DEVELOPMENT OF A RECOMMENDED APPROACH FOR RECIRCULATION OF INDUSTRIAL EXHAUST AIR

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Abstract

Recirculating exhaust systems can provide for substantial reductions in consumption of energy for conditioning makeup air, while maintaining a healthful and comfortable working environment. In some instances, it may be possible to reduce the level of toxic materials in the workplace while conserving energy. Therefore, given the reduced availability of energy sources at any price, significant savings may accrue from the use of recirculating exhaust systems in those situations where large volumes of makeup air must be conditioned to maintain worker comfort and process control.

However, industrial exhausts often contain toxic contaminants, frequently of unknown type and at unknown concentration levels. When these exhausts are emitted into the outside atmosphere, the health impacts on employees within the plants are generally small. Recirculation implies cleaning such exhausts and delivering them back into the plant. Such a procedure may lead to adverse health impacts in any of the following situations:

1. *the planned level of cleaning is inadequate;*
2. *contaminants exist in the exhaust which are not cleaned because their existence is not known;*
3. *the air cleaner fails to perform its function, resulting in the delivery of inadequately cleaned or uncleaned exhaust air into the plant; or*
4. *contaminants (such as carcinogens) exist in the exhaust for which the preferred policy is to eliminate their presence in the employees' breathing environment as completely as possible.*

It is the intent of this paper to present an outline of information which will help insure that such situations do not arise in practice.

INTRODUCTION

The recirculation of industrial exhaust air provides an engineering approach toward energy conservation that has a potentially wide application throughout

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industry. Because of the novelty of recirculating systems and the consequent lack of accumulated experience, however, the possibility exists of hazardous exposure of personnel to toxic materials in the recirculated exhaust. NIOSH has therefore sponsored two analytical studies of the safety aspects of industrial exhaust recirculation, the second of which was conducted at Arthur D. Little, Inc. This paper summarizes the approach adopted in the ADL study. For further detail, the reader is referred to the final report based on the ADL study, to be published by NIOSH in the near future.

This study represents an initial effort to develop a practical approach for exhaust air recirculation. It is recognized that, as recirculating exhaust installations become more common and as this approach is applied, modification and refinement may be appropriate. One effort for validation 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.

GOALS AND LIMITATIONS

The goal of this study was to provide guidelines to help insure that the design, installation, and operation of recirculating systems is undertaken and completed in a manner which will assure the health and safety of employees within the workplace.

The study did not take a stand on the pros and cons of recirculating exhaust systems, except in those instances in which they were clearly considered demonstrably unsafe. Instead, the study concentrated on developing general system specifications and design procedures which, if adhered to, will insure that no adverse impacts on employees' health are experienced. However, the procedures provided are such that the economic advantages of recirculating systems can be estimated and maximized.

Further, this study did not attempt to guide the detailed design of or the specification of hardware for a recirculating ventilation system. Rather, a general procedure was developed for assessing the applicability of recirculation and developing general system specifications to assure that recirculation is undertaken safely.

GENERAL PHILOSOPHY

The overall philosophy applied in ADL's study may be summarized succinctly as follows:

1. The overall goal of safety analyses of recirculating industrial exhaust systems is to insure that no person is exposed to hazardous concentrations of any chemical in the exhaust.
2. Regardless of the reliability designed into a recirculating system, it may eventually fail. The consequences of a failure must be adequately mitigated.

3. Because of the complexity and relative novelty of recirculating industrial exhaust systems, a multifaceted approach must be utilized in their design and installation. Facets are: extrapolation from past experience; in-plant surveys of airflow rates, contaminant concentration levels and transients; analytical studies; and post-installation testing.

ISSUES OF CONCERN

The main criterion guiding the ADL study was safety. This criterion required identification and consideration of numerous factors which influence the safe design and operation of a recirculating system. Overall, these factors could be categorized under the headings of safety, economics, technical feasibility, and engineering feasibility.

Safety

Inadequate safety in a recirculating exhaust system may result from one or more of the following causes:

1. The planned level of cleaning is inadequate.
2. Contaminants exist in the recirculated exhaust that are not cleaned because their existence goes unnoticed.
3. System failures occur.
4. Contaminants (such as human carcinogens) exist in the exhaust for which the preferred policy is to eliminate their presence in the employee's breathing environment as far as possible.
5. Contaminants exist for which the safe limits are nowhere clearly spelled out.
6. System components fail to meet design specifications.
7. Recirculation of an exhaust results in reduced dilution ventilation in neighboring areas.

Economics

Economic factors that will need to be taken into account in assessing a recirculating exhaust system are:

1. the availability and cost of energy;
2. the cost of design studies for a recirculating system;
3. the capital cost of air cleaners, monitors, alarms, bypasses, and ductwork; and
4. operating costs (maintenance, parts, power, personnel, training, etc.).

Technical Feasibility

Whether or not a system is technically feasible will depend principally on:

1. whether an air cleaner is available with the desired efficiency for each of the contaminants requiring cleaning; and
2. whether a technique is available for detecting reduced performance of the system.

Engineering Feasibility

An engineering feasibility assessment must address several issues including the following:

1. estimation of the input parameters required by the analytical models used in system design;
2. availability of space for installing the air cleaner;
3. feasibility of routing ductwork as required; and
4. ability to maintain the system, including the monitor, to adequate levels of performance.

AIR CLEANERS

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

1. the fractional efficiency;
2. the ratings available, defined as the volume of air each unit is capable of cleaning;
3. space requirements;
4. specificity of cleaning ability: whether the cleaner is specific to a contaminant or a group of contaminants; groups might be: particulates, organic vapors, etc.;
5. failure modes: the ways in which cleaner performance can degenerate;
6. ease of detection of failure modes;
7. reliability, or the frequency of failure;
8. ease of maintenance;
9. pressure drop, and its variation with the extent of loading;
10. method of disposal of the collected contaminant, and its possible impact on plant personnel;
11. modifications to airstream characteristics such as humidity, temperature, and ozone content, as well as the possible chemical transformation of contaminants due to reaction or decomposition; and
12. cost, both capital and operating.

It is recommended that these factors be carefully reviewed with expert help before an air cleaner is selected. Factors relating to failure modes, reliability, ease of maintenance, and airstream modification are of particular importance to the development of a safe recirculating system.

Cleaner Combinations

Apart from the variety of air cleaner characteristics listed above, the designer must also 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 similar exhausts are to be cleaned, significant safety benefits can be obtained by cleaning them in parallel, and then

mixing the cleaned exhausts before reintroduction into the work space.

2. When particulate and gaseous contaminants coexist in an exhaust, series of cleaners of different types are 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 make little economic sense. More useful (with particulates) is prefiltering to increase the life of the main filter, and the use of an absolute filter after the main filter. The absolute filter can act both as a safeguard and as a monitoring device.

CONTAMINANT CHARACTERIZATION

The types and quantities of contaminants released from a particular process have a major influence on the feasibility of recirculating the process exhaust. The contaminants' characteristics will help to determine whether recirculation is desirable, whether economical cleaning of the exhaust is possible, and whether system monitoring is feasible.

All contaminants in breathing zones and in exhausts to be recirculated must be identified and all concentration levels quantified during the initial stages of recirculation evaluation. No "shortcuts" exist for bypassing this requirement except under a few special circumstances. Thorough knowledge of existing or typical conditions near a process is a prerequisite to determining the impact of recirculation upon the plant area of concern.

Although some contaminants are intuitively more desirable for recirculation than others, the availability of adequate cleaning and monitoring equipment will permit the recirculation of virtually any contaminant. However, it is recommended that substances designated as human carcinogens by OSHA be excluded from recirculation since there are no demonstrated safe exposure levels for carcinogens. Substances suspected of being carcinogenic must be evaluated on a case-by-case basis by qualified health personnel.

DESIRED OR ALLOWED CONCENTRATION LEVELS

During the design and implementation of recirculation, one must make a conscious decision regarding the concentrations of airborne contaminants that are desirable and/or allowable in breathing zones. There are several sets of established guidelines for the definition of allowable levels of exposure to toxic substances. These include Occupational Safety and Health Administration (OSHA) regulations, NIOSH Criteria Documents, and American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs). While the latter two sources generally reflect more up-to-date judgments on industrial toxicology, the OSHA regulations are mandatory standards.

Where established guidelines for an allowable exposure level do not exist for one or more contaminants at a candidate recirculation site, available toxicological literature should be reviewed by a qualified health professional to select a "pseudo TLV." The absence of established exposure guidelines may suggest that a contaminant causes no adverse health effects, but is generally likely to mean that the contaminant's presence is not sufficiently widespread to have promoted 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.

One must also be concerned about potential synergistic effects when a mixture of substances is to be recirculated. There are situations in which the simultaneous presence of two contaminants will cause an enhancement (or inhibition) of the anticipated physiological effects of exposure. Such effects follow no recognized pattern, and may be identified only through reviews of previous exposure experience and toxicological results. 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 made by a qualified health professional.

Other factors to be considered in the selection of desired exposure levels include the aesthetic effects and chemical/physical properties of contaminants. Objectionable odors, corrosivity, flammability, and reactivity are appropriate examples.

Finally, one should consider the application of a safety factor to selected exposure levels. Although toxicologically suggested levels can be considered safe, there is no guarantee that these levels will not be exceeded upon implementation of recirculation. The design of any new process or control system entails some degree of uncertainty. Hence, the design of a recirculation system to provide marginally acceptable exposure levels may result in inadequate control upon actual system operation.

SURVEILLANCE AND RESPONSE STRATEGIES

If a recirculation system fails, the result may be rapid buildup of contaminant levels in the workplace environment. To prevent such a potentially health-threatening situation from going undetected, it is recommended that all recirculation systems include as an integral component a surveillance subsystem. The function of this subsystem will be to detect system failures and permit a timely response.

In designing a recirculation surveillance system, the approach that one would logically employ would be to consider the exhaust stream contaminants, determine what system(s) are available for surveillance, and select hardware with consideration for cost, reliability, life-span, etc. The types of monitoring approaches that might be considered range from a simple pressure-drop sensor on a particulate filter through nonspecific gas and vapor detectors (like those utilized in smoke detectors) to sophisticated automatic gas chromatograph systems. In addition, consideration might be given to the use of an intermittent, periodic sampling protocol rather than continuous sampling; and sampling of general area air rather than ventilation duct air might be considered.

Of the various approaches to surveillance, no single system is most appropriate in all situations. However, there are some clear-cut mismatches between a monitoring concept and a recirculation application. In order to assist the recirculation system planner in insuring that his contemplated surveillance system is not inappropriate, several guidelines have been developed describing suggested use conditions for various classes of monitors.

Automatic Systems

Automatic surveillance is always desirable since it reduces the possibility that human error or neglect may lead to unsafe 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 monitoring subsystem must satisfy the following operation 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, i.e., the time interval from system failure to the onset of unacceptable breathing zone concentrations (see fig. 1).

Manual Systems

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

1. the critical response time is greater than 4 hours; and
2. the sum of the time interval between samples and the time needed to implement emergency response activities is less than the critical response time; and
3. the only contaminants present are nuisance (nontoxic) materials; and/or
4. if gases or vapors which are simple asphyxiants are involved, a continuous combustible gas detector (if appropriate) and an oxygen deficiency monitor are employed.

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

1. A written monitoring protocol should be prepared and the responsibility for monitoring 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. Monitoring results should be recorded in a log, and the log should be regularly checked by plant management and/or safety personnel.

Area Systems

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

1. Contaminant level fluctuations based upon normal process operation should be well characterized quantitatively.

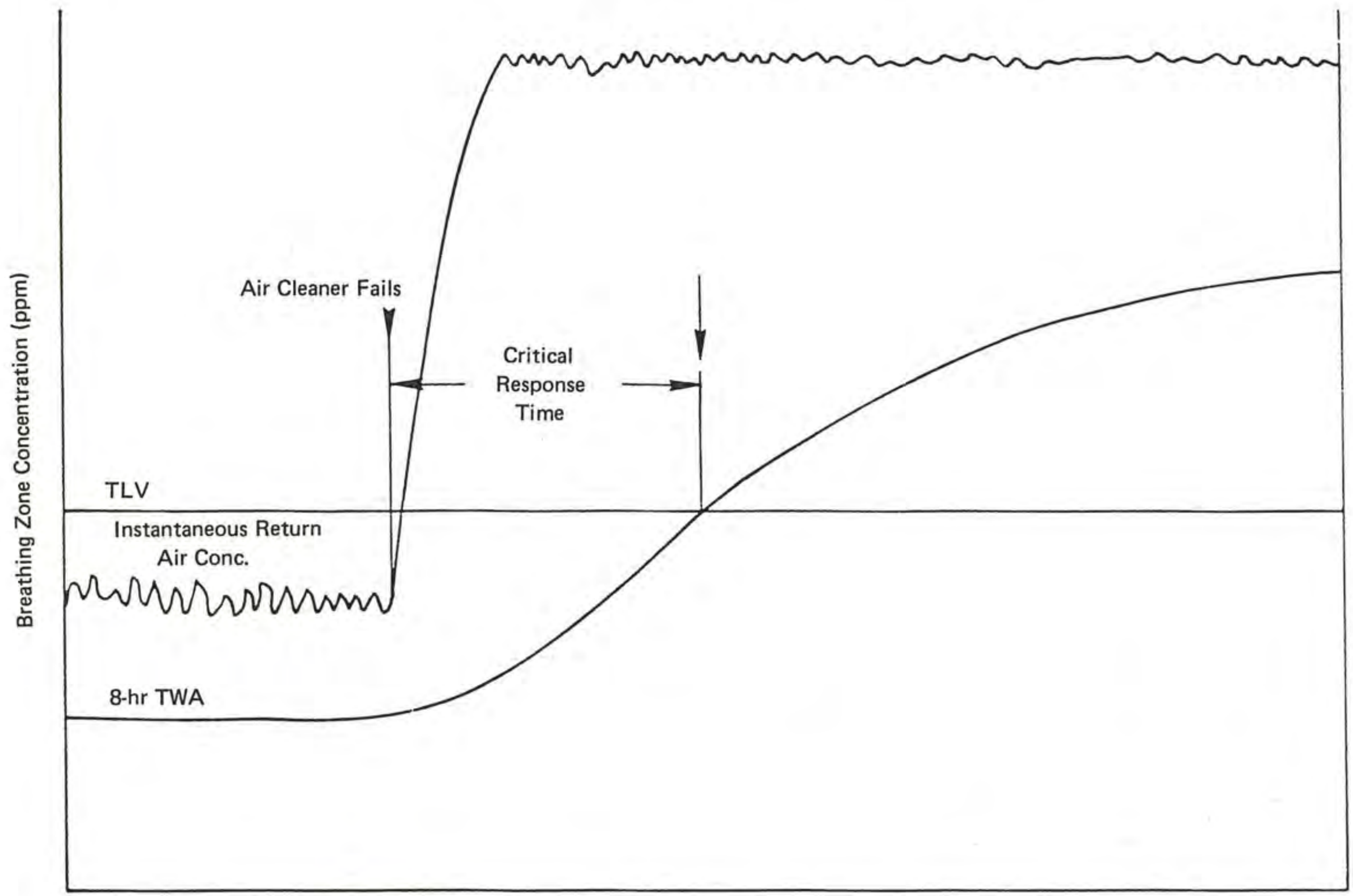

Figure 1. Sample results of transient analysis.

2. 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 fig. 1).
3. The area sensor should include those points that (based upon smoke-tube or tracer-gas airflow studies) are expected to be affected first if the recirculation system fails.
4. The only contaminants present are nuisance (nontoxic) substances.

Duct Systems

A duct system is recommended when all types of air cleaner failure can be detected, i.e., reduced airflow as well as increased contamination of return air.

Contaminant-Specific Systems

Contaminant-specific monitoring subsystems may be employed in any installation where:

1. the identities of all contaminants are known;
2. each contaminant whose acceptable level may be exceeded is monitored; and
3. the violation of any contaminant's acceptable level, or the acceptable level of the mixture present, triggers an alarm.

Nonspecific Systems

The following conditions should be satisfied by any nonspecific monitoring system:

1. The air characteristic measured must be known to change with an increase in the concentration of any contaminant, and combination of contaminants, present.
2. The trigger level selected should be tested to insure 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.

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

Automation	Location	Principle of Operation	Acceptable	Not Acceptable
Automatic	Duct	Specific	________	________
		Nonspecific	________	________
	Area	Specific	________	________
		Nonspecific	________	________
Manual	Duct	Specific	________	________
		Nonspecific	________	________
	Area	Specific	________	________
		Nonspecific	________	________

DESIGN TECHNIQUES

An Overall Perspective

It is obviously not sufficient for an individual or group interested in recirculation to approach the subject in a completely qualitative fashion. At some point in the process, it becomes necessary to quantify the various parameters which describe feasible systems, to develop firm estimates for system component specifications, and to evaluate the effects of various design options upon contaminant exposures experienced and overall system costs.

One approach to this task involves the close examination of processes conducted by industry and the development of specific system design recommendations on a case-by-case basis. The resulting information might then be presented in a format comparable to that of section 5 of the ACGIH Industrial Ventilation Manual. The design process would thus be simplified and the projected results would be supported with actual industrial experience. Many may argue that this approach is most desirable, and in many respects, they may ultimately be correct. However, the development of the necessary information would entail considerable funds and time.

A second approach requires the development of generalized analytical models capable of representing a wide variety of feasible recirculation systems. If properly formulated, and practical for utilization, such models would allow the evaluation of proposed system designs even where specific industrial experience is lacking. Additionally, they would provide a greater degree of flexibility for designing systems which best serve the needs of a particular facility. A major disadvantage of the approach, however, is that quantification of some specific parameters required by any type of model would necessitate complicated and sometimes difficult characterization of the workplace and the process conducted therein.

In recognition of the advantages and disadvantages of these approaches to recirculation system design, NIOSH has decided that a combination would be most beneficial. Consequently, it not only asked Arthur D. Little, Inc. (ADL), to develop models, but it has commissioned studies to apply the results of our efforts to various specific, common processes. These studies will serve to validate our criteria and models and will provide the specific data necessary to modify our results, where needs are identified. Additionally, they will serve to develop the process-specific type of information necessary to facilitate the implementation of safe recirculation systems in many plants.

The above discussion has been presented to give proper perspective to the scope and nature of the models developed in the ADL study. Although we believe that they are based on sound physical principles, are comprehensive, yield tractable solutions, and incorporate the most important design variables entering into a cost/benefit analysis, we are also of the opinion that they may require substantial improvement before being considered "finalized" in any sense of the word.

A Typical Model

To satisfy the need for substantial coverage of all commonly used and proposed system configurations for recirculation, a number of related, but distinctly different models were formulated. Each of these, however, is based on the same methodology and assumptions, and is similarly applied. Thus, for example purposes, it is adequate to describe only one.

Figure 2 illustrates a plant area having some amount of natural ventilation and infiltration, a number of makeup air supply units, two or more local exhaust systems, and a general mechanical ventilation system. For completeness, it also shows an inlet stream (Q'_{MU}) which represents a volume rate of makeup air not desired to be modified during the implementation of recirculation. All Q's on the figure denote volume rates of flow, and are subscripted or superscripted for differentiation. C's similarly denote concentrations.

Figure 3 shows the same area as it might appear after recirculation is implemented, although it is to be realized that one or more of the various streams or components may not be desired or appropriate. These can simply be removed from consideration in model equations by the assignment of zero values.

Major features of this particular model include the combination of local and general exhaust air before entrance to a single air cleaning section, nonrecirculation of one or more general or local exhaust streams, provision of optional exhaust air bypasses before and after the air cleaning section, and of most significance, the optional premixing of recirculated air with some amount of fresh makeup air before its return to the plant area. Other models address situations where unit collectors are used, separate air cleaning sections are provided for general and local exhaust streams, and where air is bypassed to the outdoors from some point between two air cleaners in series (as might be necessitated by air quality regulations).

Initial model development efforts, in conjunction with the basic objectives specified, led to the conclusion that the most appropriate approach involved

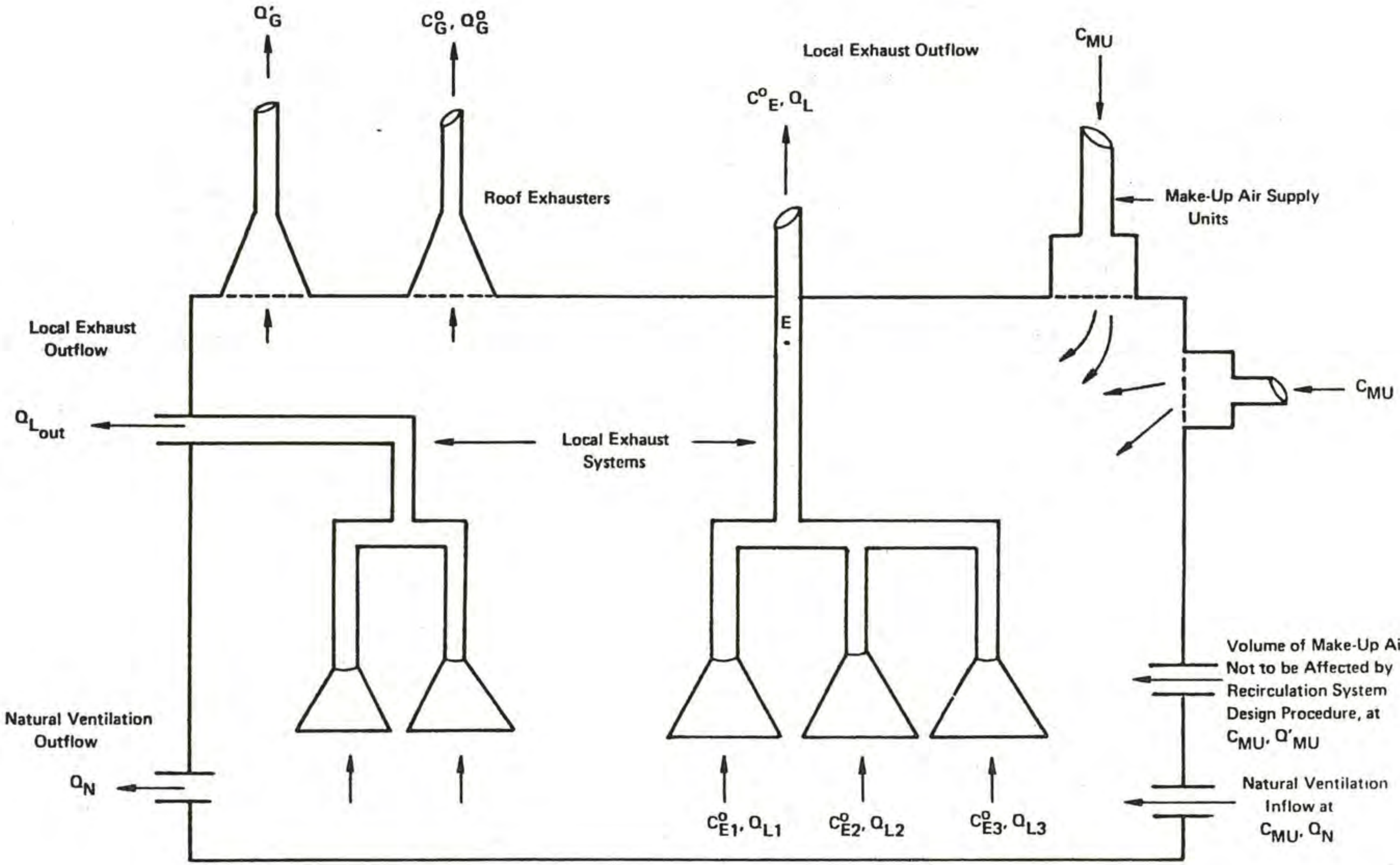

Figure 2. Plant area before recirculation.

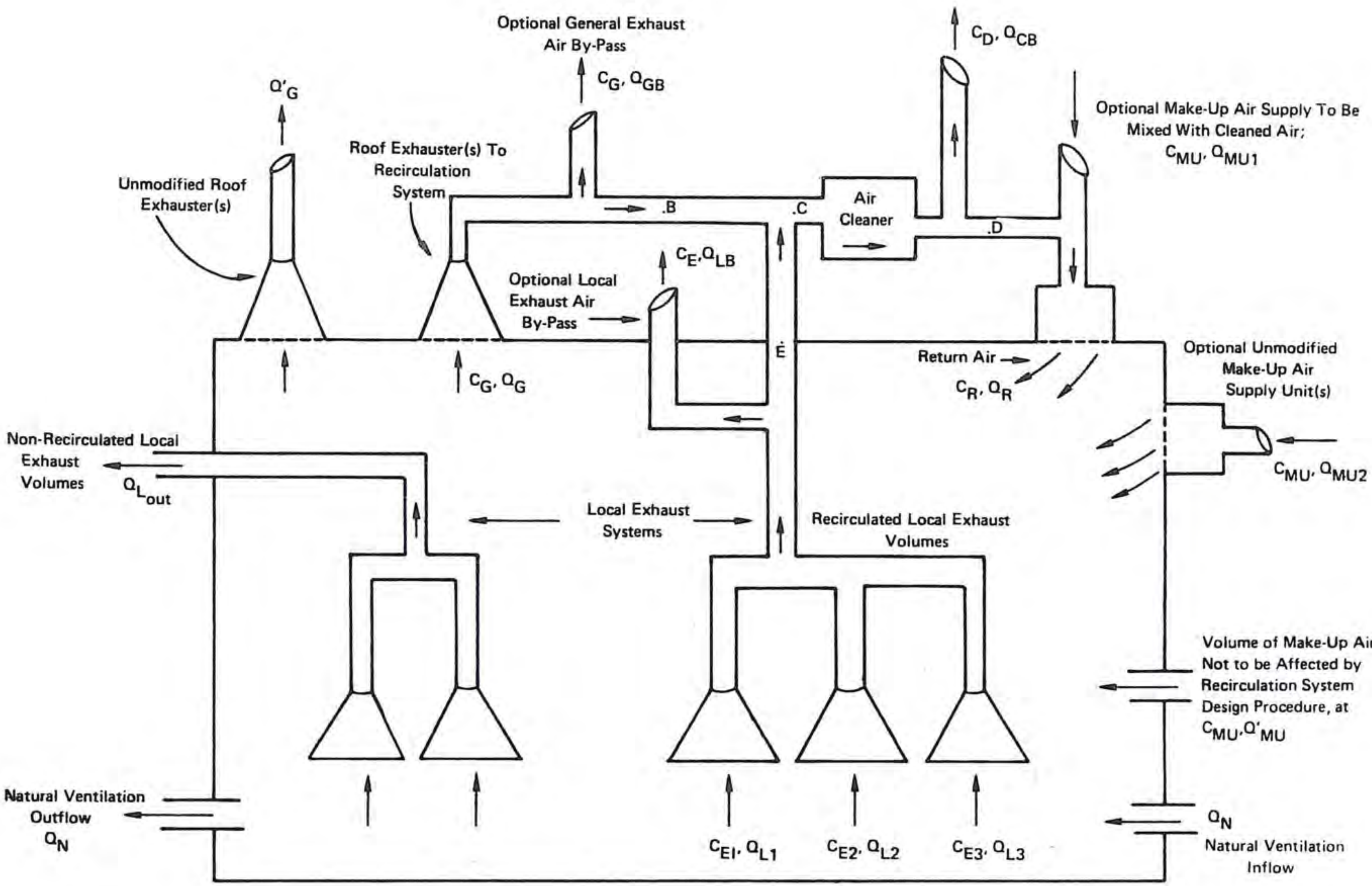

Figure 3. Plant area with recirculation--Model #1.

the major assumption of steady-state conditions. That is, it was assumed that all concentrations, flow volumes, and air cleaner efficiencies in the system could be represented by constant values for initial system design and optimization purposes. Various arguments that this would lead to overly conservative results, that some plants never achieve steady-state conditions, and others were then accounted for by stipulating that appropriate time-weighted-average parameter values must be measured or estimated for all airstreams entering or leaving the existing or proposed plant area.

Given the steady-state assumption, and a few others, it was then a straightforward procedure to develop equations that allow prediction of the return air contaminant concentration as a function of the original, prerecirculation concentrations in general and local exhaust streams, the associated flow volumes for these streams, an air cleaner efficiency, and other parameters that the user of the model specifies. The equations so developed are presented in exhibit 1. Exhibit 2 defines the flow volume balances that must be satisfied for the equations to be valid.

Definitions for all the symbols used in the expressions, except for one, can be surmised from inspection of the notation on the various exhibits. The final report discusses each parameter at length, in the context of the steady-state assumption. It also provides detailed derivations for these and other equations to demonstrate the methodology used.

The one symbol not defined in exhibit 1 is k_R. This is a factor, ranging in the closed interval of 0.0 to 1.0, which is called a "contribution factor" of return air to local exhaust systems. By definition, it represents the actual physical fraction of recirculated, locally exhausted air which comes directly from the return airstream. In all but a very few cases, it can be estimated with completely adequate accuracy, by simple inspection of the magnitude of various flow volumes entering and leaving the plant area of interest. The final report discusses how this is accomplished. Of most significance is that final results are quite insensitive to the precise value chosen for k_R, as long as the return air concentration is much less than the concentration in local exhaust streams.

The Breathing Zone Equations

Knowledge of contaminant concentrations in return airstreams is insufficient by itself for overall design purposes. Additionally, needed are methods of assessing the effect of the return air upon breathing zone concentrations, and of estimating the cost associated with each feasible system configuration.

The first of these requirements led to the development of two equations we have named "The Breathing Zone Equations." One of these is utilized to relate return air concentrations to breathing zone concentrations for employees not stationed in strong flow fields induced by local exhaust hoods. The other is for employees who may be stationed in such fields. These equations are:

EXHIBIT 1

Typical Model Equations

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

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

where

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

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

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

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

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

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

$$F = Q_R - k_R Q_L$$

EXHIBIT 2

Flow Volume Balances

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

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

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

$$Q^{\circ}_{MU} = Q^{\circ}_G + Q_L + Q'_G + Q_{L_{out}}$$

$$Q^{\circ}_T = Q^{\circ}_{MU} + Q_N$$

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

For employees not in strong flow fields:

$$C_{BZ} = \frac{Q_{T^{\circ}}}{Q_T} \left(C^{\circ}_{BZG} - C_{MU} \right) + k_{BZ} C_R + \left(1 - k_{BZ} \right) C_{MU}$$

For employees in strong flow fields:

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

where:

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

Q°_T = prerecirculation total ventilation rate in the plant;

Q_T = postrecirculation total ventilation rate in the plant;

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

C_{MU} = TWA contaminant concentration, if any, in fresh makeup air;

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

C_R = contaminant concentration in return airstreams; and

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

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

1. Return air (at concentration C_R) will physically replace some known amount of fresh makeup air (at concentration C_{MU}) that entered the plant area before recirculation.
2. 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.
3. 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).
4. The physical fraction of breathing zone air which originates in the return airstream, can be measured with a tracer gas technique or conservatively estimated.

A detailed discussion of the rationale underlying each of these concepts, and the manner in which the equations were formulated, is beyond the scope of this paper. 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 actual physical fraction of breathing zone air that originates in the return airstream. Introduction of this type of factor was considered to provide certain advantages which the commonly utilized mixing factor, k, did not. Specifically, these advantages involve the facts that k_{BZ} can only have a value in the closed interval of zero to one inclusive, that it can be determined or estimated from simple tracer gas studies in many existing plants, and that it may adequately be estimated in many plants from consideration of the volume rates of fresh makeup air and return air entering the plant, and the locations of employees in relation to inlet points.

Cost Functions

The last type of relationship that must be defined for system design and optimization purposes is one that relates the cost of the recirculation system to the volumes of air handled and other parameters of interest. It was beyond the scope of our work to address this question of economics in any great detail, but a simple cost function was formulated and utilized for example purposes throughout our final report.

Application of a Model

Close inspection of the model equations reveals that some parameters serve to characterize prerecirculation plant conditions, while others must be specified by the user in order for resultant breathing zone concentrations and costs to be assessed. These latter types of data generally include an air cleaner efficiency for the contaminant of interest, and the flow volumes of various bypass and general exhaust streams. Naturally, this leads to the question of what values should be specified for a cost-effective and adequately safe system.

The proper answer to the question requires recognition that any number of recirculation system configurations applied to a plant area may satisfy constraints imposed by health and safety considerations. The major difference among these configurations is simply one of cost. Hence, a user must decide for himself what general types of configurations are appropriate for a particular plant, and must then, by a trial-and-error, repetitive procedure, arrive at the configuration which simultaneously provides adequate safety and acceptable cost savings. The specific approach necessary is fully described, with examples, in the final report for this study.

Failure Analysis

An important step in the overall design procedure, one which merits individual attention in this paper, is a system failure analysis. The results of this analysis provide necessary data for specification of the monitoring, bypass, and alarm subsystems required for safe operation of each recirculation system configuration addressed. The need for such an analysis is predicated upon the basic assumption that any recirculation system installed may eventually fail, and that the system must be designed to respond to such a failure before hazardous conditions arise. No attempts were made, therefore, to quantify system failure probabilities or rates based on reliability data.

The approach utilized for the failure analysis involves application of model equations, with all parameters optimized, to estimate the postfailure contaminant concentration in the return airstream if the air cleaner completely fails. This concentration, along with a time factor we have called the "rise time" is then utilized to define the "critical response time" within which the monitoring, bypass, and alarm systems must react.

The "rise time" mentioned depends in a complex way upon the location of various breathing zones relative to the return air duct as well as on the nature of the airflow patterns in the plant. It is a quantity that can be measured with relative ease by simulation of failure conditions with a tracer gas release, but which, unfortunately, cannot be estimated with a simple but accurate analytical technique. Given this fact, and the realization that our approach is analogous to the use of common, analytical techniques for transient concentration analysis, it must be noted that this topic requires considerably more attention in future studies. Our approach is state-of-the-art, but that state leaves much to be desired.

A final point is that the analysis only addresses failure modes specific to the components peculiar to recirculation systems. Failures due to duct blockage, power supply interruption, fan motor malfunction, and other similar causes are not addressed. These failure modes and their consequences are not peculiar to recirculating systems. They can occur with equal likelihood in nonrecirculating systems, and it is presumed that adequate measures to deal with them are already in effect.

SUMMARY OF GUIDELINES

The following is a concise summary of the major qualitative guidelines developed in the ADL report. Several quantitative guidelines and recommendations also appear in the report. However, these are subject to misinterpretation when taken out of context, and are therefore not included here. The use of these quantitative aids must be based on a careful reading and understanding of the entire report.

The qualitative guidelines are:

1. An initial assessment of the feasibility of recirculation is desirable, if only to insure that all important factors are being taken into consideration in the design phase.
2. No known human carcinogens should be recirculated.
3. All contaminants in the exhaust to be recirculated must be identified, and their concentration levels determined.
4. A qualified health professional should establish permissible levels of these contaminants, based on an examination of the pertinent regulations or, when regulations do not exist, on available toxicological information for the contaminants of concern.
5. All major modes of failure of the recirculating systems that result in health hazards must be identified.
6. A subsystem capable of monitoring system performance, detecting each of the system failure modes, and activating an alarm is an essential requirement.
7. A failure response strategy should be chosen and implemented. Adequate training must be provided to all concerned personnel to insure satisfactory execution of the strategy.
8. The surveillance frequency and response strategy should be based on an analysis of postfailure breathing zone concentration level transients, to insure that adequate time is available for successful implementation of the response strategy.
9. Response trigger levels should be such that no employee is exposed to concentrations violating the TLV, ceiling, or other pertinent limits.
10. Return air should never be directed at an employee, since this leaves no margin of safety in the event of system failure. This is equivalent to requiring a reasonably slow transient breathing zone concentration increase after failure.
11. A performance validation program must be undertaken after installation of the recirculating system. Specific items requiring atten-

tion are: the air cleaner, the monitor, the alarm, and the failure response strategy.

12. A plan for equipment maintenance, periodic monitor calibration, and occasional system testing must be developed, and responsibilities for these assigned. Records should be maintained of these activities. Plant management must lay the greatest emphasis on the proper functioning of the monitoring system, alarm, and failure response strategy.

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Public Health Service
Center for Disease Control
National Institute for Occupational Safety and Health

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...SYMPOSIUM PROCEEDINGS

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