_{LB} + Q_{L_{out}} + Q_G' + Q_{CB} - Q_{MU}'$$

$$Q_R = Q_D + Q_{MU1}$$

$$Q_{MU}^\circ = Q_G^\circ + Q_L + Q_G' + Q_{L_{out}}$$

$$Q_T^\circ = Q_{MU}^\circ + Q_N$$

$$Q_T = Q_R + Q_N + Q_{MU}' + Q_{MU2}$$

Equation 1 above provides the user with the concentration of contaminant (C_D) in air leaving the air cleaning section. The next expression, Equation 2, utilizes C_D to compute the contaminant concentration (C_R) in the air stream returned to the workplace. The third equation provides an estimate of the time-weighted average breathing zone concentration for specified workers after recirculation is implemented.

To utilize the model, one would first specify concentrations, flow volumes, and other parameters measureable or estimable with a conventional ventilation system operating. A list of these parameters is presented in Table A1. Next, one would delete from consideration those air streams which one does not wish to incorporate into the system configuration being addressed by setting them to zero. Table A2 lists these flow volumes of interest.

TABLE A1

MODEL PARAMETERS MEASURABLE OR ESTIMABLE
WITH CONVENTIONAL VENTILATION SYSTEM OPERATING

Concentrations	Flow Volumes	Others*
C°_{BZG}	Q°_{G}	f
C°_{BZL}	Q'_{G}	k_{BZ}
C°_{G}	Q_{L}	k_{R}
C°_{E}	$Q_{L_{out}}$	η
C_{MU}	Q'_{MU}	
	Q_{N}	
	Q°_{T}	

TABLE A2

MODEL PARAMETERS WHICH FURTHER ADJUST
SYSTEM CONFIGURATION

Q_{CB}	Q_{MU1}
Q_{GB}	Q_{MU2}
Q_{LB}	

---

*Note: k_{BZ} and k_{R} are sometimes variables in the trial-and-error solution process. See the Section, "A Close Look at the Design Parameters. . ." for more details.

At this point, each of the three equations would contain one or more flow volumes which are, as yet, undefined. These will always be found to be the parameters listed in Table A2 which were not set equal to zero. Having chosen a desired breathing zone concentration (C^D_{BZ}), the user would then employ the equations in a trial-and-error fashion until a set of flow volumes is found which results in the predicted breathing zone concentration (C_{BZ}) being equal to or less than the desired concentration (C^D_{BZ}). The user would repeat this process for alternative system configurations and choices for air cleaning equipment trains finally choosing the best solution among those generated.

The proceding discussion illustrates how the model would be used to arrive at acceptable solutions for one or more specified system configurations. It also indicates that there may be more than one unique set of flow volumes and/or system configurations which result in the desired breathing zone concentration. The only difference among these valid answer sets is that each has an associated cost for implementation, and that only one solution will be of minimal cost. In consequence, the design procedure is a constrained optimization process in which cost is minimized and the independent design variables are various flow volumes and the realm of feasible system configurations. The prime constraints on the optimization are that the target concentration C^D_{BZ} may not be exceeded, and that all flow balances must be maintained.

For example purposes, consider a simple cost function for illustrating how optimal designs are determined. This takes the form:

$$\$_T = \$_1 (Q_D + Q_{CB}) + \$_2 (Q_{MU1} + Q_{MU2})$$

where

$\$_T$ = the total annual cost of the recirculation system on a per cfm basis;

$\$_1$ = the annualized capital cost and annual operating cost for cleaning one cfm of air;

$Q_D + Q_{CB}$ = the volume of air which passes through the air cleaning section;

$\$_2$ = the annualized capital cost and annual operating cost for conditioning one cfm of fresh, make-up air;

Q_{MU1} = the volume of make-up air which is mixed with air from the air cleaner; and

Q_{MU2} = the volume of make-up air not mixed with air from the air cleaner.

For actual design purposes, this cost function may be modified, depending upon how one wishes to take system cost into account.

Application of Model #1 for a Plant with General and Local Exhaust Systems

Some plant areas require that local exhaust systems be supplemented with general dilution ventilation to insure that any uncontrolled contaminants are diluted below their permissible concentrations. To illustrate the use of the recirculation model for this case, a plant area is envisioned which includes a single, locally exhausted operation, and a general mechanical ventilation system. Parameter values of interest for the existing plant are:

C_G^o = 30 ppm = concentration in general exhaust air for recirculation

Q_G^o = 100,000 cfm = general exhaust volume for recirculation

Q_G' = 0.0 cfm = general exhaust volume not to be recirculated

C_E^o = 3,000 ppm = concentration in local exhaust air for recirculation

Q_L = 30,000 cfm = local exhaust volumes for recirculation

$Q_{L_{out}}$ = 0.0 cfm = local exhaust volumes not for recirculation

Q_N = 20,000 cfm = natural ventilation and infiltration rate (estimated)

Q_{MU}' = 0.0 cfm = make-up air supply rate not to be modified

Q_{MU}^o = 130,000 cfm = make-up air supply rate before recirculation

C_{MU} $\cong$ 0.0 ppm = contaminant concentration in make-up air

The only commercially available air cleaner for the contaminant of interest is of the activated carbon adsorption type. The cleaner of interest has an efficiency of $\eta = 0.95$ and cleaning cost $\$_1 = \$0.40$ per cfm. Plant records show the cost of tempering make-up air has averaged \$0.90 per cfm over the last year ($\$_2 = \$0.90$ per cfm).

The local exhaust hoods in the workplace do not induce strong flow fields. In consequence, it is evident that the factor f for any worker in the plant area can only be zero. The time-weighted average (TWA) breathing zone concentration for workers near local exhaust hoods is 100 ppm. It averages about 20 ppm for other work locations. Thus, C^o_{BZG} is taken to be 100 ppm to account for the most severely exposed group of workers.

Air pollution regulations do not require that either the general or local exhaust air currently discharged be cleaned. Hece, Q_{CB} is set to zero, and this by-pass stream is deleted from consideration. The desire to mix any fresh make-up air with recirculated air leads to the decision to set stream Q_{MU2} to zero.

Since the major portion of air entering the plant from all sources will be from the recirculation system, k_{BZ} is assigned a value of 1.0, and k_R is assigned the maximum possible value it can have for this configuration, 1.0. Finally, it is decided that the desired breathing zone concentration C^D_{BZ} should be nearly equal to the currently experienced exposure level of 100 ppm TWA.

Alternative system configurations for study include:

- Recirculation of local exhaust air only; where Q_G must equal Q_{GB}, but the magnitude of Q_G can change;
- Recirculation of general exhaust air only; where Q_L must equal Q_{LB}, and both must equal 30,000 cfm; and
- Recirculation of general and local exhaust streams mixed; Q_G, Q_{GB} and Q_{LB} are variables, as is Q_{MU1}.

Inserting the known data into various equations for Model #1 and the cost function, we find:

$$Q_T^\circ = 130{,}000 + 20{,}000 = 150{,}000$$

$$Q_D = Q_G - Q_{GB} + 30{,}000 - Q_{LB}$$

$$Q_{MU1} = Q_{GB} + Q_{LB}$$

$$Q_R = Q_D + Q_{MU1} = Q_G + 30{,}000$$

$$Q_T = Q_R + Q_N = Q_G + 50{,}000$$

$$U = \frac{Q_G - Q_{GB}}{Q_G\, Q_D}$$

$$A = 3{,}000{,}000$$

$$B = 0.0$$

$$T = \frac{30{,}000 - Q_{LB}}{Q_D}$$

$$D = 3000 \qquad F = Q_G$$

$$E = 0.0$$

$$C_D = \frac{(0.05)(3 \times 10^6 U + 3000T)}{1.0 - (0.05)\left(\frac{Q_D}{Q_R}\right)(UQ_G + T)}$$

$$C_R = \frac{C_D Q_D}{Q_D + Q_{MU1}}$$

$$C_{BZ} = \frac{150{,}000}{Q_G + 50{,}000}(100) + C_R$$

$$\$_T = 0.40(Q_D) + 0.90(Q_{MU1})$$

The problem now is to find the set of values for the various flow volumes which will minimize cost for each of the three alternative system configurations while maintaining breathing zone concentrations at roughly 100 ppm.

For the first alternative, Q_G is set equal to Q_{GB} in the equations, the equations are simplified and rearranged, and various values for Q_G and Q_{LB} are inserted. It is quickly found from this process that any substantial amount of recirculated local exhaust air will significantly increase breathing zone concentrations at little cost savings. Table A3 lists some answers obtained from this procedure.

Use of the recirculation model for the second alternative requires that Q_L be set equal to Q_{LB} and Q_G and Q_{GB} be varied. This iteration, for which some answers are also given in Table A3, results in the observation that considerable cost savings can be realized if all local exhaust air is discharged outdoors and the current volume of general air is recirculated. The third row of answers indicates a \$67,000 annual cost with only a 1.2 ppm increment in exposure, compared to the first row, conventional system cost of \$117,000.

TABLE A3

ANSWERS COMPUTED FOR A SAMPLE PROBLEM

Alternative 1: $Q_G = Q_{GB}$; Q_{LB} and Q_G variable

Q_G or Q_{GB}	Q_{LB}	C_D	C_R	C_{BZ}	$\$_T$
100,000	30,000	-	0.00	100.00	$117,000
100,000	20,000	150.58	11.58	111.58	112,000
120,000	20,000	150,50	10.03	98.27	130,000

Alternative 2: $Q_L = Q_{LB} = 30{,}000$; Q_G and Q_{GB} variable

Q_G	Q_{GB}	C_D	C_R	C_{BZ}	$\$_T$
100,000	100,000	-	0.00	100.00	$117,000
100,000	80,000	1.51	0.23	100.23	107,000
100,000	0.00	1.56	1.20	101.20	67,000
90,000	0.00	1.73	1.30	108.44	63,000
80,000	0.00	1.95	1.42	116.80	59,000

Alternative 3: Q_G, Q_{GB} and Q_{LB} variable

Q_G	Q_{GB}	Q_{LB}	C_D	C_R	C_{BZ}	$\$_T$
100,000	100,000	30,000	-	0.00	100.00	$117,000
100,000	0.0	30,000	1.56	1.20	101.20	67,000
100,000	0.0	20,000	15.66	13.25	113.25	62,000
110,000	0.0	20,000	14.37	12.31	106.06	66,000
110,000	0.0	10,000	25.41	23.60	117.35	61,000
140,000	0.0	0.0	28.79	28.79	107.74	68,000

The third alternative allows us to vary Q_G, Q_{GB} and Q_{LB} at will. Results shown in Table A3 for these computations, compared to results for the previous alternative, clearly indicate that further savings cannot be realized without increasing exposure levels. Hence, the optimum system, from the viewpoint of cost savings and safety, is one which recirculates all general exhaust air and discharges to the atmosphere all locally exhausted air. The design is considered relatively safe because failure of the air cleaner would only result in general exhaust air at 30 ppm reentering the room. Recirculation of local exhaust air in this case entails reintroduction of air contaminated at a 3000 ppm level if the cleaner fails.

Separate General and Local Exhaust Air Cleaning Sections (Model #2)

The air exhausted by a general mechanical ventilation system is usually at a much lower concentration level and/or temperature than that from local exhaust systems. Consequently, one may find it more cost-effective under some circumstances to utilize a separate, and less expensive, air cleaning equipment train for general exhaust air, and to provide a more efficient train for local exhaust streams. Figure A9 schematically describes a typical system configuration.

For this design, C_D becomes:

$$C_D = \frac{(1-\eta_1)[U(A+B)] + (1-\eta_2)\ [T(D+E)]}{1-(1-\eta_1)\left(\frac{Q_D}{Q_R}\right)(UF) - (1-\eta_2)\left(\frac{Q_D}{Q_R}\right)(Tk_R)} \qquad (1a)$$

where:

$$U = \frac{Q_G - Q_{GB1} - Q_{GB2}}{Q_D Q_G}$$ if Q_D or $Q_G = 0$, then numerator equals 0, and $U = 0$

$$A = C^\circ_G Q^\circ_G + C_{MU}\ (Q_{MU2} + Q'_{MU} + k_R Q_L - Q^\circ_{MU})$$

$$B = \frac{C_{MU} Q_{MU1} (Q_R - k_R Q_L)}{Q_R}$$ if $Q_R = 0$, then $Q_{MU1} = 0$, and $B = 0$

$$T = \frac{Q_L - Q_{LB1} - Q_{LB2}}{Q_D}$$ if $Q_D = 0$, then numerator equals 0, and $T = 0$

$$D = C^\circ_E - k_R C_{MU}$$

$$E = \frac{k_R C_{MU} Q_{MU1}}{Q_R}$$ if $Q_R = 0$, then $Q_{MU1} = 0$, and $E = 0$

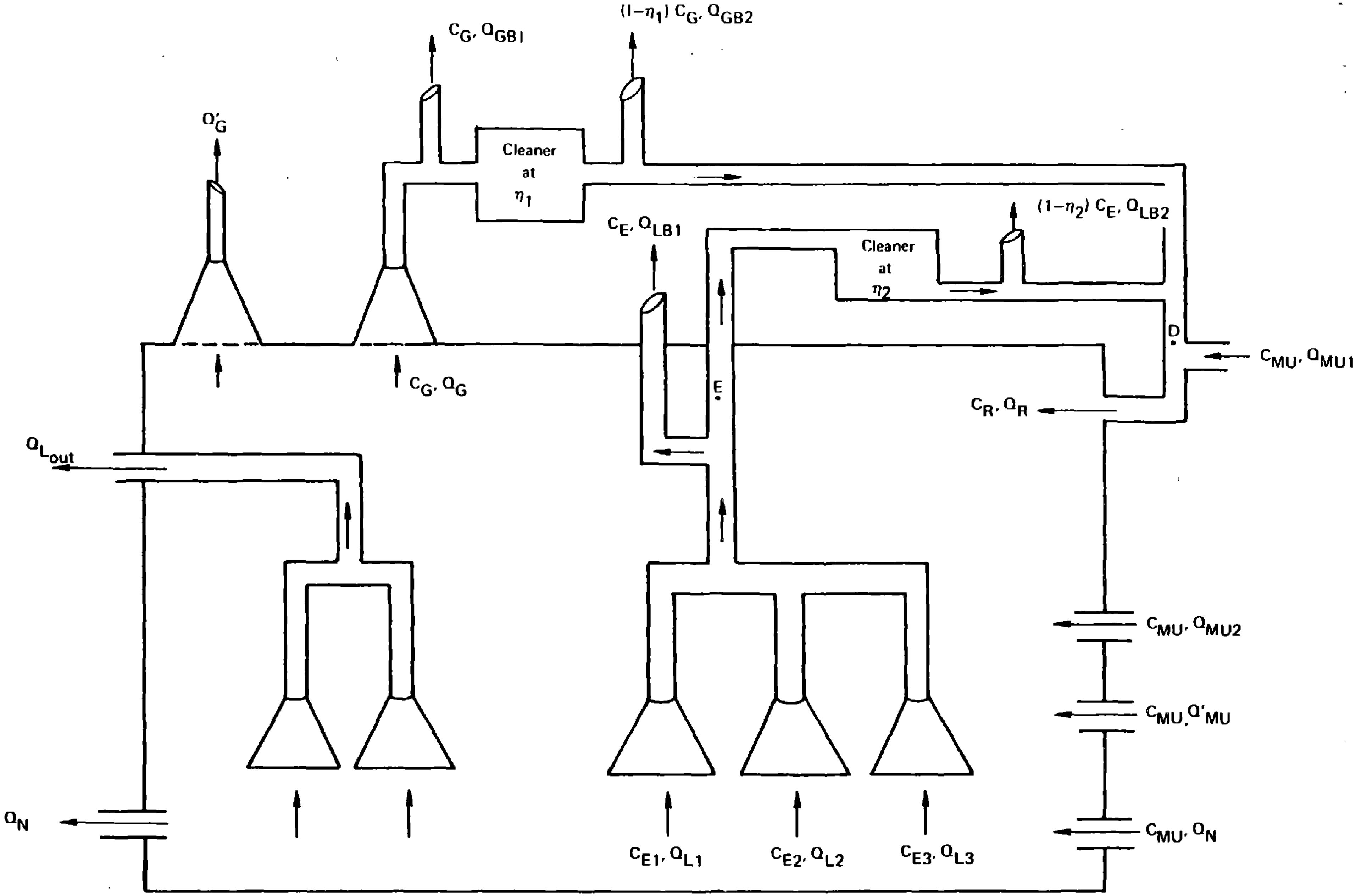


Figure A9 **PLANT AREA WITH RECIRCULATION – MODEL #2**

$$F = Q_R - k_R Q_L$$

η_1 = is the overall air cleaner efficiency for the unit(s) treating the general exhaust air;

η_2 = is the overall efficiency of the unit(s) treating the local exhaust air;

Q_{GB2} = is the rate of general exhaust air by-passed after the general exhaust air cleaner(s);

Q_{LB2} = is the rate of local exhaust air by-passed after the local exhaust air cleaner(s);

$$Q_D = Q_G - Q_{GB1} - Q_{GB2} + Q_L - Q_{LB1} - Q_{LB2};$$

$$Q_R = Q_D + Q_{MU1};$$

$$Q_{MU1} + Q_{MU2} = Q_{GB1} + Q_{GB2} + Q_{LB1} + Q_{LB2} + Q'_G + Q_{L_{out}} - Q'_{MU};$$

and all other parameters are as previously defined.

Of interest in Figure A9 is that the cleaned general and local exhaust air streams are joined together prior to being joined with the fresh make-up air stream Q_{MU1}. In practice, it makes no difference in which order these streams are mixed together, as the resulting values for C_R and Q_R will be the same. However, the validity of equations 1 and 2 require it be assumed the recirculated air streams are mixed as shown in Figure A9.

In some plant situations the general exhaust air stream will be slightly contaminated relative to permissible exposure limits of the contained contaminants. In these situations, it may be feasible to simply utilize this air to further dilute the cleaned local exhaust stream without cleaning it. Equation 1a may be used for this condition by setting the value of η_1 to zero.

As was illustrated for Model #1, the general procedure for application of this model involves:

a. Selection of values for all design parameters;
b. Use of Equation 1a to compute C_D;
c. Use of Equation 2 to compute C_R;
d. Use of Equation 3 to compute C_{BZ};

e. Comparison of computed C_{BZ} with desired concentration C^D_{BZ}; and

f. Modification of design parameters to achieve desired C^D_{BZ}.

Recirculation of Uncleaned General Exhaust Air (Model #3)

It is not unusual to find plant areas having large capacity, general mechanical ventilation systems with the sole purpose of diluting otherwise excessive breathing zone concentrations. In many cases, the reason for extracting large exhaust volumes is not because large amounts of contaminants are released, but alternatively, because the contaminants which are released are generated close to worker's breathing zones. Consequently, the large exhaust volumes are necessary only to overcome the effects of poor mixing of relatively clean air with highly contaminated air.

Figure A10 illustrates a plant area which requires general ventilation, regardless of whether or not it contains local exhaust systems. Knowing that there is a considerable waste of energy involved in simply dumping the general exhaust air outside, one may find it feasible to extract a volume of air from one end of the room, and without cleaning, return it at the other end. The equation which can be used to design such a system, along with equations 2 and 3 is:

$$C_D = \frac{A + B}{Q_G - \left(\frac{Q_D}{Q_R}\right)(Q_R - k_R Q_{LT})} \qquad (1b)$$

$$A = C^{\circ}_G Q^{\circ}_G + C_{MU}(Q_{MU2} + Q'_{MU} + k_R Q_{LT} - Q^{\circ}_{MU})$$

$$B = \frac{C_{MU} Q_{MU1}(Q_R - k_R Q_{LT})}{Q_R} \qquad \text{if } Q_R = 0, \text{ then } Q_{MU1} = 0, \text{ and } B = 0$$

where: Q_G is the volume rate of general air extracted from the plant air for recirculation purposes;

k_R is the fraction of returned air which enters all local exhaust systems and discharges outdoors;

Q_{LT} is the total exhaust volume of local exhaust systems in the plant area;

$$Q_D = Q_G - Q_{GB};$$

$$Q_R = Q_D + Q_{MU1};$$

$$Q_{MU1} + Q_{MU2} = Q_{GB} + Q_G + Q_{LT}; \text{ and}$$

$$Q_T = Q_R + Q'_{MU} + Q_{MU2} + Q_N$$

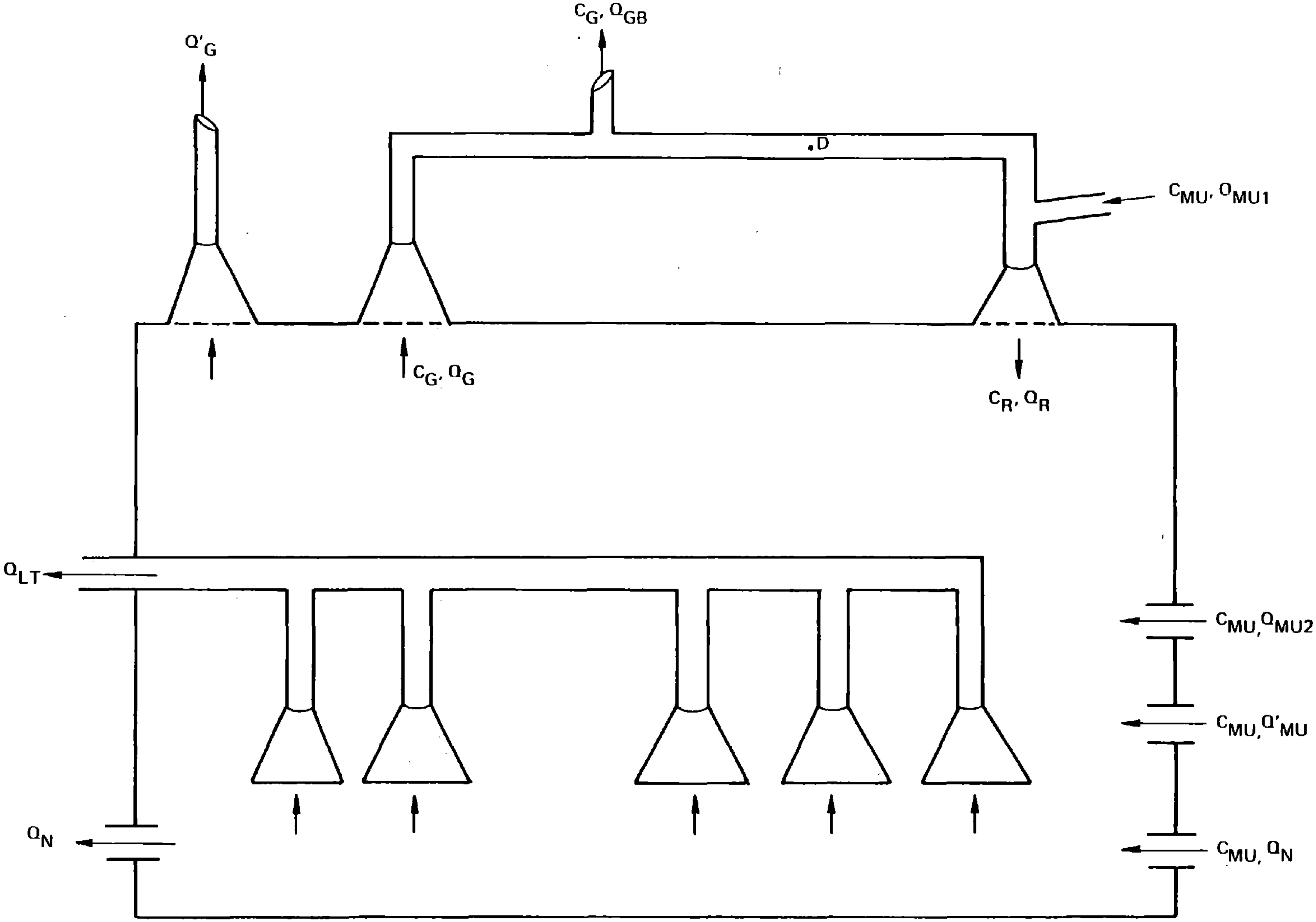


Figure A10 **PLANT AREA WITH RECIRCULATION – MODEL #3**

Limits on the value to be chosen for the parameter k_R can be computed from equations presented in "A Closer Look at the Design Parameters..." Exceptions to the outlined procedure are that Q_R is defined by the equation given directly above, and that the parameter Q_{LT} above should be used in place of Q_L. Application of the model is accomplished in a manner analogous to that previously demonstrated for Models #1 and #2. The sole difference is that Equation 1b is used in place of 1 or 1a.

7. APPLICATION OF THE MODELS TO MULTI-CONTAMINANT SITUATIONS

The preceding examples have assumed that only a single airborne contaminant exists in the work environment. This assumption is idealistic; however, the basic recirculation models can also be utilized to analyze ventilation systems containing a combination of contaminants. There are a number of possible situations which deserve consideration.

The first situation includes those types of industrial operations which generate significant amounts of particulate matter requiring removal from work place air. Depending upon the type of operation being conducted and the nature of other activities in the work area, exhaust volumes may contain only particulate matter, or particulate matter together with gases or vapors. In the former case, the following applies:

a. Determine the concentration and particle size distribution of each contaminant in each specified location. Measure or estimate all input parameters required by the recirculation model.

b. Utilize the model to design a system providing desired breathing zone concentrations for the most toxic constituent in the exhaust air, while assuming that only this contaminant is present in air.

c. Utilizing the optimum design parameters determined in the previous step, compute breathing zone concentrations for each of the several remaining contaminants. (Recognize that air cleaner efficiency depends upon particle size, not toxicity, and a less toxic contaminant may be inadequately removed while a highly toxic substance is efficiently removed.)

d. Compute the TWA concentration of the mixture in the breathing zone and assess its acceptability. In doing this carefully evaluate the possibility that two or more constituents have additive or synergistic effects. If all concentrations are acceptable, an adequate system design has been selected.

e. If all of the concentrations in the breathing zone are not acceptable, vary appropriate parameters such that a greater amount of contaminant is removed from the work environment. This may be accomplished either by selecting a higher efficiency air cleaner, or by-passing a greater amount of contaminated air to the atmosphere. Continue varying parameters until a system design is achieved which adequately treats each individual contaminant and the resulting mixture.

The next case considered is the situation where the exhaust volume contains a number of toxic, gaseous constituents. In this case, the design procedure becomes:

a. Determine the concentration of each contaminant in each specified location. Measure or estimate all parameters required by the model.

b. Select one or more air cleaning devices which, in series, and/or in parallel, will significantly reduce the concentration of each contaminant. Accurately determine the overall efficiency of the equipment train for removing each contaminant.

c. Select the single contaminant which appears most difficult to satisfactorily reduce in concentration by virtue of its high toxicity or the unavailability of a high efficiency air cleaner.

d. Utilize the model to design a system providing the desired breathing zone concentration for the contaminant directly above. In these computations, use the overall air cleaner effèciency appropriate for this substance.

e. Utilizing optimum design parameters determined in the previous step, compute breathing zone concentrations for each of the several remaining contaminants. Use the appropriate overall air cleaner efficiency for each substance.

f. Compute the TWA concentration of the mixture in the breathing zone and assess its desirability. Carefully evaluate the possibility that two or more constituents have additive or synergistic effects. If all concentrations are reasonable, an acceptable system design has been selected.

g. As in Step e listed for particulate-only situations, vary system parameters as necessary to meet design constraints if the mixture composition is not acceptable.

The design procedure for a contaminant stream containing both particulates and gaseous contaminants is similar to the procedures described above.

For guidance in computing the acceptability of contaminant mixtures, the reader is referred to Chapter 4 of this report.

8. CEILING LIMIT CHECKS REQUIRED

In actual practice, most parameters utilized in the recirculation models do not have constant values. They can vary widely due to contaminant build-up during the early part of the workday, changes in production rates, changes in air cleaner efficiencies, etc. When one or more contaminants of interest have assigned ceiling limit concentrations, the designer must ensure that no employee will be exposed to levels in excess of ceiling limits, when and if a number of parameters approach their worst-case extremes. This is accomplished by utilizing worst case parameter values in the models after a complete system design has been selected using time-weighted-average values.

If the design indicates that there is a reasonable possibility that ceiling limits can be exceeded, the design should be modified as necessary to reduce the breathing zone concentrations. This procedure only addresses the possibility of exceeding ceiling limits while all components of the recirculation system are operating normally. Poor equipment maintenance and/or system component failure may also lead to excessive exposures if sufficient safeguards are not taken.

9. ESTIMATING DESIGN PARAMETERS FOR NEW FACILITIES

Some of the preceding discussion has focused upon the procedures necessary to obtain the input data utilized in the recirculation system design models when retrofitting an existing plant. It presumes that contaminant concentrations, exhaust volumes, and other parameters can be accurately measured or estimated by experimental or other techniques.

The problems faced when designing a recirculation system for a new facility are more difficult than those associated with modifying an existing installation. The benefits and savings which may be realized by integrating such a system with the overall plant design may justify added efforts required, however. Additionally, if the observation is made that the designer will be called upon to obtain most of the information required for a recirculation system before designing a conventional ventilation system (containing an air cleaning section), it becomes evident that the degree of additional effort required is not excessive.

A detailed review of all design parameters indicates that the parameters C°_{BZG}, C°_{BZL}, D°_{E}, and C°_{G} are of most importance when new facilities are being addressed. All others are either independent design variables, completely dependent design variables, capable of being specified from available information sources, or capable of being specified conservatively without great effect upon final design results. The paragraphs below discuss some of the information sources and methods available to designers in defining the concentrations of interest.

Existing Plant Analogies

Most "new" plants are destined to house equipment and activities currently contained in other, somewhat similar plants. Therefore, previous experience with comparable equipment may provide considerable pertinent data which can be applied to the proposed facility. In many cases the facility under study can be disaggregated into a series of unit operations or processes for which considerable input data are available. An industrial hygienist should help in making these analogies and assessments.

Equipment Manufacturers

Companies which manufacture process, monitoring, or air cleaning equipment for particular types of industrial activities generally maintain technical staffs to aid potential customers in equipment selection and installation. The experience of such companies and their past customers may be of considerable assistance to the recirculation system designer; however, data and recommendations from manufacturers should be carefully evaluated by impartial experts.

For example, information can be found in the equipment catalog for a company which produces air cleaning equipment for locally exhausted grinding, buffing, polishing, and woodworking machinery. Depending upon the number, type, size and grouping of units, the catalog suggests very specific types and capacities of devices for installation. Among the types offered are units designed for recirculation and units designed for outside venting.

Experimental Studies

In air pollution engineering, it is often found that the control problem is sufficiently complicated that equipment cannot be selected solely on the basis of "assumed" contaminant loadings or even measured loadings. In such cases, design data is obtained using pilot-scale models of control devices. Such studies can thus convert the problem of equipment selection to one of equipment scale-up. Simultaneously, they allow the evaluation of materials of construction.

Recirculation system designers can utilize pilot studies for not only equipment selection purposes, but for determining contaminant loadings and breathing zone concentrations. This may be particularly true when the plant area of concern is destined to contain a number of similar contaminant-producing operations or equipment, such as spray-booths, bag filling machines, buffing lathes, welding benches, dip tanks, etc. In such cases, data obtained from one unit in an experimental study may successfully allow extrapolation of desired parameters for an array of units. It is cautioned, however, that such extrapolations are not always a simple undertaking. Multiple exhaust hoods in a plant area can interact with each other in a manner which affects the degree of control achieved, and hence, the amount of contaminant collected. Experienced ventilation system designers must therefore utilize their best judgement for incorporating study data into their final design.

Staged Installation

A conservative approach to determining contaminant concentrations and, indeed, finalizing the design of a recirculation system involves staged installation of system components. For example, a designer may wish to postpone final selection of those system components peculiar to a recirculation system until such time as accurate data are obtained from in-plant measurements of operational processes. There are problems with this approach including the need for temporary sources of make-up air and the possibility of exceeding local, state, or federal air quality standards before the air cleaning system is operational.

Solvent Evaporation Rate Estimates

"Solvents appear in modern synthetic varnishes and lacquer, in liquid compositions for coating of fabrics and the like, in industrial adhesives and cements, and innumerable other industrial processes and products. A prime function of solvents at some stage in the application process is to evaporate into the atmosphere, leaving behind a physically transformed material formerly associated with it. It is nearly always possible to estimate the rate of use of total liquid composition, and from knowledge of its solvent composition to determine the rate of evaporation. This makes it especially simple to handle solvent vapor ventilation problems on a quantitative basis."[4]

Solvent drying time data given in the appendix of the ACGIH Industrial Ventilation Manual[6] can be of assistance. These data give the relative drying times of 78 pure solvents, and may be of particular usefulness to the designer who obtains data from an existing plant utilizing similar equipment but a different pure solvent. A graph giving percent solvent loss versus time for various surface coatings is available in the Air Pollution Manual[8]. Accurate data is sometimes also available from solvent and/or coating manufacturers.

Finally, one must make note of the work of experimenters attempting to develop laboratory scale models of industrial operations with the purpose of defining specific solvent evaporation rates from coating activities. The efforts of Riley [9] and Boyle and Novak [10] are examples of particular applicability.

The Sylvan Chart for Particulates

Compiled from literature and experience in the field, the Sylvan Chart* contains commonly encountered ranges of concentration and particle size for many dusty operations. These data are given for concentrations typically conveyed through exhaust systems and can be found on page 11-21 of the ACGIH Industrial Ventilation Manual [6]. Although brief directions for use of the chart appear in this reference, a somewhat more complete description of the chart and its contents appears in a 1953 paper by Kayse [11].

According to Kayse, "For comparative or unknown conditions these data will be sufficient, although variations either exceeding or falling short of the concentrations shown will be found. For applications not illustrated, it will be necessary to select your point on the chart by comparing with an operation that is shown. This comparison can be made on the basis of type of aerosol, method of generation, capture velocity at and location of hood, and choice of excessive or minimum air volumes... Perfect pin-pointing of the concentration within the range shown for that application is not essential. The accuracy of the chart is such that any minor error made will not greatly affect the end result, which will be an approximation in any event."

Air Pollutant Emission Factors

The U.S. Environmental Protection Agency (EPA) has for many years been compiling quantitative data on the quantity and characteristics of emissions from the numerous sources that contribute to the problem [12]. These data, presented as "emission factors," are statistical averages of the rates at which pollutants are released to the atmosphere as the result of various activities. Units are generally in pounds of contaminant released divided by some level of the specific activity being addressed.

The applicability of EPA's data to the problem of defining contaminant concentrations for utilization with recirculation criteria varies. In many cases, the data describe the total amount of a contaminant which may be released during the performance of an entire series of uncontrolled operations. These data types are generally difficult to utilize, since they do not allow determination of the specific concentrations associated with individual operations in the series. However, review of EPA documents may prove useful since the agency is careful to reference the sources of its information. These sources may be found to contain the detailed breakdowns of data which lead to the generalized emission factors presented.

*The fractional efficiency curve on the Sylvan Curve for fabric filters should be disregarded.

For some activities, which are typically controlled with ventilation, systems and air cleaning devices, the EPA provides factors for emissions "downstream" of air cleaning devices. For example, where sander dust is conveyed to large diameter cyclones in the woodworking industry, EPA suggests use of the average factors of 0.055 gr/scfm (cyclone capacity) or 5 lb/hr. Typical cyclones will only effectively collect particles greater than 40 microns in diameter, and this data in combination with the emission factors may be used to specify air cleaning equipment necessary for recirculation designs.

Other Sources of Data

Specific data concerning breathing zone and other concentrations can be found through an organized search of the industrial hygiene, air pollution engineering and environmental science publications addressing a particular industry. Pertinent data may also be available from various NIOSH resources and publications. Specifically, a designer could access and review pertinent NIOSH Criteria Documents, Control Technology Assessments and Health Hazard Evaluations. The latter two sources usually contain considerable airborne concentration data and a description of the engineering and other controls utilized to achieve these concentrations. Although data so obtained may not be applicable for direct use, they can be of assistance for estimating ranges of concentrations which are feasible or for confirming the validity of experimentally derived data.

REFERENCES FOR APPENDIX A

1. "NIOSH Manual of Sampling Data Sheets," DHEW (NIOSH) Publication No. 77-159, March 1977.

2. "NIOSH Manual of Analytical Methods," HEW Publication No. (NIOSH) 75-121, 1974.

3. "ASHRAE Handbook of Fundamentals," American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, NY, 1972.

4. Hemeon, W.C.L., "Plant and Process Ventilation," 2nd Edition, Industrial Press, Inc., New York, NY, 1963.

5. Baturin, V.V., "Fundamentals of Industrial Ventilation," 3rd Enlarged Edition, Pergamon Press, New York, NY, 1972 (Volume 8 of the International Series of Monographs in Heating, Ventilation and Refrigeration.)

6. "Industrial Ventilation: A Manual Recommended Practice," American Conference of Industrial Hygienists, Committee on Industrial Ventilation. 14th Edition, Lansing, Michigan, 1976.

7. West. D.L., "Dispersion and Dilution of a Gaseous Contaminant in a Ventilated Space," PhD Thesis, University of Minnesota, March 1976.

8. Danielson, J.A., editor, "Air Pollution Engineering Manual," U.S. Environmental Protection Agency Publication No. AP-40, May 1973.

9. Riley, E.C., "Estimation of Atmospheric Concentrations of Volatile Compounds from Surface Coatings by Means of a Laboratory Model," AIHA Journal, September - October 1968.

10. Boyle, J.P., and Novak, N.P., "Predicting Ventilation Requirements for Coating Materials," Industrial Hygiene Journal, November - December 1963, pp. 606-610.

11. Kayse, J.R., "Contaminant Characteristics Encountered in Local Exhaust Systems," Industrial Hygiene Quarterly, June 1953, pp. 133-137.

12. "Compilation of Air Pollutant Emission Factors," 2nd Ed., U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, April 1973. (Six supplements have also been published to date).

APPENDIX B

SOME SYSTEM CONFIGURATION ALTERNATIVES

Introduction

This appendix describes a number of recirculation system design configurations derived from models described in Appendix A. In the following, each of these configurations is discussed and instructions are provided for their examination as alternative candidates for implementation. All concentrations and air volumes are designated by symbols previously defined in Appendix A.

System Configuration #1

Figure B1 represents a plant area containing local exhaust and general mechanical ventilation systems, as shown in the "before" recirculation diagram. In the "after" recirculation diagram, it is evident that a local exhaust stream is being recirculated, while all other exhaust volumes are maintained at former levels. To reduce contaminant concentration(s) in the return air supply volume (Q_R), a fresh make-up air volume (Q_{MU1}) is mixed with the recirculated air volume (Q_D).

Directly below the diagrams in Figure B1, a set of equations is presented. Used in order, these equations allow designers to explicitly determine what by-pass volume Q_{LB} or Q_{CB} must be for breathing zone concentration constraints to be satisfied for each contaminant of interest.

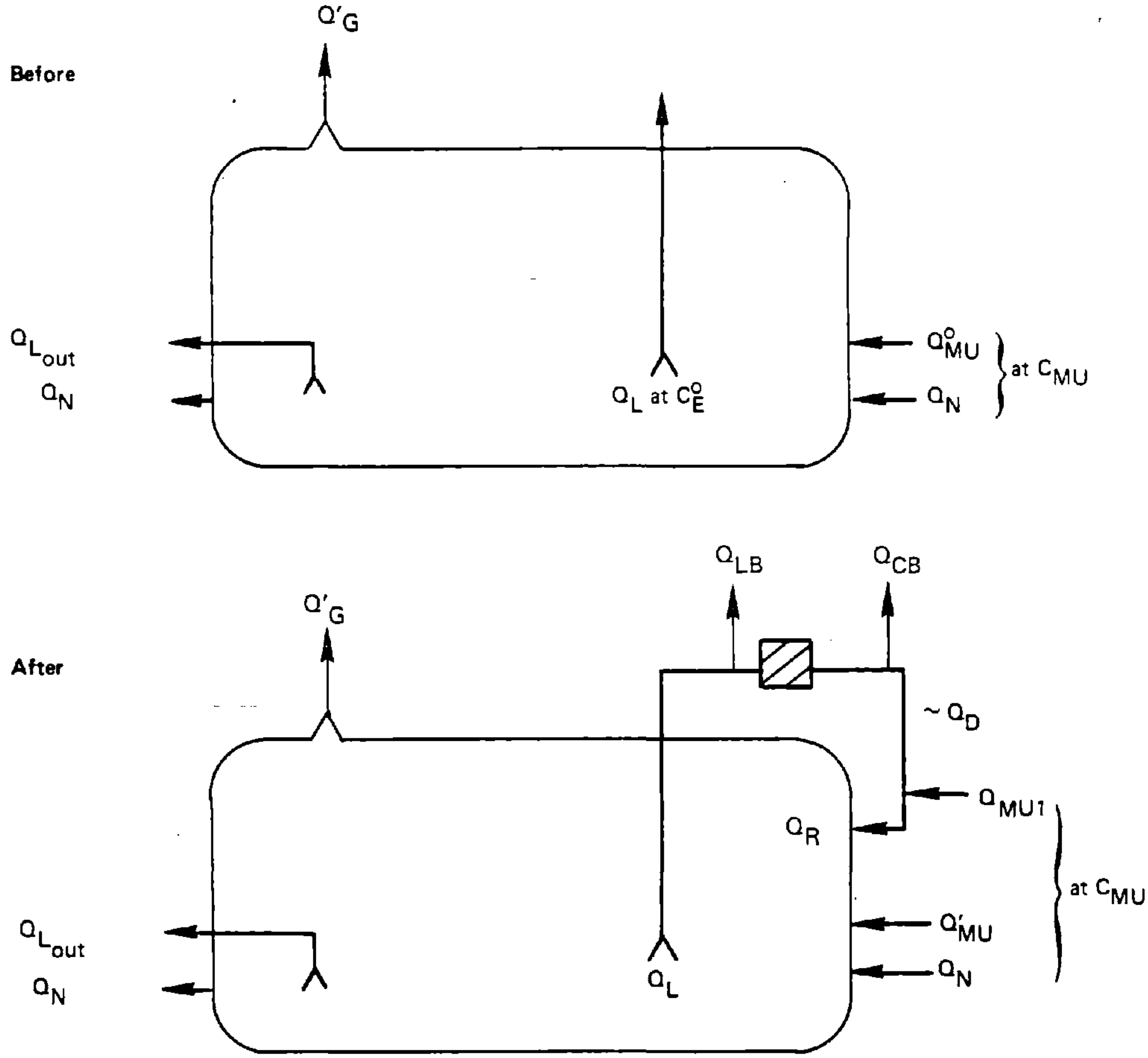
Users must be cautioned that the equations presented are valid under most, but not all circumstances. Specifically, erroneous answers may result when:

$$C_E^\circ \leq k_R C_{MU} + \frac{Q_R X}{(1-\eta) Q_L k_{BZ}} \left[1 - \left[\frac{(1-\eta) Q_L k_R}{Q_R} \right] \right] - \frac{C_{MU} Y}{(1-\eta) Q_L}$$

Satisfaction of the above equation indicates that an appropriate value for Q_{LB} or Q_{CB} is zero, if all other parameters have been defined correctly.

System Configuration #2

This configuration, shown if Figure B2, is quite similar to the first one discussed above. The major difference, that fresh make-up air is not used to dilute the recirculated air stream, is however a significant one. Its results upon the computation procedure is that the values for parameters k_{BZ} and k_R must be selected with full consideration of the



To Solve for Q_{LB} or Q_{CB}, Set One to Zero, and Compute Other From:

$$Q^o_T = Q^o_{MU} + Q_N$$

$$Q_R = Q_{L_{out}} + Q'_G + Q_L - Q'_{MU}$$

$$Q_T = Q_R + Q'_{MU} + Q_N$$

$$X = C^D_{BZ} - (1-f)\frac{Q^o_T}{Q_T}(C^o_{BZG} - C_{MU}) - f(C^o_{BZL} - C_{MU}) - (1-k_{BZ})C_{MU}$$

$$Y = Q_{L_{out}} + Q'_G - Q'_{MU}$$

$$A = C_{MU} - (1-\eta)\left[C^o_E - k_R C_{MU} + \frac{k_R X}{k_{BZ}}\right]$$

$$B = \frac{Q_R X}{k_{BZ}}\left[\frac{(1-\eta)\,Q_L\,k_R}{Q_R} - 1\right] + C_{MU}{}^{Y} + (1-\eta)(Q_L)(C^o_E - k_R C_{MU})$$

$$Q_{CB} + Q_{LB} = \frac{-B}{A}$$

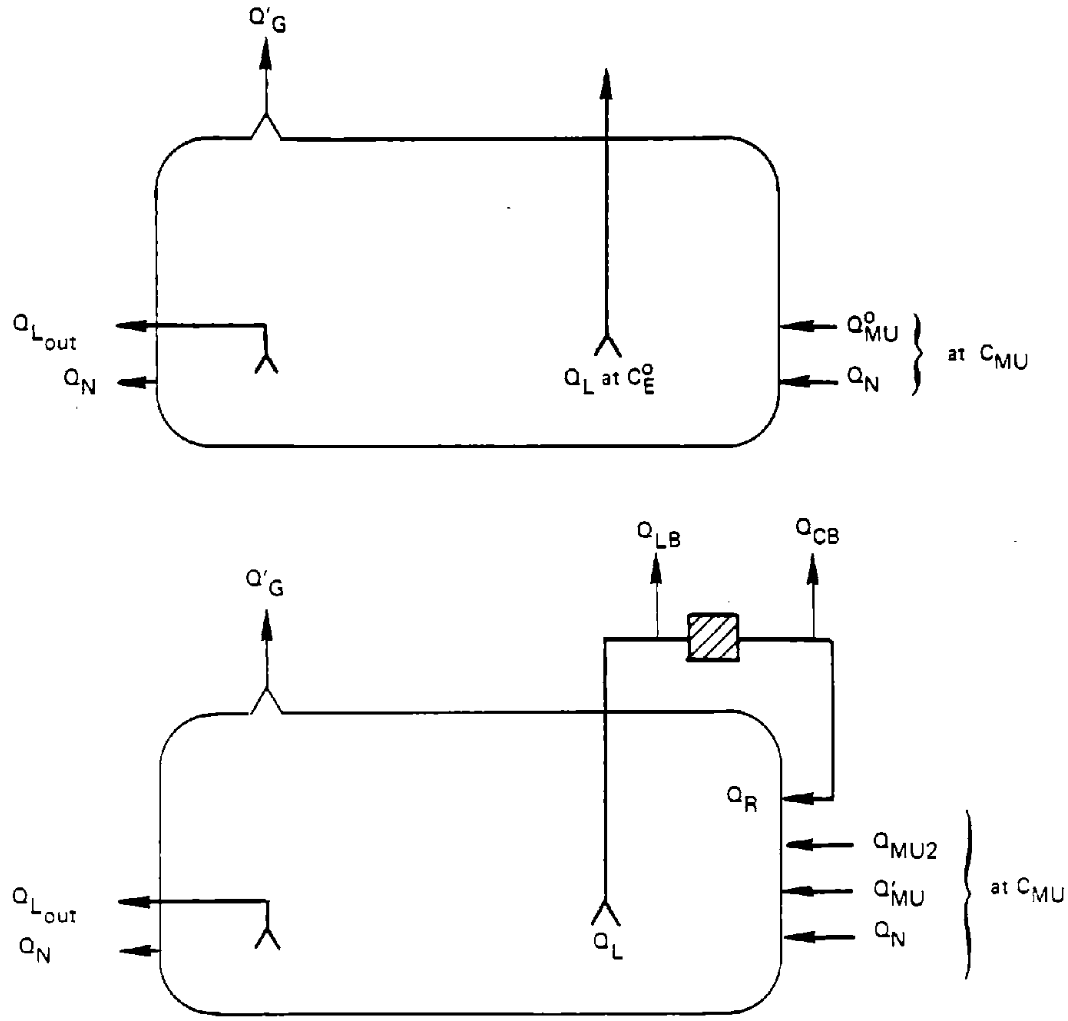
$$Q_{MU1} = Q'_G + Q_{L_{out}} + Q_{LB} + Q_{CB} - Q'_{MU}$$

Cost = User Specified Function

FIGURE B1 SYSTEM CONFIGURATION #1

Before

After



See Discussion For Proper Design Procedure. Useful Equations are:

$$Q_R = Q_L - Q_{LB} - Q_{CB}$$

$$Q_{MU2} = Q_{LB} + Q_{CB} + Q_{L_{out}} + Q'_G - Q'_{MU}$$

$$C_R = \frac{1}{k_{BZ}} \left[C^D_{BZ} - (1-f)\frac{Q^o_T}{Q_T} (C^o{}_{BZG} - C_{MU}) - f\,(C^o_{BZL} - C_{MU}) - (1-k_{BZ})\, C_{MU} \right]$$

$$\eta = 1 - \left[\frac{C_R}{C^o_E - k_R C_{MU} + k_R C_R} \right]$$

FIGURE B2 SYSTEM CONFIGURATION #2

effects of all inlet volume rates upon breathing zone concentrations. In consequence, the design procedure for the configuration is:

a. Choose a value for Q_{CB} or Q_{LB}.
b. Compute values for Q_{MU2} and Q_R.
c. Based upon the magnitudes and expected distribution of Q_{MU2} and Q_R, estimate values for k_{BZ} and k_R.
d. Compute the necessary C_R and the necessary fractional air cleaner efficiency η from the equation provided.
e. Adjust Q_{CB} or Q_{LB} and other parameters until an air cleaner efficiency η is computed which is slightly less than or equivalent to the efficiency of the equipment train intended for use.

Figure B2 lists the equations necessary to accomplish the described procedure.

System Configuration #3

Figure B3 represents a system configuration very similar to configuration #2. The only difference is that the air cleaner is a unit collector, attached to the contaminant producing local exhaust hood, and discharging directly into the room. Thus, there are no by-pass volumes Q_{LB} or Q_{CB} to contend with in computations. The equations presented, or inversions of them, are sufficient to assess the effect of recirculation upon breathing zones, once appropriate values have been estimated for all parameters.

System Configuration #4

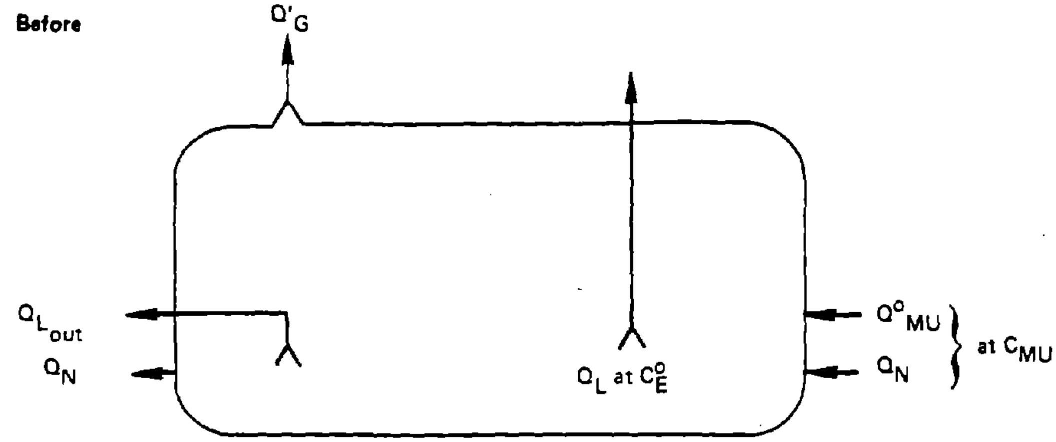
A general exhaust stream being recirculated is the subject of Figure B4. As in configuration #1, fresh make-up air volume Q_{MU1} is utilized to dilute recirculated air. The equations at the bottom of the figure allow the user to find the optimum solution for this particular configuration with a trial-and-error procedure. The independent variables of interest are volumes Q_G, and Q_{GB} or Q_{CB}.

Under many circumstances the optimum answer from the procedure will indicate that Q_{GB} and/or Q_{CB} should have a volume rate of zero. In consequence, straightforward manipulations of the equations can lead directly to a value for Q_G and the user should use an answer so obtained as a starting point for further iterations.

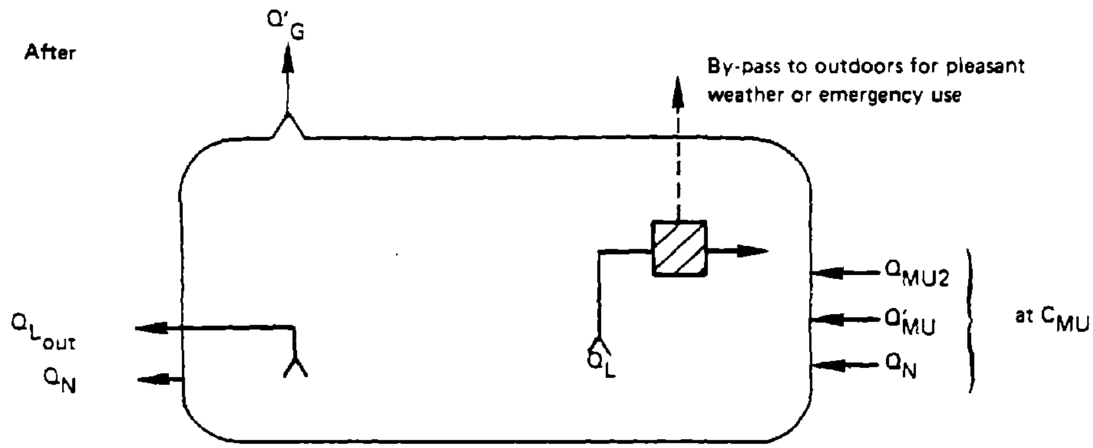
System Configuration #5

Similar to configuration #4, this configuration, shown in Figure B5, is different in its treatment of fresh make-up air volumes. Instead of being premixed with recirculated air, make-up air volume Q_{MU2} is brought directly into the plant. Independent design variables of interest are again Q_G and Q_{GB} or Q_{CB}, and all other comments made about configuration #4 apply to this one also.

Before



After



Determine Suitability of Unit Collector(s) from:

$$Q_{MU2} = Q_{L_{out}} + Q'_G - Q'_{MU} = Q^o_{MU} - Q_L - Q'_{MU}$$

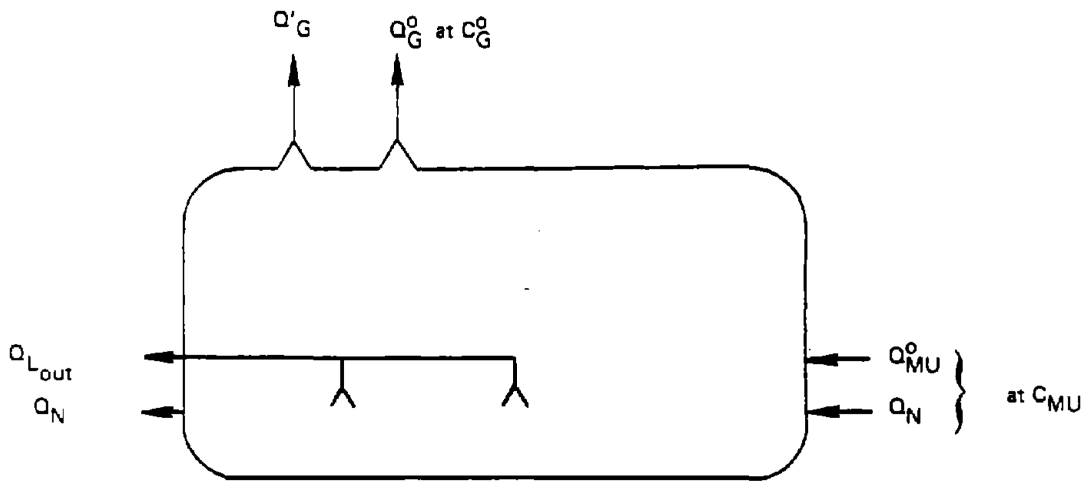
$$C_R = \left[\frac{(1-\eta)\,(C^o_E - k_R\,C_{MU})}{1.0 - (1-\eta)\,k_R} \right]$$

$$C_{BZ} = (1-f)\,(C^o_{BZG} - C_{MU}) + f(C^o_{BZL} - C_{MU}) + k_{BZ}C_R + (1-k_{BZ})\,C_{MU}$$

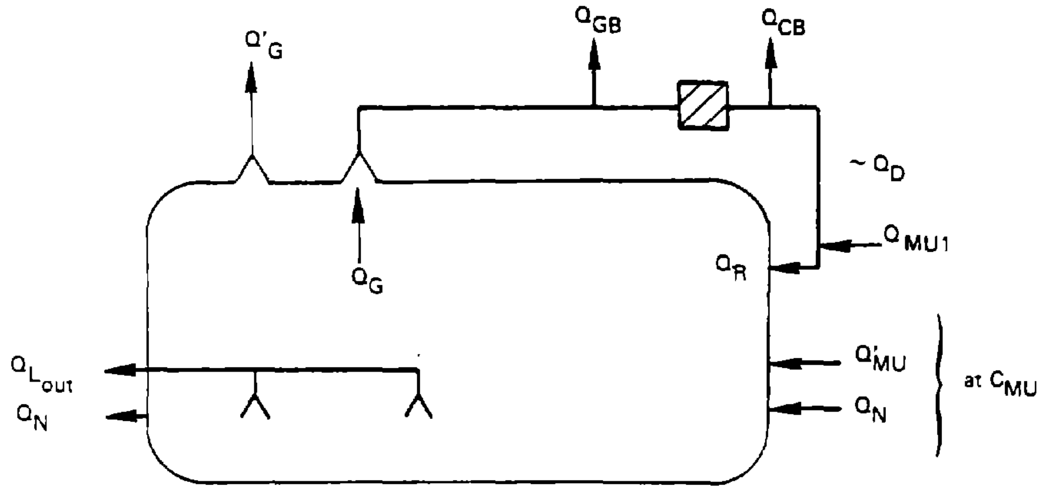
Note: Q_L should be the total volume through all unit collectors, if more than one is to be installed.

FIGURE B3 SYSTEM CONFIGURATION #3

Before



After



Find Optimum Solution by Trial-and-Error From:

$Q_D = Q_G - Q_{GB} - Q_{CB}$

$Q_{MU1} = Q_{GB} + Q_{CB} + Q_{L_{out}} + Q'_G - Q'_{MU}$

$Q_R = Q_D + Q_{MU1}$

$Q^o_T = Q^o_{MU} + Q_N$

$Q_T = Q_N + Q'_{MU} + Q_R$

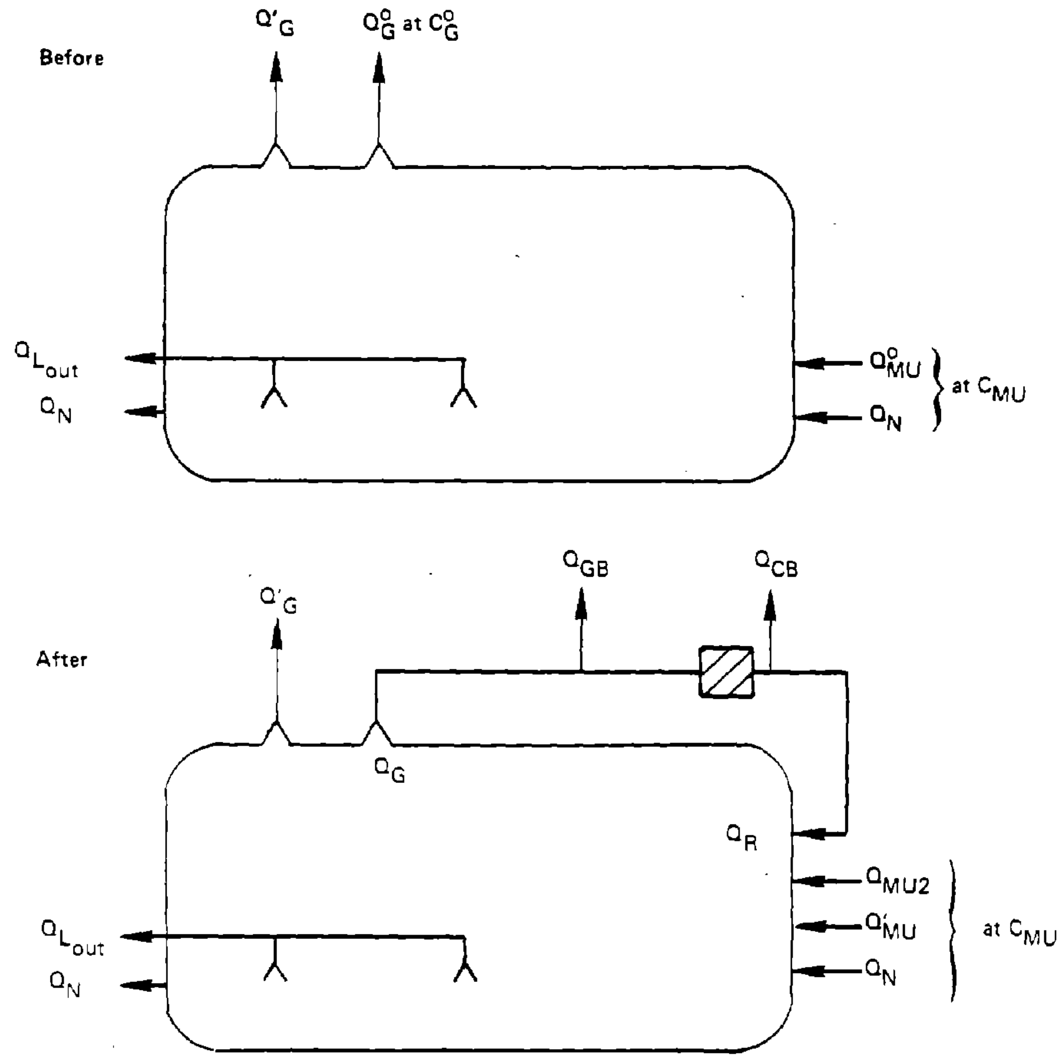
$C_R = (C_D Q_D + C_{MU} Q_{MU1})/Q_R$

$$C_{BZ} = (1 - f)\frac{Q^o_T}{Q_T}(C^o_{BZG} - C_{MU}) + f(C^o_{BZL} - C_{MU}) + k_{BZ} C_R + (1 - k_{BZ})\, C_{MU}$$

Cost = User Specified Function

$$C_D = \left[\frac{(1-\eta)\left[\dfrac{C^o_G Q^o_G}{Q_G} + \dfrac{C_{MU}}{Q_G}(Q'_{MU} + Q_{MU1} - Q^o_{MU})\right]}{1.0 - (1-\eta)\left(\dfrac{Q_D}{Q_G}\right)} \right]$$

FIGURE B4 SYSTEM CONFIGURATION #4



Find optimum solution, by trial-and-error, from:

$$Q_D = Q_R = Q_G - Q_{GB} - Q_{CB}$$

$$Q_{MU2} = Q_{GB} + Q_{CB} + Q_{L_{out}} + Q'_G - Q'_{MU}$$

$$Q^o_T = Q^o_{MU} + Q_N$$

$$Q_T = Q_N + Q'_{MU} + Q_{MU2} + Q_R$$

$$C_D = C_R = \left[\frac{(1-\eta)\left(\frac{C^o_G Q^o_G}{Q_G} + \frac{C_{MU}}{Q_G} \left(Q_{MU2} + Q'_{MU} - Q^o_{MU}\right) \right)}{1.0 - (1-\eta)\left(\frac{Q_R}{Q_G}\right)} \right]$$

$$C_{BZ} = (1-f)\ \frac{Q^o_T}{Q_T}\ (C^o_{BZG} - C_{MU}) + f\,(C^o_{BZL} - C_{MU}) + k_{BZ}\, C_R + (1-k_{BZ})\, C_{MU}$$

Cost = User Specified Function

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FIGURE B5 SYSTEM CONFIGURATION #5

The user is cautioned that the parameters k_{BZ} and k_R are somewhat a function of the magnitude of Q_{MU2} and/or Q_R, as discussed in the section concerning system configuration #2 and elsewhere. Thus, the solution procedure utilized must allow for variations in k_{BZ} and k_R as volume rates Q_{MU2} and Q_R are varied.

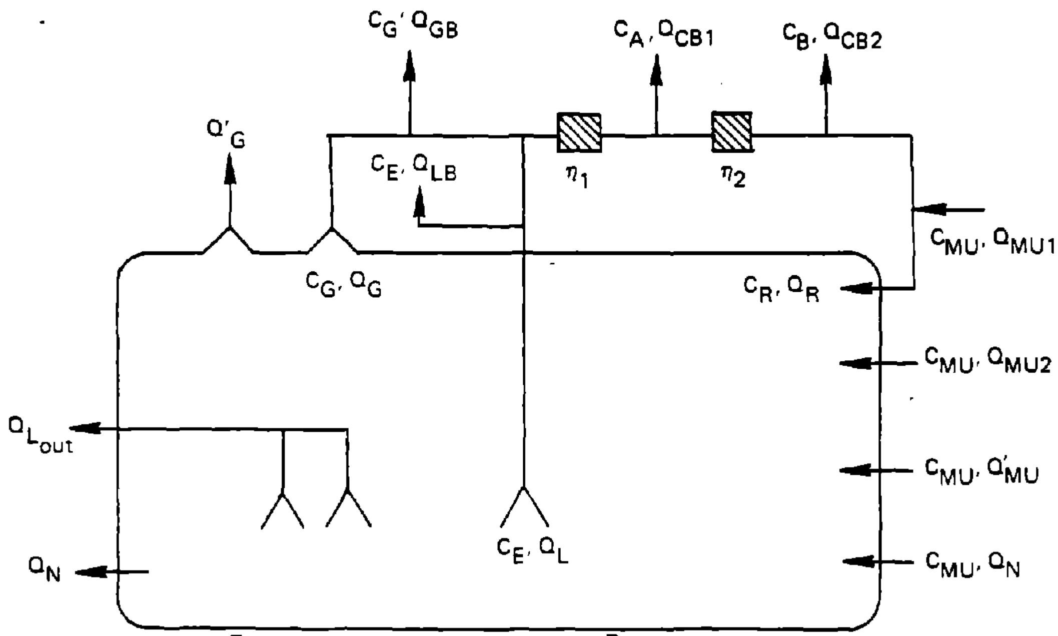
System Configuration #6

System configuration #6, illustrated in Figure B6 is a somewhat more complex version of Model #1. Features of the configuration include two air cleaning devices in series, each followed by a "cleaned" air by-pass to the atmosphere. Application of the configuration might be advantageous when the first air cleaner encountered is already in-place for compliance with air quality regulations, but an additional cleaner is required for recirculation purposes.

System Configuration #7

Model #2 provides the basis for the configuration shown in Figure B7. Similar to configuration #6 in concept, the configuration allows the user to more precisely select where and how he wishes to specify contaminated air by-passes to the atmosphere.

After



$$C_A = (1-\eta_1) \left[\frac{C_G (Q_G - Q_{GB}) + C_E (Q_L - Q_{LB})}{Q_G - Q_{GB} + Q_L - Q_{LB}} \right]$$

$$C_B = (1-\eta_2)\, C_A$$

$$C_D = \frac{(1-\eta_1)(1-\eta_2)\,[U(A+B) + T(D+E)]}{1 - (1-\eta_1)(1-\eta_2) \left(\frac{Q_D}{Q_R}\right)(UF + Tk_R)}$$

Where:

$$U = \frac{Q_G - Q_{GB}}{Q_G (Q_D + Q_{CB1} + Q_{CB2}} \qquad T = \frac{Q_L - Q_{LB}}{Q_D + Q_{CB1} + Q_{CB2}}$$

A, B, D, E and F are as previously defined for use with Models # 1 and # 2 in Appendix A.

$$Q_D = Q_G - Q_{GB} + Q_L - Q_{LB} - Q_{CB1} - Q_{CB2}$$

$$Q_R = Q_D + Q_{MU1}$$

$$Q_{MU1} + Q_{MU2} = Q_{L_{out}} + Q'_G + Q_{GB} + Q_{LB} + Q_{CB1} + Q_{CB2} - Q'_{MU}$$

$$C_R = \frac{C_D Q_D + C_{MU} Q_{MU1}}{Q_D + Q_{MU1}}$$

$$C_{BZ} = \frac{Q_T^o}{Q_T} (C^o_{BZG} - C_{MU})(1-f) + (C^o_{BZL} - C_{MU}) f + k_{BZ} C_R + (1-k_{BZ}) C_{MU}$$

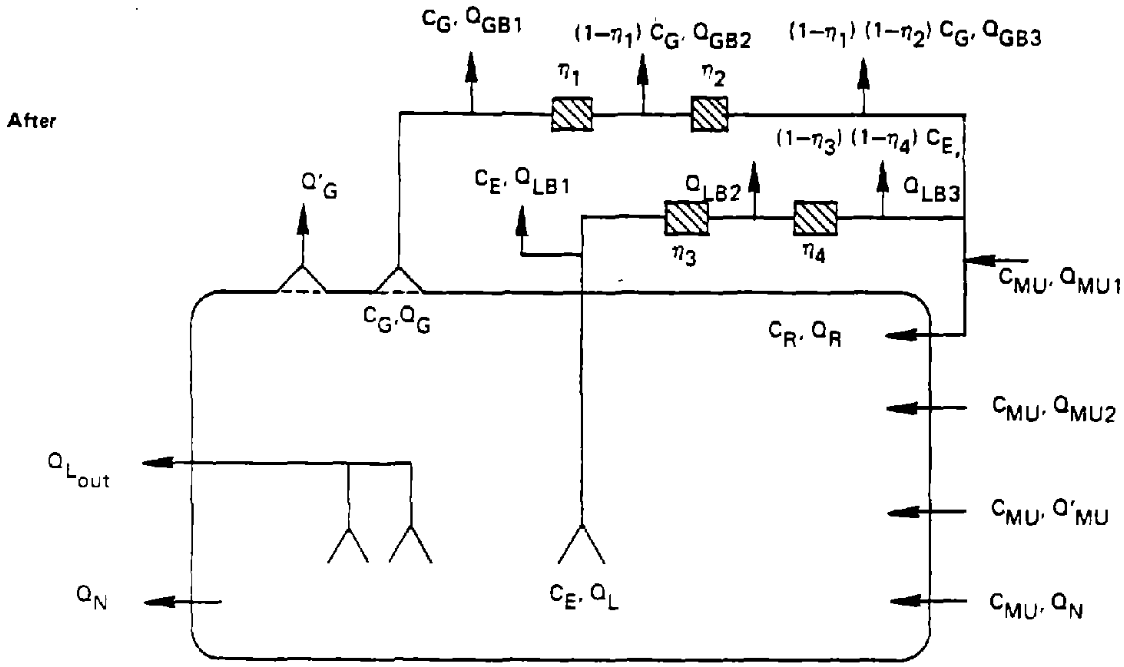
Where:

$$Q_T^o = Q_{MU}^o + Q_N$$

$$Q_T = Q_{MU1} + Q_{MU2} + Q'_{MU} + Q_N + Q_R$$

Cost = User specified function

FIGURE B6 SYSTEM CONFIGURATION # 6



$$Q_D = Q_G - Q_{GB1} - Q_{GB2} - Q_{GB3} + Q_L - Q_{LB1} - Q_{LB2} - Q_{LB3}$$

$$Q_R = Q_D + Q_{MU1}$$

$$Q_{MU1} + Q_{MU2} = Q_{L_{out}} + Q'_G + Q_{GB1} + Q_{GB2} + Q_{GB3} + Q_{LB1} + Q_{LB2} + Q_{LB3} - Q'_{MU}$$

$$C_D = \frac{(1-\eta_1)\,(1-\eta_2)\,(UA + UB) + (1-\eta_3)\,(1-\eta_4)\,(TD + TE)}{1 - (1-\eta_1)\,(1-\eta_2)\left(\frac{Q_D}{Q_R}\right)(UF) - (1-\eta_3)\,(1-\eta_4)\left(\frac{Q_D}{Q_R}\right)(TK_R)}$$

Where:

$$U = \frac{Q_G - Q_{GB1} - Q_{GB2} - Q_{LB3}}{Q_G Q_D}$$

$$T = \frac{Q_L - Q_{LB1} - Q_{LB2} - Q_{LB3}}{Q_D}$$

A, B, D, E and F are as previously defined for use with Models # 1 and 2 in Appendix A.

$$C_R = \frac{C_D Q_D + C_{MU}\, Q_{MU1}}{Q_R}$$

$$C_{BZ} = \frac{Q_T^o}{Q_T}\,(C_{BZG}^o - C_{MU})\,(1-f) + (C_{BZL}^o - C_{MU})\, f + k_{BZ} C_R + (1-k_{BZ})\, C_{MU}$$

Where:

$$Q_T^o = Q_{MU}^o + Q_N$$

$$Q_T = Q_{MU1} + Q_{MU2} + Q'_{MU} + Q_N + Q_R$$

Cost = User specified function.

FIGURE B7 SYSTEM CONFIGURATION # 7

APPENDIX C

DERIVATION OF RECIRCULATION

SYSTEM MODEL #1

Introduction

With the exception of the expression derived in "The Breathing Zone Equation" section of Appendix A, this appendix presents a detailed derivation of the equations for Model #1. Derivation of all other models presented in this report was accomplished using similar methodology. Assumptions and parameter definitions unstated in this appendix can be found in Appendix A.

Derivation of Model #1

Point E on Figure C1 has a concentration level which is the weighted average concentration of the local exhaust streams being partially recirculated. The exhaust volume at the point is the sum of volumes drawn through each branch leading to the point, minus any volume (Q_{LB}) which is by-passed. Hence, the concentration at point E(i.e., C_E) and the air flow rate at the point (i.e., Q_E) can be determined from:

$$C_E = \frac{C_{E1}Q_{L1} + C_{E2}Q_{L2} + C_{E3}Q_{L3} + \cdots}{Q_{L1} + Q_{L2} + Q_{L3} + \cdots}$$

$$= \frac{\sum_{i=1}^{i=n} (C_{Ei}Q_{Li})}{\sum_{i=1}^{i=n} Q_{Li}}$$

$$Q_E = Q_{L1} + Q_{L2} + Q_{L3} + \cdots - Q_{LB}$$

$$= \left(\sum_{i=1}^{i=n} Q_{Li}\right) - Q_{LB} = Q_L - Q_{LB}$$

where

$$Q_L = \sum_{i=1}^{i=n} Q_{Li} \text{ for brevity.}$$

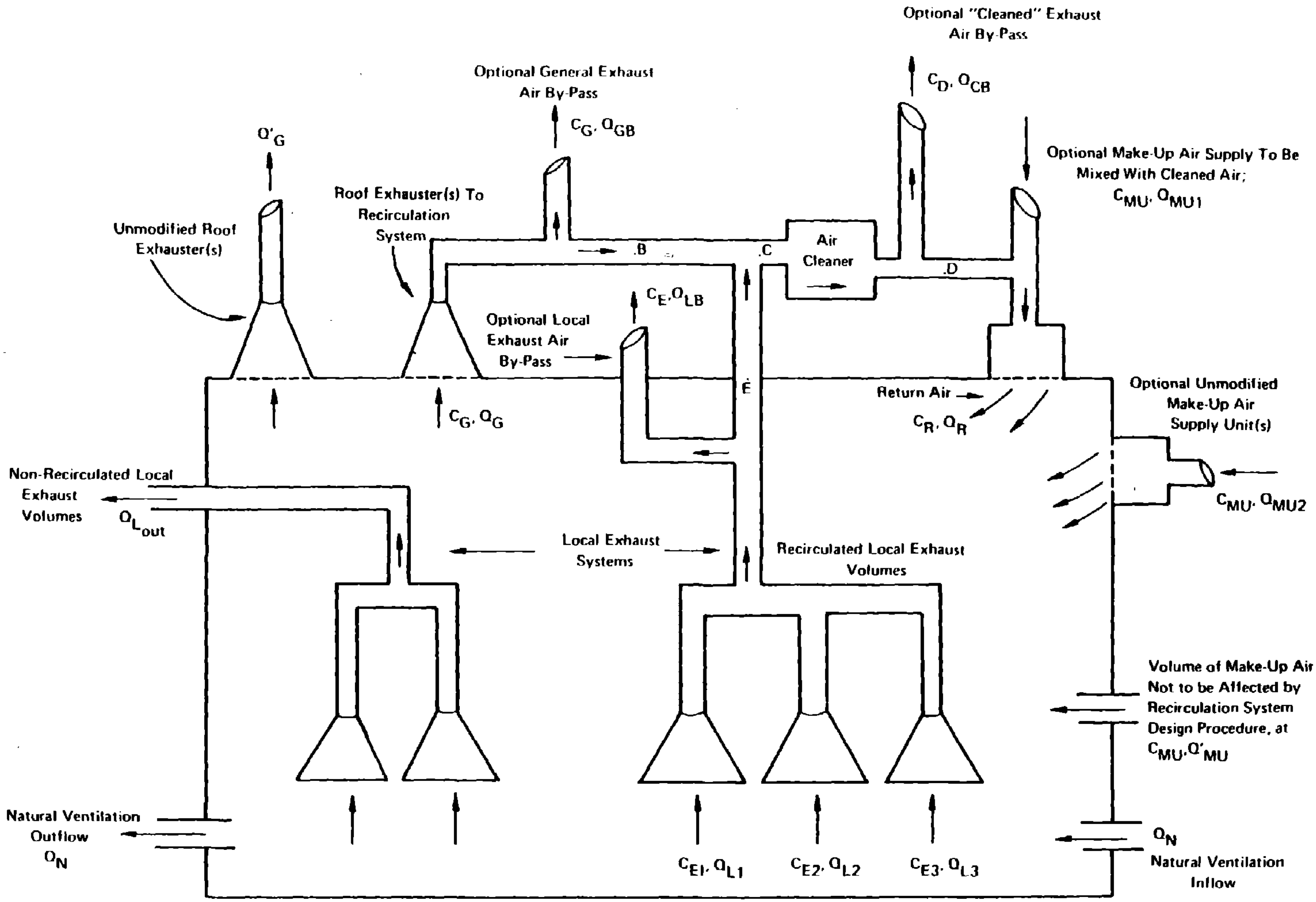


Figure C1 **PLANT AREA WITH RECIRCULATION – MODEL #1**

At point B in the system, the concentration in the duct (C_G) is the same as that at the general exhaust air outlet from the room. The exhaust volume is the general air exhaust volume extracted from the room (Q_G), minus any air which is by-passed (Q_{GB}). Therefore:

$$Q_B = Q_G - Q_{GB}$$

Point C is at the entrance to an air cleaning equipment train with overall efficiency η. The concentration and exhaust volume here are:

$$C_C = \frac{C_G Q_B + C_E Q_E}{Q_B + Q_E}$$

$$\begin{aligned} Q_C &= Q_B + Q_E \\ &= Q_G - Q_{GB} + Q_L - Q_{LB} \end{aligned}$$

Following the air cleaning section, at point D, the concentration and air volume are given by:

$$\begin{aligned} C_D &= (1 - \eta)\, C_C \\ &= (1 - \eta) \left[\frac{C_G Q_B + C_E Q_E}{Q_B + Q_E} \right] \end{aligned}$$

$$C_D = (1 - \eta) \left[\frac{C_G (Q_G - Q_{GB}) + C_E (Q_L - Q_{LB})}{Q_G - Q_{GB} + Q_L - Q_{LB}} \right] , \qquad (1)$$

and

$$\begin{aligned} Q_D &= Q_B + Q_E - Q_{CB} \\ &= Q_G - Q_{GB} + Q_L - Q_{LB} - Q_{CB} \end{aligned}$$

where Q_{CB} is the volume of any air by-passed at a point after the air cleaner.

Immediately following point D, the "clean" make-up air stream is being mixed with the flow leaving the air cleaning section. The resulting air stream, termed the "return" air stream, has a concentration (C_R) and volume (Q_R) given by:

$$C_R = \frac{C_D Q_D + C_{MU} Q_{MU1}}{Q_D + Q_{MU1}} \qquad (2)$$

$$Q_R = Q_D + Q_{MU1}$$

The next step in the modeling is to develop estimates of the exhaust concentrations C_G and C_E from an overall mass balance.

The initial rate of contaminant entry into the room (R_I) is given by:

$$R_I = \dot{m} + C_{MU} (Q_N + Q^{\circ}_{MU})$$

where $\dot{m}$ = is the total contaminant generation rate for all operations and processes within the plant area; (a term which will eventually cancel out of equations);

Q°_{MU} = the make-up air rate required by the conventional ventilation system = $Q'_G + Q^{\circ}_G + Q_{L_{out}} + Q_L$; and

C_{MU} = make-up air contaminant concentration, a weighted average for all make-up streams

After recirculation, the rate of entry of contaminant into the room (R_F) is:

$$R_F = \dot{m} + C_{MU}(Q_N + Q_{MU2} + Q'_{MU}) + C_R Q_R$$

where Q'_{MU} = the volume of any make-up air supply one does not wish to be affected by the installation of the recirculation system. This can best be thought of as some volume of make-up air which must be maintained at present levels. It is separate from volumes Q_{MU1} or Q_{MU2} which are considered "adjustable" during the system design process.

The difference between the initial and final rates represents the change in rate of contaminant entry into the plant area following installation of the recirculation system:

$$R_F - R_I = C_R Q_R + C_{MU} (Q_{MU2} + Q'_{MU} - Q^{\circ}_{MU})$$

An inherent and not immediately obvious assumption made in the above is that the volume of local exhaust streams to be recirculated is a constant, i.e., it is the same before recirculation as after and cannot be varied during the use of a model to help minimize overall system cost. This assumption is made because it is recognized that there are not sufficient data available to allow estimation of benefits derived from increasing the volume of air locally exhausted. Hence, designers wishing to modify local exhaust volumes should do so before the recirculation system design models are applied to a conventional system, and should utilize "new" exhaust volumes and concentrations in application of the models.

Relationship of C_E to C_E°

The air being drawn into local exhaust hoods comes either from the return air stream, from relatively clean make-up air streams, or from a combination of both. The physical fraction of recirculated local exhaust air that comes from the return air stream can be defined by a contribution factor k_R. The fraction of the local exhaust volume which is made up of fresh air streams is then given by the fraction $(1 - k_R)$. Consequently:

$$Q_L = \underbrace{k_R Q_L}_{\text{return air}} + \underbrace{(1 - k_R) Q_L}_{\text{fresh make-up air}}$$

The fraction of the total local exhaust volume which comes from return streams is at a concentration C_R while the fraction from fresh air streams is at a concentration C_{MU}. Therefore,

$$C_E Q_L = C_E^\circ Q_L - C_{MU} Q_L + k_R C_R Q_L + (1 - k_R) C_{MU} Q_L$$

$$C_E = C_E^\circ + k_R (C_R - C_{MU}) \qquad (3)$$

The first of these equations illustrates that the contaminant flow rate through local exhaust air streams being recirculated may be less than, equal to, or greater than the rate before recirculation, depending on the values for k_R, C_R and C_{MU}. The change in the rate is given by:

$$\Delta_G = R_F - R_I - \Delta_L$$

Relationship of C_G to C_G°

In order to be conservative in the analysis, the assumption is made that any change in the rate of contaminant entry into the room due to recirculation is balanced by changes in the concentration levels of only those exhaust streams that are to be recirculated. This assumption ensures that the concentration level in the return air is not under-estimated, if the rate of contaminant entry increases with recirculation. It also allows one to equate the quantity Δ_G to the changed contaminant flow rate in general exhaust air streams being recirculated, if such a stream is present. This reasoning permits the following manipulations:

$$R_F - R_I = C_R Q_R + C_{MU}(Q_{MU2} + Q'_{MU} - Q^\circ_{MU})$$

$$\Delta_G = R_F - R_I - \Delta_L$$

$$= C_R Q_R + C_{MU}(Q_{MU2} + Q'_{MU} - Q^\circ_{MU}) - k_R(C_R - C_{MU})Q_L$$

$$C_G Q_G = C^\circ_G Q^\circ_G + \Delta_G$$

$$= C^\circ_G Q^\circ_G + C_{MU}(Q_{MU2} + Q'_{MU} + k_R Q_L - Q^\circ_{MU}) + C_R(Q_R - k_R Q_L)$$

$$C_G = \frac{C^\circ_G Q^\circ_G}{Q_G} + \frac{C_{MU}(Q_{MU2} + Q'_{MU} + k_R Q_L - Q^\circ_{MU})}{Q_G} + \frac{C_R(Q_R - k_R Q_L)}{Q_G} \tag{4}$$

where

C°_G is the concentration near the general exhaust outlet before recirculation; and

Q°_G is the exhaust volume of general air intended to be recirculated.

Flow Balances

It is now possible to compute the concentration of contaminant in the return air stream, and the volume of the stream, given only initial contaminant concentrations and the flow volumes of streams intended for recirculation. This computation requires specification of all flow volumes within the recirculation system such that overall air flow balances in the plant area are maintained. Such balances are straightforward in derivation and it is noted that:

$$Q_{MU1} + Q_{MU2} = Q_{GB} + Q_{LB} + Q_{L_{out}} + Q'_G + Q_{CB} - Q'_{MU}$$

$$Q_D = Q_G - Q_{GB} + Q_L - Q_{LB} - Q_{CB}$$

$$Q_R = Q_D + Q_{MU1}$$

$$Q^\circ_{MU} = Q^\circ_G + Q_L + Q'_G + Q_{L_{out}}$$

$$Q^\circ_T = Q^\circ_{MU} + Q_N$$

$$Q_T = Q_R + Q_N + Q'_{MU} + Q_{MU2}$$

Consolidation of Equations

An explicit and practically useful expression for estimating the concentration of contaminant leaving the air cleaner can be derived by consolidation of equations 1, 2, 3 and 4. This is accomplished by substituting the expressions for C_R, C_E, and C_G (equations 2, 3, and 4, respectively) into equation 1, and then algebraically solving for C_D. The result of the procedure is equation 1 presented in Appendix A and below.

$$C_D = \frac{(1-n)\,[U(A+B) + T(D+E)]}{1.0 - (1-n)\left(\frac{Q_D}{Q_R}\right)(UF + Tk_R)}$$

where:

$$U = \frac{Q_G - Q_{GB}}{Q_G(Q_D + Q_{CB})}$$ if $Q_G = 0$, then $Q_{GB} = 0$, and $U = 0$

$$A = C^\circ_G Q^\circ_G + C_{MU}(Q_{MU2} + Q'_{MU} + k_R Q_L - Q^\circ_{MU})$$

$$B = \frac{C_{MU} Q_{MU1}(Q_R - k_R Q_L)}{Q_R}$$ if $Q_R = 0$, then $Q_{MU1} = 0$, and $B = 0$

$$T = \frac{Q_L - Q_{LB}}{Q_D + Q_{CB}}$$ if $Q_D + Q_{CB} = 0$, then $T = 0$

$$D = C^\circ_E - k_R C_{MU}$$

$$E = \frac{k_R C_{MU} Q_{MU1}}{Q_R}$$ if $Q_R = 0$, then $Q_{MU1} = 0$, and $E = 0$

$$F = Q_R - k_R Q_L$$

APPENDIX D

RECIRCULATION OF A SILICA-CONTAMINATED EXHAUST

CAUTION

This hypothetical case history is solely intended to provide readers with specific insights to some of the many factors which must be considered before recirculation of exhaust air. It must not be interpreted as a recommendation for any specific system design. Nor can it be considered sufficiently detailed for actual system design and implementation purposes.

Introduction

A work place near Detroit plans to install a second, silica-generating work station near an existing station.

Management realizes that installation of the new 30,000 cfm exhaust unit to service the work station is going to aggravate an already severe make-up air problem during cold weather. The extent of the problem became evident when gas supplies were curtailed the previous winter, and an attempt was made to continue production by simply discontinuing the practice of heating fresh air brought into the plant. Not only did the absenteeism rate drastically increase due to worker discomfort, but the union suggested such practices must be given consideration in upcoming contract discussions. In consequence, management has become interested in decreasing plant dependence upon fuel supplies by finding alternatives to tempered make-up air units.

Existing Conditions

A consultant retained by the firm is asked to evaluate the feasibility of exhaust air recirculation. Upon requesting certain data about the existing operation, he is provided the information shown in Table D1, and a detailed schematic diagram showing the layout of the plant and its ventilation system (drawing unshown).

Examining data items 1-6, the consultant concludes that the existing area is well-ventilated. The hood design agrees with standard practice, and the breathing zone concentrations measured are sufficiently low. Continuing his examination of the data, he finds the size distribution of dust to be typical in that 50% of the dust is respirable. Similarly, the loading on the air cleaner is about right, although the sand composition data are not what he's normally seen in other areas of the country.

The air cleaner utilized on the existing system is common, and although it works perfectly for air pollution compliance purposes, the outlet

TABLE D1

EXISTING SYSTEM DATA

ITEM #	
1	Type of Hood: Single side-draft
2	Grate area: 54 sq ft
3	Temperature of work in hand: 450°F
4	Cross-drafts: High
5	Exhaust volume: 500 cfm/sq ft grate area for total of 27,000 cfm, plus a hopper exhausted at 3000 cfm.
6	Design of installation: As recommended by the Industrial Ventilation Manual
7	Size distribution of collected dust:

Aerodynamic Diameter (microns)	Cumulative Wt % less than diameter
30	99.5
20	96
10	63
5	50
4	45
3	40
2	20
1	10
.5	1

8 Concentration in Exhaust Duct: Varies 1/2 to 2 $\frac{\text{grains}}{\text{ft}^3}$

9 Analysis of Dust in Exhaust Duct:

Quartz content of sand: 51% of total
Cristobalite content: trace
Tridymite content: None
Fused silica content: trace
Tripoli content: None
Other contaminants: steam; silicates; other minerals

10 Breathing Zone Concentrations (TWA)*:

0.7 gm/cu m respirable (7% quartz), 20% particles < .5 micron in size,
2.0 mg/cu m total (10% quartz)

11 Air Cleaner Type: Wet collector operated at 6" pressure drop

12 Air Cleaner Effluent

Characteristics: high humidity; unknown concentration

13 Other Exhaust Volumes in Plant

Roof exhausters: 154,000 cfm total
Operation A: 2000 cfm total
Operation B: 2000 cfm total
Arc Furnace: 60,000 cfm
Abrasive Blasting Room: 12,000 cfm
Sand Handling System: 20,000 cfm

14 Make-Up Air Volumes to Plant

System #1: 60,000 cfm (untempered to furnace area)
System #2: 60,000 cfm (tempered)
System #3: 60,000 cfm (tempered)
System #4: 60,000 cfm (tempered)

Concentration of particulates in make-up air $\simeq$ 0.05 mg/cu m

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* Data obtained using methods described in NIOSH Sampling Data Sheet #3.02.

stream is of high humidity. Additionally, given the loading on the device, the outlet stream is known to have a significant concentration of respirable particulates.

Development of a Recirculation System Concept

For initial design purposes, the consultant decides not to attempt to utilize the outlet stream from the wet collector for conservation purposes. He believes the dampness of the air would adversely affect the lifetime of any bag filters placed in series with the device, and "absolute" filters would load up too fast. He will check on these judgments in more detail, in any case, before finalizing his proposed design.

The next step is to review the efficiency of air cleaning device types which would be acceptable to the company and provide sufficient cleaning. The immediate choice for consideration is the general category of bag filters. The specific model to be first examined is reliable, relatively inexpensive, compact, and efficient. Indeed, the manufacturer guarantees collection of 99.9% of all particles over 0.5 micron in size.

Bag Filter Computations

To roughly assess the feasibility of using a bag filter device, the consultant performs a few computations. First, he estimates the loading characteristics of the stream which will enter the air cleaner.*

Air Cleaner loading (total)	$\simeq$ 2 gr/cu ft
	$\simeq$ 4577 mg/cu m
Non-respirable loading	$\simeq$ 50% of total
	$\simeq$ 2288 mg/cu m
Loading > .5 and < 5 microns	$\simeq$ 49% of total
	$\simeq$ 2243 mg/cu m
Loading < .5 micron	$\simeq$ 1% of total
	$\simeq$ 46 mg/cu m

Next, he wishes to estimate the characteristics of the stream which leaves the bag filter. For all particulates greater than 0.5 micron in size, he uses the "guaranteed" air cleaner efficiency of $\eta = 0.999$, although he realizes the efficiency will be very low with clean bags, and will be somewhat lower immediately after bags are shaken. Calling the equipment manufacturer, he finds that an overall efficiency of $\eta = 0.95$ is most

* The use of a 5 micron aerodynamic diameter as the borderline between respirable and non-respirable particles is not exactly correct. The practice is considered to be adequate, however, for the purposes of this example problem.

appropriate for particles less than 0.5 microns in size. He has some reservations about this answer, but continues his computations.

Exhaust concentration > 5 micron

$\simeq$ (1-η)(loading)

$\simeq$ (1-.999)(2288)

$\simeq$ 2.29 mg/cu m

Exhaust concentration > .5 and < 5 microns

$\simeq$ (1-.999)(2243)

$\simeq$ 2.24 mg/cu m

Exhaust concentration < .5 micron

$\simeq$ (1-.95)(46)

$\simeq$ 2.3 mg/cu m

Non-respirable concentration = 2.29 mg/cu m

Respirable concentration = 4.54 mg/cu m

Total dust concentration = 6.83 mg/cu m

Finally, he wishes to estimate the permissible exposure limits for these contaminants. To do this, he decides to simply use the limit for the most toxic constituent of the sand, quartz.

$$\text{Current TWA (respirable)} = \frac{10 \text{ mg/cu m}}{7\% \text{ respirable} + 2} = 1.11 \text{ mg/cu m}$$

$$\text{Current TWA (total)} = \frac{30 \text{ mg/cu m}}{10\% \text{ total} + 2} = 2.5 \text{ mg/cu m}$$

Inspection of the results of these computations cause the designer further concern. His rough estimates of air cleaner outlet concentrations are sufficiently high that they may cause vastly increased breathing zone concentrations and defeat plant efforts to keep a "clean" shop. Finally, he is worried about the fact the dust leaving the air cleaner has a higher respirable fraction than the air entering the cleaner. And what will the affect of recirculation be upon the quartz content of breathing zone samples?

Air Filters

To further reduce the concentration of dust out of the bag filter, the designer decides to investigate the use of "absolute" or HEPA filters. By definition, these are capable of removing 99.97% of 0.3 micron droplets of DOP from an air stream. He quickly learns that these filters are expensive and have a dust-holding capacity so low that even atmospheric air must be pre-cleaned for their efficient use. Additionally, he finds most types cannot be cleaned and must be thrown away when dirty. With the high loading he has estimated, their use in this situation is reluctantly rejected.

Continuing his investigation for less efficient filters, he finds that a type which has been shown capable of removing 96% (by weight) of silica dust having a mean diameter of about 2 microns. This is a simple device using wool felt which can be cleaned with a portable vacuum cleaner. Contacting the manufacturer, he learns that the overall efficiency of the unit for particles greater than 0.5 microns in size would be 88%. For all smaller particles, an estimate of 60% is given. The designer immediately decides that such a filter following the bag device would be ideal, and simultaneously allow monitoring of the exhaust stream by pressure drop measurements.

Computing the concentrations to be expected downstream of the wool felt filter, he finds:

Exhaust concentration > 5 microns

$\simeq (1-.88)(2.29) \simeq 0.27$ mg/cu m

Exhaust concentration > .5 and < 5 microns

$\simeq (1-.88)(2.24) \simeq 0.27$ mg/cu m

Exhaust concentration < .5 micron

$\simeq (1-.6)(2.3) \simeq 0.92$ mg/cu m

Non-respirable concentration = 0.27 mg/cu m

Respirable concentration = 1.19 mg/cu m

Total dust concentration = 1.46 mg/cu m

The potential for the bag device in series with the wool felt filter to provide adequate cleaning appears to be considerable at this point. The designer now turns to the recirculation systems model to finalize the design.

Use of the Recirculation System Model

Reviewing the information provided by the plant, the designer quickly specifies the following design parameters for the model.

Q_L = 30,000 cfm = local exhaust volume for recirculation

C_E° = 4577 $\frac{mg}{m^3}$ = total dust concentration in local exhaust duct

= 2243 $\frac{mg}{m^3}$ = concentration > .5 and < 5 microns

= 45 $\frac{mg}{m^3}$ = concentration < .5 micron

Q_G' = 154,000 cfm = general exhaust volume not to be recirculated

Q_{Lout} = 96,000 cfm = local exhaust volumes not to be recirculated

Q_{MU}' = 240,000 cfm = make-up air volume not to be modified

Q_{MU}° = 270,000 cfm = total make-up needed for conventional system with new work station

C_{BZG}° = 0.7 mg/m^3 = respirable dust concentration in breathing zones (TWA)

= 2.0 mg/m^3 = total dust concentration in breathing zones (TWA)

Q_G = 0.0 cfm = decision that additional general exhaust not desired

Q_{GB} = 0.0 cfm = required by Q_G = 0.0 cfm decision

C_{MU} = 0.05 $\frac{mg}{m^3}$ = particulate concentration in make-up air

η = 1-(1-.999)(1-.88) = .99988 = efficiency of cleaner series on > .5 micron particles

η = 1-(1-.95)(1-.60) = 0.9800 = efficiency of cleaner series on < .5 micron particles

The design parameters remaining to be specified include Q_{MU1}, Q_{MU2}, Q_N, k_R, k_{BZ}, and f. Each of these requires considerable thought and study.

Knowledge of how the model works allows the designer to look at Q_{MU1}, and Q_{MU2}, simultaneously. If he chooses to have a new make-up air stream mix with the air from the cleaners, he may set Q_{MU2} to zero, and solve the equation for Q_{MU1}. Alternatively, if he chooses to bring any new make-up air stream into the work place without diluting the recirculated air, Q_{MU1} can be set to zero. He likes the idea of further diluting the exhaust stream, so chooses to set Q_{MU2} to zero. Since he can place any new make-up air supply wherever he desires, this is his obvious best choice.

Checking the overall air balance of the plant, as reported, he next finds that 10,000 cfm more air are exhausted than made-up. This will cause a problem because the model assumes, and requires, that all inlet and outlet volumes are balanced. To resolve the issue, he increases the value for Q'_{MU} to 250,000 cfm instead of using 240,000 cfm. The additional volume is assumed to come from air leaks in the building, etc.

While on the subject of air leaks, he decides to next determine a value for Q_N, the natural ventilation rate through the building. He knows that this will not be easy, since the building is old, far from airtight, and contains numerous heat sources. Reviewing specific details of the model, however, he also learns that a roughly estimated answer, on the low side, will save considerable work and provide a more conservative system design. Hence, knowing that a modern, tight building has a Q_N of at least 1 air change per hour, and that a "hotshop" can have over 15 changes, he guesses that the operation of interest has at least 5 changes due to natural forces. This gives him a rate of about 70,000 cfm.

Selection of a value for k_R, the fraction of local exhaust air which is provided by the return air stream, requires that some thought be given to where the return air will enter the plant. Looking at the plant layout, the designer decides that he will simply allow the return air to enter the room from the outlet of the wool felt device, without installing any new ducting to lead it elsewhere. Since this air would return at a point about 30 feet from the operation, he decides that a k_R of 0.5 is fully adequate, and conservative.

The parameter k_{BZ} is the fraction of breathing zone air which is provided by the return air stream. Wishing to be fully conservative in his computations at this stage of his analysis, the designer picks a value of 0.9.

The last parameter to be specified is f, the fraction of their time that workers spend in an area influenced by a local exhaust flow field. Being familiar with this type of operation, noting that cross-drafts in the area of concern are high, and the work is fairly hot, the designer estimates that the worker would have to be right next to the exhaust grate to be in such a flow field. Since a worker would not approach this close when significant amounts of dust are being generated, he sets f to zero.

In summary, these last decisions have specified:

Q_{MU1} = design variable, cfm

Q_{MU2} = 0.0 cfm

Q_N = 70,000 cfm

k_R = 0.5

k_{BZ} = 0.9

f = 0.0 and

Q'_{MU} = 250,000 cfm instead of 240,000

The designer now has values for all parameters required by the model, except for those, Q_{LB} and Q_{MU1}, which he has selected as design variables. He varies Q_{LB}, solves for Q_{MU1}, and lists his results for both total dust concentrations and respirable dust concentrations in Tables D-2, D-3, and D-4 respectively. In Table D-5, he adds the various concentrations together to more comfortably inspect total dust levels expected.

Interpreting Results of the Model

Inspecting the predicted breathing zone concentrations in Table D-5, the designer sees that he can recirculate about 10,000 cfm before exceeding permissible exposure limits. Of course, he realizes that the magnitude of his answers are completely dependent upon the values of all the design parameters he guessed at. Consequently, he decides to more closely assess the effect of each of his decisions on the final answers.

There is no doubt in his mind that the parameter k_{BZ} had a substantial effect in causing increases in predicted breathing zone concentrations. Wishing to be conservative, he had picked the rather high value of 0.9; even though he knew that 90% of workers' breathing zone air wouldn't come directly from the outlet of the wool felt filter. After all, the outlet would be at least 30 feet distant, and could be pointed away from the work station. More important than that, he knows that the various air flow patterns existing in the area of concern would cause significant dilution of the outlet stream before it reached any employees constant work station. He must examine this situation in more detail.

TABLE D2

RECIRCULATION MODEL RESULTS

FOR NON-RESPIRABLE DUST

Significant Constants:

C_E° = 2288 mg/cu m

η = 0.99988

Q_R = 30,000 cfm

C_{BZG}° = Total dust concentration - Respirable concentration

= 2.00 - .70 = 1.30 mg/cu m

Assume atmospheric dust in make-up is respirable.

Q_{LB} cfm	Q_{MU1} cfm	Q_D cfm	C_D mg/cu m	C_R mg/cu m	C_{BZ} mg/cu m
0	0	30,000	0.27	0.27	1.54
4,000	4,000	26,000	0.27	0.23	1.51
8,000	8,000	22,000	0.27	0.20	1.48
12,000	12,000	18,000	0.27	0.16	1.44
16,000	16,000	14,000	0.27	0.13	1.41
20,000	20,000	10,000	0.27	0.09	1.37
24,000	24,000	6,000	0.27	0.05	1.33
28,000	28,000	2,000	0.27	0.02	1.32
30,000	30,000	0	0	0	1.30

TABLE D3

MODEL RESULTS FOR

RESPIRABLE FRACTION > .5 AND < 5 MICRONS

Significant Constants

C°_E = 2243 mg/cu m

η = 0.99988

Q_R = 30,000 cfm

C°_{BZG} = Total respirable concentration - respirable concentration < .5 micron in size

= 0.7 - .14 = 0.56 mg/cu m

Assume all atmospheric dust is of this size fraction.

Q_{LB} cfm	Q_{MU1} cfm	Q_D cfm	C_D mg/cu m	C_R mg/cu m	C_{BZ} mg/cu m
0	0	30,000	0.27	0.27	0.76
4,000	4,000	26,000	0.27	0.24	0.73
8,000	8,000	22,000	0.27	0.21	0.71
12,000	12,000	18,000	0.27	0.18	0.68
16,000	16,000	14,000	0.27	0.15	0.65
20,000	20,000	10,000	0.27	0.12	0.63
24,000	24,000	6,000	0.27	0.09	0.60
28,000	28,000	2,000	0.27	0.06	0.57
30,000	30,000	0	0	0.05	0.56

TABLE D4

MODEL RESULTS FOR RESPIRABLE

FRACTION < .5 MICRON

Significant Constants

C_E° = 46 mg/cu m

η = 0.9800

Q_R = 30,000 cfm

C_{BZG}° = Respirable concentration < .5 micron in size

= 0.14 mg/cu m

Q_{LB} cfm	Q_{MU1} cfm	Q_D cfm	C_D mg/cu m	C_R mg/cu m	C_{BZ} mg/cu m
0	0	30,000	0.93	0.93	0.98
4,000	4,000	26,000	0.93	0.81	0.87
8,000	8,000	22,000	0.93	0.68	0.75
12,000	12,000	18,000	0.93	0.56	0.64
16,000	16,000	14,000	0.93	0.43	0.53
20,000	20,000	10,000	0.93	0.31	0.42
24,000	24,000	6,000	0.93	0.19	0.31
28,000	28,000	2,000	0.92	0.06	0.19
30,000	30,000	0	0	0	0.14

TABLE D5

CONSOLIDATION OF MODEL RESULTS

WITH k_{BZ} = 0.9

Q_{LB} cfm	Respirable C_{BZ} mg/cu m	Non-Respirable C_{BZ} mg/cu m	Total Dust C_{BZ} mg/cu m
0	1.74	1.54	3.28
4,000	1.60	1.51	3.11
8,000	1.46	1.48	2.94
12,000	1.32	1.44	2.76
16,000	1.18	1.41	2.59
20,000	1.05	1.37	2.42
24,000	0.91	1.33	2.24
28,000	0.76	1.32	2.08
30,000	0.70	1.30	2.00

Next, he looks at his arbitrary choices for the parameters k_R, f, and Q_N. His choice of a particular k_R did not seem to have much significance in comparison to other terms in the equations. At best, it varied the third or fourth decimal place of computed concentrations. More significantly, he realizes that the values he chose for f and Q_N had no effects on his answers, since the total air change rate through the plant remained constant before and after recirculation.

He now reassesses his choice of 2 grains per cubic foot of air for the loading on the air cleaners. This was the value given to him as the upper limit of what plant personnel estimated for the existing operation. If he uses a lower value as an average in the range, predicted breathing zone concentrations will be decreased. He hesitates to this, however, since the cleaners might actually experience the higher loading factor for days at a time.

Finally, he wonders what the effects would be of increasing the exhaust volume through the hood to more than 30,000 cfm. Ideally, this would reduce pre-recirculation breathing zone concentrations and reduce the loading on the air cleaners. both of which are beneficial effects. He puts this thought aside, however, when he realizes that the higher control velocities might actually increase the loading by capturing more and/or larger particles. Maybe he will investigate this approach some other time, when time and funds allow some experimentation.

Reassessing k_{BZ}

Taking some measuring devices along, the designer visits the plant to gain a better insight into the specific details of the existing operation and the location of the proposed new work station. It isn't long before he realizes that it would be hard to force k_{BZ} to be 0.9, even if he wanted such a high value. Indeed, even a value of 0.2 seems conservative for these workers, if he simply points the exhaust stream away from the work area. Consequently, he precisely picks an outlet direction away from constant work stations, and returns to his office.

Recomputing Concentrations

Based on his new value of 0.2 for k_{BZ}, the designer recomputes predicted breathing zone concentrations. The results of this analysis are shown in Table D-6. Needless to say, he is quite enthused about the results. They suggest that all the exhaust volume from the shakeout can be recirculated, if the return air stream is well-mixed with existing room air before entering any breathing zones. Before he presents his proposed design to plant management, however, he makes a few more computations.

First, he tries to estimate what the quartz content of the exhaust stream will be. He does this as follows:

a) He obtains a breakdown by size fraction for quartz content of the sand being collected by the existing exhaust hood.

Aerodynamic Diameter	% Quartz
> 5	40.0
.5-5	8.0
< .5	1.0

b) For complete recirculation of exhaust air, he then estimates:

Quartz in cleaned Exhaust

≈ (.4) (.27) ≈ 0.108 mg/cu m for non-respirable dust

≈ (.08) (.27) ≈ 0.022 mg/cu m for > .5 to 5 micron fraction

≈ (.01) (.93) ≈ 0.0093 mg/cu m for < .5 micron fraction

TABLE D-6

CONSOLIDATION OF MODEL RESULTS

WITH k_{BZ} = 0.2

Q_{LB} CFM	Respirable C_{BZ} mg/cu m	Non-Respirable C_{BZ} mg/cu m	Total Dust C_{BZ} mg/cu m
0	0.94	1.35	2.29
4,000	0.90	1.35	2.25
8,000	0.87	1.34	2.21
12,000	0.84	1.33	2.17
16,000	0.81	1.33	2.14
20,000	0.77	1.32	2.09
24,000	0.75	1.31	2.06
28,000	0.71	1.30	2.01
30,000	0.70	1.30	2.00

Total Quartz % in Cleaned Air

$$\simeq \frac{0.108 + 0.022 + 0.0093}{.27 + .27 + .93} \times 100 \simeq 9.476\%$$

Respirable Quartz % in Cleaned Air

$$\simeq \frac{.022 + .0093}{.27 + .93} \times 100 \simeq 2.61\%$$

The permissible exposure limits for this stream are then computed to be:

$$\text{TWA (respirable)} = \frac{10 \text{ mg/cu m}}{2.61 + 2} = 2.17 \text{ mg/cu m}$$

$$\text{TWA (total)} = \frac{30 \text{ mg/cu m}}{9.476 + 2} + 2.61 \text{ mg/cu m}$$

Since the air cleaner outlet has a total dust concentration of 1.47 mg/cu m and a respirable dust concentration of 1.20 mg/cu m the designer is encouraged to learn that the outlet stream concentrations are well below permissible limits. This tells him he can safely direct the stream to a number of alternative locations in the plant, if breathing zone concentrations near the controlled operation exceed permissible limits due to recirculation.

Now, he estimates the effect of the recirculated air upon breathing zone quartz contents, as follows:

a) He obtains a better breakdown of quartz content for breathing zone samples taken near the existing operation.

Aerodynamic Diameter	% Quartz
> 5	12
.5-5	8
<.5	1.5

b) Original Breathing Zone Quartz Contents

$\simeq$ (.12) (1.30) $\simeq$ 0.156 mg/cu m for non-respirable fraction

$\simeq$ (.08) (.56) $\simeq$ 0.045 mg/cu m for .5 to 5 micron fraction

$\simeq$ (.015) (.14) $\simeq$ 0.002 mg/cu m for < .5 fraction

c) New Breathing Zone Quartz Contents

$\simeq 0.156 + k_{BZ}\ (0.108) \simeq 0.178$ mg/cu m for non-respirable fraction

$\simeq 0.045 + k_{BZ}\ (.022) \simeq 0.049$ mg/cu m for .5 to 5 micron fraction

$\simeq 0.002 + k_{BZ}\ (.0093) \simeq 0.004$ mg/cu m for < .5 micron fraction

d) New Breathing Zone Quartz %'s

$$\simeq \frac{0.178 + .049 + .004}{2.29} \times 100 = 10.09\% \text{ for total dust}$$

$$\simeq \frac{.049 + .004}{0.94} \times 100 = 5.64\% \text{ for respirable dust}$$

e) New Permissible Exposure Limits

$$\text{TWA (respirable)} = \frac{10 \text{ mg/cu m}}{5.64 + 2} = 1.31 \text{ mg/cu m}$$

$$\text{TWA (total)} = \frac{30 \text{ mg/cu m}}{10.09 + 2} = 2.48 \text{ mg/cu m}$$

These results confirm that breathing zone concentrations near the operation will be acceptable with the conservative value of 0.2 chosen for k_{BZ}. The designer now decides he has a feasible design for further study.

Confirmation of Model Parameters

Our friend's next step is to check upon the validity of the data provided by the plant, by the bag house manufacturer, and by the wool felt filter manufacturer. His rough calculations appear to show that he has a small safety factor in breathing zone concentrations, but he realizes that he has made a number of simplifying assumptions. Consequently, his presumed safety factor could quickly disappear if one of the numbers he has been given is significantly wrong.

A visit to the plant determines that the data given for sand compositions is probably quite accurate. Indeed, the plant frequently analyzes sand compositions, and has personnel well-qualified to perform these measurements. These personnel are confident that their results do not underestimate quartz content, or the fraction of fine particulates.

The breathing zone concentrations given represented the upper range of values measured twice a year over the last 3 years. The plant manager admits that he gave these numbers so he would have a built-in safety factor. He also cautions that the concentration given has been experienced and should continue to be used in any computations. He doesn't want expensive "fixes" after recirculation is initiated.

The loading on the air cleaner section given appears to have been picked out of the catalog of the manufacturer of the wet collector. Nobody at the plant remembers any attempts to accurately quantify the loading. All they know is that the collector was sized for this loading range and looks like it is working as intended. This is cause for immediate concern on the part of the designer.

He recontacts the baghouse manufacturer and speaks to an engineer familiar with the application of these filters to similar operations. The useful information obtained is:

a) Experiments with fine dusts through the particular model device being considered have provided the following results:

Particle Size (microns)	Cleaner Efficiency	Remarks
0.14	.249	Clean bags
0.14	.9682	Loaded
0.14	.8905	Shaken
0.28	.222	Clean
0.28	.9646	Loaded
0.28	.8825	Shaken
1.00	.479	Clean
1.00	.9997	Loaded
1.00	.9902	Shaken

b) Advertised efficiencies of 0.999 for particles greater than 0.5 micron in size are weighted averages of efficiencies occurring throughout the load-shake-load cycle of the device. The efficiency curve for the device is essentially flat for all sizes above 0.5 micron.

c) The estimated efficiency of 0.95 for particles less than 0.5 micron in size is "about right" for the particular device.

d) The air cleaner loading range of 0.5 to 2 grains/cu ft for this operation, as suggested by the catalog, is a roughly estimated average for typical operations. In actual practice, loadings can vary widely, and can approach, or slightly exceed 3 grains per cu ft.

Assimilating this information, and data provided by the wool felt filter manufacturer, the designer concludes that the cleaner efficiencies he utilized in computations are essentially correct, and not cause for concern. Alternatively, he realizes that the maximum loading of 2 grains per cu ft he used may or may not be correct. If the actual value is very much lower than this, he will have vastly overdesigned the system. If it is higher, he runs the risk of exceeding permissible exposure limits. Consequently, he recomputes his findings with a loading of 3 grains per cu ft and reports his results in Table D-7.

TABLE D-7

MODEL RESULTS WITH MAXIMUM PROBABLE LOADING ON CLEANER

	Results with 2 grains/cu ft	Results with 3 grains/cu ft
Total C_R	1.47 mg/cu m	~ 2.21 mg/cu m
Respirable C_R	1.20	~ 1.80
Non-respirable C_R	.27	~ 0.41
Total C_{BZ}	2.29	~ 3.44
Respirable C_{BZ}	0.94	~ 1.41
Non-respirable C_{BZ}	1.35	~ 2.03

Inspection of results reveals that the stream leaving the air cleaners does not by itself exceed permissible exposure limits. He could still direct it to a "clean" part of the plant if limits in the shakeout area are exceeded. Predicted concentrations in the work area with the higher loading are, however, above permissible levels for both total and respirable dust.

Developing a Contingency Plan

The designer now realizes he had better give some thought to what must be done to "correct" the system, if it provides unsatisfactory performance. Listing his options, he finds:

A. He can direct some part or all of the outlet stream to the outdoors and install a make-up air supply system;

B. He can install a second wool felt filter in series with the first;

C. He can direct the outlet stream to a "clean" part of the plant, if he can find such a place;

D. He can somewhat dilute the outlet stream by mixing it with air taken from somewhere inside the plant; or

E. He can further reduce k_{BZ} by better air distribution.

Option A requires that he provide the equipment necessary to partially or fully divert the outlet stream to the outside and to temper the resulting necessary amount of make-up air. The designer realizes that, since he intended to provide a by-pass to the outdoors for the stream in any case (for "emergency" situations and warm weather use), the additional cost involved would be only for the make-up air unit. Since the plant would most likely have bought a bag filter device for new emissions control instead of another wet collector, only the cost of the wool felt filter would be forfeit if no recirculation took place.

Option B is feasible, but not desired because of the increased floor space which would be used and the increase in maintenance which would be necessary. Nevertheless, it is a possible "fix" that would cost approximately the same before or after recirculation is initiated.

Option C is of presently unknown feasibility. It would require numerous breathing zone studies throughout the plant to determine if some group of workers could be safely exposed to the cleaner outlet stream. Then it would require ducting to lead the air stream to these workers, if they accepted the idea of being exposed to this air.

The last option, D, requires that relatively clean air found somewhere in the plant be collected and ducted into the cleaner outlet stream. This also is feasible, but may require considerable ducting.

Reviewing these options carefully, the designer decides that none require him to take the cost of modification into account before he finalizes his design for the recirculation system. For conservatism, he must only ensure that the damper he installs at the by-pass duct junction is fully adjustable, and that space exists for installing a second wool felt filter if needed.

System Monitoring

Review of wool felt filter device specifications reveals that the pressure drop across the filter rises from 0.1 in wg when clean to 0.5 in wg when loaded. To allow simple, inexpensive and reliable monitoring of system performance, the designer locates a pressure drop measurement device which will sound an audible alarm at a preset value. Activation of the alarm will indicate to area workers that the wool felt filter must be vacuumed, and/or that a bag has burst in the primary air cleaner, and that exhaust air must temporarily be by-passed to the outdoors.

System Testing

To ensure that the installed system works as intended, the designer prepares a detailed sampling program timetable. The timetable calls for frequent system testing when newly installed, with the frequency decreasing to a constant time interval after the system has been shown to be reliable and safe.

Results of the Study

Having received approval from plant management to go ahead with installing the system, the designer finalizes all design details of the system, and arranges for delivery and installation of all equipment. This requires a thorough analysis of the economics of recirculation, the performance of a system failure analysis, recalculation of his figures using a more rigorous approach for estimating expected breathing zone concentrations, development of a maintenance and inspection schedule, and most steps normally required for designing and installing a conventional ventilation system. Three months later, everything is installed and operating, and breathing zone samples show acceptable contaminent concentrations.

APPENDIX E

A CASE HISTORY FOR VAPOR DEGREASING

CAUTION

This hypothetical case history is solely intended to provide readers with specific insights to some of the many factors which must be considered before recirculation of exhaust air. It must not be interpreted as a recommendation for any specific system design. Nor can it be considered sufficiently detailed for actual system design and implementation purposes.

Introduction

A small machine shop currently utilizes a 4' by 8' trichloroethylene (TCE) vapor degreaser for removing cutting oils, grease and other surface contaminants from metal parts. Specializing in low-volume, high-precision items, the shop has historically found a single unit more than adequate for its usual business volume. However, as a result of nearby industrial expansion, the machine shop has contracted to deliver a substantial increase in parts under a long-term contract.

Problem Acknowledgement

Immediately evident to the shop owners is that their single degreasing unit will no longer be adequate when full-scale production begins. Indeed, given a typical cycle time of 15 minutes, and the number and type of parts which can be treated in a single cycle, it is estimated that two additional degreasing units of comparable size will be required to ensure that delivery schedules are met.

Investigating the most cost-effective method of adding degreasing capacity, the shop owners learn that local environmental pollution regulations do not allow discharge into the atmosphere of more than 420 pounds of photochemically reactive solvent per day, nor more than 28 pounds per hour, unless said discharge has been reduced by at least 85 percent of its original value. TCE is specifically noted as being a photochemically reactive solvent for which this rule applies. The machine shop was in compliance with this rule for its infrequently used single degreasing unit, but would be in violation if three degreasers were used simultaneously. Three continuously operating units would have a total emission rate averaging 48 pounds per hour (at an average generation rate of 0.5 lb/sq ft/hr).

Of further interest is that OSHA is in the process of promulgating a new health standard which will reduce current permissible exposure limits for airborne TCE. Therefore, haphazard installation or improper use of the degreasing units could cause excessive emissions which, if repair is required, could lead to disruption of production and additional expense in the future. Degreaser manufacturers' representatives advise the shop owners to plan to conform to the proposed rules, since a change in regulation is imminent.

Since it has become apparent that installation of increased vapor degreasing capacity will not be the simple matter that was envisioned, the machine shop operators hire a consulting industrial hygiene engineer to help ensure that any new equipment installed will meet local, state, and Federal requirements.

Problem Definition

The consultant engineer's first order of business is to learn all the facts about the desired installation and the rules and regulations which will apply. He is particularly concerned with OSHA regulations, since these may be the most difficult to satisfy.

Reviewing a copy of the proposed OSHA rule for TCE, published in the Federal Register of October 20, 1975, he finds that OSHA has proposed a 100 ppm 8-hour TWA permissible exposure limit along with a 150 ppm ceiling. These limits are compared to the current limits of 100 ppm TWA, 200 ppm ceiling, and 300 ppm peak for 5-minutes in any 2-hour period.

Perchloroethylene and methyl chloroform are considered and rejected as possible substitutes for TCE. OSHA is considering new regulations for these materials. Further, perchloroethylene usage would require 25% higher energy consumption and entail high operating temperatures and other problems. Use of methyl chloroform would cause high vapor losses and a more difficult control problem.

The engineer also investigates aqueous cleaning systems but these are dropped from further consideration because they would require increased water consumption, create contaminated water effluents requiring treatment and raise the possibility that certain metals might be adversely affected by the alkaline detergent solutions. More specifically, he is concerned about possible pitting of aluminum parts which are to be finish machined.

The air pollution regulations with which the engineer is concerned are quite straight forward. These regulations include firm performance specifications, and suggest that emissions may be controlled by incineration, adsorption, or similarly effective methods. Being familiar with the control of solvent emissions, the engineer realizes that incineration or adsorption in activated carbon are the two most practical approaches, and that solvent recovery with available adsorption equipment may lead to overall reductions in operating costs.

Next, the engineer visits the machine shop to examine its physical configuration, the nature of engineering controls presently installed and existing TCE exposure levels. The collected information is listed in

Table E1. From these data, it is concluded that solution of the TCE degreaser problem entails installation of:

A. Two degreasers similar to the existing unit;

B. An air cleaning device to reduce TCE emissions from the shop; and

C. An increase in the make-up air supply rate by at least 3200 cfm, assuming that each new unit will also be locally exhausted by a conventional ventilation system at a rate of 50 cfm/sq ft of surface area.

Evaluation of Possible Alternatives

The first phase of the evaluation includes an examination of the alternative air cleaning devices which may be appropriate. Based upon available information, an activated carbon unit is selected as being satisfactory. The manufacturer claims it has an efficiency greater than 98% for collected vapors, where most units of this type achieve about 95% efficiency. Specifications for the unit are listed in Table E2.

Examination of incineration devices reveals impractical energy requirements and other problems. For direct thermal oxidation to be effective, the off-gases must be heated to a temperature of 1400 to 1600°F and held at this temperature for a period of time. For catalytic combustion with the same effect, temperatures of 600 to 900°F are required. The economics of this treatment are not determined but it is realized that heating 4800 cfm of air-solvent mixture to these temperatures for 16 hours per day would be prohibitively expensive. It is also realized that the decomposition products of chlorinated hydrocarbons may contain chlorine, hydrogen chloride, and phosgene, depending upon the conditions of oxidation. Air pollution regulations would require that these products be removed from the gas stream prior to discharge to the atmosphere, creating yet another air cleaning problem.

Other effective emission control measures for degreasers include covers (for when the unit is not being used), refrigerated freeboard chillers, and improved work practices. The engineer does not anticipate that the use of covers will be effective since, although the new degreasing units have covers, their effectiveness is negated by the proposed continuous two-shift operation.

Freeboard chillers consist of a second set of condenser coils located above the primary vapor condenser coils found in degreasing tanks. The function of these devices is to limit the diffusion of solvent vapors from the vapor zone into the work atmosphere by creating a cold-air blanket above the vapor zone. Commercially available systems usually operate with a heat exchange temperature difference of 20°F. These low temperature units require timed defrost cycles to remove ice from coils, and added

TABLE E1

MACHINE SHOP DATA

Workroom Size: 100' x 150' x 20'

Building Construction: Cement block and glass. Windows sealed.

Degreaser Data: 4' x 8' open-surface type with cover; steam heated (steam readily available for purchase from plant next door); exhaust volume is 50 cfm per square foot of surface, for total of 1600 cfm.

Ventilation Systems: Shop has an air conditioning system with fresh air inflow rate of 30,000 cfm. The combined local exhaust volume for all machinery in the shop is currently 31,500 cfm.

Layout of Ventilation Systems: Machines with local exhaust systems are evenly distributed throughout room. Tempered air enters at ceiling level from 24 well-spaced diffusers.

Initial TCE Concentrations: Experimentation with the degreaser results in the determination that TCE breathing zone concentrations of 60 - 80 ppm (TWA) can be expected. Peak concentrations measured were in the 125 - 130 ppm range. Concentrations in the local exhaust duct for the degreaser average 150 ppm during a 15 minute cycle. Peak duct concentrations measured for brief instants were 400 ppm. Duct concentrations averaged 200 ppm for the 5 minute time span with the highest average. TCE concentrations 10 feet from the degreaser never exceeded 10 ppm.

TABLE E2

SPECIFICATIONS FOR ACTIVATED CARBON ADSORPTION DEVICE

CFM Capacity Required: 3 units x 1600 cfm = 4800 cfm. Closest standard size has unit capacity of 5500 cfm with two tanks.

Lbs Carbon: 2800

Adsorptive Capacity: 220 lbs/hour TCE

Efficiency: > 98% claimed for vapors entering unit; 50-65% overall reduction in TCE emissions is not uncommon with properly designed and operated system.

Utility Requirements: Steam, water, and electricity

Motor HP: 20

Price: $27,000 including shipping and installation

Useful Life: 15 years claimed

water contamination of the vapor degreaser system is not uncommon. Calling manufacturers' representatives for such equipment, the engineer obtains the data in Table E3.

Numerous studies have indicated that operating practices on the part of employees can affect airborne concentrations adjacent to degreasers by a factor of three to six. Poor work practices involve the dragout of liquid solvent, overloading the degreaser, spraying above the vapor line, excessive work velocity, and poor control of heat balance.

A few simple computations result in the determination that covers, freeboard chillers, and/or improved work practices are not sufficient to reduce TCE emissions for compliance with air pollution regulations. Therefore, it is decided to recommend the carbon adsorption device. With an assumed overall efficiency of 50% for reducing solvent loss, the adsorption system will keep total emissions below 24 lbs per hour and 384 lbs per day. Other computations (shown in Table E4) indicate that savings resulting from the recovery of solvent from contaminated exhaust air would more than pay for the unit on an annual basis.

Examination of the system indicates that 4700 cfm of additional make-up air are required for a balanced system. This quantity of make-up air would under normal design procedures require the installation of an additional make-up air supply unit. However, the volume of air passing through the carbon adsorption unit could satisfy the requirements for a balanced system, and the recirculation of this air is considered to be a feasible option.

Designing a Recirculation System

The preliminary analysis has not considered the application of recirculating systems. However, the secondary evaluation indicates that such a system is feasible.

The proposed recirculation system configuration is presented in Figure B1 of Appendix B. The appropriate input parameters include:

$Q_{L_{out}}$ = 31,500 - 1600 = 29,900 cfm

Q'_G = 0 cfm

Q'_{MU} = 30,000 cfm

$Q_{MU2} \cong$ 0 cfm

η = 0.95 (conservative estimate)

C°_E = 150 ppm average for 15-minute cycle; 200 ppm average for "worst" 5-minute span

TABLE E3

REFRIGERATED FREEBOARD CHILLER DATA

Refrigeration HP Needed: 1.5 for degreasers with 24 peripheral feet

Price: $5,400 including installation

Effectiveness: Freeboard chillers are usually used alone or with an automatic cover. Carbon adsorption is not considered to complement freeboard chillers since the chiller relies on its ability to isolate solvent-laden air within the cleaning operation, and ventilation systems for carbon adsorption tend to disturb air within the degreaser. A 35% overall efficiency is expected for emissions control with chillers, when all fugitive emissions sources are taken into account.

TABLE E4

CALCULATION OF YEARLY SAVINGS/COST

FOR CARBON ADSORPTION UNIT

Solvent Savings (Vapors in Exhaust Air Only)

150 ppm (at 4800 cfm) = 14.45 lbs/hr

14.45 lbs/hr x 80 hrs/wk x .98 = 1133 lbs/wk

1133 lbs/wk ÷ 12.14 lbs/gal x $2.20/gal
x 50 wks/yr = $10,265

Approximate Cost of Adsorption Unit

Capital*

	$6,300

Operating

Steam	100
Electric	1,595
Water	5
	$8,000

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* Annual cost when amortized

C_{MU} = 0 ppm

C°_{BZL} = (not needed)

C°_{BZG} = 10 ppm for workers distant from degreasers;

80 ppm for workers near degreasers.

The variables which must be defined include f, k_{BZ}, and k_R. The engineer understands that the low-volume slot hoods on the degreasers cannot develop strong flow fields, so f is set to zero. Since the adsorption unit is to be installed near the degreasers, to take advantage of the steam supply inlet location, both k_{BZ} and k_R are set to one. This represents a very conservative or worst-case situation. Completion of the calculations shows that the predicted concentration of contaminant in the return air stream is only about 5 ppm. The predicted TWA breathing zone concentration for workers near the degreasers is then 85 ppm, and for other workers in the general room area it is no more than 15 ppm. The maximum 5-minute breathing zone concentrations expected during normal operations is 135 ppm. These numbers are quite encouraging, but other issues regarding detection of reduced system performance and response to system failures remain to be addressed.

To partially resolve one problem, the engineer decides to duct the air from the adsorption device to ductwork of the air conditioning system. By doing this he not only takes advantage of the well-designed air distribution system in the shop, but reduces the probability that the section of the shop containing the degreasers will be uncomfortably warm. This action also has the effect of prolonging the time period for contaminant build-up in the event of air cleaner failure.

Finding an appropriate monitoring system for TCE proves to be a more difficult task. Gas sampling tubes are one possibility, but he is sure that the shop owners would never be willing to bother with such manual sampling measures. Other applicable techniques such as gas chromatography or the use of photoionization detectors are believed too expensive and sophisticated for this application. It would be less costly and easier to simply install another make-up air supply unit.

Calling upon a friend who has more knowledge of gas detection devices than himself, the engineer is told about a solid state sensor that a Japanese company has been developing. Currently used in a few $30-40 home fire alarm devices on the market, the sensor is quite sensitive to low concentrations of almost any combustible gas or vapor. Once severely exposed to heavy hydrocarbons, it loses its sensitivity for prolonged periods of time, but replacement sensors only cost a few dollars and can be simply plugged into place. Since his friend indicates that a few of the available alarm devices could be easily modified for use with the recirculation system, the engineer decides that he has the monitoring problem sufficiently well-solved. This continuous, automatic, non-specific, duct-based monitoring system is well-suited to the degreasing operation. Since a by-pass damper is planned to permit rapid response to failures, a transient analysis of breathing zone concentrations in the event of system failure becomes unnecessary.

Conclusion

The partners in the machine shop are initially dismayed to learn that an additional $27,000 - 30,000 capital outlay will be required for air cleaning, over and above the cost of new vapor degreasers. However, they are eventually convinced that the adsorption unit will more than pay for itself, and agree to the installation of the system proposed by the engineer. They particularly appreciate the fact that he has made every effort to minimize their expenses.

Start-up of the new systems requires considerable experimentation with, and debugging of, the monitoring system. Additionally, it requires that all new employees working near the degreasers be instructed in their proper operation and maintenance. Nevertheless, all problems are eventually solved and full-scale production begins in a comfortable and healthy environment.

APPENDIX F

TRANSIENTS IN RECIRCULATING SYSTEMS

1. Post-Failure Return Air Concentrations

Appendices A and B provide design equations for a number of generalized recirculation system configurations. Specifically, each configuration has an associated expression describing the concentration, C_D of contaminant in the stream following the air cleaner(s). C_D is generally a function of the various flow volumes which comprise the total ventilation system, the contaminant concentrations associated with these streams, and the overall air cleaner efficiency for the contaminant of concern.

As described in various chapters and appendices of this report, the system designer has the option of mixing the recirculated air stream with fresh make-up air before introduction into the workspace. Hence, the concentration, C_R, of the return air stream is given by the expression:

$$C_R = \frac{C_D Q_D + C_{MU} Q_{MU1}}{Q_D + Q_{MU1}}$$

where:

Q_D is the volume rate of air leaving the air cleaner(s), minus any amount subsequently by-passed to the outdoors; and

Q_{MU1} is the volume rate of fresh make-up air, if any. pre-mixed with the recirculated stream Q_D.

One can determine the post failure return air concentration after air cleaner failure, C_R^F, for any system configuration by:

- Choosing the appropriate expression for C_D from Appendix A or B;
- Setting $\eta = 0.0$ in this expression
- Computing C_R^F from the general expression for C_R presented directly above and the C_D value computed.

The basic assumption of this procedure is that any air cleaner malfunction results in complete and instantaneous breakthrough. Although partial failures are more likely, this is the preferred, conservative approach for purposes of an overall system failure analysis.

For multi-contaminant situations, the preceding procedure must be applied for each contaminant present. In doing so, care must be taken to use the appropriate cleaner efficiency and pre-failure concentrations for each contaminant.

2. Breathing Zone Concentrations

The breathing zone concentration after a system failure exhibits a transient due to the sudden increase in the return air concentration. The expression for the instantaneous post-failure breathing zone concentration $C_{BZ}^{F}(t)$ will have the form:

$$C_{BZ}^{F}(t) = A - B \, e^{-\left(\frac{t}{t_o}\right)}$$

where A, B and t_o are constants. The superscript F on the concentration indicates that failure has occurred.

Such an expression can be assumed to hold quite generally, without undue error. The rise time t_o can be estimated by tracer gas measurements. The constants A and B are such that

$A + B = C_{BZ}$ = pre-failure breathing zone concentration, and

A = Steady-state post-failure breathing zone concentration, C_{BZ}^{FS}

Thus,

$$A = C_{BZ}^{FS}, \quad B = C_{BZ}^{FS} - C_{BZ} \quad .$$

A reasonable estimate of C_{BZ}^{FS} can be obtained by introducing the post-failure return air concentration C_R^F (Section 1 of this Appendix) into the appropriate breathing zone equation.

3. Critical Response Times

The expression for the transient breathing zone concentration can be used to estimate the critical response time, T_C. The critical response time is defined as being the smaller of the following two:

a. the time for $C^F_{BZ}(t)$ to reach the ceiling, should one exist; this is denoted by T_{C1};

b. the time for the 8-hour time-weighted average to reach the TLV, denoted by T_{C2}.

The time to reach the ceiling level (which is denoted by $C_{ceiling}$ is readily obtained by setting $C_{BZ}(t) = C_{ceiling}$ and solving for t:

$$T_{C1} = t_o \ln \left(\frac{C^{FS}_{BZ} - C_{ceiling}}{C^{FS}_{BZ} - C_{BZ}} \right)$$

The 8-hour time-weighted average breathing zone concentration can be shown to be equal to

$$TWA(t) = \frac{t}{8} C^{FS}_{BZ} - \frac{t_o}{8} (C^{FS}_{BZ} - C_{BZ}) [1 - e^{-(t/t_o)}]$$

$$+ \begin{cases} \frac{8 - t_c}{8} C_{BZ} & \text{for } t \leq 8 \text{ hours} \\ 0 & \text{for } t > 8 \text{ hours.} \end{cases}$$

Assuming, as is likely, that the TLV will be exceeded within 8-hours of failure, the critical response time depends on the parameter

$$T^* = \frac{8}{t_o} \left(\frac{TLV - C_{BZ} - (C^{FS}_{BZ} - C_{BZ}) \frac{t_o}{8}}{C^{FS}_{BZ} - C_{BZ}} \right) - 1$$

The value of (T_{C2}/t_o) is shown in the following table as a function of T^*.

T^*	-1	0	1	1.5	2	3	4
(T_{C2}/t_o)	0	0.57	0.91	1.28	2.12	3.02	4

The true critical response time T_C is then the lower of T_{C1} and T_{C2}.

4. Measuring the Rise Time t_o

The rise time "t_o" for any given breathing zone depends in a complex way on the location of that breathing zone relative to the return air duct, as well as on the nature of the air flow in the plant. It is inconceivable that simple but accurate analytical estimates of t_o could be made. However, t_o can be measured with relative ease by simulating failure conditions.

The measurement technique involves the release of a tracer gas into an air supply duct near where the return air duct is planned to be installed. This air supply duct should preferably have an air flow rate comparable to the planned return air rate. The tracer gas is released from time t = 0 at a steady rate. The expected breathing zone concentration of the tracer gas is:

$$C_{BZ}(t) = B\left[1 - e^{-\left(\frac{t}{t_o}\right)}\right]$$

where:

$$B = k_{BZ}C_D$$

C_D being the tracer gas concentration in the supply duct.

The breathing zone concentration is measured at times $t = t_1$ and $t = 2t_1$. Then

$$C_{BZ}(t_1) = B\left[1 - e^{-\frac{t_1}{t_o}}\right]$$

$$C_{BZ}(t_2) = B\left[1 - e^{-\frac{2t_1}{t_o}}\right]$$

Defining $e^{-\frac{t_1}{t_2}} = X$, and dividing $C_{BZ}(t_2)$ by $C_{BZ}(t_1)$.

one obtains:

$$\frac{1 - X^2}{1 - X} = \frac{C_{BZ}(t_2)}{C_{BZ}(t_1)},$$

or

$$X = \frac{C_{BZ}(t_2)}{C_{BZ}(t_1)} - 1.$$

This finally leads to

$$t_o = \frac{t_1}{\ln \left\{ \dfrac{C_{BZ}(t_1)}{C_{BZ}(t_2) - C_{BZ}(t_1)} \right\}} .$$

5. A Numerical Example

Measurement of t_o, k_{BZ}, k_R

Assume that in the tracer gas measurements, the following values are obtained:

$$\left. \begin{aligned} C_{BZ}(t_1) &= 10 \text{ ppb} \\ C_{BZ}(2t_1) &= 18 \text{ ppb} \end{aligned} \right\} \quad \text{with } t_1 = 0.1 \text{ hrs (6 minutes)}$$

Then, according to the last equation in the preceding section,

$$t_o = \frac{0.1}{\ln \left(\frac{10}{8}\right)} = \underline{0.45 \text{ hours}}.$$

If the steady-state duct and breathing zone concentrations are measured, k_{BZ} can be estimated. Assume that the following values are obtained:

C_D = 30 ppb

B = 20 ppb. (Steady-state breathing zone concentration.)

Then, according to the second equation in section 4, above,

$$k_{BZ} = \frac{B}{C_D} = \frac{20}{30} = \underline{0.67} \, .$$

Estimating the Critical Response Time

Purely as an example, assume the following values are obtained for the various parameters:

$$TLV = 1000 \text{ ppm}$$

$$C_c = 1500 \text{ ppm} \quad \text{(ceiling concentration)}$$

$$C_{BZ}(o) = 300 \text{ ppm}$$

$$C_E = 500 \text{ ppm.}$$

Then

$$T_{C1} = 0.45 \ \ell n \ \frac{0.67 \times 5000}{300 + 0.67 \times 500 - 1500} = \underline{0.2 \text{ hours}}.$$

This is the time taken to reach the ceiling concentration in the breathing zone.

The equation in Section 3 for the parameter T^* yields

$$T^* = \frac{8}{0.45} \left\{ \frac{1000 - 300}{0.67 \times 5000} \right\} - 1 = 2.73 \, .$$

Interpolating from the table following the equation for T^*, it is found that

$$\frac{T_{C2}}{t_0} = 2.75, \text{ or } T_{C2} = 2.75 \times 0.45 = 1.24$$

Thus the critical response time is $T_C = T_{C1} = 0.2$ hours. If a ceiling level did not exist, the critical response time would be $T_C = T_{C2} = 1.24$ hours.