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VALIDATION OF A RECOMMENDED APPROACH TO RECIRCULATION OF INDUSTRIAL EXHAUST AIR

VOLUME II

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Abstracts: An evaluative supplement to a previous NIOSH publication on the design, installation, and operation of a recirculation system for exhaust air is presented. Evaluations of recently installed recirculating air exhaust systems, including breathing zone, workplace, and in duct contaminant concentrations measurements, were conducted in four facilities, involoving lead (7439921) battery assembly, woodworking, wet grinding, and enamel blending. Results of the evaluations were appled retrospectively in in accordance with the previously prescribed guidelines to determine whether findings supported or contradicted the recommended apprroach. Case histroies, complete with conclusions and recommendations, are included. Conclusions addressing the overall effectiveness of the original document are detailed. The author research and development to bridge the gap between theory and practice.

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VALIDATION OF A RECOMMENDED APPROACH
TO RECIRCULATION OF INDUSTRIAL EXHAUST AIR -- VOLUME II
(Lead Battery, Woodworking, Metal
Grinding, and Enamel Blending Operations)

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NOTE: This publication is intended to supplement and expand upon a previous publication: "A Recommended Approach to Recirculation of Exhaust Air," DHEW (NIOSH) Publication Number 78-124. Effective use of this document requires familiarity with the contents of that previous report.

PREFACE

These studies were undertaken to verify the approach to recirculating industrial exhaust air recommended in NIOSH Publication No. 78-124. The plants which were chosen for study were not necessarily the best possible recirculation systems. The criteria for choosing systems for study included an attempt to cover as many different types of contaminants (particles, mists, vapors, and fumes) and as many different types of air cleaners (fabric filters, baghouses, scrubbers, electrostatic precipitators, and carbon absorbers) as possible within the scope of the contract. Given this fact, this report should be used as a guide to better utilize the information in the recommended approach for design of working industrial recirculation systems.

ABSTRACT

This report presents the findings of a National Institute for Occupational
Safety and Health (NIOSH) study of exhaust air recirculation systems. The
purpose of the study was to evaluate recommendations of a previous NIOSH-
funded study, "A Recommended Approach to Recirculation of Exhaust Air",
DHEW (NIOSH) Publication NO. 78-124.

The study was performed by conducting evaluations in four plants which
recently had installed exhaust air recirculation systems, then applying
the results in a retroactive assessment of the design process using the
approach recommended in NIOSH Publication No. 78-124. An overview of the
case studies discusses how the retroactive assessment supported or
contradicted the conclusions and recommendations contained in the
recommended approach. Conclusions concerning the recommended approach, as
well as recommendations for their improvement and future research, are
presented.

The results of this study indicated that the recommended approach provided
a useful method for examining the feasibility of recirculating exhaust
air. Suggestions were made to clarify and emphasize conclusions which were
made in the recommended approach concerning the feasibility assessment and
modeling approach.

Further research is needed on the practical design aspects of recirculation
because a large gap between theory and practice still exists. A recommenda-
tion was made and a format proposed for the development of a practical
field manual to supplement the recommended approach. This manual would
draw together important information relating to the design, construction,
operation, maintenance and testing of recirculations systems.

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INTRODUCTION

BACKGROUND

The recirculation of industrial exhaust air is one of a number of engineering approaches which are available for the conservation of energy in industry. A "recirculating exhaust system" or recirculation system refers 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. Recirculating exhaust systems have a potentially wide application throughout industry because the practice of tempering large amounts of air requires considerable energy consumption. Although the practice of recirculation can result in substantial energy savings by reducing the need to temper air, a safe and healthful workplace must be maintained.

Realizing the need for guidelines for the design of recirculation systems, the National Institute for Occupational Safety and Health (NIOSH) began a program to develop guidelines which would enable industry to recirculate exhaust air while maintaining a safe and healthful workplace. The program began with a contract effort in 1974, followed by a symposium which presented the results and discussed the topic of recirculation. (This research effort and the symposium proceedings are available as NIOSH Publication No. 76-186). The next step was to build upon this knowledge by developing a recommended approach toward recirculation. This task resulted in a report titled, "A Recommended Approach to Recirculation of Exhaust Air" (NIOSH Publication No. 78-124), commonly referred to as Reference One throughout this report. The objective of the Reference One report, as stated by the authors, was to provide a methodology by which the design, installation, and operation of a recirculation system could be undertaken and completed in a manner which ensures the health of employees within the workplace.

STUDY OBJECTIVES AND APPROACH

To ensure that the recommended approach was useful and applicable to individuals in industry considering recirculation as an energy saving alternative, the present study was undertaken to evaluate the recommendations and design guidelines developed in Reference One. This effort to "validate" the recommended approach was to be accomplished by the performance of field surveys in plants which either were planning to install a recirculating exhaust air system or which had systems already installed.

Much difficulty was experienced in locating plants which had recently decided to pursue recirculation and were willing to accept the time frame of this

study for the preliminary evaluation, design, construction and testing of their systems. One such plant agreed to participate, and a field evaluation study was begun. However, it was terminated after a short period when it became apparent that recirculation was probably impractical. Eight plants with partially or completely constructed systems were found which were willing to participate in the validation study. From this list, the NIOSH project officer chose four plants for study, representing a wide variety of operations which generated particulate contaminants at the extremes of toxicity, i.e., lead and wood dust, and contaminant characteristics, i.e., wet and dry, large and small particles. The results of the studies are presented in four case studies contained in the Appendix of this report. These case studies are titled:

> Case Study 1 - Evaluation of a Lead Battery Assembly Operation
> Case Study 2 - Evaluation of a Woodworking Operation
> Case Study 3 - Evaluation of a Wet Grinding Process
> Case Study 4 - Evaluation of an Enamel Blending Process

Each case study is essentially a mini-report describing the process, sampling methods, and discussion of results. The evaluation of the recirculation system consisted chiefly of measurements of breathing zone, workplace, and in-duct contaminant concentrations. The presentation and discussion of results is followed by a major section dealing with the application of the survey findings to the recommended approach. This section is called "retroactive assessment".

RETROACTIVE ASSESSMENT

To evaluate the design criteria in Reference One, the results of each survey were applied "retrospectively" according to guidelines prescribed in the recommended approach. This retroactive assessment of the design problem proved to be very useful because it allowed the specific design steps and the model analysis presented in Reference One to be applied in real-life plant situations. This resulted in the surfacing of many observations concerning the usefulness of the recommended approach, as well as specific areas which are in need of further clarification and refinement.

There are several limitations of the retroactive assessment to be noted, however. The first problem concerns the lack of pre-recirculation data. Reference One requires in the design process that measurements be made before the recirculation system is installed because knowledge of these levels has an important impact in the model analysis. In three of the four plants surveyed, such data was either not available or was not meaningful. Realizing that the lack of such data would detract from the model application, attempts were made to simulate the conditions which existed before recirculation by ducting the exhaust air outdoors through a bypass. This technique was very useful because it allowed the impact of recirculation to be assessed through a comparison of "before" and after measurements. This practice did not provide meaningful pre-recirculation data in one survey, however.

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A second problem encountered in the retroactive assessments concerned a continuing conflict between the approach recommended in Reference One and the system configuration which had already been installed by the company. Consequently, design steps leading to the recommendations of specific equipment are often not as exhaustive as required by Reference One because in all cases a collector and a particular monitoring scheme had already been specified and installed by the company. As an alternative to choosing a particular piece of equipment according to the recommended approach, the discussions involve the evaluation and analysis of the particular configuration or system component chosen by the company. Comments relating to the adequacy of the design are then made. These digressions are very useful because they allow differences between the recommended approach and the company design to be compared, resulting in conclusions pertaining to relative strengths or limitations of both approaches.

A NOTE TO THE READER

It is to be noted that this study is intended to supplement the findings of Reference One and it should not be taken to stand alone as a guide to the design of recirculation systems. The retroactive assessments in the case studies followed the recommended approach, but did not usually attempt to re-explain it, except as occasionally found necessary to clarify specific points. For this reason, the reader is advised to be familiar with the general content of Reference One, and in some cases (such as the models) be well versed with the approach and its underlying concepts.

The reader should note that the case studies vary somewhat in scope and content because it was desired not be repetitious but, at the same time, cover all of the pertinent aspects which Reference One addresses. Thus, every issue is not always specifically addressed within each case study to avoid lengthy digressions and repetitous comments. The retroactive assessments often address specific problems or observations which are unique to the situation at hand. Since the issues evolved while performing the surveys, reading the case studies in the order in which they were conducted (and hence presented) will provide a better understanding of the overall conclusions of the study.

Conclusions and recommendations pertaining to the individual case studies appear at the end of each report.

A general discussion of the sampling methods and procedures followed in the surveys is presented in the Methods section. Each of the case studies is then briefly summarized in the Overview of Case Studies section. Following this, the Results and Discussion of Findings section deals with case study findings as they pertain to the conclusions and recommendations of this study. Lastly, the Conclusions and Recommendations sections are presented. The four case study evaluations are presented in the Appendix of this report.

METHODS

In this section, the general sampling methods and analytical procedures utilized to conduct the field surveys will be described.

SAMPLING METHODS

Several methods were employed to determine the concentrations and particle size distributions of contaminants in process exhaust air streams and in the industrial workplace. The in-stack methods which were employed during the survey will be first presented, then a description of the in-plant sampling methods and analysis procedures will follow.

Particulate Measurement Methods (In-duct)

Three methods were employed to extract representative samples from moving air streams. The EPA Method 5, "Determination of Particulate Emissions from Stationary Sources" was the most commonly used method for particulate extraction. The second method involved the use of the standard control module pulling a sample through an in-stack filter holder. This method was employed at one plant where the EPA Method 5 would have been too cumbersome. The third method was developed in this study to extract samples at a much higher flow rate than the standard method. Its principal advantage was the ability to obtain enough sample for analysis when concentrations were too low for conventional sampling.

Particle size measurements were made with two multistage fractionating impactors. The Sierra Series 226 impactor was used in the first two surveys, while the Sierra Series 228 impactor was used in the remaining surveys.

The particulate sampling and particle size methods which were employed in this study are summarized in Table 1. Simultaneous inlet and outlet samples were taken in Case Studies no. 3 and no. 4. Sampling was not performed simultaneously in Case Study no. 2 because the equipment and time necessary to sample five inlet and seven outlet ducts could not be justified. In Case Study no. 1, the inlet and outlet were not simultaneously sampled because the second sampling train, the high volume sampling method, had not been developed at that time.

In Case Studies no. 1 and no. 4, no outlet particulate size analysis could be made because the particulate concentration was too low to allow capture of sufficient sample for analysis. In Case Study no. 1, the inlet particle size sample could not be plotted because not enough of the material was present in size ranges below the cut-off size of the impactor's

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Table 1. Summary of in-duct particulate sampling methods.

Case study number	Inlet method	Outlet method	Simultaneous	Inlet particle size	Outlet particle size
1	Method 5	Method 5	No	Sierra 226*	No†
2	In-line	In-line	No	Sierra 226	Sierra 226
3	Method 5	High volume	Yes	Sierra 228	Sierra 228
4	Method 5	High volume	Yes	Sierra 228	No†

* Data could not be plotted.
† Attempt was made but sample weight was too low for analysis.

pre-cleaning cyclone.

EPA Method 5 Sampling Train--
The EPA Method 5 sampling apparatus and method is a well documented procedure for isokinetically withdrawing particulate matter from a source and determining its weight gravimetrically. A schematic of the Research Appliance Company (RAC) "Stacksamplr" sampling apparatus is shown in Figure 1. The sampling train consists of two functional parts. The "front half", which collects the sample, is composed of a pitot tube, nozzle, probe, filter holder, filter, manometer, impingers, check valve, and various temperature sensors, all housed or connected to the sample module. Air is drawn through the front half through a vacuum line by the control case or "back half". The control case consists of a vacuum gauge, main valve, air tight pump, dry gas meter, thermometers, and a flow regulating orifice. The sampling probe was a 0.91-m (3-ft), glass-lined, heated tube through which the sample was drawn. Nozzles were sized and selected to withdraw a representative sample from the gas stream at a velocity equal to that of the stream, i.e., isokinetically.

Samples were collected on 10.2 cm (4 in.) glass fiber filters located in a heated chamber. The sampling rate depended on the nozzle size chosen, but the typical flow rate was 0.014 m³/min (0.5 cfm).

Throughout the sampling period, temperatures, pressures, flow rates, and flow volumes were recorded. The flow volume measured was adjusted to standard conditions of 21°C and 760 mm Hg.

Sample sites and velocity traverses were selected according to procedures specified in EPA Method 1, "Sample and Velocity Traverses for Stationary Sources". Sample port locations were chosen according to Method 1, but in several tests sampling locations were not ideal, necessitating that extra points be sampled. Following each run, the filter was removed and the probe, nozzle, and filter holder were thoroughly backwashed and brushed with acetone into a clean container to recover the portion of particulates deposited prior to the filter.
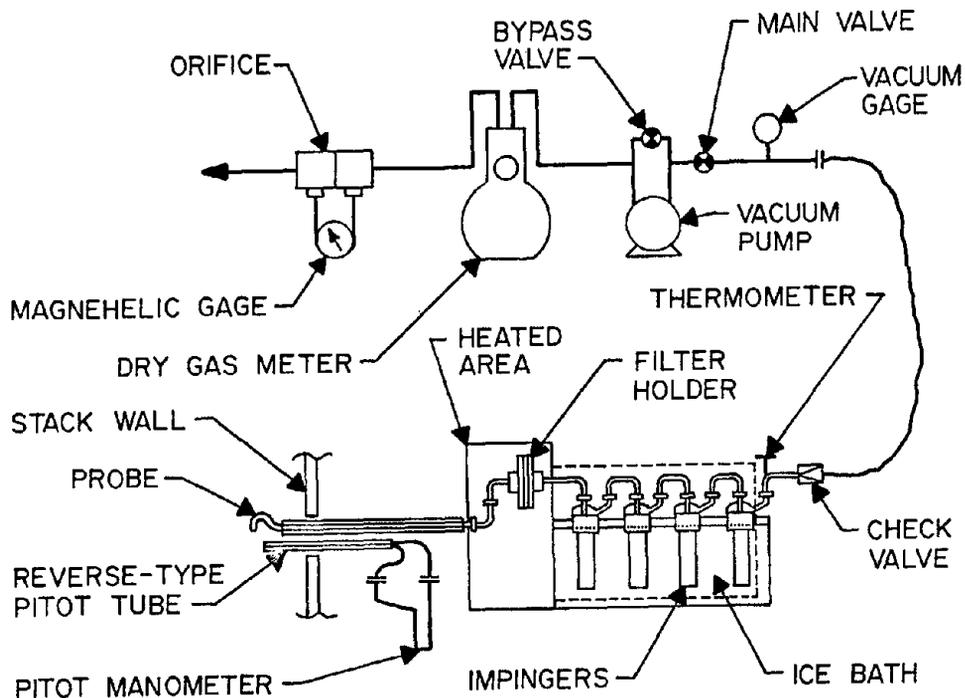
Figure 1.   EPA method 5 sampling train.

In-Stack Filter Method--
In Case Study no. 2, particulate samples were withdrawn from five inlet and seven outlet ducts consecutively, using the sampling apparatus shown in Figure 2.   This sampling train consisted of a Gelman 47-mm in-line filter, holder, nozzle, probe, pitot tube, silica gel trap and a RAC control case.   The pitot tube was strapped to the side of the sampling probe to allow the simultaneous measurement of velocity pressure which is required for isokinetic sampling.   Samples were collected on 47-mm glass fiber filters.

The nozzle and filter inlet were backwashed with acetone into a clean container for subsequent gravimetric analysis.   Traverse points and sampling sites were selected according to EPA Method 1.   Other sampling procedures were conducted in accordance with EPA Method 5.

High Volume Sampling Method--
In several case studies, a high volume sampling method was used to collect a larger amount of sample in the outlet, particularly in exhaust streams where concentrations were low.   As shown in Figure 3, the sampling train consisted of a Rader 47.8 mm (1 7/8 in.) diameter sampling nozzle, a Millipore 142 mm diameter PVC filter holder, a Roots model 5M125 positive displacement gas meter, and a Clements model HP 33 high volume blower which was regulated by a Variac variable transformer (0-120V).   Samples were collected on Gelman Type A glass fiber filters.

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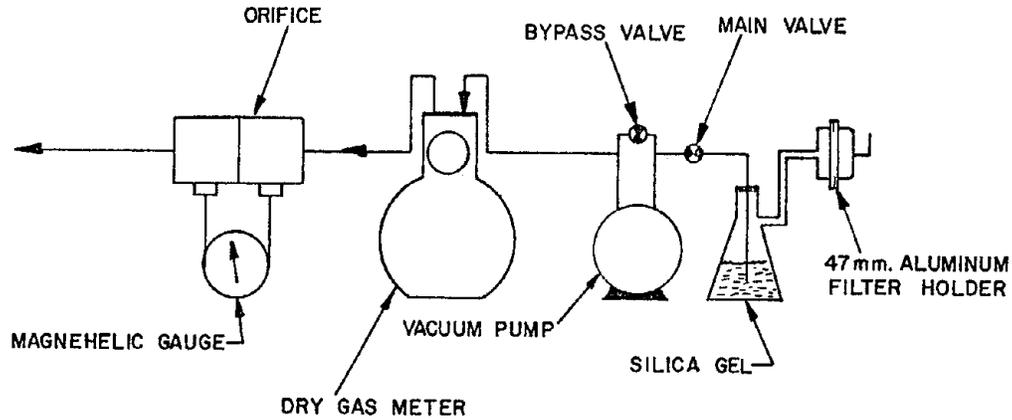
Figure 2. In-stack sampling train.
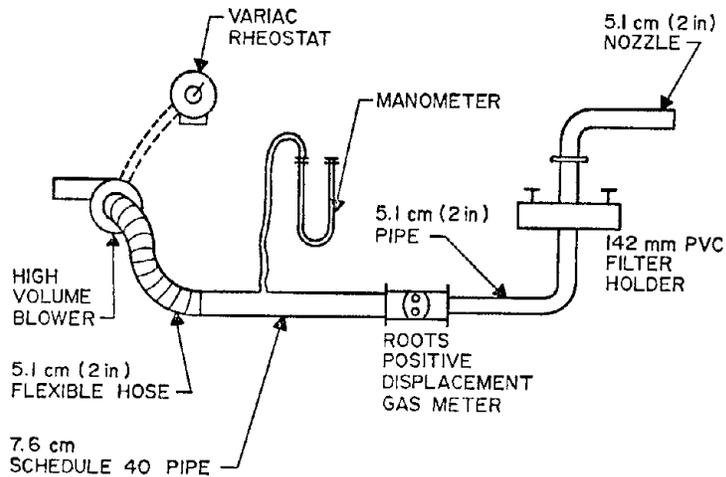
Figure 3. High volume sampling train.

The sampling rate was adjusted by varying the current to the blower. The total flow through the system was measured by taking the difference between the initial and final readings on the Roots meter. The temperature and the pressure at the meter were monitored so that the volume could be corrected to standard conditions. The range of flow rates was typically 0.17-1.14 m^3/min (6-20 cfm). The flow rate was limited by the size of the filter holder. With a later modification, 1.42 m^3/min (50 cfm) was able to be drawn through a 203 mm x 254 mm (8 in. x 10 in.) filter and holder.

The outlet sample was extracted at one location in the duct at the point of highest velocity. Sampling at one location is not ideal but is still meaningful when particles are small, i.e., <5 micrometers because small particles will follow streamlines, and thus be evenly dispersed with the air flow. Following each inlet run the filter was removed, then the probe, nozzle, and filter holder were thoroughly backwashed and brushed with acetone to recover the portion of the particulates deposited prior to the filter.

Particle Sizing--
A particle size analysis was performed with the Sierra Series 226 and 228
impactors. The Model 226 is a six stage impactor with a pre-cyclone for
longer sampling. The Model 228 has eight stages but no cyclone. To
obtain a measure of the particle size distribution, air was extracted at
approximately 0.010 m^3/min (0.35 cfm). The sample was withdrawn at
a flow rate close to the flow of the moving air stream (near isokinetic).

A cascade impactor is made up of a number of classification stages consisting
of a nozzle (or slit) and an impaction plate. In each stage, an aerosol
stream passes through the nozzle and impinges on the plate. Particles in
the aerosol stream which have a large enough inertia will impact upon the
plate. Smaller particles will pass as an aerosol to the next stage.
Because each successive stage is designed to have a higher aerosol velocity
in the nozzle, smaller diameter particles will be collected on each
stage. Particles too small to be collected in the last stage are collected
in a back-up stage.

Each stage has a plate holding a 47 mm glass fiber filter with holes or
slots to allow particles to reach successive stages. The amount of material
caught on each stage is determined gravimetrically.

In-Plant Sampling

Workplace measurements were made using Bendix Model BDX 44 and Mine Safety
Appliance Model "S" portable battery-operated vacuum pumps. Total dust
and metal samples were extracted at 2.0 l/min while respirable dust
samples were extracted at 1.7 l/min. Flow rates were measured with a
pre-calibrated rotometer, and were checked and readjusted several times
throughout the workday.

Total dust and metal samples were collected on 37 mm Millipore type BD
membrane filters with a pore size of 0.6 micrometers, or glass fiber filters.
The filters were sealed in a Millipore filter housing prior to entering
the manufacturing facility and were not opened for analysis until returning
to the laboratory to guard against possible contamination. Workplace
samples were taken with doors and windows shut to avoid possible interferences
from cross-drafts and to simulate the "closed" conditions of winter.

In Case Study no. 2, workplace measurements were also made using the GCA
Technology Respirable Dust Monitor Model No. RDM-101. This instrument
is a portable device which measures dust concentrations by drawing an air
sample for a pre-set sampling period (4 minutes), allowing particles to
impact on a sticky plate, then measuring the concentration by sensing the
amount of beta radiation which is attenuated by the particles collected on
the plate.

To assist in the interpretation of workplace sampling results, ventilation
patterns were measured throughout the work area. A Model 6,000-P Alnor
Velometer was used to measure room air velocities. General circulation
patterns were assessed using Mine Safety Appliance Ventilation smoke tubes.

ANALYTICAL PROCEDURES

Prior to weighing filters, a 24-hour period was allowed for desiccation. Filters were weighed to the nearest 0.01 mg using a Model H20T Mettler balance. To determine the metal content of the filter samples, the pads were first digested in strong nitric acid solution, then analyzed with a Perkin Elmer atomic absorption spectrometer. Blank pads were also analyzed to determine background metal content of the filters.

Backwash catches from in-duct sampling were filtered through preweighed type A glass fiber filters. These filters were postweighed and then submitted for metal analyses, if necessary. The silica content of filters was determined by submitting the samples to an AIHA accredited commercial laboratory which analyzed them for percent crystalline silica using X-ray diffraction.

TRACER GAS STUDIES

Tracer gas studies were performed in three of the four case studies to determine estimates for two parameters which were used in the modeling approach, k_R and k_{BZ}. The method used to conduct the studies will first be discussed, then some of the problems encountered during the tracer study will be presented.

Measurement Method

The tracer gas, sulfur hexafluoride (SF_6), was injected into the collection system directly from a commercial "F" size cylinder. The gas pressure was regulated with a special valve and the flow rate was measured with an in-line pre-calibrated rotometer. The room concentration of SF_6 were measured with a Wilks Model 1A portable gas analyzer (MIRAN) which operated on the principle of infrared spectroscopy. The instrument's output was recorded on an Esterline Angus Miniservo strip chart recorder. The MIRAN was set up to analyze for SF_6 by setting the following adjustments:

Wave length	10.7 micrometers
Slit	1 mm
Gain	High
Gain adjustment	1.5
Pathlength	0.75 m
Range	0 - 1 angstroms
Recorder speed	2 cm/min

Problems Encountered

One problem noted during the measurements involved the determination of k_{BZ}, defined in Reference One as (p. 87):

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

Where:

C_P is the peak tracer gas concentration in the breathing zone.
C_R is the tracer gas concentration in air out of the supply air duct.

In several of the tracer gas studies, the determination of C_R was compli-
cated by a build-up of tracer gas during the time room measurements were
being made. This was especially noted in Case Study no. 3 when the
concentration of trace gas in the inlet increased from 29 ppm to 35 ppm
during a 25-minute period in which room concentrations were being made
(Table 3-5). Since the value of C_R rose during the survey, there was some
question as to what values were more appropriate to use in the calculation
of k_{BZ}. With the final inlet concentration, the value for k_{BZ} would have
been 11% lower than the estimate made using the initial value.

Another problem encountered in the survey pertained to the method which
was used to measure the tracer gas. In the first two tracer gas studies,
a full cylinder of gas barely contained enough gas to conduct each
study. In the last study, it was found that the measurement could be
made on the most sensitive scale on the MIRAN, thus requiring much less
gas. The third measurement only consumed an estimated 10% of the cylinder's
contents.

OVERVIEW OF CASE STUDIES

INTRODUCTION

The following sections are brief summaries of the individual case studies. Pertinent aspects of the process, recirculation system, measurements and the tracer gas studies are presented first under "survey findings". Following this, a brief synopsis of the "retroactive assessments" is presented. The summaries do not attempt to state the conclusions of each study, because the major conclusions are summarized at the end of each case study, and are more fully discussed in the Results and Discussion of Findings section. The purpose of this section is to give a broad overview of each of the case studies to provide a better understanding of the approach taken and the results obtained.

EVALUATION OF A LEAD BATTERY ASSEMBLY OPERATION

Survey Findings

An evaluation was made of a prototype recirculation system at a lead-acid battery plant. Dusty exhaust air containing lead oxide from a lead plate stacking operation was cleaned using a small unit collector located at the work station. The unit collector consisted of two high efficiency particulate aerosol (HEPA) filters installed in series. The first filter was able to be cleaned using a motorized rapping mechanism which was activated four times a day. The second filter was not recleanable and was used primarily as a means to monitor breakthroughs of the first filter. Breakthroughs of the first filter would result in blinding of the second filter, thus increasing the pressure between the filters which would trip a switch and sound an alarm. The effluent from the unit collector was reintroduced to the work station through an overhead plenum at a rate of 40 m^3/min (1400 cfm).

During the field evaluation phase particulate measurements were made in the inlet and outlet of the unit collector. Workplace and breathing zone samples which were taken were also supplemented by the plant's own data whenever possible. The field study phase also included a tracer gas study to determine ventilation parameters which were used when applying the model approach from Reference One.

The results of the sampling program showed that the unit collector provided its rated high efficiency performance, and that the average return air concentration of lead into the workplace was 0.032 mg/m^3. Lead exposure levels rose slightly after recirculation.

Retroactive Assessment

An initial assessment of the feasibility of recirculation found that there were no apparent technical barriers to recirculation, but a proposed ban of recirculation of exhaust streams containing lead imposed serious legal questions. An analysis of the double HEPA collector suggested that the anticipated high efficiency was a definite advantage, but that the pressure switch monitoring method was not completely adequate because it would not provide a response to small breakthroughs of both filters. The concept of returning the cleaned air directly to the worker's breathing zone was critiqued, and it was determined that the present method places too great a constraint on the system reliability. Redistributing the cleaned air into the workplace was encouraged.

In the modeling analysis, the approach taken was to attempt to comply with the Reference One recommendation of maintaining pre-recirculation breathing zone concentrations through recirculation. This recommendation was followed because it was realized that it is undesirable to increase breathing zone contaminant concentrations of toxic materials. The levels were to be maintained by allowing the dilutory effect of the increase in the total ventilation rate through the plant area to offset the increase in contaminants resulting from the return air stream. Since the result of this exercise was the specification of an unrealistic collection efficiency, alternative design options were considered, e.g., return the air into the general plant area instead of the breathing zone. Examination of this latter option also resulted in an unrealistic collection efficiency. It was then concluded that some increase in the post-recirculation breathing zone concentration would be necessary with the collector chosen for use. This increase was seen to reduce the present margin of safety between current levels and the current and proposed standards.

The modeling equations were also used to compare predicted breathing zone levels to levels actually measured. The close agreement which was found suggested that the modeling equations are based upon sound concepts.

EVALUATION OF A WOODWORKING OPERATION

Survey Findings

A new recirculation and heating system had recently been installed at a wood working plant which consisted of new ductwork, a collection system, and a wood waste boiler. The new installation was motivated by a need to comply with ambient air pollution regulations, although the overall result of the plant changes was the elimination of natural gas and coal usage. The woodworking operations involved wood cutting, sawing, and sanding operations.

The dust collection system consisted of a modular fabric filter which was specially designed to collect wood dust and transport the waste to the boiler. The collection system included explosion and fire hazard protection features. Efficiency tests indicated that the collection system operated at an average efficiency of 99.65%, but that the efficiency will be even higher when

the malfunctioning modules which were found are repaired. Workplace dust measurements indicated that there was no discernible difference between pre-recirculation and post-recirculation measurements, and that both levels were a small fraction of the current threshold limit value for wood dust.

Retroactive Assessment

A preliminary assessment of the major design issues indicated that there were no apparent technical barriers to recirculation, but that the potential lowering of the recommended level for wood dust would have a significant impact on the design. A more in-depth evaluation of the technical aspects resulted in the examination of visual monitoring for possible use as the surveillance strategy. Visual monitoring is a very attractive method because automatic monitoring would likely require monitors in each of the return air ducts and thus be economically prohibitive. Before visual monitoring is to be judged acceptable, it was recommended that tests be conducted to determine the effectiveness of the technique for detecting various types and severities of failures.

The modeling analysis found that the collector specified for use in the design was capable of achieving post-recirculation breathing zone concentrations near 20% of the TLV for wood dust. Through the application of the model, it was also discovered that the Reference One assumption of air-balanced plants did not allow direct use of modeling operations without some modifications. The modifications centered around re-defining the term describing the natural ventilation rate. This change allowed the effect of negative and positive air pressures to be incorporated both before and after recirculation.

A final observation was made concerning the simplification of the modeling equations to more familiar forms. The simplifications which were noted led to the realization that, in many cases, a rigorous application of the modeling analysis need not always be performed.

EVALUATION OF A WET GRINDING PROCESS

Survey Findings

A grinding machine was connected to a new wet dust collector because of a need to comply with ambient air quality regulations. In the grinding operation, large cup-shaped castings composed of high manganese steel were set on a rotating platform, while rotating grinding wheels ground the inner and outer surfaces of the casting.

The wet collector consisted of a rotating impellor and a water nozzle. The liquid utilized in the scrubber was recycled machine coolant. The new collection system was the first of seven which were planned to be installed in the work area. There was no source of mechanically provided make-up air in the manufacturing room.

The efficiency tests determined that the collector was operating at an efficiency of 97.9%. Problems encountered during the testing indicated that the system had not been thoroughly debugged.

Workplace and breathing zone concentrations showed a significant increase in contaminant levels as a result of recirculation. The greatest percentage of the dust was iron oxide; manganese was found to be present in relatively small percentages. A tracer gas study indicated that workers were breathing, on the average, about 20% recirculated air. Measurements of relative humidity showed that the collector did not appear to be humidifying the plant air a significant amount.

Retroactive Assessment

The initial assessment of the feasibility of recirculation identified several issues which should be addressed further. Most notable of the issues were the likely presence of a suspected carcinogen in the scrubber water, and the potential for the return air stream to contain objectionable odors and possible high humidity levels. Further analysis showed that the present method of monitoring, i.e., a water pressure sensor on the line leading to the spray nozzle, was not by itself adequate to provide detection of all major failure modes.

The modeling analysis provided additional insights regarding the required collection efficiency. Using the efficiency estimates provided by the manufacturer, the model showed that the respirable dust content of the return air stream would be too high to achieve acceptable breathing zone concentrations in the present configuration. An alternative configuration in which adequate make-up air would be provided was then analyzed. With this assumption, the collector specified for use would produce breathing zone concentrations of approximately 50% of the permissible exposure level (PEL) for respirable nuisance dust. A check of the collector efficiency for manganese levels also indicated that the collector would provide suitable removal for this contaminant.

A failure analysis of the chosen configuration resulted in the conclusion that breathing zone concentrations of respirable dust would exceed the PEL within one minute after failure. This calculation makes the recommended assumption that the collection efficiency will be zero upon failure.

A comparison of model predictions to actual measured contaminant concentrations supported the earlier conclusion that the modeling equations are based upon sound concepts.

EVALUATION OF AN ENAMEL BLENDING PROCESS

Survey Findings

A process which blended a dry enamel powder with small amounts of pigments was retrofitted with improved local exhaust control measures and a new collection system. The enamel powder was manually loaded and unloaded in small ball mills or slightly larger blenders by workers in the "color room".

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The powder was retrieved by the workers from a neighboring "white room" where it was manufactured. The powder was known to contain about 16% lead and compounds. A few of the pigments contained zinc and cadium in small amounts.

Dust was generated mostly by the unloading and loading of mills and by periodic "blowing out" of the mills with air nozzles. A new collector was installed by the company to improve breathing zone control of workers. The new system consisted of new total enclosing hoods, new ductworks, and a collector which was sized for a considerable increase in volumetric flow rate. To offset the increased flow rate, recirculation of the air was included in the design as an energy savings feature.

The dust collector was found to be operating at a 99.83% efficiency during the survey. The breathing zone measurements which were made were not indicative of the recirculation system performance because the samples were affected by the contamination the workers received when they periodically entered the white room, and by bad work practices e.g., blowing out the mill enclosures. A positive effect of the recirculated air was the prevention of infiltrating dusty air from the white room. As expected, a tracer gas study showed that workers breathed almost 100% recirculated air.

Retroactive Assessment

There were no apparent technical barriers which surfaced in the initial feasibility assessment. However, the possibility that a proposed standard may prohibit the recirculation of exhaust streams containing residual amounts of lead could provide a legal barrier to recirculation.

The monitoring method utilized by the company at the time of the survey was a differential pressure sensor across the fabric filter. This surveillance method was judged to be, by itself, inadequate because small but significant breakthroughs may still be able to occur.

The modeling analysis was not able to be applied in the same manner as in the other case studies. However, the model was used to calculate a post-recirculation breathing zone concentration with the assumption that pre-recirculation levels were well controlled. Another assumption in the calculation was that company estimates would be used for the contaminant generation rate instead of actual measurements. Because of this latter assumption, the required collection efficiency was unreasonably high. When the measured generation rate was utilized in the equation, the required collection efficiency was a feasible value. This exercise showed that inaccurate model estimates will give inaccurate results and emphasized the need to assign parameter values based upon actual measurements.

RESULTS AND DISCUSSION OF FINDINGS

INTRODUCTION

In this section, the major findings and conclusions from the individual
case studies are presented and discussed. The framework of this discussion
follows the organization of Reference One to facilitate cross-referencing
between the two documents.

INITIAL FEASIBILITY ASSESSMENT

In the four case studies, the preliminary evaluation criteria presented in
Reference One were useful because they brought out important issues which
deserve more attention in an in-depth evaluation. The issues presented in
Reference One for initial consideration are all important enough to deserve
a more thorough evaluation than suggested. In the case studies, the topics
of legal issues, energy consumption, contaminant classification, and
ventilation system design aspects were expanded in scope to include a more
detailed analysis.

Concerning legal issues, it was seen that the designer must not only be
aware of current laws which restrict or prohibit recirculation, he must also
be knowledgeable of impending laws, e.g., the proposed changes in the lead
standard (Case Study nos. 1 and 4) and the future lowering of the
recommended level for wood dust (Case Study no. 2). At the time the
companies were designing their systems, the proposed lead standard called
for a reduction in the permissible exposure level and a ban on recirculation
for exhaust streams containing lead. In addition, the possible lowering
of the recommended level for wood dust may result from an assessment of
health studies in a forthcoming NIOSH criteria document.

The issue of energy consumption was expanded to include the concept of
incorporating recirculation into a broad program of energy conservation
measures. As noted in Case Study No. 2, the plant undertook recirculation
with a change in their boiler to allow the recovery of wood waste. The
overall result of the program was the total elimination of natural gas
usage in the plant.

Recirculation was seen to have another benefit besides energy conservation
in Case Study No. 4. The system which was installed in one process
area had the advantageous effect of causing a positive pressure which
prevented dust from a nearby room from infiltrating into the first work area.

In the preliminary classification of contaminants, the designer should
evaluate the potential for odorous emissions in the proposed design concept.

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As noted in Case Study no. 3, the collection system chosen by the company emitted an exhaust air stream which contained objectionable odors.

The initial assessment of ventilation system design aspects is also an important preliminary step. In Case Study no. 2, the inclusion of seven return air ducts had important implications on the feasibility of choosing an adequate monitoring system.

The Reference One suggestion that in-plant systems should be optimized before pursuing recirculation was a very important concern in all of the case studies. The optimization of in-plant controls is always the best approach before considering recirculation. By optimizing, the design team is assured that in-plant levels are well controlled and that breathing zone and collector efficiency data are truly representative of conditions before recirculation. Exhaust system optimization also allows the effects of recirculation to be predicted with the modeling approach presented in Reference One.

However, as a practical matter, this study has shown that recirculation is often accompanied by other ventilation changes, e.g., increased flow rate (Case Study nos. 3 and 4), a new collector (nos. 1, 2, 3 and 4) or new hooding (no. 4), which may complicate the direct application of Reference One. This is not a criticism of the Reference One approach; on the contrary, it emphasizes the need to optimize ventilation systems before recirculation. Without optimizing, the design team will often not be able to accurately predict or assess the effects of recirculation.

The remaining topics presented in the initial feasibility assessment were useful in the case studies for the identification of important factors influencing the design. For example, the examination of the issue of air quality regulations provided the insight that the high collection efficiency required for the control of ambient lead emissions was also an incentive to consider recirculation.

CONTAMINANT CHARACTERISTICS

Chapter 2 of Reference One presents a discussion of the physical and chemical characteristics, and health effects of contaminants for consideration in the design process. The discussions may be amplified by several of the case studies.

In two surveys (nos. 2 and 3) the plant did not have knowledge of pre-recirculation contaminant levels in the breathing zone, and thus, did not have a firm basis for a design analysis. However, this did not result in a faulty collector selection in Case Study no. 2 chiefly because of the high efficiency of the collector which was selected, the low toxicity of wood dust, and the apparent low contaminant concentrations in the workplace prior to recirculation.

Inaccurate knowledge of the contaminant generation rates in Case Studies nos. 3 and 4 would have presented difficulties for the designs in the model

analysis. In the former case, the plant engineer assumed a generation rate based on an inconclusive stack test. This would have produced inaccurate model results if it had been utilized in the design. In the latter case, inaccurate generation rate which had been assumed by the company was used in the model analysis. This resulted in a collection efficiency which was unreasonably high.

The establishment of allowable contaminant levels may sometimes be hampered by regulatory uncertainties. In the case of wood dust, OSHA does not have a specific permissible exposure level. Because of uncertainties concerning the definition of nuisance dust, OSHA enforces the level of wood dust under a "general duty clause". Because of the lack of a permissible exposure level, the designer is forced to recognize the level recommended by ACGIH for wood dust for design purposes.

In the identification of toxic substances in the feasibility assessment, the designer should not overlook the possibility of the scrubber water containing harmful substances. In Case Study no. 3 the use of a water-base machine coolant in the scrubber would have resulted in the emission of nitrosamines, a suspected carcinogen, in the return air stream. In general, this emphasizes that every possible source of contaminant generation must be evaluated in the design process.

Finally, the suggestion that allowable levels be reduced by a safety factor to account for vagaries in the design was seen to present difficulties in several of the case studies relating to deciding an acceptable level. The health professional should not only establish the allowable levels for contaminants, he should advise the design team in setting the appropriate safety margin in the design. The designer usually needs more advice pertaining to the acceptable safety margin than in establishing maximum safe limits since this is usually the TLV or OSHA standard.

The specification of an acceptable safety margin will depend on such factors as the standard deviation of contaminant concentrations and the reliability of the collector and monitoring system. Further research should be conducted on such factors to provide a reasonably scientific basis for deciding acceptable safety margins.

The discussion in Chapter 5 concerning temporal, seasonal and process-related variations in the breathing zone and emission levels were reinforced in the case study evaluations. During the surveys, at least three days of sampling was normally performed to identify day-to-day variations in emission levels as well as workplace levels. The highest results obtained were normally used as a basis for the design, especially in the case of toxic contaminants. To be thorough, seasonal variations also needed to be considered because, in many cases, recirculation systems are installed during July plant shutdowns and are ready for testing during the late summer months. Since the validation step in Reference One recommends that the system be checked before production operations begin, the fall evaluation is a typical first evaluation before heavy winter use. A follow-up evaluation should also be performed in the winter, however, because contaminant levels are usually worse in winter.

In the surveys, "worst case" conditions were simulated during fall evaluations by closing doors and windows during measurements in the plant area affected by recirculation. The technique was useful in that it prevented cross drafts and dilution of fresh air from outdoors, but conditions were probably not truly representative of the "worst case" situation because the remainder of the building was not as closed as it could have been.

CLEANING THE EXHAUST

Chapter 5 of Reference One presents a discussion of the important considerations for choosing a collector. The discussion provides a thorough treatment of air cleaner characteristics, efficiencies and possible failure modes. The case studies supported the discussion in Reference One by showing that the reliability of air cleaning devices is an important concern during the evaluation, and that air cleaners can adversely affect the quality of the air. For example, in Case Study no. 1, the issue of air cleaner reliability was considered important enough for the company to investigate the long term filter life of the double HEPA filter collector. In Case Study no. 3, the fouling problems and malfunctions which were observed during the survey also indicated that reliability is an important issue and that good preventative maintenance is essential to the reliability and continued performance of the dust collector. Evidence of the collector affecting the quality of the air was seen in Case Study no. 3, where the collector was observed to increase the odor levels and perhaps humidify the room. In general, the reliability of the air cleaning devices seemed adequate. In particular, the reliability of the fabric collectors in Case Studies nos. 2 and 4 seemed to be high, indicating fabric filtration may be a good choice for recirculation when certain types of particulates are involved.

The discussion of air cleaner failure modes in Reference One was supplemented in each of the case studies by evaluation of the interrelationships between types of air cleaner failures, major failure effects, and the effect of failures on pertinent system parameters which may be monitored. This analysis was facilitated by the use of a chart which succinctly showed these interrelationships.

SURVEILLANCE AND RESPONSE STRATEGIES

Chapter 6 of Reference One presents a very thorough treatment of the general types of surveillance strategies and a rationale for their selection. Possible types of responses to system failures are also discussed. The case studies provided additional insights toward this issue which deserve mention.

Surveillance Strategies

The presence of a substance with a regulated ceiling concentration added complexities to the assessment of available monitoring strategies in Case Study no. 3. Fortunately, the substance was not present in sufficient concentration to merit a separate recommended monitoring method.

As part of the in-depth evaluation of the design approach in the case studies, all principal failure modes were listed together on a single chart. The chart indicated that most major system failures would result in a reduction of the hood capture efficiency because of a reduced air flow. This under-scores the need to pay special attention to air flow reduction failures.

With respect to specific monitoring methods, in-duct contaminant monitors for particulates are becoming more available. The in-duct monitors have a number of inherent advantages over area monitors, e.g., faster response to air cleaner efficiency failures and the need for fewer monitors. Usually, however, the failure mode charts showed that monitoring only in-duct contaminant levels would not result in the detection of all of the probable failures. The in-duct monitor must be used in conjunction with other monitors such as with devices which sense ventilation system parameters. Not only would such a combination provide for a response to all of the major failure modes, it would also provide some degree of redundancy and thus higher system reliability.

The analysis of monitoring approaches in the case studies indicated that the need for adequate monitoring is crucial, but in several surveys, it was difficult to judge what was adequate. In Case Study no. 2, for example, visual monitoring appeared to be a viable approach for surveillance, but it was concluded that further study was needed to determine the effective-ness of detecting failures by only visual means.

In three case studies (nos. 1, 3 and 4), the prospect of monitoring the return air stream with a continuous particulate monitoring device was discussed; however, no recommendations for specific devices were given The determination of which devices are adequate for a particular application is an area which needs much more research and definitive guidelines. Problems concerning the application of monitors involve questions of reliability, cost, sampling probe losses and interfacing with appropriate response strategies.

One problem which became evident in the failure analyses was that although each of the systems was monitored, in no case were all of the failure modes adequately addressed in the company design. Most systems employed a single monitor, usually a pressure sensor. To address all of the failure modes, in most cases a device would be required to sense increased outlet contaminant levels, as well as a device for monitoring one of the ventilation system parameters, e.g., air flow or static pressure. At the woodworking plant (Case Study no. 2) it was demonstrated that it may not always be necessary to monitor all of the major failure modes when a non-respirable contaminant with low toxicity is involved. On the other hand, when a toxic substance such as lead is involved, it may be necessary to monitor all major failure modes by automatic means.

Response to System Failures

The provision to bypass was seen to be an important aspect of the design in the case studies, although the primary purpose for its inclusion in the

design was not always for use in the event of a failure. In Case Study no. 2, the bypass was primarily included for warm weather use; but in Case Study nos. 3 and 4, the bypass was to be used in the event that recirculation was not determined to be feasible. In Case Study no. 1, a "bypass" mode could be provided by rerouting the stacker machine's exhaust to a large fabric collector because the process could still be connected to the original collection system by means of a damper.

Although the bypass duct in Case Study no. 4 was intended for use in the event of collector failure, under the present conditions process shutdown must accompany system bypass. The bypass mode alone is unacceptable because, with the exhaust air bypassed, infiltrating dusty air causes excessive contaminant levels in the room. In such instances where process shutdown is the only acceptable failure response, the company must be willing to accept the potential for lost worktime when assessing the preliminary feasibility of recirculation.

DESIGNING A RECIRCULATION SYSTEM

Design Optimization

Chapter 7 in Reference One summarizes all of the design steps previously mentioned, and additionally presents the concept of the modeling approach for analysis of feasible system configurations. In general, it was found that the modeling approach was a very useful tool for applying the various system configurations chosen for further analysis. One possible exception to this was found in Case Study no. 2, where it was reasoned that a non-rigorous approach may have produced acceptable results due to the expected high collection efficiency, the low toxicity of wood dust, and the apparent low concentrations in the breathing zone before recirculation. Even though an in-depth analysis was not essential in this case study, knowledge of the modeling concepts still provided a better understanding of the plant situation in the feasibility assessment.

A prevalent aspect of the recirculation systems which were studied was the practice of returning the cleaned air directly to the breathing zone of the worker. In general, the evaluations of the case studies supported the recommendation that cleaned air should not be returned directly at an employee. In Case Study nos. 1, 2 and 4 the companies' decisions to return the air directly at an employee suggested that the monitoring strategy should be nearly fail-safe and that the failure response time be almost immediate. In addition to these stringent requirements, Case Study no. 2 demonstrated that space constraints within a building can be such that it becomes difficult to return the air in a manner which will not cause over-cooling of workers and reentraining of dust from the floor. In this particular case, the company attempted to alleviate these problems through the use of baffles near the outlets to direct the air flow. Overcooling of workers could also be a problem in Plant no. 4 because a temperature drop typically results when the collector is located outdoors.

Returning air directly on workers can cause problems of overheating workers as well as overcooling them, even in colder months. In Plant no. 1, a temperature increase through the collector caused by the blower compelled the company to install a cooling system to improve worker comfort.

The concept of the desired breathing zone concentration was another important idea introduced in Chapter 7. As noted previously, choosing an appropriate value for this parameter is sometimes difficult without some guidance for deciding what level is acceptable. Reference One suggests that with toxic substances, it is desirable to maintain or reduce pre-recirculation breathing zone concentrations through recirculation. This can be accomplished by specifying higher exhaust flow rates when the system is designed. This practice was followed by the company designers in Case Studies nos. 3 and 4. Another method of reducing pre-recirculation levels through recirculation was attempted in retroactive assessments in the two case studies which experienced an increase in the total ventilation rate as a result of system installation. In these cases, an attempt was made to offset the increase in the breathing zone concentration resulting from the return air stream with the increased dilutory effect of the change in the total ventilation rate. In Case Study no. 1, this exercise resulted in the require-ment of virtually unobtainable collection efficiencies because the increase in the total ventilation was too small in comparison to the increased contaminants in the return air stream. In Case Study no. 4, an acceptable collection efficiency was specified which accomplished the intended goal. In general, the offset technique is a useful design tool which should not be overlooked by the design team, especially when it is desirable not to increase the breathing zone level of toxic contaminants through recirculation.

System Failure Analysis for Feasible Configurations

The discussions in this section of Chapter 7 present a more in-depth look at failure modes and monitoring strategies. This presentation is very useful in the understanding of failures and their effects on the breathing zone. Several minor points concerning failure analysis were noted when applying the recommended approach which deserve further mention.

The discussion in Reference One concerning the necessity of monitoring, states that adequate monitoring techniques and response strategies now exist for exhaust system failures which result in reduced system air flow. Subsequently, the discussion is limited to the monitoring of air cleaner failures, not exhaust system failures. Although instrumentation for the continuous measurement of ventilation parameters such as air flow and static pressure are available, there still is a general lack of knowledge concerning the application of such systems. The ACGIH Industrial Ventilation Manual (4) does not, for example, present methodologies for the continuous measure-ment of air flows. Because such monitoring may be a necessity for systems involving toxic materials, this information should be compiled and/or developed in future research dealing with monitoring of recirculation systems.

Chapter 7 also indicates that critical response times should be determined and used for developing a monitoring strategy to assure that employees are

warned of a failure before concentrations rise to unacceptable levels in the breathing zone. As noted in three of the four case studies, the company practice of returning cleaned exhaust air directly to the breathing zone of workers indicates that, in this circumstance, the critical response time will be short enough to mandate continuous monitoring without the need to perform a formal failure analysis.

SYSTEM PERFORMANCE VALIDATION

Once recirculation is implemented, Chapter 8 recommends that the exhaust system's performance be checked by evaluating the air cleaner, surveillance system, and response strategy. The case study evaluations demonstrated the need for this important step, and provided additional considerations for performance validations.

Checking Air Cleaner Performance

The obtaining of an "efficiency gurantee" by the company designer in Case Study no. 4 resulted in the conclusion that such guarantees must not be solely relied upon, and that the air cleaner performance must be further checked after installation by in-duct measurements. It was also noted in this evaluation that the extremely low contaminant concentration expected in the collector outlet would present measurement problems when simultaneously sampling the collector inlet and outlet. With conventional stack sampling methods, during a simultaneous test in the inlet and outlet of the same duration, the outlet sample would not have sufficient weight for analysis. This problem was solved in the case study evaluation by use of a high volume extractive method in the collector outlet. The problem of conveniently extracting enough sample for a particle size test remains to be solved, however.

Designers should be warned that the respirable nature of collector exhausts may warrant determination of the levels of respirable dust in the workplace even if pre-recirculation respirable dust levels may not have been significant. As noted in Case Study no. 3, because of the expected high percentage of respirable dust in the workplace, the respirable nuisance standard became the limiting influence in the design process.

Testing the Failure Response Strategy

There were no specific tests conducted which evaluated the plant's failure response strategy in this study. Due to the constraints of field studies, the disruption of production activities had to be minimized. However, appropriate responses to failures were reported at Plants no. 1 and 2. At Plant no. 1 the process engineer reported that the pressure switch was activated following a failure of the first filter, resulting in exhaust system shutdown. The process was allowed to continue operating by "bypassing" the dust to an alternate fabric filter. In Plant no. 2 the unhooking of two bags in a fabric collector was reported to have been detected by workers soon after the system had been installed. This failure resulted in high visual levels of dust emitting from the return air outlet. The modules which contained the failed bags were put out of service until repairs were made.

Chapter 8 recommends that the air cleaner performance be checked before actual production operations begin. In all of the plants which have cleaned exhaust air returning directly to the worker's breathing zone, workers involved with pre-production testing should be outfitted with proper respiratory protection to prevent overexposures in the event that the system was not functioning properly.

The visual surveillance method in use in Plant no. 2 should also be "checked" before full implementation. A validating procedure for visual monitoring might involve sampling the air stream while creating successively larger fabric filter failures and observing the worker's ability to detect increased levels. In this case, such failures could be simulated by unhooking bags within a collector module.

Maintaining and Operating a Recirculation System

Procedures for operating and maintaining ventilation system components, monitoring equipment, and air cleaners are presented in Chapter 9 of Reference One. Recommendations are also made for conducting air sampling studies, keeping proper records, and planning failure responses.

In the retroactive assessments, no specific evaluations were made regarding the adequacy of worker training for response to failures; however, it was observed that workers generally had not been well instructed regarding the function and consequences of the recirculation system. In several of the plants, worker comments indicated they viewed the recirculation system with mistrust or misunderstanding, indicating that they had not been well informed.

This study was not of sufficient duration to make a complete assessment of the effectiveness of each company's operation and maintenance procedures. However, it was the observation of researchers that routine maintenance was not performed to the extent recommended in Chapter 8. One exception to this was noted in Case Study no. 1, where company evaluations included routine maintenance and thorough inspection of the experimental system. The company also retested the air cleaner quarterly; breathing zone concentrations were measured weekly.

In general, the maintenance level of air cleaning equipment did not appear to be at the high level required by recirculation. In Case Study no. 2, the failure of the company to detect the broken bag which was found during the evaluation indicates the general lack of the company's desire to detect failures and the insufficiency of their preventive maintenance program. In Case Study no. 3, the collector malfunctions which were noted indicate that a system must be thoroughly debugged and tested prior to full operation as a recirculation system.

APPENDIX A - MODELING OF INDUSTRIAL VENTILATED SYSTEMS WITH RECIRCULATED AIR

As noted in previous discussions, the modeling approach presented in Reference One was very useful for evaluating the feasibility of recirculation. In the process of applying the modeling approach, however, many observations were

made concerning the model parameters and assumptions of the modeling equations. These observations are made in the following sections.

Assumption of Air Balanced System

One of the assumptions of the modeling approach is that plants have an air balance both before and after recirculation, i.e., all mechanically extracted air is mechanically made up. In none of the surveys did the plants have an air balance either before or after recirculation. Because air imbalances are common within industry, the modeling equations deserve some modifications to allow their more widespread use. Since the fundamental concepts upon which the models were developed are essentially sound it is a relatively simple matter to account for air imbalances. One method of doing so was proposed in Case Study no. 2 in which the definition of the term Q_N, the natural ventilation rate, was expanded in scope. This procedure is more fully explained in the following section.

Q_N - The Natural Ventilation Rate--
This term has been defined in Reference One to account for dilution ventilation from naturally occurring sources, e.g., heat sources and wind forces. The effects of natural forces did not appear to be a significant factor in the cases studied because of the general lack of heat sources and the prevalence of closed ventilation conditions while sampling. For these reasons, dilution ventilation due to naturally occurring forces was not relied upon in the design to achieve a reduction in existing breathing zone levels. This assumption is not overly conservative because, in winter, plants will generally be closed as tightly as possible, indicating that the effect of wind forces would be negligible at that time.

None of the plants had perfect air balances in the area of interest, and two plants had substantially more exhaust than supply air prior to recirculation. Although such an imbalance is not desirable, the negative (and positive) pressures had to be considered in the retroactive assessment. Although not originally intended for that purpose, the term Q_N was re-defined to account for infiltration or exfiltration due to air pressures in the modeling equations. In addition, a new term was introduced, Q_N^O, the ventilation rate before recirculation due to pressure induced infiltration or exfiltration.

The proposed modification of Q_N enabled the designer to understand and account for the overall effect which recirculation had upon their particular situation. In Case Study no. 2, for example, recirculation had the effect of increasing the total ventilation rate, causing the negative air pressure to become positive. In Case Study no. 3, the effect of recirculation was to decrease the amount of pressure-induced infiltration because the plant had a severe negative pressure problem before and after recirculation. Because of this negative pressure, it is important to note that recirculation did not increase the total ventilation rate as it would have in a plant which started with an air balanced system.

The use of Q_N to describe only infiltration or exfiltration due to air pressures may not be suitable in plants which have significant amounts

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of ventilation due to natural forces. In these cases, an alternate means
of accounting for pressure-induced infiltration or exfiltration could be
developed by separately accounting for the infiltration or exfiltration
due to natural forces and air imbalances.

System Configurations

The system configurations presented in Reference One provide a readily
accessible means for using the modeling approach. However, it should be
more carefully explained that System Configuration no. 3, which is implied
for use with unit collectors, should not be used when there has been an
increase in the total ventilation rate. Plants which have an air imbalance
before and after recirculation (Case Study no. 3), or which desire not to
decrease the air make-up after recirculation (Case Study no. 1), should not
use this configuration even though a unit collector is utilized in the design.

Actually, the model presented in System Configuration no. 3 could have been
utilized in Case Study no. 3, but only because of an air imbalance which
existed in that plant before and after recirculation. When a plant has a
negative pressure condition before and after recirculation, the effect
of recirculation is to lessen the amount of the air make-up deficit by the
amount recirculated. As a result, this does not change the total amount
of air flowing through the plant area (total ventilation rate) as it would
in a plant which had a balanced condition prior to recirculation.

Assigning Parameter Values

Several of the most important parameters in the modeling approach have
been selected to allow comments to be made concerning the ease or difficulty
in assigning appropriate values. Generally, the discussion of model
parameters in Appendix A of Reference One provided an adequate and useful
basis for selecting appropriate values for each of the model parameters. In
a few cases the appropriateness of the parameter is discussed, but in most
cases the comments only reflect observations which were made as a result of
the study.

C_{BZ}^{D} - Desired Breathing Zone Concentration--
In the case studies, it was difficult to decide what safety margin is
acceptable. Small safety margins, especially with toxic substances, are
not desirable, although large safety margins may cause the design to be
economically unattractive (Case Studies nos. 1 and 4).

C_{BZG}^{O} - Initial Breathing Zone Concentration in General Plant Areas--
Both breathing zone and general area samples were useful in determining
workplace contaminant concentrations; however, except in one case study only
breathing zone samples were used in the modeling equations. As a conservative
measure, the highest breathing zone concentration measured was usually
assigned to C_{BZG}^{O}, especially when toxic substances were involved (Case
Studies nos. 1, 3 and 4). In Case Study no. 2 the highest general area
measurement of wood dust was assigned to C_{BZG}^{O} because there were
breathing zone measurements taken before recirculation. This difference

mattered little in the design because area and breathing zone concentrations were noted to be virtually indistinguisable after recirculation.

Many measurements were taken in Case Studies no. 1, 3, and 4 to account for variations in workplace levels of toxic substances. In contrast, few measurements were made in Case Study no. 2 because the low toxic nature of wood dust did not demand such a careful assessment.

Total dust samples were mostly taken because permissible exposure levels (PEL's) applying to nearly all of the contaminants measured were regulated by a total dust PEL. In Case Study no. 3, respirable dust sampling should also have been performed because the respirable fraction of the return air stream was high, causing the respirable nuisance dust PEL to be of more importance than the total dust PEL. In general, due to the respirable nature of many collector outlet streams, the respirable nuisance dust's PEL may be the most restrictive in many cases.

C_E^O - Initial Concentration of Local Exhaust Streams--
A conservative estimate of this parameter was typically made by assigning it the highest of three concentrations measured in the inlet duct.

In Case Study nos. 1, 3 and 4 the time period of each sampling run closely represented a full-shift operation. Care was taken during sampling to only measure inlet concentrations when the process was fully operational, thus break-times, lunch hour and process disruptions were excluded from the sampling period. This provided a good basis for comparing before and after measurements, but this practice slightly overestimates the actual 8-hour time-weighted average breathing zone concentration and thus provides a conservative element to the design.

C_{MU} - The Concentration of Contaminants in Make-Up Air--
This parameter is most important when contaminants are present in the external air in significant concentrations. The importance is further increased when toxic substances are involved, and thus deserves assessment in the cases. As noted in Case Study no. 1 the presence of lead was checked by sampling at the air inlet to the air make-up unit because it had a large potential for affecting the model analysis.

In many other plant situations, on a case-by-case basis this parameter may be only briefly checked or assumed to be zero when sufficient information is known about the process and surrounding plant area. As noted in Case Study no. 2, the concentration of wood dust in the make-up air was not measured because of the large margin between room concentrations and the PEL for wood dust, and because the area surrounding the air make-up intake was visually free from external contamination.

k_R - Concentration Factor of Return Air to Local Exhaust Systems--
In designs involving air cleaners with high collection efficiencies, the effect of this parameter is negligible (when C_{MU} is 0). In all the case studies, the estimate of this parameter had little bearing on the design and did not affect the outcome of the design approach.

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k_{BZ} - Contribution Factor of Return Air to Breathing Zones--
This parameter usually had a significant effect on the design and thus its determination is very important. The introduction of k_R and k_{BZ} is a significant improvement over the previously used "mixing factor" because the terms represent physically understandable quantities which may be estimated, and in some cases, may be measured with a tracer gas study. A tracer gas study was able to be conducted in the case studies because the attendent ductwork was available to disperse the injected gas into the workplace with the recirculated air. However, this techinque would not have been useful to the design team during the feasibility assessment because the necessary ductwork has not usually been installed at that time. A tracer gas study is more useful with staged or pilot operation approaches, or in a final validation evaluation of the installed system.

A conservative estimate of 1.0 for k_{BZ} is easily justified when workers are located near the return air plenum. This was the case in Case Study nos. 1, 2 and 4. Since the cleaned air was not returned directly at an employee in Case Study no. 3, the tracer gas study was able to provide a good estimate for k_{BZ}. It is interesting to note that the measured value, 0.20, was very close to a value which was estimated by assuming the return air ideally mixed with infiltrating air, 0.21. This suggests that estimating procedures may, in some cases, produce results as accurate as tracer gas measurements. Additionally, since a conservative estimate for k_{BZ} is more desirable in the design process, the use of an accurate measurement technique, even if it were widely applicable, is not really a necessity in most cases.

One additional drawback to tracer gas studies is that the test requires the use of special equipment to dispense and measure the gas. Unless a company already had such equipment, the company would have to purchase the equipment (or rent it, if possible) to perform the study. The equipment used in this study cost about $6000 in 1976.

Estimating Design Parameters for New Facilities

In several of the case studies, the companies dealt with the problems of estimating parameters in new facilities in a manner which closely parallels the suggestions made in Reference One concerning new plant facilities (p. 125). In Case Study no. 1, for example, the company chose to utilize an experimental pilot scale system to provide data for a new plant installation. Also, in Case Study no. 3, the design procedure chosen by the company is similar to the suggestion for staged installation in Reference One. The company evaluated the effects of recirculating the first collector's exhaust before proceeding with the remaining installations in this case.

Failure Analysis

When the analysis of system failures was applied in Case Study no. 3, several observations were made concerning Appendix F in Reference One, "Transients in Recirculation Systems". These are summarized below:

1. The equation on the top of page 181 is incorrectly derived. The correct equation should be:

$$T_{C1} = t_o \ln \left[\frac{C_{BZ}^{FS} - C_{BZ}}{C_{BZ}^{FS} - C_{ceiling}} \right]$$

2. A simplification for the second equation on page 181 is given, but no method is given for calculating T_{C2} when $t > 8$ hours.

3. It would be beneficial to have expressions for C_{BZ}^{FS} derived for the various model parameters. This would eliminate the need for the reader to derive the expression, and thus ensure that the concept is correctly applied.

4. The example presented on pages 183 - 184 is somewhat confusing, as evidenced by the following observations:

    a. Apparently there is a typographical error for the value given to C_E. The correct value is 5000 ppm.

    b. The names given for the variables are inconsistent with the previously derived expression. For example,

    C_c should be $C_{ceiling}$

    $C_{BZ}(o)$ should be C_{BZ}

    C_E should be C_R^F

    c. The substitutions into both equations do not follow the method presented on page 181.

    d. Although the title of the example on page 183 mentions k_R, there is no further use of it in the section.

    It is suggested that the example be clarified in future editions of the publication.

FUTURE RESEARCH AND DEVELOPMENT

Although the fundamental principles and design guidelines concerning recirculation have been and are being investigated, there still exists a rather large gap between theory and practice. Many questions concerning the proper application of air cleaning technology need to be resolved. The correct selection of a monitoring strategy which will ensure a system's continued safe operation is still an area of considerable uncertainty. Research is particularly needed to demonstrate the proper application of particulate monitoring devices to ensure that they will be effective and reliable once installed. Procedures for sampling and evaluating recirculation systems also need to be more thoroughly explored.

State of the Art Applied Technology Document

There is a present need to draw together important information relating to the selection, design, construction, operation, maintenance and testing of recirculation systems into a "hands-on" field manual (or manuals) for use by designers and users of recirculation systems. Existing technical information (including the Reference One report) on the subject of recirculation has been mostly research reports directed principally toward the occupational health professional. The unique contribution of the proposed manual is that it would be specifically intended for field use, and would then be written for all individuals who are involved with the design, construction, and evaluation of recirculation systems: plant engineers, sheet metal contractors, safety directors, maintenance supervisors, health professionals, OSHA inspectors, etc. A practical, field-oriented manual or manuals could serve the present need and, if periodically updated, could incorporate new findings of research, development, and case studies into a readily usuable source of information.

It is envisioned that a state-of-the-art manual would have the following general organization:

1. Air Cleaning Equipment
   Air cleaning techniques should be described for the major available devices. Each class of collector, e.g., fabric collector, wet scrubber, electrostatic precipitator, should be subdivided to identify and discuss the unique advantages and disadvantages which various configurations of the equipment present, e.g., pulse jet versus shaker baghouses, primary filters followed by afterfilters, etc.

2. Monitoring Schemes
   For each general class of air cleaning equipment, major failure modes could be identified and response strategies established for varying degrees of contaminant toxicity. Profiles should be presented of the available monitors and their operating characteristics, limits of detectability, and reliability (where known). Because monitors are purchased as specific components and not measurement systems suitable for installation into recirculation systems, guidelines for system installation should be presented, including design of probes and interfacing with warning, automatic shutdown, and/or recording systems.

3. System Design
   This section should supplement the Reference One approach and the Industrial Ventilation Manual of ACGIH by presenting methods and equipment for redistribution of cleaned system effluent and techniques for partial or total bypass and fresh or tempered air mixing. Methods to perform an economic assessment should be outlined including updated cost factors for capital expenditures for equipment, construction, operational and maintenance costs. Methods of calculating energy paybacks should be specified.

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4. Sampling Methodology
    This section should discuss in detail the methods for determining
    a suitable sampling train for contaminants present in varying
    concentrations and the technique for gathering the samples.
    Special discussions should be presented for low concentration
    outlet sampling, particle sizing and tracer gas studies.

5. Operation and Maintenance Procedures
    This section should provide procedures to assure the continual
    effective performance of specific recirculation system components.
    Fail-safe and/or warning techniques should be detailed, as well as
    stocking of replacement components and methods for testing the
    integrity and operational variables of pollutant removal devices
    and monitors.

CONCLUSIONS

The objective of this report was to investigate the applicability of
Reference One by applying the recommended methodology in case studies
involving actual plant installations. Since the major findings of the
recommended approach are summarized in a separate conclusions and recommenda-
tions section (on pages 68-70 of that report), the conclusions of the
validation studies are presented in a manner which address each conclusion
in the Reference One report. In addition, many of the case studies'
conclusions which pertain to the modeling approach are presented in a
separate section which follows.

PERTAINING TO THE CONCLUSIONS OF REFERENCE ONE

1. The preliminary evaluation criteria provided a useful method for
    pre-screening the major factors likely to affect the success of the
    design, although in several case studies the concepts of legal issues,
    energy consumption, and ventilation system design were expanded. In
    addition, the consideration of odorous emissions was proposed to
    be added to the initial assessment.

2. The Reference One suggestion that existing ventilation controls be
    improved before undertaking recirculation system design was reinforced
    by the case study evaluations. Because several of the plants under-
    took recirculation system design concurrently with ventilation
    improvements, the modeling approach could not be directly applied.
    When plants do not optimize before recirculation, or attempt to
    recirculate while making other ventilation changes, the direct
    application of the recommended design approach is often complicated.

3. The Reference One recommendation that contaminant concentrations
    must be identified prior to recirculation was supported by several
    case studies in which the lack of breathing zone measurements or
    in-stack measurements, or the use of inaccurate measurements and
    poor estimates of in-stack measurements, would have complicated the
    specification of an adequate collection efficiency. In one case
    study, the lack of such measurements did not produce barriers to
    recirculation, chiefly because the contaminant was not toxic, the
    collection efficiency was high, and the in-plant concentrations were
    apparently well-controlled prior to recirculation.

4. This study reinforced the recommendation that contaminants designated
    as human carcinogens not be recirculated. Designers of recirculation
    systems should also be aware of the potential for the scrubbing fluid

to contain harmful, and perhaps carcinogenic substances. In addition, when carcinogenic substances are present in the process, the designer should attempt to substitute safe compounds when they are available.

5. Although a qualified health professional should establish acceptable workplace levels, in practice it is sometimes difficult to establish what "safe" level is best in the design. The establishment of the safety margin will often be a tradeoff between what is desired and what is feasible. Furthermore, with substances which have very low regulated standards, the need to set a safe level may present serious barriers to recirculation.

6. The recommendation that the interaction of exhaust air volumes with airflow patterns be determined is simplified by defining convenient boundaries for areas which are well isolated from a ventilation standpoint.

7. The case study evaluations emphasized the recommendation that variations in breathing zone and emission levels due to temporal, seasonal, and process-related considerations be determined.

8. The evaluation of an air cleaner's reliability, efficiency, and its impact on the return air stream which was suggested by Reference One was a necessary part of the case study evaluation. The case studies showed that air cleaner characteristics such as the filter life of HEPA filters are an important concern during the design evaluation, and that air cleaners can adversely affect the quality of the air by introducing odors and harmful contaminants when a scrubbing fluid other than water is used in a wet scrubber.

9. The use of two HEPA filters in series in one case study emphasized that redundant air cleaners can help achieve a higher overall cleaning efficiency and that they may additionally provide a means for detecting failures of the first filter.

10. The application of the modeling approach in several case studies utilized the suggestion that various options of combining air flows may be evaluated in the formulation of the final design concept.

11. The suggestion that recirculation may provide an economical means to reduce existing breathing zone levels by increasing air volumes was well supported in two case studies in which the company designers purposely increased the collector flow rate while recirculating. An alternate method of reducing or maintaining pre-recirculation breathing zone concentrations was also introduced in two case studies which experienced a change in the total ventilation rate. This procedure involves offsetting the increase in contaminants from the return air stream with the dilutory effect of the increase in the total ventilation rate.

12. The case studies emphasized that the rigorous design and modeling approach presented in Reference One is very useful for determining the feasibility of recirculation. In some cases, however, a non-rigorous approach may produce equally acceptable results.

13. The thorough analysis of all possible system failures modes in the case studies supported the recommendation that all major failure modes must be identified in the feasibility assessment.

14. This study emphasized the need for adequate detection of system failures, and expanded on the evaluation of air cleaner failure modes and effects. An understanding of the interrelationship between monitoring and the various failure modes, e.g., reduced air flow and air cleaner efficiency failures is necessary when selecting failure response strategies which address all of the major failure modes, especially when toxic substances are involved. It may not always be necessary to monitor all of the major failure modes when a non-respirable contaminant with low toxicity is involved.

15. The recommendation that a system bypass be used in the event of a failure was a design aspect which helped assure that contaminated exhaust air was not recirculated following a collector failure in one case study. The use of a bypass also had the benefit of allowing air to be exhausted outdoors in warmer months.

16. The case studies supported the recommendation that cleaned air should not be returned directly at an employee. In three of the four case studies, the direct return of return air to the worker's breathing zone placed severe requirements on the monitoring strategy, and left virtually no margin of safety in the event of a system failure.

17. The adequacy of the response to failures and worker training noted in this study emphasized the need to implement a well-planned failure response strategy. In instances where process shutdown is the only acceptable failure response, the company must be willing to accept the potential for lost worktime during a shutdown when assessing the preliminary feasibility of recirculation. Furthermore, it was observed during the case studies that workers had not been well instructed nor well informed about the function and consequences of recirculation.

18. An analysis of post-failure breathing zone levels is a useful means of determining appropriate response times to failures. However, the methods presented in Reference One should be clarified for easier use.

19. The system validation step involving the measurement of contaminant levels in the collector exhaust should be conducted with proper respiratory protection when the recirculated air is returned directly to the worker and there is no means to bypass the collectors exhaust.

20. The frequent collector malfunctions and the lack of new system
    debugging which were observed in the surveys emphasized the urgent
    need for adequate preventative maintenance in recirculation systems.

Note: There were no conclusions specifically made with respect to
    conclusions no. 19 and 22 of Reference One since the issue of
    trigger levels and ventilation system changes was not discussed
    in the case studies. Therefore, conclusion nos. 19 and 20 in
    this report refers to the Reference One conclusion nos. 20 and 21,
    respectively.

PERTAINING TO THE RECOMMENDED MODELING APPROACH

The following conclusions pertain to various aspects of the modeling approach.

1. The possibility of the respirable dust standard being restrictive should
    be emphasized when recirculation systems are evaluated because air
    cleaners are generally less effective at removing respirable-sized
    particles.

2. A more widely applicable method for assessing the contribution factor
    of return air to breathing zones, k_{BZ}, is desired because this parameter
    usually had a significant influence on the design. A tracer gas
    analysis is capable of measuring k_{BZ}; however, this technique can only
    be performed when the air cleaner (or fan) and return air ductwork
    are already in place.

3. Although Reference One recommends that an air balance be achieved prior
    to recirculation, in many cases recirculation is considered as a means
    of reducing negative air pressure. The retroactive assessment in
    several case studies found that it was sometimes necessary to modify
    the modeling equations to account for infiltration and exfiltration due
    to air imbalances.

4. It should be noted that system configuration no. 3 (in Reference One)
    is not applicable when there has been an increase in the total ventila-
    tion rate, even though unit collectors may be involved.

FUTURE RESEARCH AND DEVELOPMENT

1. Although the fundamental principles and design guidelines concerning
    recirculation have been and are being investigated, there still
    exists a rather large gap between theory and practice.

2. There is a present need to draw together important information relating
    to the selection, design, construction, operation, maintenance, and
    testing of recirculation systems into a "hands-on" field manual for use
    by designers and users of recirculation systems.

RECOMMENDATIONS

1. It is recommended that the approach to recirculation of exhaust air presented in Reference One be used for determining the feasibility of recirculation and for establishing recirculation system design and operational parameters.

2. Reference One should be supplemented by a manual which addresses the specifics of recirculation system design including:

   a. Description, availability and effectiveness of recirculation system equipment components, especially air cleaners and monitors.

   b. Identification of failure modes and the establishment of specific response strategies for various system configurations and degrees of contaminant toxicity.

3. Some methodology should be devised for determining safety factors to be used for establishing acceptable breathing zone concentrations after recirculation, especially in the case of toxic substances. These safety factors would allow a contaminant level to be established far enough below the allowable limit to account for unforseen circumstances and misjudgments in the design, as well as to provide added safeguard in the failure response strategy.

4. The treatment of failure modes in Reference One should be amended to include a more thorough discussion of failures which result in reduced air flow and the identification of the interrelationship between the various failure modes and operational parameters. This added information would provide a more thorough and useful basis for selecting a response strategy.

5. It should be emphasized that recirculated exhaust air streams are likely to contain a high percentage of respirable dust because available air cleaners are much more efficient at removing large particles than small.

6. Because the contribution factor of return air to local exhaust systems, k_{BZ}, has a significant influence on the design, efforts should be directed to develop a more widely applicable means of accurately estimating this parameter in cases where a tracer gas analysis is not applicable.

7. Because many plants use recirculation as a method to reduce the imbalance between supply and exhaust air, some modification to the modeling approach should be considered to permit consideration of infiltration and exfiltration due to such factors.

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CASE STUDY NO. 1
EVALUATION OF A LEAD BATTERY ASSEMBLY OPERATION
NOVEMBER 1977

CONTENTS

FIGURES

TABLES

INTRODUCTION

An evaluation was made of a prototype recirculation system which had recently been installed at a lead-acid battery manufacturing plant. The collected and cleaned effluent from an exhaust hood on a lead plate stacking machine was being recirculated directly back to the area of the machine operator (Figure 1-1). A unit collector which removed lead dust from the exhaust was located immediately adjacent to the operation.

This particular operation was chosen by the company to demonstrate the recirculation potential of the unit collector because it generated greater lead levels than any other operation which was being considered as a candidate for recirculation. Thus, the company's tests represented "worst case" conditions for the collector, providing a good indication to plant personnel of the applicability of the collector to other plant operations.

PLANT DESCRIPTION

The lead plate stacking machine was located amid other attendant process operations in a large room at the center of the plant (Figure 1-2). The lead plates processed in the stacker were manufactured in a remote area of the plant by covering metal grids with a lead oxide paste, then allowing them to dry. After manufacture, the lead plates were transported to the cases at an adjacent operation called a universal burner.

Besides the processing of lead-coated grid plates, several other process operations were located in the same general area. Nearby were assembly areas and lead melting pots. In a distant corner was a maintenance welding booth.

PROCESS DESCRIPTION

At the stacker work station, the operator removed lead battery plates from one of several skids and manually aligned the plates, first on one tamping stand, and then on another. Whenever a defective plate was found, he discarded it into a nearby ventilated scrap barrel. When the plates were fully aligned, he inserted stacks of plates into the stacker machine which interlaced them with plastic separators and automatically discharged them on a conveyor for transport to the universal burner.

The operator had other duties which required him to move throughout the room, but about 70% of his time was spent at the work station. After the machine was fully loaded with plates and separators, it functioned automatically while the operator retrieved skids filled with lead plates or opened boxes of plastic separators. At the end of the workshift, the operator spent some time cleaning the production equipment with an industrial vacuum cleaner. He also cleaned the surrounding floor area using a sweeping compound and a broom.

1-2
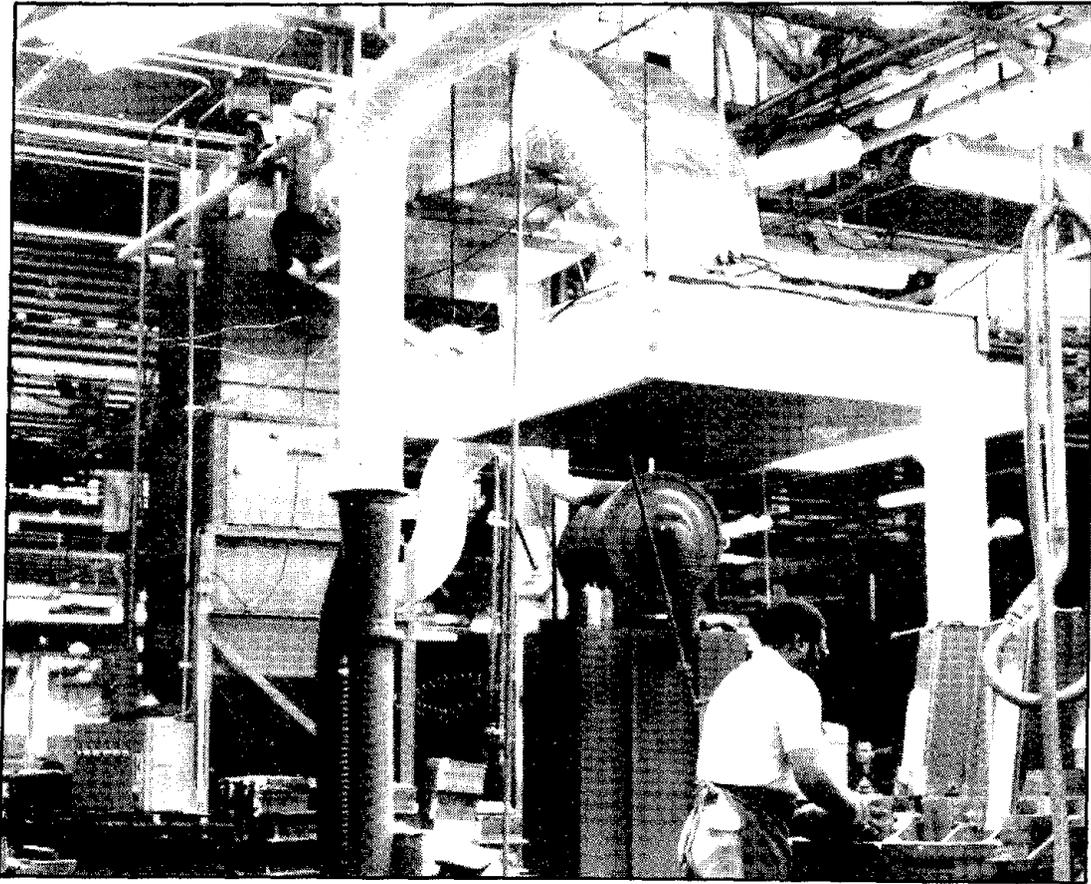
Figure 1-1. View of worker station and collection system.
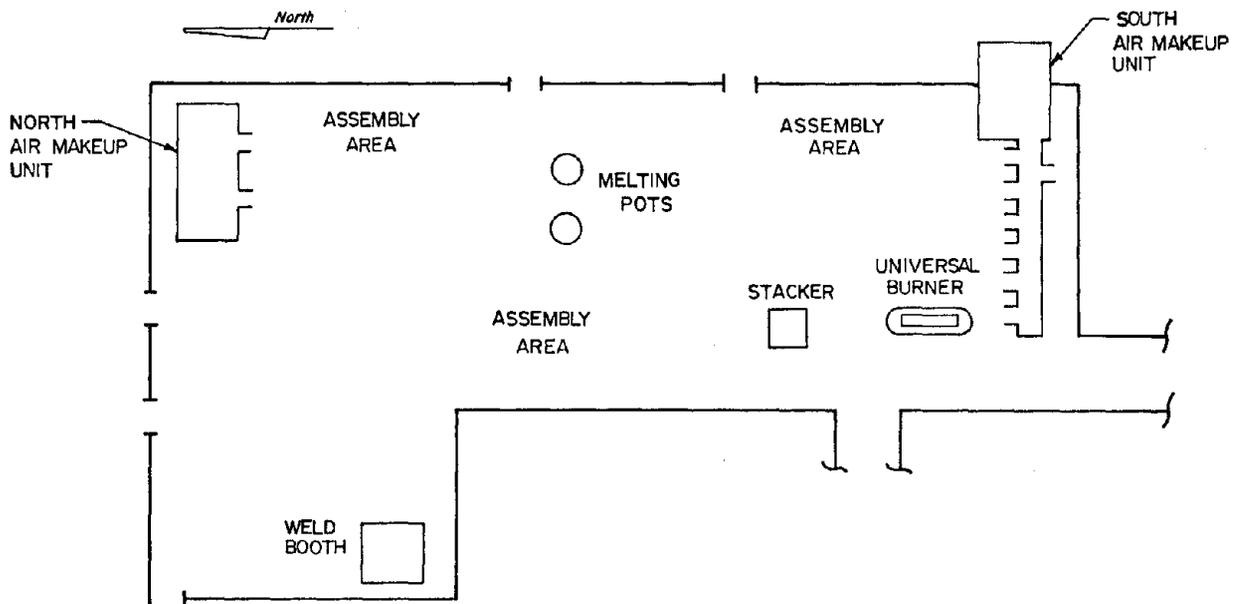
Figure 1-2. Plant layout.

VENTILATION SYSTEM

Exhaust System

Lead oxide dust generated at one tamping stand and from the operation of
the stacker machine was exhausted to the experimental dust collection system.
The specifications and characteristics of the collection system are summarized
in Table 1-1. Most of the other processes and assembly operations in the
room were exhausted to a large fabric filter collection system. The
exhaust volumes of the processes in the room are summarized in Table 1-2.

Table 1-1. Collector specifications and characteristics.

Capacity:	56.6 m^3/min (2,000 cfm)
Filter media:	Self-cleaning HEPA primary filter. Sealed-in HEPA secondary filter.
Air to media ratio:	5.7:1
Fan motor:	7.46 KW (10 hp), New York Blower GI-15
Fan rpm:	3277
Static pressure:	40.6 cm W.G. (16 in. W.G.) - design 25.4 cm W.G. (10 in W.G.) - actual
Total height:	3.8 m (12 ft - 4.5 in.)
Total width:	1.0 m (3 ft - 2.5 in.)
Total length:	1.0 m (3 ft - 2.5 in.)
Shaker mechanism motor:	0.25 KW (1/3 hp)
Power:	440 V, 3 phase, 60 cycles
Cost (1976):	Basic unit with blower and hopper $4,080 Extra capacity blower - add 625 TOTAL ... $4,705
Replacement filter cost:	$275
Cleaning cycle:	Automatic or manually operated shaking mechanism. In manual mode, shaker is operated during worker breaks, at lunch time, and between shifts.

Recirculation System

Cleaned air from the stacker dust collector was returned to the work station
through a return air plenum located above the work station (Figure 1-1).
The collector's operational flow rate of 40 m^3/min (1400 cfm) was lower
than the design flow rate for the dust collection system of 57 m^3/min
(2000 cfm) because the company dampered the flow back to attain the same
flow rate at which the machine was previously exhausted.

Table 1-2. Exhaust and air make-up supply rates.

Description	Air volumes	
	m^3/min	cfm
Local exhausts		
Assembly processes	595	21,000
Two melting pots	113	4,000
General exhausts		
Weld booth	142	5,000
Universal burner	99	3,500
Recirculated exhaust		
Stacker	40	1,400
Air make-up supply		
South unit	991	35,000
North unit	85	3,000
Air flow rate balance		
Local exhaust	708	25,000
General exhaust	241	8,500
Total exhaust	949	33,500
Total make-up air supply	1,076	38,000

The dust collection system for the stacking operation consisted of two
high efficiency particulate aerosol (HEPA)* filters installed in series.
The first HEPA filter was treated with a release agent so that dust could
be periodically removed by activating a shaking mechanism. The cleaning
cycle lasted a few minutes and was performed by manual (or timer controlled)
activation of the control mechanism four times a day, during work breaks.
The second filter (not recleanable) helped assure a high overall cleaning
efficiency but primarily acted as a warning system in the event the first
filter failed, i.e., developed a leak. Following a primary filter failure,
the system was designed to respond to increased pressure resulting from
rapid loading of the second filter. This increased pressure would activate
a pressure-sensing device, causing an alarm to sound and the exhaust system
to shut down.

Air Make-Up

Good general ventilation was achieved by two air make-up units located at
opposite ends of the room (Figure 1-2). As Table 1-2 shows, more air
was supplied than exhausted, indicating that the room was under positive
pressure. This is especially true for the south end of the room in the

---

*HEPA filters, according to the manufacturer, are filters rated at 99.99%
 efficiency for particles greater than 0.3 micrometers in the DOP (dioctyl
 phthalate) aerosol test.

vicinity of the recirculation system because of the close proximity of the large south air make-up unit.

METHODS

In-Duct Sampling

Particulate measurements were made in the inlet and outlet duct according to the EPA Method 5 procedure which is fully described in the Methods section of this report.

In-Plant Sampling

Workplace and breathing zone air samples were made according to the general procedures outlined in the Methods section of this report. Measurements made by the industrial hygiene staff of the manufacturing facility also were obtained to document the variability of the workplace lead concentrations from week to week and to provide concentration measurements prior to recirculation for comparison purposes.

Total dust was not measured during the evaluation. From previous plant experience, it was known that the emissions from the stacker operation consisted almost entirely of lead. Because of this, and also because the allowable exposure limit for lead was many times lower than the limit for total dust, lead was used as the indicator of recirculation system performance.

In addition to the personal and workplace samples, a measurement of lead concentration was made at the inlet to the air make-up unit using a Gast vacuum pump and a filter cassette containing a 37-mm Millipore type BD membrane filter with a pore size of 0.6 micrometers. The pump was operated at a flow rate of 12 l/min.

Tracer Gas Study

A study was performed using a tracer gas to estimate two model parameters, k_R and k_{BZ}. A detailed description of the general procedure and set is discussed in the Methods section of this report.

The specific procedures for conducting tracer gas (SF_6) concentrations in this plant involved injecting the gas into the inlet to the collector, then measuring gas concentrations around the work station in the general vicinity of the breathing zone. The gas was injected from a commercial cylinder through a length of teflon tubing. The flow was regulated by a pressure valve. The measurements were made with a MIRAN model IA infrared gas analyzer set at the appropriate wavelength for the tracer gas. The instrument was set on a platform in the work area, while a sample was withdrawn through a long flexible teflon hose in various room locations. The MIRAN analyzer was connected to a strip chart recorder to obtain a continuous record of the gas measurements.

RESULTS OF SAMPLING PROGRAM

In-Duct Measurements

Particulate Measurements--
Source sampling was conducted in the inlet and outlet ducts of the stacker
machine dust collector to characterize the performance of the collector
and to determine particulate contaminant concentrations. It was found
that the collector operated at an average lead removal efficiency of 99.96%.
The average return air concentration of lead from three sampling runs was
0.032 mg/m^3. The concentrations and mass emission rates of lead and lead
oxide in the inlet and outlet ducts are summarized in Table 1-3. A complete
summary of the raw sampling data can be found in Table 1-4.

Variations in the dust loadings found in the inlet and outlet of the
collector can be attributed to variations in contaminant generation rates,
as well as to possible experimental errors. The intermittent nature of
the machine's contaminant generation rate is further emphasized by comparing
lead concentrations measured during differing time intervals. For example,
1-hour particulate test in the dust collector inlet resulted in an average
mass rate of 3.4 gm/min of lead, whereas a 10-minute particle sizing test
resulted in a 6.0 gm/min mass rate of lead. A statistical treatment of
random errors indicated that variation in the particulate measurements
could be attributed to experimental errors in analyzing lead samples and
measuring flow volumes. This sampling error was more pronounced when the
sample weight was low, i.e., in the collector outlet, which could explain
the larger standard deviation of outlet concentration measurements.

Particle Sizing--
According to process information supplied by the company, dust from the
lead oxide paste was comprised of particles as small as 0.9 micrometers.
An in-stack particle size analysis in the collected inlet revealed that
the majority of the dust produced from the stacker operation was above the
submicron range. These measurements indicated that 98.4% of the dust was
greater than 6.1 micrometers.

Several attempts were made to determine the efficiency of the collector in
removing particles under 6 micrometers in size. However, the time necessary
to obtain sufficient sample in these low size ranges was prohibitive because
of the low percentage of particles in the size range below 6 micrometers.

In-Plant Measurements

Breathing Zone Measurements--
A comparison of the average breathing zone concentrations throughout the
entire workshift (with the exclusion of lunch and breaktime) showed that
the lead exposure levels from the stacking operation rose slightly after
recirculation. A summary of breathing zone measurements taken both before
and after installation of the recirculation system are presented in Table 1-4.
Although some of the difference between the average measurements can be

Table 1-3. Results of in-duct measurements for lead.

Run number	Location	Lead concentration, mg/m^3
1	Inlet	79.43
2	Inlet	79.03
3	Inlet	102.96
Average		87.14
Std. dev.		13.70
1	Outlet	0.037
2	Outlet	0.012
3	Outlet	0.049
Average		0.032
Std. dev.		0.019

Table 1-4. Summary of in-duct sampling data.

Location	Run	SP (avg), in. H$_2$O	$\sqrt{VP}$ (avg), in. H$_2$O	ΔH (avg), in. H$_2$O	V$_m$, ft^3	Lead on filter, mg	Lead in backwash, mg	Total sample weight of Pb, mg	T$_s$, °C	Concentration, mg/m^3
Outlet	2	1.04	0.214	1.31	36.26	0.015	0.025	0.040	23	0.037
Outlet	3	0.91	0.521	2.94	53.22	0.007	0.013	0.020	22	0.012
Outlet	4	0.98	0.176	2.18	46.38	0.028	0.038	0.066	22	0.049
Inlet	5	5.18	1.135	1.78	42.04	20.0	74.6	94.6	23	79.43
Inlet	6	6.32	1.109	1.58	39.03	15.9	71.4	87.3	23	79.03
Inlet	7	6.22	1.069	1.47	38.90	15.0	89.2	104.2	23	102.96
Blank						0.002				

attributed to experimental sampling errors, an analysis of all experimental errors and a statistical comparison of means showed that the difference between before and after measurements was significant at the 95% confidence level, but was not significant at the 90% level.

Because the cleanup operation during 15-30 minutes of the workshift resulted in dust exposure from a source unrelated to the stacker exhaust hood and recirculation system, measurements made after installation of the recirculation system were taken during periods which both included and excluded the cleanup operation. The results of these measurements showed the effect of the cleanup operation in adding to worker exposure (Table 1-5).

Table 1-5. Summary of breathing zone measurements.

	"Before recirculation"			
	Including end-of-shift cleanup		Excluding end-of-shift cleanup	
Date sampled	Sample time, hours	Concentration, mg/m^3	Sample time, hours	Concentration, mg/m^3
1/25/77	7.42	0.052*		
2/22/77	7.33	0.064*	No measurements were made	
3/26/77	6.66	0.039*	which excluded end-of-shift	
4/18/77	7.25	0.036*	cleanup period prior to	
5/20/77	7.08	0.041*	recirculation	
6/22/77	6.66	0.046*		
Average		0.046		
Standard deviation		0.010		
	"After recirculation"			
9/13/77	5.23	0.062*		
9/15/77	6.83	0.081*	6.47	0.073*
9/27/77	6.75	0.089*	6.35	0.089*
10/4/77	6.93	0.065*	6.66	0.045*
10/21/77	6.86	0.054*	6.66	0.035*
11/1/77		**	6.50	0.010
11/3/77		**	3.67	0.027
11/10/77	6.67	0.047	6.46	0.045
Average		0.066		0.046
Standard deviation		0.016	0.016	0.025

* Company measurements
** Sample result invalidated due to process interference

General Area Measurements—
Measurements made in the surrounding plant area before and after recircula-
tion are summarized in Table 1-6. With the recirculation system operating,
eight 15-minute samples were made throughout the area by the company on
four separate days. Full shift samples were also made by the study team on
three separate days. The locations of all general area samples are shown
in Figure 1-3.

Workplace (area) lead concentration measurements taken before and after the
system was installed did not show an appreciable change as a result of
recirculation. Company measurements consisting of eight 15-minute high
volume [0.99 m^3/min (1.69 cfm)] air samples showed a slight increase after
recirculation, but this small change is not statistically significant
because the change is not discernable from systematic errors due to sampling.

The fact that the recirculation system was not significantly contaminating
either the breathing zone of the stacker machine operator or the adjacent
plant area was shown by the low reading below the outlet plenum (location A3).
Ventilation measurements, taken to identify the mode of dispersion of
particles, showed that the area was subjected to a prevailing northerly flow
pattern (Figure 1-4), primarily due to the air makeup unit on the south
end of the room (Figure 1-1). Because of this prevailing air pattern, the
location of sampling points established by the plant before recirculation,
and later resampled by the study team after recirculation, should have
included more downwind samples.

Tracer Gas Study

A tracer gas study was performed to quantitatively assess two model parameters,
k_R and k_{BZ}. The parameter, k_R, is a value between zero and one which
indicates the volume fraction of air entering a local exhaust hood which
originated in the return air stream. The parameter, k_{BZ}, also between
zero and one, indicates the volume fraction of air in the breathing zone
which originated in the return air stream. The injection points, sampling
locations, measurement procedure and results of this evaluation are
summarized in Figure 1-5.

On the basis of the tracer gas study, a value of 0.11 was assigned for the
parameter, k_R, because the concentration in the duct leading back to the
collector was 11% of the value read in the overhead exhaust plenum. The
parameter, k_{BZ}, was assigned a value of 0.89 because the peak tracer gas
reading in the breathing zone of the worker below the return air plenum was
89% of the value in the return duct.

Use of a peak reading for assigning a value to k_{BZ} is somewhat conservative
because the worker moves around under the return air plenum and thus is
probably exposed to more of an average concentration. Hence, an average
reading of 0.39 would be more accurate though less conservative for k_{BZ}.
Noting that the worker spends much less of his time toward the "upwind" side
of the plenum, it may be appropriate to average the three non-zero tracer
gas measurements, resulting in an average value of 0.56 for k_{BZ}.

Table 1-6. Summary of workplace measurements.

—————— Short duration company measurements - before and after recirculation ——————

Location description	Plot plan location*	Sample time, hours	Sample volume, m³	Concentration before recirculation, mg/m³			Concentration after recirculation, mg/m³		
				4/4	4/20	Avg.	5/5	9/7	Avg.
NW of stacker	B1	0.25	0.73	0.011	0.029	0.020	0.007	0.029	0.018
N of stacker	B2	0.25	0.73	0.018	0.033	0.026	0.110	0.055	0.083
Center of stacker	B3	0.25	0.73	0.019	0.023	0.021	0.081	0.029	0.055
W of stacker	B4	0.25	0.73	0.011	0.019	0.015	0.007	0.026	0.017
W of stacker	B5	0.25	0.73	0.014	0.015	0.010	0.007	0.053	0.030
W of conveyor	B6	0.25	0.73	0.021	0.019	0.020	0.011	0.036	0.024
E of stacker	B7	0.25	0.73	0.049	0.075	0.062	0.021	0.027	0.024
S of stacker	B8	0.25	0.73	0.032	0.036	0.034	0.014	0.011	0.013
Average				0.021	0.031	0.026	0.032	0.029	0.033

—————— Full shift samples after recirculation ——————

Location description	Plot plan location*	Sample time, hours	Sample volume, m³	After recirculation		
				9/7	11/1	11/3
S of work station	A1	7.70	0.924	0.019	0.002	0.002
S of conveyor	A2	7.68	0.922	0.024		
1 m below return plenum	A3	7.70	0.924	0.015		
On stacker	A4	7.73	0.928	0.033	0.004	
E of stacker	A5	7.68	0.922	0.027		
On beam NE of worker	A6	7.68	0.922	0.026		
On collector support	A7	7.70	0.926	0.015		
Average				0.023	0.003	0.002

* Sample locations are shown on Figure 1-3.
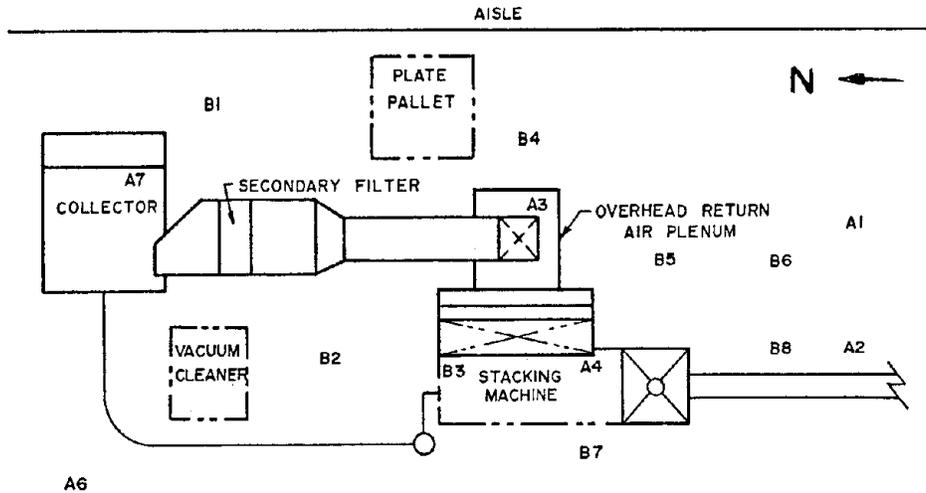
Figure 1-3. Area sampling locations.
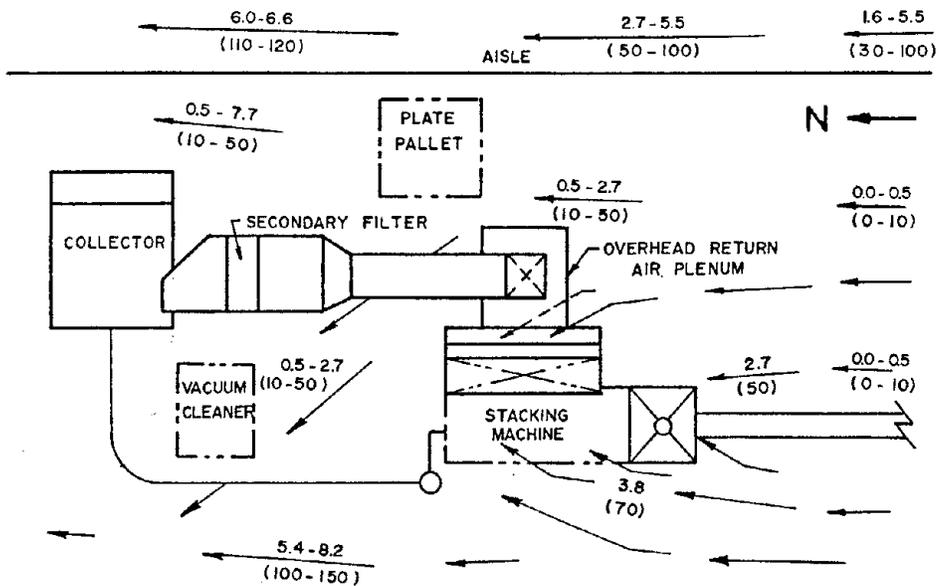
Figure 1-4. Air velocity patterns, m/sec (ft/min).

PLATE
PALLET

D (IN PLENUM)

COLLECTOR

SECONDARY FILTER

OVERHEAD RETURN
AIR PLENUM

VACUUM
CLEANER

STACKING
MACHINE

C B

A

INJECTION POINTS AND SAMPLING LOCATIONS.
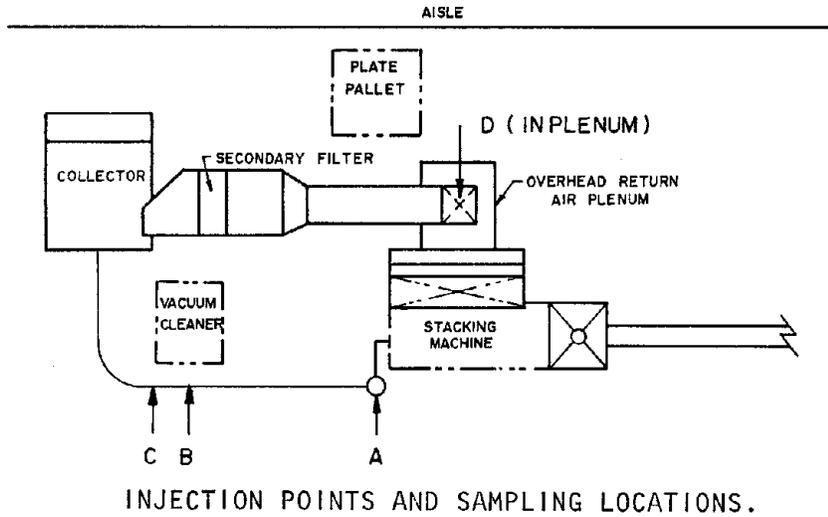
TOP VIEW
OF DISCHARGE
PLENUM

O4   2O

O5

O3   1O

$\overline{k_{BZ}}$
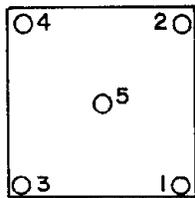
$\underline{\text{Measurement Procedure}}$

$\overline{k_R}$

1. Inject at pt. A.
2. Measure at pt. B.
3. Measure breathing
    zone concentration.

1. Inject at pt. C.
2. Measure at pt. D.
3. Measure at pt. B.

SIDE VIEW
OF DISCHARGE
PLENUM
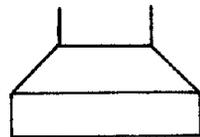
MEASUREMENTS
MADE AT
BREATHING ZONE

STACKER MACHINE
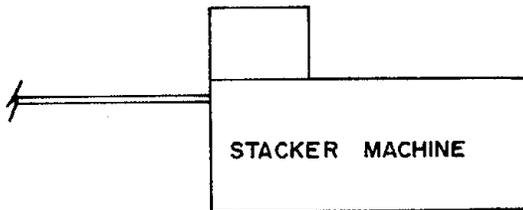
$\underline{\text{Results}}$

Concentration (ppm) at

Point	D	Breathing zone	A	Percent
1	370	160	–	43
2	370	130	–	35
3	360	0	–	0
4	360	0	–	0
5	360	320	–	89
B	280	–	30	11

Figure 1-5.   Results of tracer gas study.

Operational History

To investigate the ability of the collector to maintain its rated high
efficiency, the company undertook an experimental program to check its
performance. The company measured the pressure differential across the first
filter on a daily basis, and measured full-shift breathing zone concentrations
once per week. Frequent area measurements were also taken. Breathing zone
and workplace measurements were also taken several months before the system
was installed to provide a basis for comparison. Parameters such as air
temperature, noise and odor were also evaluated. When air temperatures
were found to increase while passing through the collector, the company
installed a cooling system in the outlet duct for use principally during
warmer months. No significant increases in noise or odor levels were found.

The long term evaluation of the collector was not completed at the time
of this study; however, the daily pressure differential measurements
did not significantly increase over several months of observations. Since
the time of the study, however, the company evaluated alternate methods
of cleaning the first filter because of concern over its deterioration due
to the violent nature of the shaking cleaning method.

Realizing that pressure monitoring may not, in itself, be adequate to assure
the safe performance of the system, the company is evaluating a continuous
particulate monitor called a nephelometer.

Summary of Sampling Program

1. Lead dust was the predominant hazard at the stacker operation from which
    cleaned exhaust air was recirculated to the workplace.

2. The measured lead removal efficiency of the double HEPA filter (99.96%)
    was almost identical to the rated efficiency of one HEPA filter (99.99%).

3. The average return air concentrations of lead into the workplace, 0.032
    mg/m^3, was about the same concentration level as area measurements.

4. The greatest percentage of the dust, 98.4%, was greater than 6 micro-
    meters in size.

5. A comparison of the average breathing zone concentrations throughout
    the entire workshift showed that the lead exposure levels from the
    stacking operation rose slightly after recirculation. This increase
    was found to be significant at the 95% confidence level.

6. Workplace (area) lead concentrations taken before and after the system
    was installed did not show an appreciable change as a result of
    recirculation.

7. Company investigations revealed that a cooling system should be
    installed in the outlet duct to maintain worker comfort during warmer
    months.

8. No significant increases in noise or odor were observed after recirculation.

9. Alternate methods of cleaning the first filter were being investigated by the company because of a concern over the effect of the shaking method on filter life.

RETROACTIVE ASSESSMENT OF DESIGN APPROACH

In the following section, a retroactive assessment of the recirculation system design is presented using the evaluation criteria presented in Reference One. The discussion will begin at the point at which plant management began to consider the technical feasibility of recirculating the exhaust from the stacker machine, a process which at that time was being exhausted to a fabric dust collector.

As the design team considers recirculation, an initial feasibility assessment is first performed. The purpose of this preliminary step is to pre-screen a series of eight factors affecting the likelihood of success in an attempt to uncover aspects of the program which may prevent recirculation. Thus, unnecessary efforts and expenses for field sampling, hardware evaluation and design optimization can be prevented. Following the initial assessment, a more in-depth investigation of contaminants, air cleaners, and monitors is presented. The modeling approach presented in Reference One will be used to assist in selecting a required collector efficiency and finalizing a system configuration which will achieve acceptable breathing zone concentrations.

Initial Feasibility Assessment

Legal Issues--
Although no legal considerations now exist which would restrict recirculation in the present case, at this time OSHA has proposed a regulation prohibiting the recirculation of an exhaust stream containing residual amounts of lead (2)*. The existence of this proposed regulation must be seriously considered by the design team in their decision to pursue recirculation.

Energy Consumption--
The issue of energy consumption is an important concern to this plant because a new plant is planned to be built in an area where natural gas is a high-priced and interruptible fuel. If the experimental system is successful, the cost savings from one unit ($526 from methods in Reference 4) will be derived from many such units. In later applications a calculation of the exact cost savings resulting from the implementation of recirculation at the new facility is a complicated procedure involving many factors which were not disclosed during the evaluations, and thus is beyond the scope of this study. After the final design is formulated, however, the

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*As of the date of this writing, the new lead standard, effective March 1, 1979, does not prohibit the recirculation of exhaust streams containing lead (3).

design team should attempt to project the anticipated costs and savings to arrive at a decision concerning the economic feasibility.

Contaminant Classification--
From knowledge of the process, it is known that only a single contaminant, lead oxide, is generated by the stacker machine because lead plates which are handled by the worker and the machine are covered only with a dried lead oxide paste. The dust produced is a dry non-reactive particulate with a specific gravity of 9.75 (5).

Although the flow rate and constituents of the exhaust stream are both known, the concentration of lead dust is not. The contaminant generation rate cannot easily be estimated without some type of sampling test. No in-duct sampling results are available, nor can an estimation of dust loadings be made by weighing the catch from the dust collector since the stacker is one of many processes presently exhausted by the system. Without conducting an actual field sampling test, the design team would not know if the generation rate was too high to prevent the specification of a suitable dust collector.

The toxicity of lead should be a major factor in the decision to recirculate. Reference One recommends that the recirculation of less toxic contaminants is preferable to highly toxic contaminants, especially when the toxic effects are acute. The toxic nature of lead will dictate that a highly efficient collector will probably be required and that system performance be adequately monitored to protect the stacker machine operator and the adjacent workers from the possibility of overexposure due to a system malfunction.

Air Quality Regulations--
A Federal air quality regulation for lead requires industries that emit lead to control emissions so that the ambient standard of 1.5 $\mu g/m^3$ will be achieved (6). The high removal efficiency that is typically needed to meet this standard may provide an added incentive to consider recirculation.

Air Cleaner Availability--
Knowing that a dry particulate dust is being generated, the design team could choose either filtration or electrostatic precipitation as available collection methods which would likely provide the high degree of efficiency required. Among their options, they would find a number of collectors available: fabric filters, cartridge-type filters, double HEPA filters, and electrostatic precipitators (ESP) single pass or double pass. Besides efficiency, the suitability of any particular collector will depend on size, cost, required maintenance, reliability and energy requirements.

Monitor Availability--
Adequate detection of reduced system performance is crucial because of the toxic nature of lead. The failure response mode should be automatic

and the response should result in an action which will adequately protect
the worker. Process shut down and/or exhaust by-pass are acceptable
failure response strategies, but the detection method needs to be
investigated further. The actual choice of the type of monitor which might
be necessary in the final design will depend largely on the collector
chosen. There are several different monitoring techniques which could be
used for this application. For example, pressure sensing devices are
available which can detect certain failures of filtration collectors.
Several types of particulate monitors can detect increased outlet concentra-
tions.

Process Emission Profile--
Discussion with the production engineers revealed that the contaminant
generation rates are both variable and intermittent, and are highest when
the worker is loading dusty plates.

Ventilation System Design--
The breathing zone of the stacker operator is already protected by the
present exhaust system. Recirculation will require disconnecting the
present exhaust stack and reconnecting the exhaust outlet to the experimental
recirculation system which would be designed to draw the same amount of
flow.

Summary of Initial Feasibility Assessment

Although none of the eight factors presented obvious barriers to recircula-
tion, the preliminary assessment was useful in that several issues were
raised which should be addressed by further evaluations. Among these are:

1. The possible risks imposed by the acute toxic effects of lead
    should be weighed against predicted economic benefits.

2. The existence of a proposed standard prohibiting recirculation of
    lead must be weighed heavily against the possible economic risks
    of going ahead with the prototype recirculation evaluation at
    this time.

3. Highly efficient collectors are available, but further evaluations
    are needed to determine whether they are efficient and reliable
    enough.

4. A type of collection system must be selected which will not be
    adversely affected by fluctuations in dust generation rates and
    which will maintain a relatively constant outlet concentration
    of residual amounts of contaminants.

5. Several monitors are capable of detecting failures, although
    further study is needed to evaluate important factors such as
    reliability and sensitivity.

6. Although the high removal efficiency of lead removal required by
    air quality regulations, as well as possible shortages of fuel

are incentives to proceed with recirculation, a comprehensive
cost-benefit analysis should be performed after system design
to determine whether the proposed use of recirculation for the new
plant will be economically justifiable.

In-Depth Design Evaluation

Following the initial assessment, an in-depth evaluation of contaminants,
collectors and monitoring approaches is conducted as part of the design
process to eliminate uncertainties raised by the preliminary feasibility
assessment. These topics are discussed further in the following three
sections.

Contaminant Characteristics--
Prior to recirculation system design, no exhaust sampling was performed.
Had it been done at that point, it would have been found, as it was during
the present evaluation, that the average concentration of lead at the
inlet to the collector was 87.1 mg/m^3, and that 98.4% of the particles
were larger than 6.2 micrometers.

The OSHA permissible exposure limit (PEL) for lead in the breathing zones
of workers was 0.20 mg/m^3 (7)* at the time of the survey, although a proposed
standard of 0.10 mg/m^3 was being considered at that time (2). The ACGIH
Threshold Limit Value was 0.15 mg/m^3 (8). NIOSH recommends a level of
0.10 mg/m^3 (9).

Selection of Air Cleaning Equipment--
The type of dust generated does not pose particular difficulties in selecting
a collection method, except that the toxic nature of the dust dictates that
the method be very efficient. Filtration is a good choice for collection
because the dust is a single phase, dry particulate with no unusual properties
which might make cleaning difficult. Filtration is also capable of very
high collection efficiencies, providing that the dust does not contain an
appreciable amount of particles in the submicron range.

From the various, available filtration devices, e.g., bag and cartridge
filters, HEPA filters, etc., the company chose a unit collector containing
two HEPA filters in series. Some of the supporting reasons for the choice
are the following:

1. The HEPA filter has a high design efficiency (99.99%), an appealing
    feature when dealing with a highly toxic substance.

2. The collector has a built-in failure detection feature. The
    collector was designed to allow detection of a failure of the first
    filter by means of a pressure switch between it and the second
    filter. After such a failure, the second filter will overload,
    then activate a buzzer and alarm.

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*At the time of this writing the new OSHA PEL had been changed to 0.05 mg/m^3,
effective March 1, 1979.

3. The company was attracted to the unit collector concept because the return air could be used in an overhead air make-up plenum to improve breathing zone control. In other areas of the plant, individual fresh air make-up plenums were commonly used for this purpose.

4. Unit collectors have the advantage of not requiring long duct runs and have better operational flexibility. For example, if only one process is operating, then only the unit collector associated with that process needs to be operating, thus, economizing the amounts of air exhausted. Furthermore, when large scale exhaust systems break down, all of the processes connected to it are affected, whereas a unit collector failure would only affect a small portion of a process during a breakdown.

One major disadvantage to unit collectors is that the use of multiple units in place of one large collector will certainly increase the amount of attention and maintenance which will be required. This factor should be considered when weighing the benefits ascribed to unit collectors above.

The use of two HEPA filters in series agrees with the suggestion in Reference One regarding the benefits of redundant air cleaners. In this case, redundancy is essential because it provides backup filtration which protects workers from failures in the primary filter.

Evaluation of Monitoring Strategies--
A failure detection strategy should address the principal failure modes and have a response which adequately protects the stacker operator, and adjacent workers, from overexposure.

In this discussion, the possible modes of system failure will be identified and then the present failure response strategy will be discussed.

Failure modes--The principal means by which the present system could fail are listed in Table 1-7. Failure modes may be classified under two headings:

   -Failures of the filtration media.
   -Failures of the remaining exhaust system components.

Common filter failures include:

   -Breakthroughs, e.g., holes and tears in the media or leaky seals.
   -Blinding, e.g., clogging of the media with contaminants which cannot be removed by the cleaning mechanism or due to an inadequate cleaning cycle.

It must be noted that, in the present system, only the first filter is recleanable, thus the buildup of significant amounts of contaminant on the second filter will always lead to blinding of that filter.

Failures of the other exhaust system components include:

Table 1-7. Principal modes of failure and effects.

Failure types	System parameter		Modes of failure	
	First filter, ΔP	Second filter, ΔP	Outlet concentration	Hood capture efficiency
Air cleaner failures				
Failure 1 – Blinding of first filter.	↑	↓	↓	↓ —
Failure 2 – Breakthrough of first filter; blinding of second.	↓	↑	↑↓	↓ —
Failure 3 – Breakthrough of second filter.	↑	↓	↑	↑
Failure 4 – Breakthrough of both filters.	↓	↓	↑ —	↑
Exhaust system failures				
Failure 5 – Hood or duct blockage.	↓	↓	↓	↓ —
Failure 6 – Fan or drive failure.	↓	↓	↓	↓ —

↓ or ↑ denotes deviation from steady-state performance.

—— Major failure effects

1. Increased restriction to flow, e.g., closing off of the hood inlet or recirculation outlet plenum, or debris in the ductwork.

2. Failures of the fan and drive system, e.g., slipping belts, motor failure or bearing failure.

On the chart, major failure effects are identified (underlined) as those which cause overexposure of the stacker operator either due to:

1. Recirculation of excessive amounts of lead.
2. Decrease in the exhaust flow rate to the point that the hood is only partially effective and dust escapes directly from the process into the breathing zone.

All of the identified failures but one could lead directly to overexposure. Breakthrough of the second filter may not increase the outlet concentration sufficiently to cause overexposure, but does eliminate the redundancy which the second filter provides, as well as its use as a means for detecting failures.

The obvious system failure of operating the process without the exhaust system can be classified as a major failure mode, but is not listed in Table 1-7 because its effect is a complete absence of performance, rather than a deviation from steady state.

Present monitoring method--The monitoring method chosen for the experimental recirculation system involved the use of differential pressure gauges, which one could use to visually measure pressure drops across each filter, and a pressure switch. The pressure switch, located upstream of the final filter, would sound a buzzer, turn on a light, and shut off the exhaust system in the event that pressure would rise above a preset limit. In the present response strategy, response to collector failure is by worker notification of plant personnel. There is no lockout mechanism for assuring that the process is not operated without the collection system functioning.

It can be seen from Table 1-7 that readings on both differential pressure gauges would deviate from their steady-state values with any of the failure modes occurring. Deviations would occur as either rises or drops in differential pressure so that visual monitoring could be expected to identify failures as occurring. The pressure switch, however, would only respond to failures which caused pressure at the second filter to rise. Such a condition would occur in only the second of the potential failure modes, and it would only occur if the second filter were intact. The fact that only one of the ways that the system could fail would activate an alarm conflicts with the conclusion of Reference One that detection methods must be provided for all failure modes.

The monitoring of only one failure mode was automatic: sensing of a breakthrough of the first filter. The detection of this method of failure is important because of the violent nature of the primary filter rapping mechanism. However, the monitoring system would not provide a sufficient

warning of all potential system failures. Rather, the majority of failures would have to be detected through visual surveillance of the differential pressure gauges as they indicate changes from steady-state readings.

Return air location--The concept of the overhead return air plenum was one of a number of engineering approaches which the company employed to achieve and maintain an acceptable level of breathing zone control. However, the use of this technique as a means of reintroducing return air is in direct conflict with the recommendation of Reference One that whenever possible, air should be directed away from employees. In the present design, the practice of returning air directly to the worker reduces the margin of safety which should be provided in the event of system failure. Furthermore, excessive levels of contaminants which may result from failure would directly enter the breathing zone of the stacker operator. The recommendation that return air should be well distributed throughout an area is a practice which should be followed whenever possible.

Alternatively, the advantages of the push-pull concept could still be utilized by supplying fresh, tempered make-up air through the overhead return air plenum in the place of the return air while directing the return air into the general plant area. Returning the cleaned exhaust in this manner reduces the urgency of the response by increasing the time necessary for a system response to a failure (critical response time). Additionally, it further reduces the necessity for the system response to failure to be completely fail-safe.

Design Optimization Using the Modeling Approach

Choosing an Appropriate Model--
The process of optimizing a design involves a carefully controlled balance of variables which may affect the outcome. The approach taken in Reference One is to balance pertinent factors by a series of equations defined as a "model". In the following section, the modeling approach presented in Reference One is followed using the results obtained during the evaluation of the studied system.

From a generalized modeling approach presented in Reference One, the authors have developed a number of simplifications which provide modeling equations for several types of recirculation systems commonly found. Each of the simplifications, called a model, is summarized in Appendix B of Reference One on a separate page. Configuration no. 2 has been reproduced as Figure 1-6 in this report.

The top part of the figure illustrates the plant area in a simplified schematic before recirculation is implemented. The middle part of the figure illustrates the situation in the plant after recirculation. The equations listed below the figures are specifically derived for use with the plant situation depicted.

The situation in this case study could be described by Configuration nos. 1, 2 or 3 because they represent a local exhaust system, with one exception
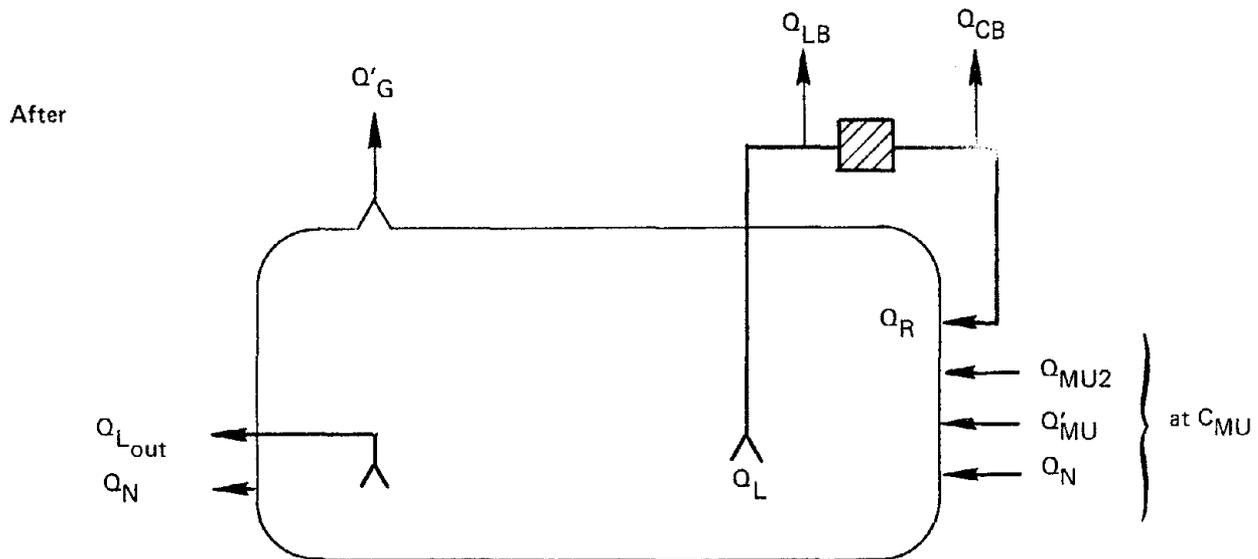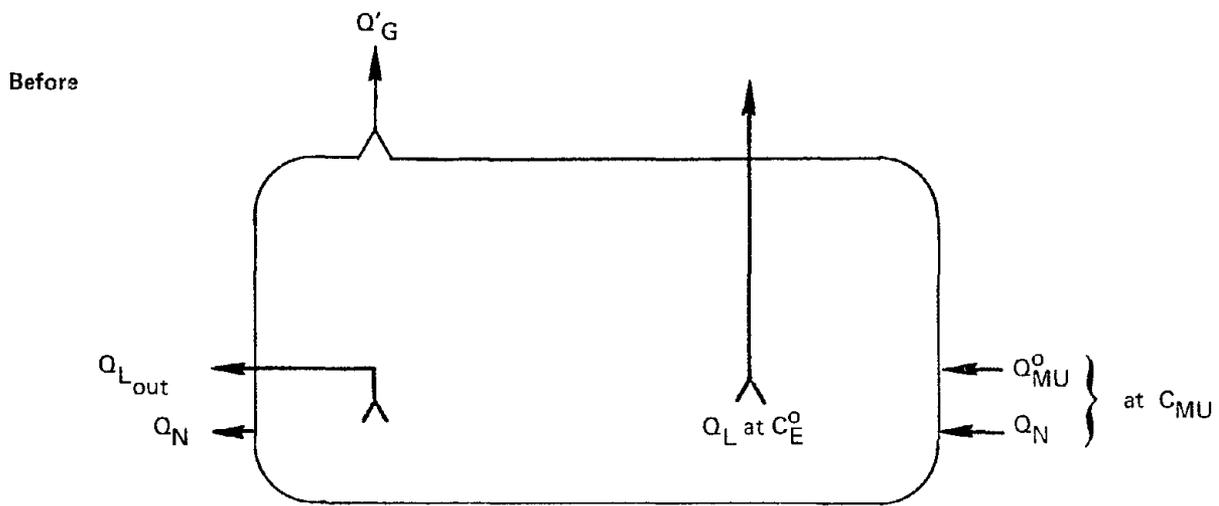
Before

Q'_G

$Q_{L_{out}}$

Q_N

Q_L at C^o_E

Q^o_{MU}

Q_N

at C_{MU}

After

Q_{LB}

Q_{CB}

Q'_G

Q_R

Q_{MU2}

Q'_{MU}

Q_N

at C_{MU}

$Q_{L_{out}}$

Q_N

Q_L

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 1-6.   System configuration.

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noted. Configuration no. 3 does not provide for an increase in the total ventilation rate as a result of recirculation. As a matter of explanation, the total ventilation rate is a summation of all of the ventilation rate inputs which act to cause contaminant dilution of the breathing zone of a worker. Good examples of air flows which comprise the total ventilation rate are natural ventilation (due to wind flows and heat sources), air make-up rates, and recirculated air volumes. In this plant, the total ventilation rate will increase after recirculation is implemented because the plant did not reduce the air make-up an equivalent to the amount recirculated. The effect of this was to increase the rate of air flowing through the breathing zone of the worker, hence an increase in the total ventilation rate. One reason why the plant did not reduce the amount of make-up air was because the air make-up unit is a fixed rate device which cannot be easily reduced. Secondly, the system was a small experimental unit which had more important energy implications on possible future plant applications. In general, wide use of fixed rate make-up air units indicates that it may not be uncommon for a plant to recirculate while not reducing the amount of make-up air provided.

Configuration no. 3 could have been erroneously chosen in this case because the caption under Figure B3 in Reference One implies that this configuration applies to all unit collectors. It is important to note that this configuration would not be applicable in plants which have experienced changes in the total ventilation rate as a result of recirculation, as was noted in this plant situation.

Thus, comparing Configurations nos. 1 and 2, the latter is chosen to represent this case study because it presents the option of providing that additional fresh air (Q_{MU2}) is introduced in a location separate from the return air stream. This assumption better represents the present situation because presently make-up air is separated from the return air stream. In future applications of this recirculation system, if found acceptable, the plant should attempt to combine recirculated and make-up air because the ideal mixing assures that the best possible dilution of contaminants is achieved.

Configuration no. 2 has several differences between it and the system actually studied which should be noted. The actual installation has no bypass for pleasant weather or emergency use. Additionally, the actual system "boundary" is considered to be the manufacturing room rather than the entire plant. Ventilation conditions in the room are well isolated from other rooms in the plant, implying that the chosen boundary is a valid assumption which greatly simplifies the model analysis.

Assigning Parameter Values

The equations appearing below Configuration no. 2 contain parameters which describe the components of the contaminant mass rate and volumetric flow rate balances in the schematic diagrams. Before the modeling equations can be utilized, it is important to assign appropriate values to each of the parameters. The approach which is followed is to assign somewhat conservative estimates to the parameters initially, then to refine their estimates as necessary in the course of the design optimization. A

summary of the parameters, their values and a brief rationale for the value
given is presented in Table 1-8.

Table 1-8. Model parameter values.

Parameter	Description	Value	Rationale
Q_{MU}^{o}	Make-up rate for conventional systems prior to recirculation	1076 m^3/min	The rated capacity of the air make-up units (Table 1-2).
Q_L	Initial volume of local exhaust stream	40 m^3/min	The amount of local exhaust to be recirculated (Table 1-2).
Q_{MU}'	Fixed make-up supply rate	0	There are no fixed sources of make-up air in the plant.
$Q_{L_{out}}$	Local exhausts other than what is recirculated	708 m^3/min	Local exhaust rate (Table 1-2).
Q_G'	General exhaust rate not recirculated	241 m^3/min	General exhaust rate (Table 1-2).
c_E^{o}	Initial concentration of local exhaust stream	102.96 mg/m^3	This is the highest lead concentration measured in the inlet (Table 1-3).
c_{BZG}^{o}	Initial breathing zone concentration	0.046 mg/m^3	Average of six breathing zone samples taken prior to recirculation (Table 1-5).
C_{MU}	Make-up air concentration	~ 0	Concentration of lead in inlet to air make-up unit was measured at 0.002 mg/m^3, a level which can be considered insignificant.
k_R	Contribution factor of return air to local exhaust systems	1.0	As a conservative estimate, assume all return air re-enters hoods.
k_{BZ}	Contribution factor of return air to breathing zones	1.0	While beneath the plenum, the worker will only be breathing return air.
f	Local exhaust system influence factor	0	No large volume exhaust hoods are presented in the area of interest.

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Table 1-8 (continued).

Para-meter	Description	Value	Rationale
Q_R	Rate of return air	40 m^3/min	The rate of exhaust air returned to the building (Table 1-1).
Q_N	Natural ventilation rate	0	Assumed to be negligible due to the positive pressurization of the room, the lack of large heat sources, and the tight nature of the building in winter months.
Q_T^O	Total ventilation rate before recirculation	991 m^3/min	The summation of make-up and natural ventilation air volumes before recirculation: $$Q_T^O = Q_{MU}^O + Q_N$$ $$Q_T^O = 991 + 0$$ $$Q_T^O = 991$$
Q_T	Total ventilation rate after recirculation	1031 m^3/min	The summation of return air, make-up, and natural ventilation volumes after recirculation: $$Q_T = Q_R + Q_{MU2} + Q_{MU}' + Q_N$$ $$Q_T = 40 + 991 + 0 + 0$$ $$Q_T = 1031$$
Q_{LB}	"Dirty" bypass exhaust volume	0	There is no provision to bypass exhaust in the present configuration.
Q_{CB}	"Clean" bypass exhaust volume	0	There is no provision to bypass exhaust in the present configuration.

Design Approach--
Following assignment of values to the various parameters, the following
computational steps are presented in Reference One for use with Configura-
tion no. 2:

1. Choose a value for Q_{CB} or Q_{LB}.

2. Compute values for Q_{MU2} and Q_R.

3. Based upon the magnitudes and expected distribution of Q_{MU2} and
   Q_R, estimate values for k_{BZ} and k_R.

4. Compute the necessary C_R and the necessary fractional air cleaner
   efficiency η from the equation provided.

5. Adjust Q_{CB} or Q_{LB} and other parameters until an air cleaner
   efficiency η is computed which is slightly less than or equiva-
   lent to the efficiency of the equipment train intended for use.

The above approach will be followed in the following section in an effort
to obtain a design configuration which results in acceptable contaminant
concentrations in the workers' breathing zone.

Modeling Results--
The equations presented at the bottom of Figure 1-6 are utilized in the
following sections to make decisions concerning the various design alterna-
tives. Table 1-9 summarizes all of the calculations which are made in
the following sections.

Calculation of the amount of return air, Q_R--As shown in Table 1-8, the
amount of return air, Q_R, is equivalent to the amount exhausted from the
process, Q_L, when the exhaust volumes Q_{LB} and Q_{CB} are set equal to zero.

Calculation of the make-up supply rate for air not mixed with recirculated
air, Q_{MU2}--The parameter Q_{MU2} is calculated to determine the amount of
make-up air which should be brought to the room after recirculation. The
amount of make-up air is normally reduced by the amount recirculated to
realize the cost savings. But as was noted previously, for various reasons
the plant chose not to reduce the amount of make-up air, resulting in an
increase in the total ventilation rate as a result of recirculation. Using
the values defined in Table 1-8, the ratio of the old to new ventilation
rates can be calculated:

$$\frac{Q_T^o}{Q_T} = \frac{991}{1031} = 0.961$$

The significance of this change in ventilation rate is seen in the next
section in the calculation of the required value for the return air concentra-
tion, C_R. In that calculation, a ratio of the old to new ventilation rates

is utilized in an equation to account for the effect of increased dilution from the increase in the total ventilation rate.

Calculation of the return air concentration, C_R and required collector efficiency, η--These two design steps are discussed together because the result of the first calculation, C_R is utilized in the next equation to calculate a required collection efficiency. The third equation appearing in Figure 1-6 is utilized to calculate a required C_R.

Initially, the third equation can be simplified by noting that there are no large volume exhaust hoods in the plant area of interest, a situation which is accounted for by a parameter, f. Additionally, the value for C_{MU}, the contaminant concentration in the make-up air, can be considered negligible as a result of measurements which indicated that the lead concentration in the air make-up stream was 0.002 mg/m^3. Since this measured value was near the lower end of the sensitivity of the method, for practical purposes it can be considered zero. The measurement of the air make-up consideration is, in general, a worthwhile exercise when dealing with toxic substances with low PEL's. If the measured value had been much higher, it could have had been a significant source of contamination in the area of the plate stacking machine.

Equation no. 3 may now be used to calculate a planned C_R and required η once an appropriate value has been set for C_{BZ}^D, an important parameter describing the breathing zone concentration which is desired after recirculation.

Guidelines given in Reference One for choosing an appropriate value for C_{BZ}^D imply that, if possible, attempts should be made to lower the existing breathing zone level by recirculation, especially when toxic substances are involved. Furthermore, it is suggested that an appropriate safety factor be applied when choosing the design value. Realizing that some dilution ventilation will result from an increased ventilation rate, as first step the design team might choose to calculate an air cleaner efficiency which maintains the present average breathing level of 0.046 mg/m^3. The efficiency obtained, 99.99$^+$% is obviously unrealistic for a design goal, indicating that the desire not to allow the breathing zone concentration to increase is also probably not realistic (equation no. 3).

Realizing that the collector intended for use is not able to maintain existing breathing zone levels, the design team could consider some of the possible options:

1. Choose a more efficient collector.
2. Return the exhaust air into the plant area instead of breathing zone.
3. Perform option no. 2 above, and introduce fresh make-up air into the overhead plenum.

Table 1-9. Model application calculations.

1. Equation No. 1

$$Q_R = Q_L - Q_{LB} - Q_{CB}$$

$$Q_R = 40 - 0 - 0 = 40 \ m^3/min$$

2. Equation No. 2

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

$$Q_{MU2} = 0 + 0 + 708 + 241 - 0$$

$$Q_{MU2} = 949 \ m^3/min \ (\text{actual value was } 991 \ m^3/min)$$

3. Equation No. 3

$$C_R = \frac{1}{k_{BZ}} \left[C^D_{BZ} - (1-f) \frac{Q^O_T}{Q_T} (C^O_{BZG} - C_{MU}) - f (C^O_{BZL} - C_{MU}) - (1-k_{BZ}) C_{MU} \right]$$

Simplification: $C^O_{BZL} = f = C_{MU} = 0$

$$C_R = \frac{1}{k_{BZ}} \left[C^D_{BZ} \frac{Q^O_T}{Q_T} (C^O_{BZG} - C_{MU}) - (1-k_{BZ}) C_{MU} \right]$$

a. First estimate: $(k_{BZ} = 1.0, \ C^D_{BZ} = 0.046 \ mg/m^3)$

$$C_R = \frac{1}{1} \left[0.046 - 0.961 \ (0.046) \right]$$

$$C_R = 0.002 \ mg/m^3$$

b. Second estimate: $(k_{BZ} = 0.50, \ C^D_{BZ} = 0.046 \ mg/m^3)$

$$C_R = 0.004 \ mg/m^3$$

c. Third estimate: $k_{BZ} = 0.50, \ C^D_{BZ} = 0.075 \ mg/m^3)$

$$C_R = 0.062 \ mg/m^3$$

d. Fourth estimate: $(k_{BZ} = 0.04, \ C^D_{BZ} = 0.075 \ mg/m^3$

$$C_R = 0.770 \ mg/m^3$$

Table 1-9 (continued).

4. Equation No. 4

$$\eta = 1 - \left[\frac{C_R}{C_E^o - k_R C_{MU} + k_R C_R} \right]$$

a. First estimate: $C_R = 0.002 \text{ mg/m}^3$

$$\eta = 1 - \left[\frac{0.002}{102.96 + 0.002} \right]$$

$$\eta = 0.9999+$$

b. Second estimate: $C_R = 0.004 \text{ mg/m}^3$

$$\eta = 0.9999+$$

c. Third estimate: $C_R = 0.062 \text{ mg/m}^3$

$$\eta = 0.9994$$

Since a collector efficiency of 99.96% is difficult to improve upon, the design team might seek alternative no. 3. This option will have the effect of reducing C_{BZ} by reducing k_{BZ} and k_R. This is advantageous from the aspect of surveillance, because the monitoring scheme will not have to be so fail-safe and be so immediate. Estimates of k_R and k_{BZ} can now be made to continue the design process.

A maximum estimate for k_R could be obtained by accounting for the computed flow volumes as shown in Reference One, however, no refinement of k_R is necessary when the collection efficiency is high and the contaminant concentration in the air make-up is low. A full explanation of this effect appears in Reference One under the discussion of model parameters.

The necessity for a good estimate of k_{BZ} is very important, however, because small changes in its value have a pronounced affect on the calculated breathing zone concentration. A tracer gas study would not have been able to be employed by the design team in the feasibility assessment of the experimental unit because the fan and ductwork would not have been installed. Similarly, in the new plant situation the tracer gas study would also not be able to be utilized. The use of k_R and k_{BZ} is a significant improvement over the "k factor" previously used to describe an

estimated degree of mixing in a plant area; however, the inability to directly measure k_{BZ} in plant situations which do not have a fan and the attendent ductwork installed severely limits the concept's usefulness.

Although there is no direct way of measuring k_{BZ} for the new configurations without conducting a tracer gas study, estimates can be made of its upper and lower limit. It is known that, for example, the effect of redirecting the return air and introducing fresh make-up air will substantially reduce the estimate of k_{BZ}. The lower estimate could be found by assuming that the return air ideally mixes with the total amount of fresh air brought in:

$$\frac{40 \ m^3/min}{991 \ m^3/min} = 0.04$$

With a well designed distribution plenum good mixing could easily be achieved, but to be conservative, the estimate for k_{BZ} will be assumed to be somewhat poorly mixed, with an assumption that some employees will breathe 50% return air ($k_{BZ} = 0.50$). This assumption may be still somewhat conservative because it is not difficult to design a return air plenum which results in good mixing within the workplace. Of course, ideal mixing could be achieved by pre-mixing the return air stream and the air make-up source. This configuration is covered by Model no. 1, but will not be discussed in depth here because in the present configuration the return air stream and make-up plenum are physically separated. In further plant applications the prospect of combining return air streams and air make-up supplies should be investigated by plant personnel because it affords an inherent safety factor resulting from dilution of return air streams.

With the new configuration, the second estimates of equation nos. 3 and 4 indicate that C_R will be 0.004 mg/m^3, resulting in the same high collection efficiency as before: 99.99$^+$%. Thus, the assumption that the return air being well-mixed in the room does not by itself reduce the required collection efficiency. This is because of the severe limitations placed by the "no increase" philosophy.

At this point, the design team would have to choose to increase the breathing zone if recirculation is to be further considered. The amount of the increase should be determined by a health professional based on what will be considered "safe". In view of the proposed standard of 0.10 mg/m^3 at the time of the evaluation, the design team might consider some safety factor below this level as the absolute maximum level of C_{BZ}^D. The actual safety factor used should be dependent on the other factors such as the standard deviation of the data and, to some extent, on the dependability of the monitoring system.

Reference One does not give guidance in the choice of the safety factor. It would be appropriate, therefore, to develop employee exposure risk curves which may be used to allow the application of statistical methods based on, among other things, the standard deviation of the data and the dependability of the monitoring strategy. Although not necessarily recommended, a 25% safety factor will be assumed for the sake of discussion. Assuming that the design team would consider the lead standard which was proposed at the time of their evaluation, 0.10 mg/m^3, the safety factor chosen indicates that the value for C_{BZ}^D is 0.075 mg/m^3.

With the new estimate for c_{BZ}^D, the third estimate of equation no. 3 calculates a return air concentration of 0.062 mg/m^3 indicating a required efficiency of 99.94% (third estimate, equation no. 4). This is somewhat conservative because the k_{BZ} of 0.50 could be improved upon. With ideal mixing ($k_{BZ} = 0.04$), the calculated return air concentration would be 0.770 mg/m^3 (fourth estimate), indicating a required efficiency of 99.26%.

These calculations indicate that some increase in breathing zone concentrations will result after recirculation with the collector intended for use. Although such increases are not prohibited, the raising of the breathing zone levels will have the adverse affect of reducing the present margin of safety with respect to the lead standard. Furthermore, this margin of safety would be decreased in half if the standard proposed at the time of the evaluation were enacted. Thus, recirculation is not prohibited by this approach, but the design team should realize that recirculation will reduce the safety margin between present levels and the lead standard, and should judge their decision to recirculate accordingly.

System Performance Validation

Once a recirculation system is designed and installed, Reference One suggests that a system should be checked prior to actual production, presumably to protect the worker from overexposure if the system is not adequately designed. In the present design this type of pre-production testing should only be performed with respiratory protection because the worker who is required to operate the process could unknowingly be exposed to excessive contaminant levels from the return air stream if, for some reason the collector was defective.

Checking Air Cleaner Performance--
Once a recirculation system is designed and installed, the system should be checked to ensure that its performance meets design specifications. Since a 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. Reference One presents a method for calculating a planned C_R which must satisfy the following constraint (for employees in general plant areas):

$$C_R \leq [c_{BZG}^D - c_{BZ}^O \frac{(Q_T)}{Q_T}] + c_{MU}$$

Substituting,

$$C_R \leq \frac{1}{0.50} [0.075 - 0.046 (0.961)] + 0$$

$$C_R \leq 0.062 \text{ mg/m}^3$$

With the configuration described in this evaluation, the measured return air concentration should be less than 0.062 mg/m^3 to ensure that the air cleaner performance meets design specifications.

The performance of the air cleaner and configuration which was actually installed by the company can also be checked by comparing the model's predictions to values actually measured.

Equation no. 3 can be used to solve for c_{BZ}^D, which in this context refers to the breathing zone concentration predicted by the model after recirculation. The calculation below is a simplified form of equation no. 3 (see Table 1-9):

$$C_R = \frac{1}{k_{BZ}} \left[c_{BZ}^D - \left(\frac{Q_T^o}{Q_T}\right) \right]$$

Substituting in measured values,

$$0.032 = \frac{1}{0.39} \left[c_{BZ}^D - \frac{991}{1031}(0.046) \right]$$

Solving for c_{BZ}^D,

$$c_{BZ}^D = 0.057 \text{ mg/m}^3$$

The average breathing zone concentration actually measured was 0.066 mg/m^3. A further refinement in the prediction could be made by noting that the average k_{BZ} value, 0.39, includes 2 zero measurements made near the "upwind" side of the plenum. Noting that the worker spends more time in the downwind side of the plenum, an average k_{BZ} calculated with the three non-zero concentrations, 0.56, would probably be more appropriate for use in this calculation. Substituting, the predicted breathing zone concentration is 0.062 mg/m^3, a value which more closely agrees with the average value actually measured, 0.066 mg/m^3.

Testing the Surveillance System and Alarm--
No deliberate test of the surveillance system was performed in this study, however, a malfunction of the air cleaner earlier in the company's testing program provided evidence that the pressure sensor will initiate an appropriate response to certain failures. According to the company, the failure occurred when a piece of the shaking mechanism worked loose and damaged the first filter. This caused the second filter to overload, sound the alarm and shut down the collector. The process was subsequently shut down until the filter was replaced.

A failure of the collection system could also be artifically induced without creating an actual failure of the filters. This might be accomplished by dampening back the air flow in the return air plenum until the back pressure on the second filter increased to a level which would cause the pressure switch to trip and the alarm to activate.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions from the evaluation reinforced conclusions and recommendations in Reference One.

1. The approach recommended by Reference One generally provided a useful method for investigating the technical feasibility of recirculation.

2. The company choice of the pilot study approach to evaluate the feasibility of recirculation in the proposed new plant was seen to support the recommendation in Appendix A of Reference One that experimental studies be conducted to estimate design parameters in new facilities. The pilot study approach is an attractive method of evaluation because it can minimize the potential economic risks by providing useful technical data upon which to base a decision.

3. The practice of returning the cleaned exhaust directly to the breathing zone of the worker violates the recommendation of Reference One that whenever possible, return air should be well-distributed throughout the plant area. The company practice is undesirable because it places a severe design constraint by demanding the monitoring method to be nearly fail-safe.

4. A comparison of the breathing zone concentration predicted by the modeling equation and the average value actually measured showed close agreement, indicating that the modeling approach presented in Reference One appears to be based upon sound concepts.

5. The measurement of lead concentrations in the air stream from the make-up air unit was considered to be an important model input because, if even small contaminant levels had been present, the design outcome could have been significantly affected. In general, the value of the parameter C_{MU}, the contaminant concentration in the make-up air, is important when dealing with a toxic substance which has the potential for re-entering the plant through air make-up units.

6. The monitoring method chosen by the company violated the Reference One recommendation that adequate detection of reduced system performance must be provided. The use of a double HEPA filter as a monitoring device is not considered adequate because small breakthroughs of filters could result in worker exposure to excessive contaminant levels which might go unnoticed.

The following conclusions from the evaluation expanded upon the conclusions and recommendations in Reference One.

7. The discussion of legal issues in Chapter 3 of Reference One does not emphasize that the design team must be cautious when applying the guidelines when dealing with substances which have impending regulations or restrictions. In this case study it was seen that the uncertainty of the regulatory position concerning the level of the lead standard and the possible prohibition of recirculating exhaust streams containing residual amounts of lead posed serious questions to the design team in their initial assessment of the feasibility of recirculation.

8. The introduction of the parameters k_R and k_{BZ}, terms used in the modeling approach, are a significant improvement over the previous "K factor" mixing concept because they represent physically understandable concepts. However, their inability to be measured in many plant situations limits their usefulness. A tracer gas study would not have been able to be employed by the design team in the feasibility assessment of the experimental unit because the fan and attendant ductwork had not been installed.

9. Reference One does not stress that an investigation of possible monitoring strategies should include a study of the interrelationships between the principal failures types, the parameters which may be monitored, and the principal failure effects.

10. The model simplification labelled "Configuration no. 3" in Appendix B of Reference One is implied for use with designs involving unit collectors, however, this model simplification cannot be used when there has been a change in the total ventilation rate because the simplified equation omits terms dealing with the total ventilation rate. As was seen in the case study, a ventilation rate change will result when a plant with an air balance does not reduce the make-up supply rate following implementation of recirculation.

11. Plants which have fixed make-up air supplies may have difficulty following the Reference One procedure of lowering make-up air supply rates after recirculation. This procedure is implicit in the flow balance equations accompanying each model configuration.

12. In situations involving toxic substances with low permissible exposure levels, it may be difficult to follow the Reference One suggestion that design teams should maintain or even lower existing breathing zone concentrations, whenever possible, in the process of implementing recirculation. The application of the modeling approach in this case study indicated that some increase in the breathing zone concentration will result in spite of attempts to specify a collector which can maintain the pre-recirculation breathing zone level. The attempts failed primarily because the dilutory effect of an increase in the total ventilation rate due to recirculation was too small to offset the increased contaminant levels in return air stream.

13. The Reference One recommendation that acceptable breathing zone concentrations i.e., the TLV or PEL, be reduced by some safety margin is difficult to follow because there is no guidance for deciding what margin of safety is acceptable after recirculation.

14. In the present design, the Reference One suggestion that checks of air cleaner performance be conducted prior to the start of actual production operation should be followed with caution. Pre-production testing should only be performed with proper respiratory protection because the worker who is required to operate the process could unknowingly be exposed to excessive contaminant levels from the return air stream if for some reason the collector was defective.

RECOMMENDATIONS

1. The pilot scale approach for assessing the feasibility of recirculation should be encouraged whenever technical questions are unanswered and economic risks of a large scale system are great.

2. The system which was evaluated in the survey should be supplemented by a means to detect all system failures which could result in excessive worker exposures.

3. It should be understood that in the initial feasibility assessment the decision to pursue the feasibility of recirculation should be cautiously made when dealing with substances having proposed lower levels and the possibility of a restriction which may prohibit recirculation.

4. A note of explanation should accompany model Configuration no. 3 to warn the reader of the restrictions governing its use.

5. The measurement of contaminant concentrations in the inlet to air make-up units should be encouraged in recirculation and conventional exhaust systems when one is suspicious of contaminant entry or when highly toxic substances are involved.

6. The practice of directing return air exhaust streams away from employees should continue to be recommended and perhaps be further emphasized.

7. The analysis of failure response should include an investigation of the interrelationship between failure types, system perameters to be monitored, and the principal failure effects. Reference One should note that with toxic substances, attempts to offset increased return air concentrations with dilution ventilation resulting from increases in the total ventilation rate will probably be unsuccessful unless the total ventilation rate increase is unusually large.

8. Further research should be made on the factors involved in deciding an acceptable safety margin between the level desired in the design and the allowable level. The research effort should address the possibility of developing employee risk curves which should incorporate factors such as deviation of the data, the reliability of the air cleaner and monitoring system, and the effects of various response times and consequences of failures.

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CASE STUDY NO. 2
EVALUATION OF A WOODWORKING OPERATION
MARCH 1978

CONTENTS

FIGURES

TABLES

INTRODUCTION

An evaluation was made of a woodworking plant which had recently installed
a new dust collection system which recirculated exhaust air into the work-
place. Although the collector was installed to comply with local air
pollution regulations, the concept of recirculation was introduced into
the design to reduce the requirement for additional make-up air capacity.

PLANT DESCRIPTION

At the woodworking plant, bedroom, and living room furniture were manufactured
by over 100 workers who were employed in a variety of operations, including
wood cutting, sanding, gluing and spray painting. Woodworking operations
were located in three manufacturing rooms located on the first floor of
the building. Gluing was performed in an adjacent room while spray painting
was accomplished on the second floor. All but two of the machines were
located in the two largest manufacturing rooms (Figure 2-1). Since gluing
and spray painting operations were conducted remote to the woodworking
operations, gases and odors associated with these operations did not affect
the air quality within the machine rooms containing woodworking machines.

PROCESS DESCRIPTION

All woodworking processes were performed on specially designed machines
which either sawed, planed, or sanded the wood into desired shapes. Each
machine was usually operated by one worker, but a few large machines
required two. Not all machines were operated at once, and some machines
were operated for only a few hours until the desired number of pieces
were made. Table 2-1 lists each woodworking process and indicates whether
the machine was operated during the evaluation and the type of dust it
generated. As seen in Figure 2-1, all but two processes (no. 13 and no. 36)
were located in the two manufacturing rooms shown. Although one process
(no. 37) was not connected to the dust collection system, it did not
generate enough dust to be of concern.

The contaminant generated by the various processes was, for practical
purposes, 100% wood dust. It is likely that sanding operations generated
minute amounts of dust which originated from the deterioration of sanding
abrasives. However, it was determined that the trace amounts of abrasive
which may be present would not constitute a health hazard because of the
small amount used and the low toxic nature of the materials. Of the three
materials used for sanding - garnet, silicon carbide, and aluminum oxide,
silicon carbide comprised only 5% of the number of abrasive belts used.

VENTILATION SYSTEM

Exhaust and Recirculation System

Dust-laden air was exhausted through five large blowers to a common inlet
plenum, was filtered and then returned to the room through seven plenums

2-2
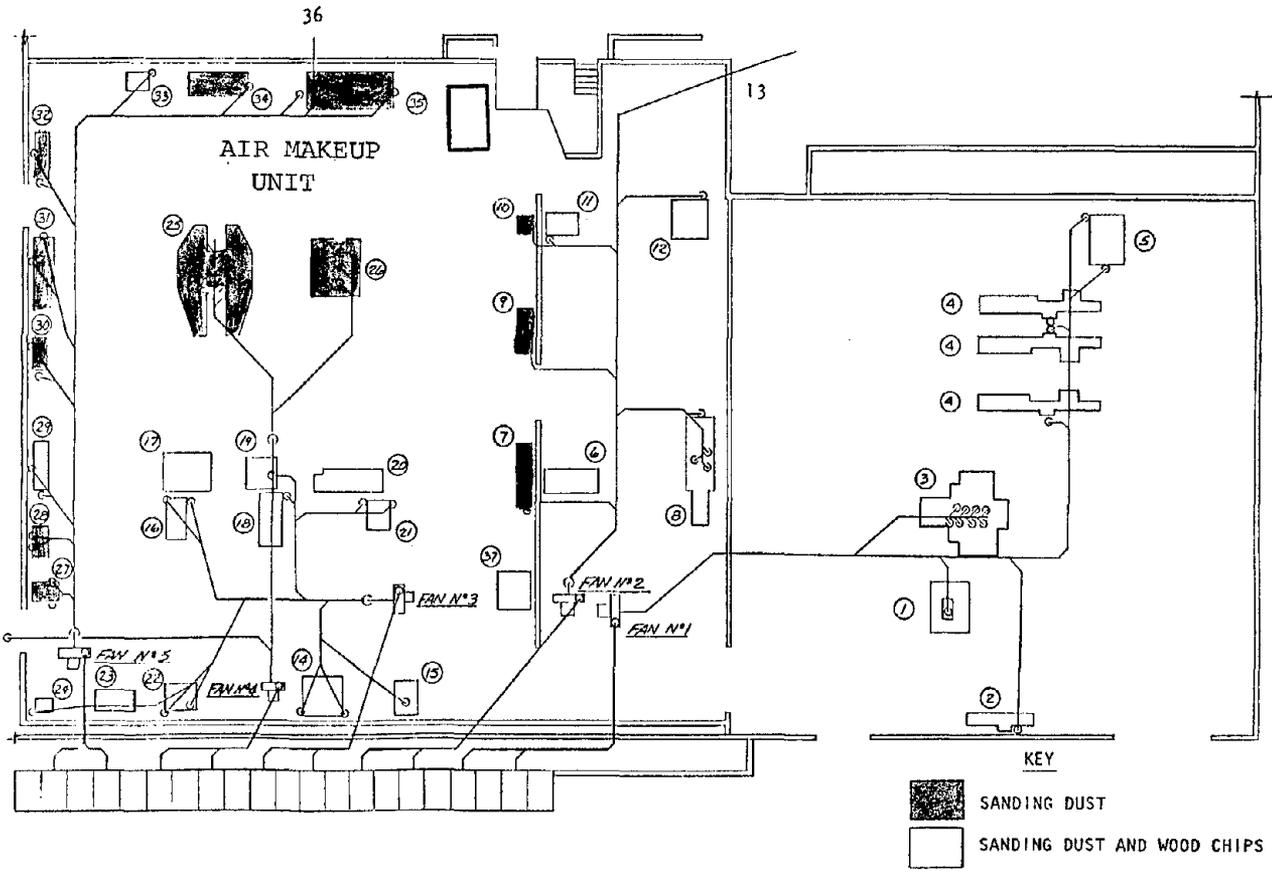
Figure 2-1. Plant layout.

which were located in the two manufacturing rooms mentioned previously. The dust collection system, which is pictured in Figure 2-2, consisted of a bank of 21 modular bag filter compartments which were specially designed for handling wood waste. The collector was designed such that wood chips entering the inlet plenum fell to a double chain conveyor for transport to a collection hopper which fed a wood waste boiler. Some of the pertinent design characteristics of the collector are summarized in Table 2-2.

Table 2-2. Dust collector summary.

Design flow rate	1242.7 m^3/min (43,850 cfm)
Number of modules	21
Module size	1.22 m x 1.83 m (4 ft x 6 ft)
Air to cloth ratio	7.2 : 1
Bag material, length	Cotton, 177.8 cm (70 in.)
Static pressure drop	3.6 cm H$_2$O (1.5 in.)
Explosion hazard protection	Explosion venting, spring latch on doors

Table 2-1. Woodworking machines connected to collector.

Connected to fan No.		Type of dust generated§	Location in Figure 2-1	Operated on sampling days
1	Surface planer	S-WC	1	Yes
	Radial arm chop saw	S-WC	2	Yes
	Double end tenon machine	S-WC	3	Yes
	Chop saw (3)	S-WC	4	Yes
	Gang rip saw	S-WC	5	Yes
2	Variety saw	S-WC	6	No
	Polisher	S	7	Yes
	Moulder	S-WC	8	Yes
	Edge sander	S	9	Partial
	Polisher	S	10	No
	Boxing machine	S-WC	11	No
	Single end tenon machine	S-WC	12	No
	Belt sander	S	13	No
3	Double spindle shaper	S-WC	14	Yes
	Router	S-WC	16	Yes
	Bandsaw	S-WC	16	Yes
	Vertical multi-bore	S-WC	17	Yes
	Variety saw	S-WC	18	Yes
	Router	S-WC	19	Yes
	Mortise machine	S-WC	20	No
	Variety saw	S-WC	21	Yes
	Automatic shaper	S-WC	22	Yes
	French dovetail	S-WC	23	Partial
	Vertical boring machine	S-WC	24	Partial
4	Double end edge sander	S	25	Partial
	Wide belt sander	S	26	Yes
	Truck connection	S-WC	-	No
5	Pump drum sander	S	27	Yes
	Vonnegut lead flap sander	S-WC	28	No
	Automatic profiler	S-WC	29	No
	Edge sander	S	30	Partial
	Moveable mold block sander	S	31	Yes
	Hand block sander	S	32	Yes
	Router	S-WC	33	No
	Fixed mold block sander	S	34	No
	Belt sander	S	36	No
Not connected	Horizontal boring machine	S-WC	37	Yes

§ S denotes sanding dust only.
  S-WC denotes sanding dust and/or wood chips.
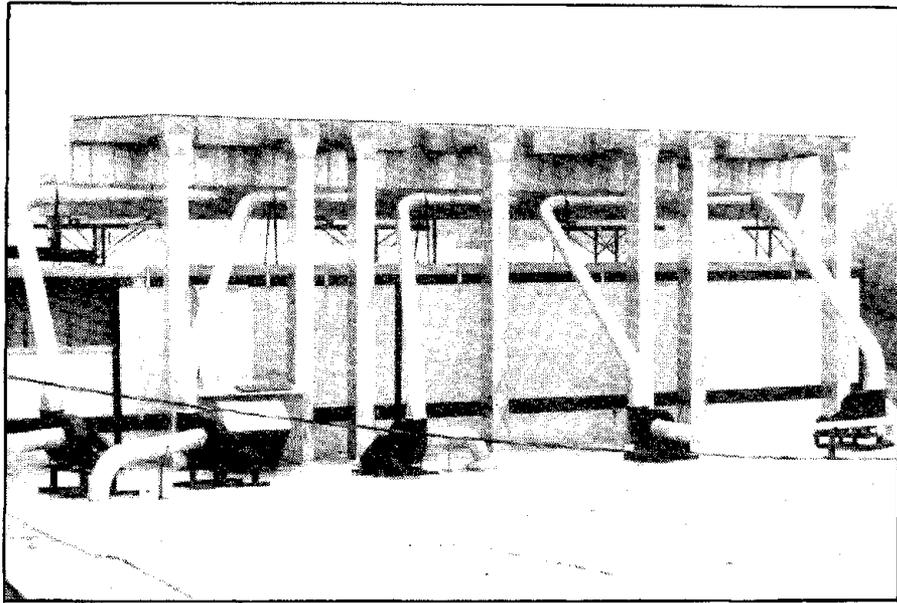
Front view of inlet ducts, fans, collector modules, and
outlet ducts. Woodworking room is located below roof in
foreground.
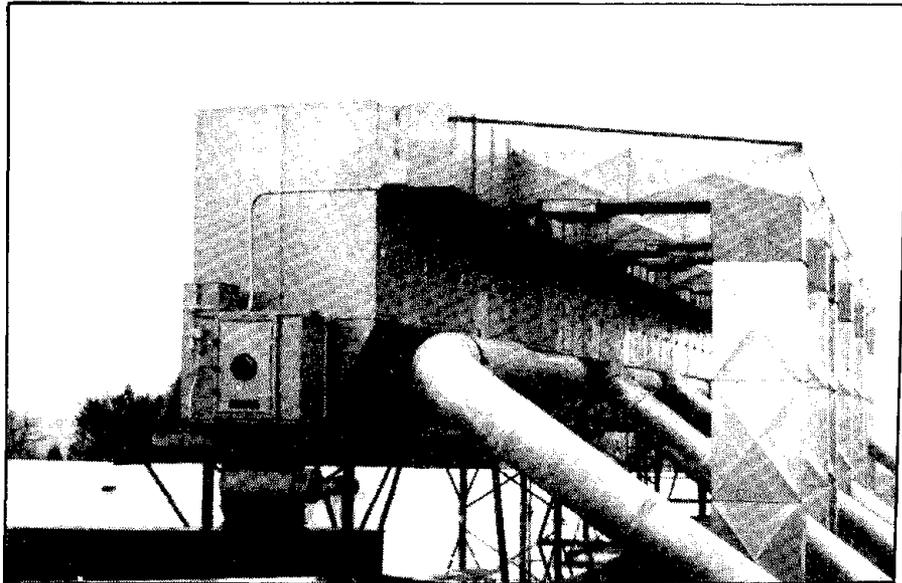
Side view of collection system with conveyor transfer
point in left foreground

Figure 2-2., View of dust collection system.

Table 2-2 (continued).

Fire hazard protection	Whenever the temperature exceeds 71°C, fire dampers will close between modules and fans will shut down; internal sprinkler system will activate
Cleaning mechanism	Pressure redirection in each module, one at a time, with a 1.12 KW (1.5 hp) fan
Initial cost of collector, installed	$74,700
Ductwork	$36,700

Air Make-Up

A large make-up air supply was located in the larger of the two machine rooms shown in Figure 2-1. The capacity of the unit was 850 m^3/min (30,000 cfm).

METHODS

In-Duct Sampling

Particulate concentrations were determined by isokinetically sampling the air cleaner inlet and outlet air streams. Because the logistics of simultaneous sampling of the inlet and outlet were prohibitive, five inlet ducts and seven outlet ducts were sequentially sampled to obtain an "average" particulate catch. The sampling apparatus which was used to perform the tests consisted of an in-stack filter holder, nozzle, pitot tube, and other necessary sampling hardware. The sampling methods and apparatus are fully described in the Methods section of this report.

Particle size measurements were made by isokinetically sampling with a Sierra Model 226 Source Cascade Impactor. A full description of the impactor and the sampling method also appears in the Methods section.

In-Plant Sampling

Breathing zone measurements were made using personal sampling pumps. Work-place measurements were also made with sampling pumps in conjunction with a portable dust measuring instrument. Again, the sampling procedures and a description of the equipment is presented in the Methods section.

RESULTS OF SAMPLING PROGRAM

In-Duct Measurements

Particulate Measurements--
The objective of the in-duct particulate sampling tests was to characterize

the performance of the dust collector by determining the concentration of particulate in the inlets and return air streams. The tests found that the collector operated at a 99.65% average efficiency during the survey. The efficiency must be called "average" because the sampling was performed sequentially on the five inlet ducts and seven outlet ducts, respectively. A summary of the sampling results is found in Table 2-3. A tabulation of pertinent data relating to the particulate and particle size tests is presented in Table 2-4.

Table 2-3. Results of in-duct measurements.

Stack number (refer to Figure 2-2)	Dust collected, mg	Sample volume, sm^3	Concentration, mg/m^3
Inlet			
1	185.01	0.118	1,567.9
2	1.66	0.122	13.61
3	111.61	0.115	970.5
4	36.67	0.997	367.8
5	4.58	0.102	44.9
		Average	592.9
Outlet			
6	0.33	0.567	0.582
7	0.19	0.554	0.343
8	0.19	0.527	0.360
9	0.19	0.506	0.376
10	4.65	0.507	9.172
11	0.50	0.194	2.577
12	0.22	0.203	1.084
		Average	2.071

The average outlet concentration in the return air was 2.071 mg/m^3 Comparing the individual return air concentrations, it was apparent that one end of the collector was not operating as efficiently as the remainder of the collector. The average concentration in stack numbers 10, 11 and 12 was 4.28 mg/m^3, a value much higher than the average concentration of 0.42 mg/m^3 for stack numbers 6 through 9. This indicates that there may have been a leak in one or more of the bags. Even one hole could explain the higher readings in several ducts because the collector outlet plenum was common to all return air ducts. Noticing that one filter pad collected more dust than the others, the maintenance crew was alerted to investigate the problem. After a thorough inspection, it was found that one of the bags was unattached at the bottom, and that another had developed a small tear. It should be noted that workers in the room did not appear to notice or report the collector malfunction.

Assuming that the filtration efficiency in the section of the baghouse exhausted by stack numbers 10, 11, and 12 will be similar to the other

Table 2-4. Summary of in-duct sampling data.

Location	Duct No.	SP (avg), in. H$_2$O	$\sqrt{VP}$ (avg), in. H2O	ΔH (avg), in. H$_2$	V_M std. m^3	Weight on filter, mg	Backwash weight, mg	Loading, mg/m^3
Inlet	1	6.8	1.42	0.65	0.118	181.23	3.78	1567.9
Inlet	2	6.0	1.47	0.75	0.112	1.30	0.36	13.61
Inlet	3	6.5	1.46	0.70	0.115	55.65	55.96	769.7
Inlet	4	6.0	1.24	0.50	0.099	32.98	3.69	367.8
Inlet	5	7.2	1.08	0.40	0.102	2.21	2.37	44.9
Outlet	6	0.5	0.36	2.0	0.567	0.33	0	0.582
Outlet	7	0.5	0.32	2.0	0.554	0.19	0	0.343
Outlet	8	0.5	0.35	4.0	0.527	0.19	0	0.360
Outlet	9	0.5	0.35	4.0	0.506	0.19	0	0.376
Outlet	10	0.5	0.34	3.5	0.507	4.10	0.55	9.172
Outlet	11	0.5	0.36	2.0	0.194	0.39	0.11	2.577
Outlet	12	0.5	0.39	2.0	0.203	0.08	0.14	1.084
Particle sizing								
Outlet (A)	7	0.5	0132	0.6	0.179	0.99	0	5.531
Outlet (B)	8	0.5	0.35	0.6	0.229	1.47	0	6.419
Inlet (C)	4	6.0	1.24	0.6	0.068	2.54	34.79	548.97

sections after repairs are made, the average outlet concentration would be 0.42 mg/m^3. The overall collection efficiency would then be 99.93%.

The inlet tests indicated an extremely wide range of dust loadings, ranging from a low of 13.61 mg/m^3 to a high of 1567.9 mg/m^3. The wide variability in inlet dust concentrations is evidently due to two factors:

1. Differing numbers of machines were operated on the various branch ducts during the survey.

2. Different machines produced vastly dissimilar amounts of dust. For example, the low inlet concentration measured in stack no. 2 reflected the fact that only two of eight machines on that duct branch were operated during the test.

Although inlet concentrations were highly variable, the outlet concentrations in the good sections of the baghouse were very constant during the sequential in-stack tests. However, the mass concentration measured in particle size tests (also shown in Table 2-4) indicate much higher concentration than expected in outlet ducts no. 7 and no. 8. The possible explanation of this finding is that either:

1. Some cross-contamination of dust may be originating from the neighboring malfunctioning ducts.

2. Since the tests were performed sequentially, not simultaneously, a much higher inlet loading may have occurred in the suspected sections of the collector during the particle size test than in the previous particulate tests.

Particle Sizing--
Not susprisingly, the particle size measurements in the outlet indicated that the particles leaving the collector were typically very much smaller than inlet particles. Particle size tests in outlet ducts no. 7 and no. 8 indicated that the mass median diameter of particles leaving the collector was 6.7 and 11.0 micrometers, respectively. The outlet size distributions are plotted in Figure 2-3. Raw data is presented in Table 2-5. The results of the inlet tests are presented, but unfortunately they could not be meaningfully plotted. As the data show, 93% of the particles were captured in the impactor's cyclone, indicating that this fraction had a mass median diameter larger than 50 micrometers.

In-Plant Measurements

General Area and Breathing Zone Measurements--
During the survey, general area and personal measurements were made to characterize in-plant emission levels. Of the ten to fifteen persons operating machines at any one time, four machines were selected for personal sampling which represented varying distances from the return air plenum. Additionally, two of these were selected based on the plant manager's judgement that they operated machines which generated the greatest amount of dust. Two sampling pumps were situated in the room to characterize concentration levels both close to and distant from the return air outlet ducts.
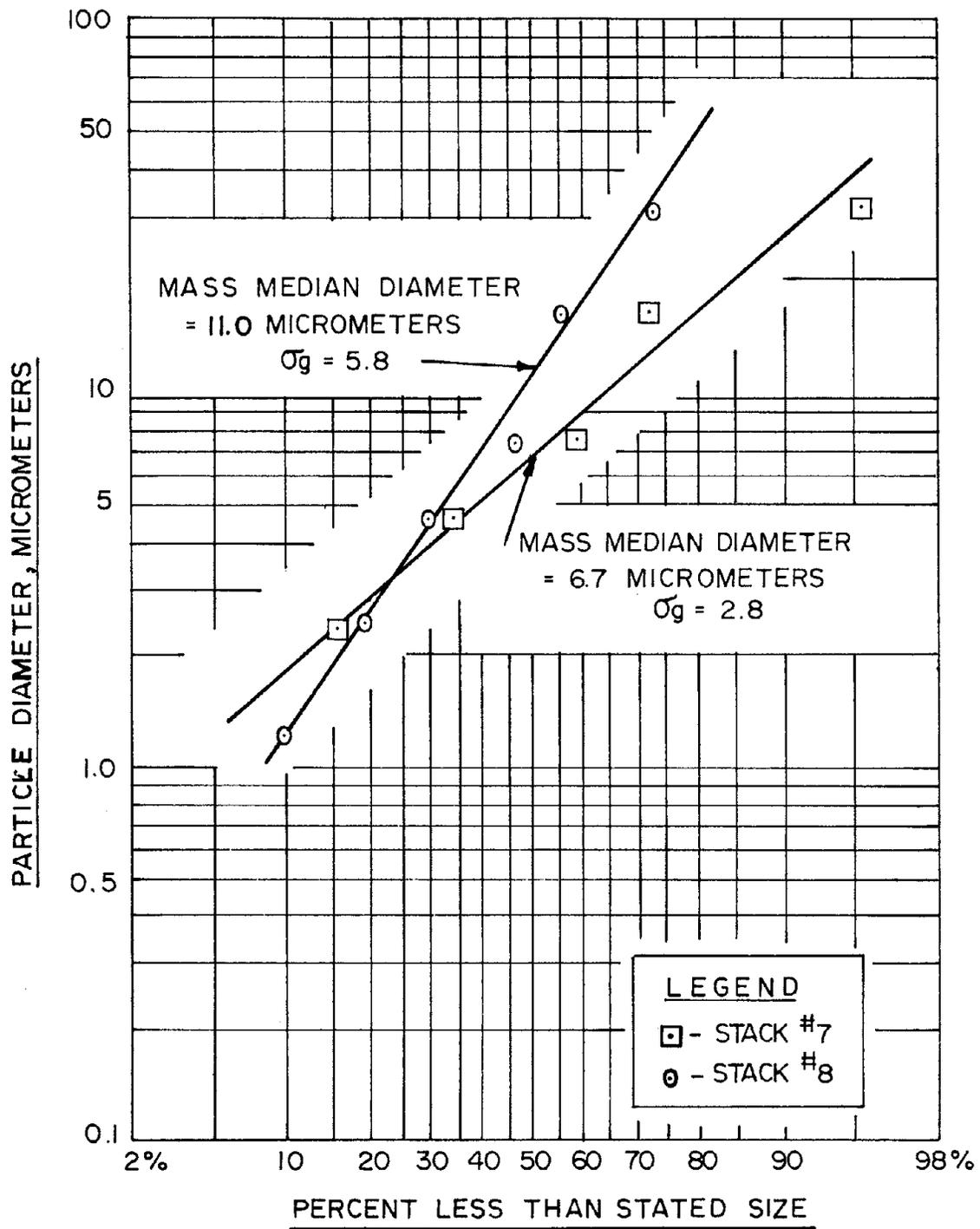
Figure 2-3. Outlet particle size distributions.

Table 2-5. Results of particle size tests.

Stack	Stage	Weight on filter, mg	Particle diameter, micrometers	Percent in range	Cumulative percent less than lower size
7 (outlet)	0	0.05	>30.2	5.0	95.0
	1	0.23	16.3 - 30.2	23.2	71.8
	2	0.14	7.4 - 16.3	14.2	57.0
	3	0.24	4.5 - 7.4	24.2	33.4
	4	0.17	2.3 - 4.5	19.2	16.2
	5	0.16	1.2 - 2.3	16.2	0
	6	0	$\leq$1.2	0	0
	Total	0.99		100.0	
8 (outlet)	0	0.39	>30.2	26.6	73.4
	1	0.28	16.3 - 30.2	19.0	54.4
	2	0.12	7.5 - 16.3	8.2	46.2
	3	0.24	4.5 - 7.4	16.3	29.9
	4	0.15	2.3 - 4.5	10.2	19.7
	5	0.14	1.2 - 2.3	9.5	10.2
	6	0.15	$\leq$1.2	10.2	0
	Total	1.47		100.0	
3 (inlet)	Cyclone	34.79	>50	93.0	7.0
	0	0.18	30.2 - 50.0	0.5	6.5
	1	0.27	16.3 - 30.2	0.7	5.8
	2	0.66	7.4 - 16.3	1.8	4.0
	3	0.53	4.5 - 7.4	1.4	2.6
	4	0.22	2.3 - 4.5	0.6	2.0
	5	0.55	1.2 - 2.3	1.5	0.5
	6	0.18	<1.2	0.5	0
	Total	37.38			100.0

In-plant measurements indicative of plant conditions without the recirculation of exhaust air were made on a pre-survey trip. Eight total dust measurements were made with a portable, direct reading monitor while the exhaust air was bypassed to the outdoors. Being a mild day in mid-fall, the plant was generally more open than during the later evaluation, a condition which undoubtedly contributed some reduction in concentrations within the workroom. Nevertheless, some doors and windows were allowed to be shut and measurements are believed to be indicative of the approximate concentration range present in the room. Concentration measurements were generally made as close to worker as possible to obtain an idea of the approximate level of contaminants in the breathing zone.

All in-plant measurements are presented in Table 2-6, while the sampling locations are indicated by their number surrounded by a triangle in Figure 2-4. For reference, return air duct locations are presented by their number enclosed by a square.

Table 2-6 indicates that there is not much difference between measurements taken before and after recirculation. Indeed, the average area measurement was slightly lower after recirculation than before. Two personal measurements (nos. 1 and 2) taken after recirculation on processes known to generate high dust levels resulted in the highest measured dust concentrations, 0.62 mg/m^3 and 0.67 mg/m^3, but even these levels were almost on order of magnitude lower than the 5 mg/m^3 level recommended by ACGIH for non-allergenic wood dust (8).

As expected, the area measurement (no. 6) farthest from the return air streams in a remote corner was lower (0.07 mg/m^3) than the measurement (no. 5) taken directly in the air path of recirculated air (0.18 mg/m^3). Pre-recirculation measurements were all low and were approximately the same level as was measured after recirculation at the more typical woodworking machines and in general plant areas.

The air patterns in the machine rooms which were observed during the survey are shown in Figure 2-5. Because all the return air ducts and the air make-up unit (occasionally operated) were located in one machine room, the room was under positive pressure. Prior to the survey, plant personnel noted that high air velocities at the return duct locations caused dust on the floor to occasionally become airborne after recirculation and caused over-cooling of workers. This problem was later partially corrected, before the survey, by placing baffles around the return air openings to direct the flow down aisles and away from workers.

Summary of Sampling Program

1. Particulate tests indicated that the collector operated at an average efficiency of 99.65%, although during the test a small breakthrough was found to have occurred at one end of the collector. Assuming that the repaired collector will have outlet concentration levels similar to the good test results, the collector efficiency may be as high as 99.93%.

Table 2-6. Summary of workplace measurements.

Sample location	Sample type	Total dust concentration, mg/m^3
After recirculation		
1	Personal	0.62
2	Personal	0.67
3	Personal	0.24
4	Personal	0.18
5	Area	0.07
6	Area	0.18
Average - Personal		0.43
Average - Area		0.13
Average - Personal and Area		0.33
Before recirculation		
7	Area[*]	0.18
8	Area[*]	0.30
9	Area[*]	0.19
10	Area[*]	0.36
11	Area[*]	0.10
12	Area[*]	0.20
13	Area[*]	0.30
14	Area[*]	0.12
Average		0.22

*Indicates measurement by automatic monitor.

Figure 2-4. Air sampling locations.

KEY

☐ RETURN AIR DUCT LOCATION
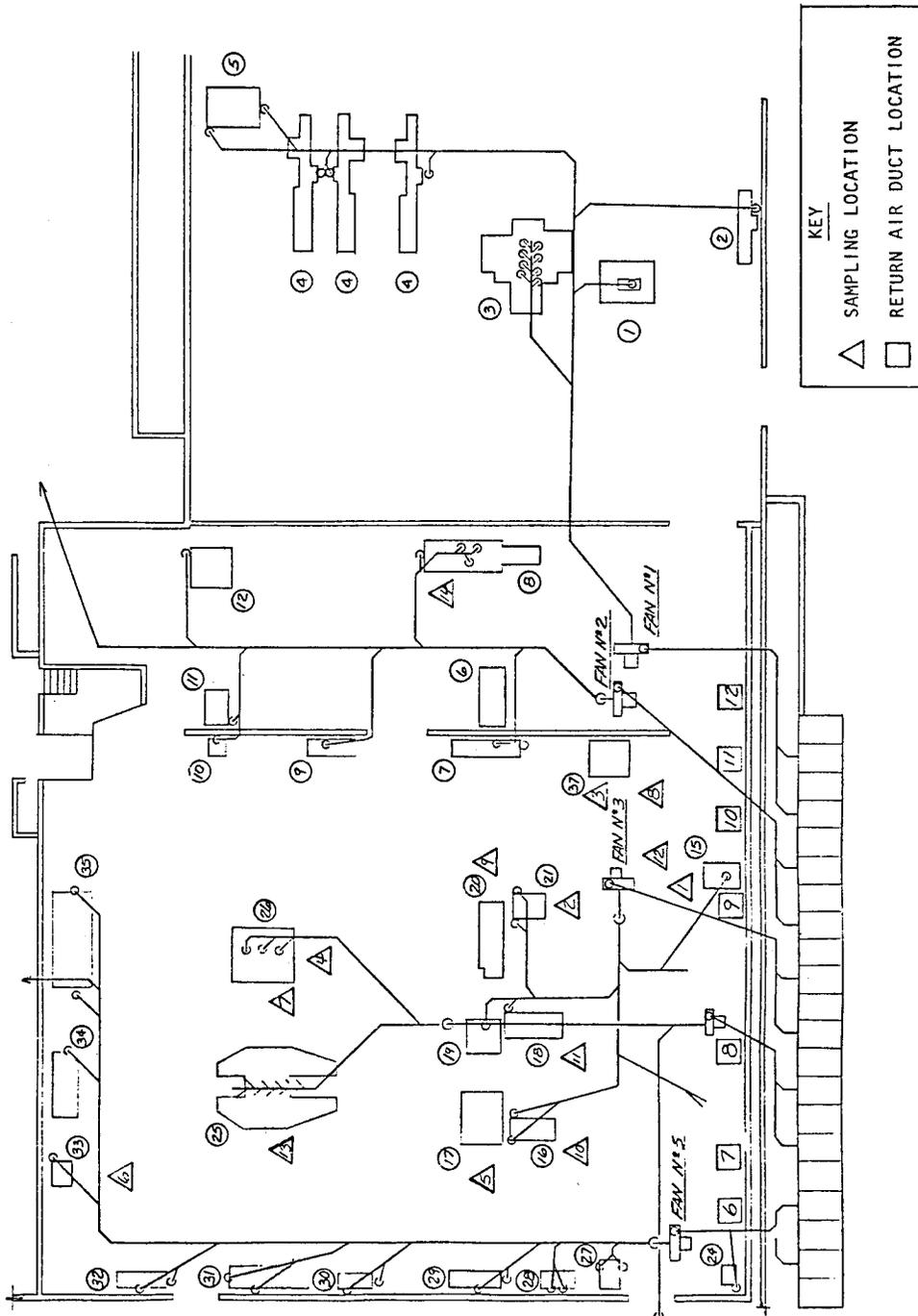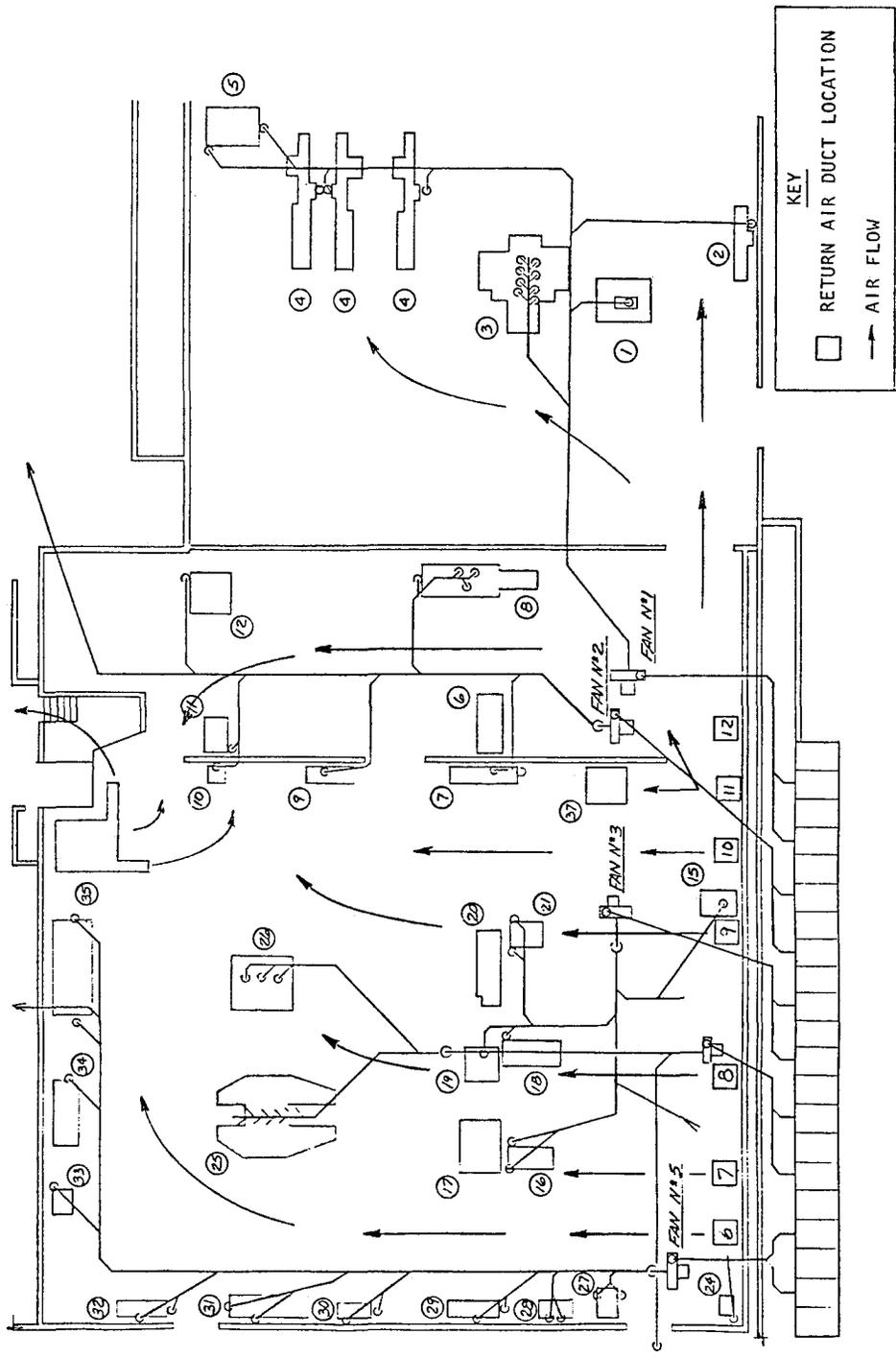
→ AIR FLOW

Figure 2-5. Air velocity patterns in machine rooms.

2. Impactor measurements indicated that particles in the outlet were 6.7 to 11.0 micrometers in diameter, while particles in the inlet dust stream were very large, typically greater than 50 micrometers.

3. Wood dust was not a hazard before or after recirculation. Measurements taken before and after recirculation did not indicate a noticeable change in total dust concentrations as a result of recirculation.

RETROACTIVE ASSESSMENT OF DESIGN APPROACH

Introduction

The preceding evaluation described the characteristics of the process, ventilation, and contaminant concentration levels, but it did not address all of the issues which a design team must face when considering recirculation, nor did it address the methodology presented in Reference One. Therefore, to evaluate the usefulness of the design approach recommended by Reference One, a retroactive assessment of this plant situation will be made using the criteria provided by Reference One. As a first step, an initial feasibility assessment will be performed utilizing the criteria presented in Chapter 2 of that document.

Initial Feasibility Assessment

The purpose of the initial feasibility assessment is to pre-screen major issues which will likely affect the chances of the design's success in an attempt to uncover insurmountable aspects of the program which may prevent recirculation. Through this step, unnecessary efforts and expenses for field sampling, hardware evaluation, and design optimization can be prevented. Following this preliminary assessment, a more in-depth evaluation of contaminants, air cleaners, and monitors would be performed. After key aspects of the design are understood, the modeling approach presented in Reference One would then be used to determine the required efficiency of a collector, and to finalize a system configuration which would achieve acceptable breathing zone concentrations.

Initial Feasibility Assessment

Legal Issues--
State and federal regulations governing the recirculation system currently do not prohibit recirculation providing breathing zone contaminant concentrations do not exceed permissible exposure levels. Thus, no legal considerations currently exist which would restrict recirculation of wood dust.

At the time of this writing, however, a criteria document for wood dust is being reviewed by NIOSH (10). Among its considerations is the possibility that the recommended limits be substantially reduced based on studies associating wood dust with increased incidences of nasal cancer. Even at this time, however, considerable controversy exists over the implications of these health studies and the effect they will eventually have on the recommended levels. In view of the uncertainty of these health studies and the as yet

unannounced recommended level, the remainder of this evaluation will consider the current, applicable recommended levels and standards. Designers of future recirculation systems involving wood dust should keep abreast of new evidence from health studies and possible lowered recommended levels.

Energy Consumption--
The use of natural gas to heat make-up air was not only a significant expenditure for this plant, the threat of gas curtailments was also an important concern. Consequently, it was desirable to install a new collector and wood waste boiler system which eliminated the plant's dependence on natural gas. The primary factor motivating the plant to install a new system was, however, the need to comply with local air pollution regulations. Table 2-7 summarizes the changes in fuel use experienced by the plant following installation of the collector and boiler.

Table 2-7. Comparison of energy requirements
before and after installation.

Factor changed	Before	After
Fuel source	Boiler fired with wood, natural gas and coal.	Boiler fired only with wood.
Air make-up and conditioned air	Ten unit heaters fueled by natural gas.	All unit heaters used steam heat from boiler.
	Two air make-up units fueled by natural gas.	Both air make-up units used steam heat from boiler.
		Recirculation of collector exhaust.

The new boiler represented a great improvement from the previous system because it was solely fired by wood scraps from the new collector and from other scraps hauled from another woodworking plant nearby. With the use of recirculated air and the wood-fired boiler, this plant completely eliminated its use of natural gas and other non-wood boiler fuels.

The actual cost savings attributed only to recirculation can be roughly estimated by calculating the cost to heat an equivalent amount of make-up air with natural gas (4). Such a calculation would show that the cost savings from recirculation is approximately $3,900 per year, or $3.10 per m^3/min (8.8¢ per cfm).

Comparing this to the total capital and installation cost of the system, $101,400, one can see that recirculation is not cost-effective in itself but helps to offset required expenditures. The benefits derived from burning of wood scraps for process heating would represent an additional increment of savings for the plant.

Contaminant Classification--
Wood dust, being the only contaminant present in the machine room, is
generated in various sizes and amounts depending on the operation. Estimates
of the amount generated could be made by reviewing various collector
manufacturers' literature or by knowledge of similar processes in other
plants. Although the amount generated by the woodworking machines is not
precisely known, the lack of an exact generation rate should not be a
barrier to recirculation.

It is also important to have knowledge of contaminant concentrations in the
workplace and in the breathing zone prior to recirculation. The plant did
not make any measurements in the workplace, presumably because they assumed
that the contaminant levels were below the permissible exposure levels
through visually observing the airborne dust and/or previous knowledge of
the concentration levels to be expected.

With regard to the permissible exposure level, there is currently some
controversy as to whether wood dust may be considered a nuisance dust for
regulation purposes. The Occupational Safety and Health Review Committee
has held that the nuisance dust standard is appropriate for mineral dust
only, not organic dusts, of which wood happens to be an example(11). This
ruling does not completely clarify the situation, however, because it
does not leave the industrial hygienist with a regulated standard upon
which to base a control strategy or, in this case, a design. In the
absence of a permissible exposure level, the design team could refer to the
ACGIH Threshold Limit Value of 5.0 mg/m^3 for non-allergenic wood dust (8).
This value will be used as a basis for design in the following discussion.

In addition to the effect of wood dust on respiratory functions, some
varieties of wood dust, such as red cedar, may cause certain individuals to
be sensitized. However, the common varieties used at this plant, e.g.,
pine, oak, gum, hickory, and poplar, do not usually cause such reactions (12).

Air Quality Regulations--
Compliance with ambient air quality regulations clearly provided an
incentive for the plant to install the new collector. However, economic
benefits prompted the decision to recirculate the cleaned exhaust once
the decision was made to purchase the collector.

Air Cleaner Availability--
Since the contaminant generated in this process is a dry particulate,
collection by filtration should be an effective method of reducing the
contaminant levels. In the wood industry, fabric filtration has proven
to be a highly efficient and useful method for capturing wood dust, and
thus represents a likely choice for the design team.

Monitor Availability--
Assuming that fabric filtration is selected in this design, the issue of
surveillance is directed toward the failure modes of the fabric filter.
Reduced performance of fabric filters may be automatically detected by one
of the following methods: broken bag detector (opacity monitor),
differential pressure sensor, or particulate monitor. Although visual

monitoring also is an attractive choice because of its obvious low cost, no choice is made in the preliminary step. It is not necessary for the design team to choose the best method of detection in the initial assessment but only that they realize that several options are available.

Process Emission Profile--
Woodworking machines produce differing quantities and particle sizes of a single contaminant. However, it is probably not critical that these fluctuations be considered in the system design. High removal efficiencies are expected, consequently small variations in outlet concentrations would have little adverse impact on the quality of the return air. This assumption should be verified after the generation rates are measured, however.

Ventilation System Design--
This issue concerns whether or not the proposed design of the recirculation system will be adversely affected by aspects of existing ventilation systems or by the effects of proposed changes that will result from the design. No major barriers relating to existing ventilation systems are evident at this point in the design. Some consideration must obviously be given to the placement of the new collection system and the method of introducing the return air, i.e., the number of return air duct locations. Designing a system with multiple ducts may, for example, complicate the use of the methods available for monitoring system failures.

Summary of Initial Feasibility Assessment--
Although none of the eight issues presented immediate barriers to recirculation, the preliminary assessment was useful in that it forced the design team to consider the major aspects of a proposed program, and to address important issues in further evaluations. Among its significant findings, it was noted that the lowering of recommended levels may affect the suitability of the design; that the energy savings from recirculation are substantial; that there is no OSHA PEL to design around; that air quality regulations provide the major incentive for a new collection system; that suitable air cleaning and monitoring equipment are available; that the variation in generation rates will have to be quantified to determine the effect on the final design, and that the prospect of having seven return air ducts may pose serious questions concerning surveillance with automatic monitors.

In-Depth Design Evaluation

As the design team investigates the feasibility of recirculation further, an in-depth evaluation of the contaminant types, the availability of collectors, and the available monitoring strategies is performed to finalize important aspects of the design.

Contaminant Characteristics--
The woodworking machines generate a mixture of sanding dust and wood chips on an intermittent basis. According to the literature, wood chips are often several centimeters in size while much of the sanding dust is below 15 micrometers. One manufacturer's bulletin has suggested that dust generated from woodworking operations may be grouped into the following size and concentration categories (13).

Table 2-8. Typical concentrations and sizes of wood dust.

Operation	Concentration, mg/m^3	Mass median diameter, micrometers
Planing	4600-6900	>15
Sawing	1100-6900	7-15
Sanding	1100-6900	7-15

Prior to installation of the dust collection system, the company made one calculation of the expected generation rate from sanding operations using information supplied in an equipment bulletin (14). Based on a generation rate of 0.013 m^3/hr of sanding dust with a density of 0.64 gm/cm^3 (40 lb/ft^3), a 1133 m^3/min (40,000 cfm) dust collector would experience an inlet concentration of 126 mg/m^3. The disparity between this value and the previous concentration estimate for sanding dust (1100-6900 mg/m^3) emphasizes the danger in using information from sales bulletins for design purposes.

Obviously, the best estimate of the inlet concentration could have been made by conducting source tests on the various inlet ducts of the old collection system. Had the design team done this, results similar to the inlet concentrations presented in Table 2-3 would have been found.

The current uncertainties regarding the toxicity of wood dust have already been discussed, so no further explanations will be presented on the OSHA regulated and ACGIH and NIOSH-recommended levels. It is important to recognize, however, that wood dust is also hazardous from the standpoint of flammability and explosivity. These characteristics are important considerations when selecting an air cleaner.

The fact that the plant did not measure workplace or breathing zone concentrations prior to recirculation adds a degree of uncertainty with respect to the suitability of the design, especially in view of the possible lowering of the recommended level. It is always advisable to make pre-recirculation measurements regardless of the level of toxicity of the contaminant or apparent degree of control existing in the working environment.

Selection of Air Cleaning Equipment--
In the wood industry, both cyclones and fabric filters are commonly selected to collect wood dust, depending on the degree of control required by ambient regulations. Because the old system utilized a cyclone which did not have a high enough efficiency required for recirculation, it will be assumed in this discussion that a fabric filter has been specified by the design team.

The particular fabric filter installed at the plant was chosen because of the plant's familiarity with the characteristics of the air cleaner in other woodworking applications. Additionally, the feature of recirculation was appealing to the company because the concept was advocated by the manufacturer in their sales literature and supported by reasonably scientific tests appearing in their brochure (14). For example, the tests showed that the average dust content in the outlet exhaust stream from a collector exhausting a wood polishing machine was 0.322 mg/m^3. In that test, the

collector operated at a 99.74% efficiency on primarily small sanding dust
particles. Because the collector chosen in this case study was similar
to the one tested, it could reasonably be assumed that an efficiency
approaching this reported value might be expected. A higher efficiency
might even be expected in this application because the collector manufacturer
expressed the belief that the collector could be expected to operate at
minimum efficiency of 99.9% for particles greater than 5 micrometers, and
at an efficiency of 99.6% for particles less than 5 micrometers (15).

Selection of Surveillance Equipment--
Reduced performance of the collector is addressed by first identifying all
of the possible ways a system could fail, and then selecting a strategy
which will adequately protect the worker's breathing zone for each of the
major failure modes identified. Each of the failure modes are first
identified for the chosen collector, then various approaches for selecting
an appropriate monitoring strategy are discussed.

Failure Modes--
The three major failure modes by which the collection system could fail are
identified in Reference One and are summarized below:

1. Air flow is reduced.
2. Air cleaner efficiency is reduced or becomes zero.
3. Uncleaned exhaust is discharged (leak in duct).

In this study, the third failure mode would not be applicable because a
leak between the exhaust fans and the collector would not affect in-plant
concentrations because this element of the system is located on the building
roof.

Once the major failure types are known, it is important that the inter-
relationships between system parameters which may be monitored and the
effects of the failures be identified during steady-state operation
conditions. Table 2-9 attempts to do this by showing how some major types
of failures may affect the outlet concentration, hood capture efficiency
and a system parameter, the pressure differential across the collector.
As shown, an increase in outlet concentration will result from a break-
through in the air cleaning media (failure no. 2). Reduced hood capture
efficiencies may result from bag blinding (failure no. 1), hood or duct
blockages (failure no. 3), or a failure of the fan or drive (failure no. 4).

The obvious system failure of operating the process without the exhaust
system can technically be classified as a major failure type, but it is
not presented in Table 2-9 because its effect is a complete absence of
performance, rather than a deviation from steady state.

Evaluation of Monitoring Strategies--
In the preliminary assessment, four monitoring methods were presented for
further scrutiny. One of these methods, visual monitoring, is suggested in
Reference One for consideration when a non-respirable dust with low toxicity
is the only contaminant present. Indeed, the use of visual monitoring is
attractive because the suggested restrictions of the method are not applicable.

Table 2-9. Principal modes of failure and effects.

Failure type	System parameter	Failure effects	
	Collector ΔP	Outlet concentrations	Hood capture efficiency
Air cleaner failures			
Failure 1 – Bag blinding due to overload, severe air failure	↑	↓	↓ (major)
Failure 2 – Media breakthrough, e.g., bag tear, burn holes, seal failures	↓	↑ (major)	↑
Exhaust system failure			
Failure 3 – Hood or duct blockage	↓	↓	↓ (major)
Failure 4 – Fan or drive failure	↓	↓	↓ (major)

↓ or ↑ denotes deviation from steady-state performance.

⎯⎯⎯ Major failure effects.

2-22

In this situation, i.e., only one particulate contaminant is generated, and the contaminant, wood dust, is presently considered to have low toxicity.

One particular concern of visual monitoring methods is that a small but significant failure of the collector might be able to occur without being noticed. Whether the exhaust stream would be immediately evident to the worker is a matter which should be settled under actual field conditions.

Evidence from the evaluation indicated that workers in this plant would not likely detect a substantial increase in the outlet concentration. During the evaluation, workers did not notice a collector malfunction which produced a concentration of approximately 9 mg/m^3 in one of the return ducts, and considerably higher than normal levels in two adjacent ducts. One explanation for their apparent lack of attention may be due to the almost immediate dilution of the partially contaminated return air streams with the higher quality air in the remaining ducts. Another plausible reason for the non-observance was that the employees were not adequately instructed to notice and respond to visual changes in the outlet loading.

Returning to the issue of whether or not visual monitoring should be considered, visual monitoring is obviously appealing because alternate strategies involving the use of automatic in-duct sensing devices are clearly uneconomical because seven monitors would be needed to simultaneously measure the seven return air ducts. Similarly, the prospect of monitoring room concentrations instead of in-duct concentrations would likely require multiple, automatic monitors which also would be uneconomical. It is clear that the present configuration involving multiple return air ducts encourages the use of a visual monitoring strategy as a means of failure detection.

There are uncertainties with visual monitoring which should be investigated by the company before the decision is made to recirculate, however. The plant could take one of two courses of action in this matter:

1. The effectiveness of similar recirculation systems could be evaluated prior to the committment to recir .late.

2. The company could proceed with the design and then conduct failure tests of the system room after installations.

In this latter strategy, the plant must be willing to accept the economic loss from a "no" decision, i.e., additional ductwork expense, time and expense for the failure evaluations, and the possible need to provide additional make-up air should the recirculation system prove infeasible. Additionally, the plant would considerably increase the likelihood of the success of the visual monitoring strategy through the implementation of an adequate worker education and training program.

Design Optimization Using the Model Approach

Choosing Appropriate Model--
The process of optimizing a design involves a carefully controlled balance of variables which may affect the outcome. The approach taken in Reference

One is to balance the variables by the use of a series of equations defined as a "model". From a generalized modeling approach presented in Reference One, the authors have developed a number of simplifications to provide modeling equations for several types of recirculation systems commonly found. The situation in this case study could be described by configuration no. 2 which is presented in Appendix B in Reference One and Figure 2-6 in this report. Either system configuration no. 1 or 2 would have been appropriate because both depict systems where local exhaust streams are recirculated. However, configuration no. 2 was chosen because this model better represents the case study since no provision is made for additional fresh air to be introduced into the return air stream.

Assigning Parameter Values--
Each of the parameters on the right hand side of the equations presented at the bottom of Figure 2-6 must be assigned an appropriate value to be able to calculate the following (left hand side) quantities:

Q_R - Return air volume rate.

Q_{MU2} - Make-up air supply rate for air not mixed with recirculated air.

C_R - The concentration of contaminants in the return air stream (to be predicted by the model).

η - The air cleaner efficiency which is required in the design to achieve the desired return air and breathing zone concentrations.
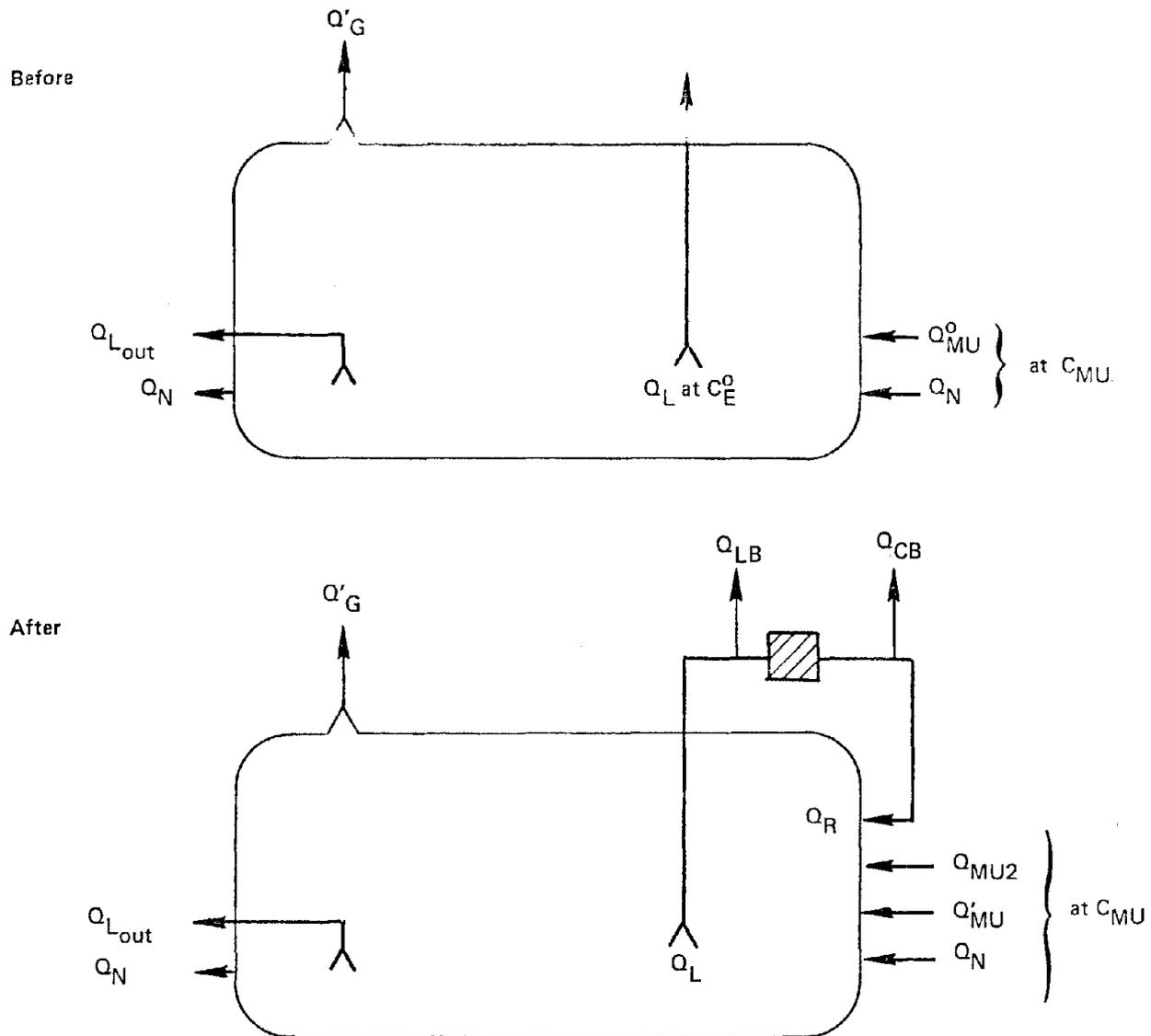
A summary of the remaining parameters, their assigned values, and a brief rationale for the value given is presented in Table 2-10. Since each of these parameters are fully discussed in Appendix A of Reference One, the discussion in this text will primarily be limited to the use of the parameters in the design optimization.

Design Approach--
In Figure 2-6, three equations are presented which may be used to predict the effects of recirculation on the breathing zone and to help select an air cleaner. The first equation merely allows for the possibility of bypassing air before or after the collector. The term Q_{LB} accounts for the bypass volume before the collector, while Q_{CB} denotes the rate of air bypassed after the collector. Hence, when no air is bypassed, the local exhaust rate from the process, Q_L, equals the rate returned, Q_R.

The second equation is simply an air balance on the room after recirculation. Its purpose is to find Q_{MU2}, the amount of make-up air brought into the room after recirculation, by calculating the amount of make-up air which should be provided to attain an air balance. Hence, the difference between this value and the make-up air rate before recirculation, Q_{MU}^O, is the savings in make-up air to be realized.

The next equation on the figure utilizes various parameter values to predict the contaminant concentration in air leaving the collector (C_R). It is

Before

Q'_G

$Q_{L_{out}}$

Q_N

Q_L at C_E^o

Q_{MU}^o

Q_N

at C_{MU}

After

Q_{LB} Q_{CB}

Q'_G

Q_R

$Q_{L_{out}}$

Q_N

Q_L

Q_{MU2}

Q'_{MU}

Q_N

at C_{MU}

See Discussion For Proper Design Procedure. Useful Equations are:

$$Q_R = Q_L - Q_{LB} - Q_{CB}$$

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

$$C_R = \frac{1}{k_{BZ}} \left[C_{BZ}^D - (1-f) \frac{Q_T^o}{Q_T} (C^o_{BZG} - C_{MU}) - f(C_{BZL}^o - C_{MU}) - (1 - k_{BZ}) C_{MU} \right]$$

$$\eta = 1 - \left[\frac{C_R}{C_E^o - k_R C_{MU} + k_R C_R} \right]$$

Figure 2-6. System configuration no. 2.

Table 2-10. Model parameter values.

Parameter	Description	Value	Rationale
Q_{LB}	Exhaust volume bypassed before collector	0	As a first approximation, assume all exhausted air returns to room.
Q_{CB}	Exhaust volume bypassed after collector	0	As a first approximation, assume all exhausted air returns to room.
$Q_{L_{out}}$	Local exhausts other than what is recirculated	0	There are no other local exhaust systems in the vicinity of the machine rooms.
Q_L	Initial volume of local exhaust stream	1242 m^3/min	Flow rate of old collector.
Q_{MU}^o	Make-up rate for conventional sysems prior to recirculation	850 m^3/min	Capacity of air make-up unit in machine room.
Q_{MU}	Fixed make-up supply rate	0	There are no fixed make-up sources in the area of interest, i.e., heat recovery sources.
k_{BZ}	Contribution factor of return air to breathing zones	1.0	Ventilation measurements indicate that workers near the return air ducts breathe only return air.
k_R	Contribution factor of return air to local exhaust systems	1.0	Ventilation measurements show that most of the machines receive only returned air. As a conservative estimate, a value of 1.0 is chosen.
Q_N^o	Infiltration rate before recirculation	392 m^3/min	Infiltration rate is the difference between the total amount exhausted and amount mechanically made up: $$Q_N = Q_{L_{out}} + Q'_G - Q_{MU}^o$$ $$Q_N = 1242 + 0 - 850 = 392$$

Table 2-10 (continued).

Parameter	Description	Value	Rationale
Q_T^O	Total ventilation rate before recirculation	1242 m^3/min	The total ventilation rate is the sum of the incoming rates due to make-up air and infiltration: $$Q_T^O = Q_{MU}^O + Q_N^O$$ $$Q_T^O = 850 + 392 = 1242$$
Q_R	Amount of exhaust returned to building	1242	Identical to the amount exhausted since there are no bypass rates specified in the design.
Q_N	Exfiltration rate after recirculation	850 m^3/min	The exfiltration rate is the excess amount of air leaving the room after recirculation due to the operation of the air make-up unit. It is identical to Q_{MU}^O.
Q_T	Total ventilation rate after recirculation	2092 m^3/min	The total ventilation rate is the sum of the recirculated air flow and exfiltration: $$Q_T = Q_R + Q_N$$
C_{MU}	Make-up air concentration	0	Assumed negligible
C_{BZG}^O	Initial breathing zone concentration in general plant areas	0.37 mg/m^3	Highest room measurement made prior to recirculation (Table 2-6).
C_{BZL}^O	Initial breathing zone concentration in the influence of large volume exhaust systems	0	No large volume local exhaust hoods are present in the area of interest.
f	Local exhaust system influence factor	0	No large volume local exhaust hoods are present in the area of interest.
C_E^O	Initial concentration of local exhaust stream	592.9 mg/m^3	Average inlet collector concentration (Table 2-3).

Table 2-10 (continued).

Parameter	Description	Value	Rationale
c_{BZ}^{D}	Desired breathing zone concentration	1.5 mg/m^3	As a first estimate, assume the desired concentration is 30% of the TLV for wood dust: $$0.3 \ (5.0) \ = \ 1.5 \ mg/m^3$$

followed by an equation which estimates the collection efficiency, η, required to achieve the previously calculated return air concentration.

These equations are used in the following design approach presented in Appendix B of Reference One:

1. Choose a value for Q_{CB} or Q_{LB}.

2. Compute values for Q_{MU2} and Q_R.

3. Based upon the magnitudes and expected distribution of Q_{MU2} and Q_R estimate values for k_{BZ} and k_R.

4. Compute the necessary C_R and the necessary fractional air cleaner efficiency η from the equation provided.

5. 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.

Modeling Results--
All of the calculations presented in this section are summarized in Table 2-11.

Calculation of the amount of air to be returned, Q_R--Use of the first equation results in the finding that the volumetric rate of air returned to the room is the same rate which is exhausted from the process. As noted previously, this simply is a consequence of not providing for bypass volumes before or after the collector in the design.

Calculation of the amount of make-up air required after recirculation, Q_{MU2}--The second equation indicates that no additional make-up air should be provided after recirculation, i.e., $Q_{MU2} = 0$. Since there are no bypass volumes (Q_{LB}, Q_{CB} = 0), no other locally exhausted processes ($Q_{L_{out}} = 0$), no general ventilation ($Q_{G}' = 0$), and no "fixed" sources of make-up air e.g., heat recovery from waste heat streams ($Q_{MU}' = 0$), then it is evident that the value of zero obtained for Q_{MU2} indicates that the air make-up rate provided before recirculation does not have to be supplemented. Indeed, the combined

Table 2-11. Model application calculations.

1.1. Equation No. 1

$$Q_R = Q_L - Q_{LB} - Q_{CB}$$

$$Q_R = 1242 - 0 - 0 = 1242 \text{ m}^3/\text{min}$$

2. Equation No. 2

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

$$Q_{MU2} = 0 + 0 + 0 - 0 = 0$$

3. Equation No. 3

$$C_R = \frac{1}{k_{BZ}} \left[C_{BZ}^D - (1-f) \frac{Q_T^o}{Q_T} (C_{BZG}^o - C_{MU}) - f (C_{BZL} - C_{MU}) - (1 - k_{BZ}) C_{MU} \right]$$

Simplification: $\quad C_R = \frac{1}{k_{BZ}} \left[C_{BZ}^D - \frac{Q_T^o}{Q_T} (C_{BZG}^o) \right]$

a. First estimate $\quad (C_{BZ}^D = 1.5 \text{ mg/m}^3)$

$$C_R = \frac{1}{1.0} \left[1.5 - \frac{1242}{2092} (0.37) \right]$$

$$C_R = 1.28 \text{ mg/m}^3$$

b. Second estimate $\quad (C_{BZ}^D = 1.0 \text{ mg/m}^3)$

$$C_R = 0.78 \text{ mg/m}^3$$

4. Equation No. 4

$$\eta = 1 - \left[\frac{C_R}{C_E^o - k_R C_{MU} + k_R C_R} \right]$$

Table 2-11 (continued).

---

a. First estimate $(C_R = 1.28 \text{ mg/m}^3)$

$$\eta = 1 - \frac{1.28}{592.9 - 0 + (1)\ (1.28)} = 0.9978$$

b. Second estimate $(C_R = 0.78 \text{ mg/m}^3)$

$\eta = 0.9978$

c. Third estimate $(C_R = 0.78 \text{ mg/m}^3, k_R = 0.62)$

$\eta = 0.9987$

---

effect of recirculation and the unchanged air make-up rate provides the area of the machine rooms with a positive air balance.

Calculation of the required return air concentration, C_R--The third equation presents a means to calculate the return air concentration once appropriate values have been determined for the parameters involved. To simplify the equation, several assumptions are first made. First, the concentration of contaminants in make-up air is assumed to be negligible ($C_{MU} = 0$). Second, the concept denoted by the term f does not apply in this plant, hence its value and the value of an associated parameter C^O_{BZL} can be considered 0. Both parameters are used in the model whenever there are local exhaust controls at which a worker's breathing zone is totally affected by changes in the total ventilation rate in the room. An example of such an exhaust control is the large walk-in spray paint booth. This concept is more fully explained in Appendix A of Reference One. The result of these initial assumptions is presented as a simplification of the third equation in Table 2-11. The five remaining parameters, k_{BZ}, C^D_{BZ}, Q^O_T, Q_T and C^O_{BZG}, will be discussed in their order of appearance.

The parameter k_{BZ} denotes the volume fraction of return air entering the breathing zone of workers. Because the cleaned exhaust air is returned directly to the working area, it is not conservative to assign this parameter a value of 1.0.

The term C^D_{BZ} has an important effect on the design because it denotes the breathing zone concentration which is desired after recirculation. Since the level of C^D_{BZ} which is chosen depends, in part, on the pre-recirculation concentration of contaminants, it is realized that the lack of such data would cause the design team some difficulty in deciding what level below the permissible exposure level is an acceptable value for C^D_{BZ}.

In the absence of pre-recirculation measurements, the measurements which were made with the installed system in the bypass mode (see Table 2-6) will be used in the design because they are representative of the general contaminant level in the breathing zone. Since the highest concentration measured, 0.36 mg/m^3, is substantially below the ACGIH recommended level of 5.0 mg/m^3, an initial choice of a c_{BZ}^D of 1.5 mg/m^3, for example, leaves a considerable margin of safety in the design. Of course, the final level may be even lower if the collector selected for use in the design has a higher efficiency than what is specified in the calculations.

The terms describing the total ventilation rate before (Q_T^O) and after (Q_T) recirculation are defined in Reference One as either the sum of all volume rates of air mechanically made-up before (or after) recirculation, or alternatively, it can be considered the sum of all exhaust flows (plus the recirculated air flow after recirculation). This definition of the total ventilation rate has two inherent assumptions:

1. That all mechanically extracted air is mechanically made-up, i.e., an air balance exists both before and after recirculation.

2. That the model input term denoting the rate of natural ventilation, Q_N, represents ventilation caused only by naturally occurring forces, and that this rate is the same both before and after recirculation.

The first assumption is violated because in this case study, there was a deficit of make-up before recirculation in the machine rooms. This lack of make-up air caused air to infiltrate into the room because of the resultant negative pressure condition. Conversely, after recirculation was implemented, the company did not reduce the amount of make-up air provided, resulting in a positive pressure condition. This positive pressure caused air to exfiltrate from the room. These deviations from the assumed conditions, namely, the lack of an air balance and the resultant effects of pressure-induced infiltration and exfiltration, need to be re-evaluated before equation no. 3 can be applied to this plant situation.

Before recirculation, the amount of infiltration is the difference between what is extracted and what is mechanically made up. This infiltration rate can be denoted by a new term, Q_N^O, which is now defined as the combined rate of natural ventilation and infiltration before recirculation. Similarly, the combined rate of exfiltration and natural ventilation after recirculation will be denoted by the term, Q_N. To simplify this analysis, it is assumed that the ventilation rate from naturally occurring sources, i.e., wind forces is negligible, resulting in these two terms describing only pressure-induced infiltration and exfiltration. The values for these terms are presented in Table 2-10.

The total ventilation rate may now be calculated. The total ventilation rate before recirculation is the sum of the amount of air made up and the amount of infiltration (Q_N^O):

$$Q_T^O = Q_{MU}^O + Q_N^O$$

Substituting (see Table 2-11 for assigned values of Q_N^O and Q_{MU}^O),

$$Q_T^O = 850 \ m^3/min + 392 \ m^3/min$$

$$Q_T^O = 1242 \ m^3/min$$

Similarly, the total ventilation rate after recirculation is the sum of the recirculated air flow plus the amount of exfiltration:

$$Q_T = Q_R + Q_N$$
$$Q_T = 850 \ m^3/min + 1242 \ m^3/min$$
$$Q_T = 2092 \ m^3/min$$

Note that the total ventilation rate substantially increased after recirculation was implemented.

The only remaining term, C_{BZG}^O, has already been assigned a value in the discussion of the desired breathing zone concentration.

Now that all of the parameters have been defined, the third equation may be used to predict several values of C_R. As noted on Table 2-11, the first estimate of C_R, 1.28 mg/m^3, corresponds to a C_{BZ}^D of 1.5 mg/m^3. Knowing that the choice of C_{BZ}^D has a direct effect on C_R, the design team may wish to make a second calculation based on a lower desired value, say 1.0 mg/m^3. The second estimate of C_R with this assumption is 0.78 mg/m^3. Now, the fourth equation is used to calculate the collection efficiencies required to achieve these return air concentrations.

Calculation of the Required Collection Efficiency, η--
Several model parameters must be assigned values before this equation may be used. The terms remaining to be defined are C_E^O, the initial contaminant concentration, and k_R, the physical fraction of return air re-entering the local exhaust hoods.

The value of C_E^O should be found by direct measurement whenever possible. As noted previously, estimates of contaminant generation rates in the literature may dramatically differ from actual measurements. In this case study, the contaminant generation rate of the new ventilation system should be very nearly the same as in the previous collection system because, according to the plant manager, the exhaust rates and hood efficiencies were not increased by the new system.

The fact that the company did not actually measure the contaminant generation rate implies that they:

1. Either knew from experience that the collector could handle whatever inlet loading was generated, or

2. Didn't consider the consequences of choosing a collector which may not have an efficiency capable of reducing outlet concentrations to acceptable levels.

With the sometimes high generation rates which were noted, the lack of measured data could be a cause for concern. For example, with the highest inlet concentration measured, 1567.9 mg/m^3, a 99.63% collection efficiency (the average measured) results in an outlet concentration of 5.8 mg/m^3, a level which may be unacceptable if a worker breathes this directly. However, the dilutory effects of the remaining "cleaner" return air ducts may be sufficient to reduce the effects of an overloaded section of the collector, especially since the return air ducts all connect to a common outlet plenum before entering the room. Because of this, the average inlet concentration, 592.9 mg/m^3 will be assigned to the term C_E^O.

The remaining term, k_R, can conservatively be assigned a value of 1.0, since the majority of the local exhaust hoods are under the influence of the return air streams. A non-conservative estimate could be also made by noting which of the local exhaust hoods are under the influence of the air make-up unit, then computing the amount of return air drawn in compared to fresh air. With this latter procedure, a value of 0.62 was estimated for k_R.

The first estimate of the required collection efficiency indicates that a level of 99.78% is needed to achieve a C_R of 1.28 mg/m^3 and a C_{BZ}^D of 1.5 mg/m^3. Investigating the possibility of lowering the C_{BZ}^D to 1.0 mg/m^3, the second estimate computes a level of 99.87%. Using the "non-conservative" estimate of k_R, the required collection efficiency is also 99.87%. The fact that the same efficiency was calculated indicates that the choice of a value for k_R is not critical, an observation which agrees with the statement in Reference One that changes in k_R are inconsequential when the collection efficiency is high and the contaminant concentration in make-up air is low.

The preceding calculations indicate that the collector chosen for use in the design is adequate to achieve breathing zone levels near 20% of the ACGIH recommended level. The collection efficiency of the fabric filter (when repaired) was theorized to be 99.93%.

Model Simplifications--
It is interesting to note that the fourth model equation, when simplified by noting that $C_{MU} = 0$ and $k_R = 1.0$, is essentially the same as the familiar efficiency equation:

$$\text{Efficiency} = \frac{\text{inlet concentration} - \text{outlet concentration}}{\text{inlet concentration}}$$

$$\eta = \frac{C_E^O - C_R}{C_E^O} \quad \text{or}$$

$$\eta = 1 - \frac{C_E^O}{C_E^O - C_R}$$

Similarly, had there not been a change in the total ventilation rate, as would be the case in any plant which has an air balance before and after recirculation, the third equation is merely a convoluted form of an equation which expresses the concept that the return air concentration is directly additive to the concentration already present in the breathing zone:

New (or required) concentration = old concentration + return air concentration

$$C_{BZ}^D = C_{BZG}^O + C_R$$

$$C_R = C_{BZ}^D - C_{BZG}^O$$

This is exactly the simplified form of equation no. 3 when k_R and C_{MU} are equal to zero and there is no change in the total ventilation rate.

These observations lead to the realization that, in many cases, a rigorous application of the modeling analysis need not be performed when there obviously is much leeway in the design due, for example, to:

1. A high collection efficiency.
2. Low contaminant concentrations in the breathing zone, and
3. A non-restrictive permissible exposure limit.

System Performance Validation

Once the recirculating system is designed and installed, Reference One suggests that the system performance should be evaluated before production actually begins. This suggestion is made to protect the worker from over-exposure in the event that the system is not adequately designed or properly installed. The evaluation should consist minimally of a check of the air cleaner and surveillance system.

The air cleaner performance may be easily checked by conducting particulate tests in the outlet and inlet ducts, then comparing the results to the required efficiency value and the planned return air concentration level. Additionally, breathing zone concentrations should be measured.

The visual surveillance strategy may be checked by creating a partial collector failure while measuring and observing the dust in the outlet plenums. The response of the workers should also be verified during this failure by noting whether or not the failure was observed and an adequate response was taken. In addition, worker response can be considerably enhanced by the implementation of an adequate education and training program. Indeed, such a program is essential for the successful implementation of the visual monitoring strategy.

Maintenance

It is imperative that regular, preventative maintenance be consciensciously applied throughout the operation of the system. Without such a high level of attention, the risk of overexposure is greatly increased.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions which support the conclusions and recommendations of Reference One can be derived from this study.

1. The motivation for installing a new collection system, i.e., compliance with air quality regulations, provided the initial impetus for the installation of a new wood waste recovery system and a collector which incorporated the concept of recirculation. While this essentially confirms the discussion in Chapter 2 of Reference One concerning energy consumption and air quality regulations, it further shows that the concept of recirculation may be incorporated into a broader energy savings program.

2. The current lack of an identifiable permissible exposure level for wood dust justifies the use of the ACGIH recommended level for design purposes. This reinforces the discussion in Chapter 4 of Reference One that several sets of established guidelines may be used for the definition of allowable exposure levels for toxic substances.

3. The difficulty encountered when attempting to specify an automatic system for monitoring of the seven return air ducts in the company design reinforces the statement in Chapter 2 of Reference One that the design of the proposed ventilation system can have a marked effect on the feasibility of recirculating exhaust air.

4. The disparity of emission generation rates found in sales bulletins compared to concentrations actually measured indicates that designers should not normally use sales bulletins as a primary source of information.

5. The possibility that the visual monitoring strategy may be unable to adequately detect serious collector failures supports the Reference One recommendation that methodologies must be implemented which allow detection of reduced system performance.

6. The failure of employees to notice high dust levels during the survey suggested that the Reference One recommendation concerning adequate worker training to failures had not been implemented by the plant management.

7. The fact that the model parameter k_R did not have an effect on the estimate of collection efficiency reinforces the discussion in Appendix A of Reference One which states that a specific value of k_R will not have a significant impact on the design when the collection efficiency is high and the contaminant concentration in make-up air is low.

8. The collection malfunction which was discovered during the survey suggested that the plant's level of preventative maintenance was not sufficient to uncover normal system failures. This supports the recommendation in Reference One that an adequate inspection and maintenance plan must be implemented.

The following conclusions can be derived from this study which do not fully support the conclusions and recommendations of Reference One:

9. The prospect of a new recommended level for wood dust adds considerable uncertainty in the initial feasibility assessment. This aspect was not mentioned in the discussion of "contaminant classification" in Chapter 3 of Reference One.

10. Although the plant did not have knowledge of the contaminant generation rate or breathing zone concentrations of workers prior to recirculation, the final design incorporated a collector with sufficient efficiency and resulted in breathing zone levels which were acceptable. Although it is always advisable to have knowledge of pre-recirculation contaminant levels, the adequacy of the company design with regard to this issue suggests that, in some cases, it may not be necessary to actually measure these concentrations.

11. The need to modify model flow balance equations indicated that the modeling approach which includes an air balance assumption should be expanded upon to allow wider application to plants which do not have perfect air balances.

12. Since the definition of the terms Q_N and Q_T do not now incorporate the concepts of infiltration and exfiltration due to air imbalances, their use would be limited, without some modifications, in plants which have such air imbalances.

13. The model simplifications which were noted suggest that, in some situations, a non-rigorous design approach may be followed instead of the analytical procedures outlined in Appendices A and B of Reference One.

RECOMMENDATIONS

1. The discussion of "contaminant classification" in Chapter 3 of Reference One should be expanded to warn designers of systems involving substances under new health reviews to consider the prospect that standards may be lowered.

2. Although it is always advisable to have knowledge of pre-recirculation contaminant levels, it should be suggested that, in some cases, e.g., involving high collection efficiencies and low contaminant toxicity, it may not be necessary to actually measure the concentrations.

3. The modeling equations should be expanded to incorporate non-ideal flow balances to allow plants with such imbalances to easily use the modeling approach.

4. The definition of the terms Q_N and Q_T should be expanded to scope to allow for consideration of infiltration and exfiltration due to air imbalances.

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CASE STUDY NO. 3
EVALUATION OF A WET GRINDING PROCESS
OCTOBER 1978

CONTENTS

FIGURES

TABLES

INTRODUCTION

This report contains the evaluation of an air recirculation system which was recently installed on a wet grinding process at a large fabrication shop which produces heavy equipment parts for the mining and crushing industry.

The recirculation system was installed on the first of seven grinders which the company planned to retrofit with new collectors. This report considers only the results of the first collector that was installed.

PLANT DESCRIPTION

The grinder that was evaluated was located in one corner of a long, high bay containing milling and equipment assembly processes. A layout of the end of the high bay area in which the grinders were located is presented in Figure 3-1. The entire bay measured 22 m x 101 m x 16 m high (73 ft x 332 ft x 52 ft) and contained seven grinding mills, a paint spray booth, one welding station, and several equipment assembling operations.
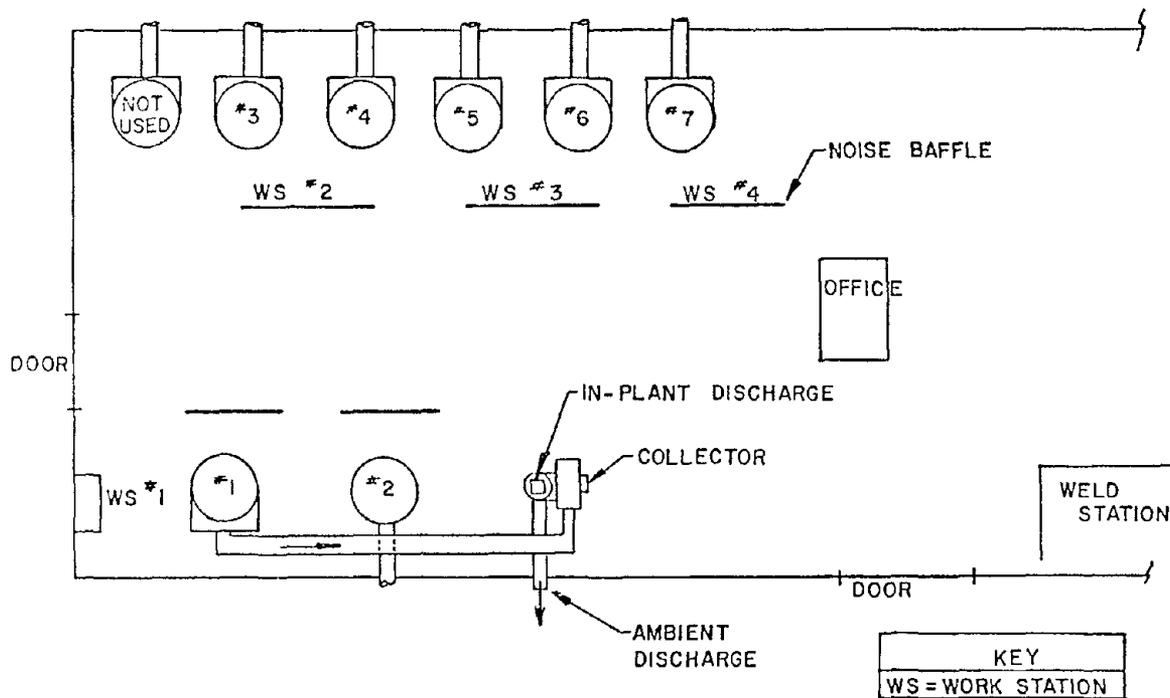
Figure 3-1. Layout of grinding area at one end of high bay area.

PROCESS DESCRIPTION

Process Operation

The purpose of the grinding operation was to attain the necessary tolerance on the inner and outer surfaces of a cup-shaped casting which formed the main components of rock crushers. The castings were composed of a high

manganese content steel alloy called austenitic manganese or Hadfield's manganese steel, a material which "work hardens" under crushing loads. The grinding wheels were composed of resin-bonded aluminum oxide.

The grinding operation was performed using seven large grinding mills or "hydraulic grinders". Each grinder consisted of a 2.4 m (8 ft) rotating table platform and two large hydraulically operated arms, each holding a rotating grinding stone. The casting was brought to the table with the aid of a bridge crane. It was secured in place on supports, then hydraulic arms were adjusted to allow the grinding wheel to contact the inner and outer surfaces of the casting. At the beginning of the cycle the table was first set in rotation, then each hydraulic arm began a slow up and down stroke which caused the rotating grinding wheel to abrade the casting surface on each successive pass. Once set, the hydraulic arms automatically indexed toward the casting at a pre-set rate until a exact tolerance was eventually attained. A front view of a typical grinding machine is shown in Figure 3-2.
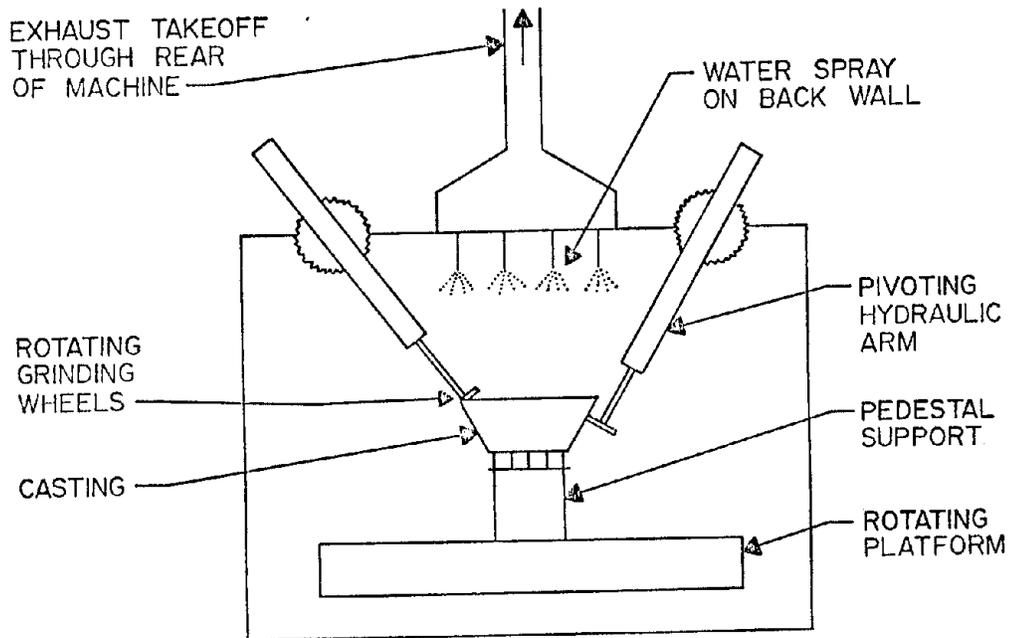
Figure 3-2. Front view of grinding machine showing details of process and hood.

Grinding was performed wet to control the temperature of the workpiece and to reduce escaping dust particles. Once the grinding cycle was started, the process was mostly automatic. The grinding operator's chief duty was to "set-up" the piece on the machine, but the worker also periodically monitored the grinding operation and made minor adjustments to the machine as necessary. Each worker operated one or two machines. Some machines ground 2.1 m (7 ft) diameter castings but, during most of the evaluation, grinder no. 1 (from which the air was recirculated) ground 1.2 m (4 ft) diameter pieces.

Emission Rate

The grinding operation emitted varying concentrations of particulates on an intermittent basis. At the beginning of the cycle, the grinding wheels only touched "high spots", liberating small quantities of dust at periodic intervals. As the cycle continued and the wheel gradually indexed toward the workpiece, successively larger amounts of dust were liberated at more frequent intervals.

Emission levels also varied depending on whether one or two grinding wheels were contacting the piece at a time. At the beginning of the cycle both wheels abroaded the piece; near the end of the cycle one wheel was turned off, allowing the remaining wheel to finish the work.

VENTILATION SYSTEM

Exhaust System

Dust emitted from the wet grinding process was evacuated from the grinding mill through the back of the machine. Machine cutting fluid was sprayed on the back wall of the machine to create a "water wall" which partially captured dust generated in the process. Particles not removed by the water wall were carried to a wet collector located inside of the building (grinder no. 1 only).The exhaust from the remaining grinders was discharged from the building without collection.

The wet collector operated on the principle of "dynamic precipitation" by which particles are removed by direct contact with a water spray then are separated by centrifugal forces in a chamber containing a rotating impeller. The dirty air entering the device is first subjected to a fine water spray from a nozzle. The mixture of water and dust, being heavier than air, is forced to impinge on the blades of the impeller, and then is directed into a cylindrical chamber where large droplets remaining in the air stream are removed by a cyclone action.

A summary of all local and general exhausts in the high bay area is presented in Table 3-1. Note that the exhaust rate from grinder no. 1 is considerably higher than the other grinders. When the new collection system was installed the plant engineer increased the flow rate from 195 m^3/min to 425 m^3/min, resulting in better capture of the grinding dust.

It is to be noted that the paint spray booth was omitted from the total tabulation of exhaust volumes because the booth was not operated on a regular basis, and because its effect on the air balance in the vicinity of the grinders was minimized by its close location to a large doorway leading to an adjacent plant area.

Air Make-up

There were no make-up air supply units in the high bay area in which the grinders were located. "Make-up" air was induced through a number of large

Table 3-1. Exhaust rates.

Description	Exhaust volume	
	m^3/min	cfm
Local exhausts		
Grinder No. 2	195	6,900
Grinder No. 3	195	6,900
Grinder No. 4	98	3,450
Grinder No. 5	98	3,450
Grinder No. 6	98	3,450
Grinder No. 7	98	3,450
Paint spray booth	1,360	48,000
Arc air/weld booth	28	1,000
General exhaust		
Overhead roof ventilator	793	28,000
Recirculated exhaust		
Grinder No. 1	425	16,440
Total exhaust (with spray booth)	2,963	104,600
Total exhaust (without spray booth)	1,603	56,600

doors, some connecting to adjacent plant areas, and others to the outdoors. During summer, the majority of make-up air was drawn through large open doors leading to the outdoors. During winter, these doors were closed and the majority of make-up air came from other plant areas. Unit heaters were used during winter months to temper the plant air.

Recirculated Exhaust

Cleaned air from the scrubber was either discharged to the room or outside depending on the position of a manually operated damper. The inside discharge plenum was located above the collector at a height of 7.6 m (25 ft) from floor level. The discharge opening was capped by a square plenum containing louvered grilles located on three sides to evenly distribute the recirculated air. An "expansion chamber" on the collector exhausted about 10% of the cleaned air back into the room at all times irrespective of the position of the bypass damper. The function of the expansion chamber was to allow discharge water to accumulate and drain away from the collector.

A unique feature of the collection system was that the spray water used for collection was the same coolant/lubricant water used in the grinding process and water wall. The primary reason for using the coolant in the scrubber was because the plant would not have been allowed to discharge the contaminated scrubber water to the sewer system, and they did not have their own means to treat the waste. Using the water for two purposes also saved the expense of providing fresh water to the scrubber, although a

traveling microscreen filter had to be installed prior to the scrubber to remove fine particles which would affect nozzle life by excessive abrasion. Figure 3-3 presents a flow diagram showing the complete air and coolant cycles.
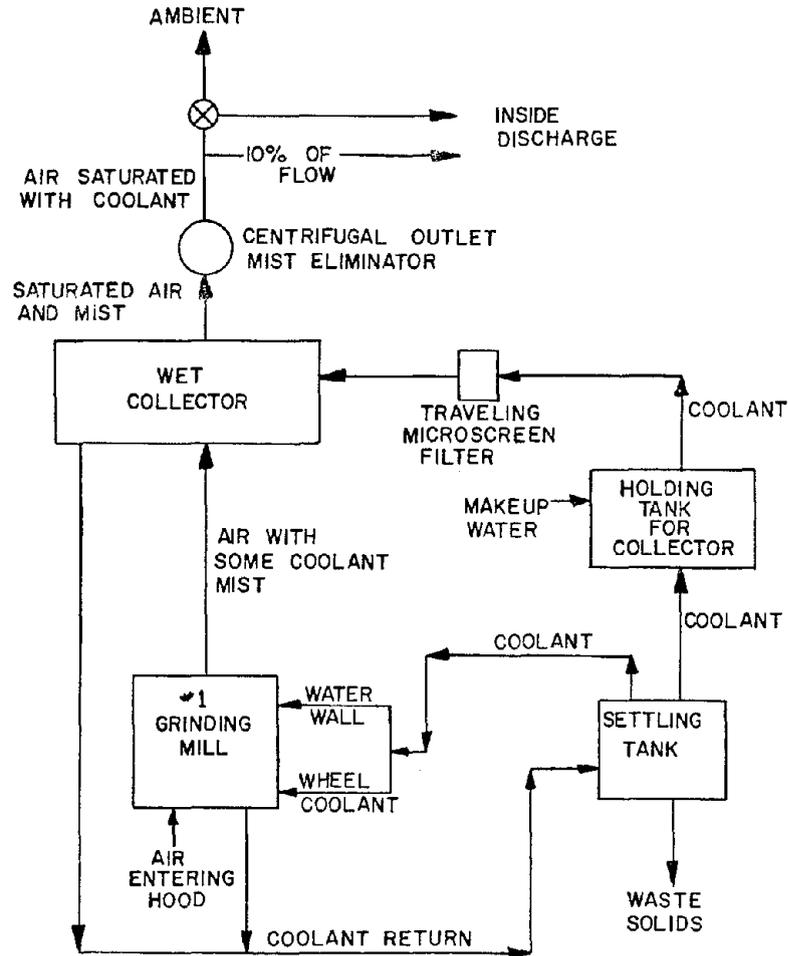
Figure 3-3. Air and coolant cycle.

The coolant was actually a cutting fluid concentrate which is diluted with 60 parts water before use. According to the lable, the coolant is supposedly non-toxic: "Even at higher than recommended strengths, this material is non-toxic by ingestion or inhalation, is not a primary skin irritant or corrosive material, is not an eye irritant, and is not flammable". The coolant did have a characteristic and somewhat disagreeable odor, however. To minimize the odor, the company occasionally added a small quantity of a fungicide to the coolant to retard the growth of odorous or harmful fungi.

METHODS

In-Duct Sampling

Inlet and outlet particulate measurements were made simultaneously to obtain an actual collector efficiency for each sampling run. Samples were extracted from the collector inlet with an EPA Method 5 particulate sampling train and approved procedures. Outlet samples were obtained with a high-volume sampling train operating at a flow rate of 0.17-0.28 m^3/min (6-10 cfm). Particle size tests were made using a Sierra Series 220 multistage in-stack impactor. The methods and procedures for these tests are described in the Methods section of the main report.

In-duct humidity measurements were made by inserting wet and dry bulb thermometers into the moving air stream. These temperature readings were then translated into relative humidity using a psychrometric chart. A continuous particulate monitor, called a nephelometer, was also evaluated for possible use in a failure detection strategy. Its performance was checked by recording its output while simultaneously sampling the outlet with an in-stack filter holder containing a 0.6 micrometer pore size membrane filter. This sample was withdrawn at 0.028 m^3/min (1 cfm) through a 91.4 cm (3 ft) glass-lined probe heated to 43°C (110 °F) to avoid condensation. All samples were withdrawn at near-isokinetic flow rates using appropriately sized nozzles. The monitor's output was continuously recorded on an Ester-line Angus Miniservo strip chart recorder.

In-Plant Sampling

Workplace and breathing zone measurements were made with battery-operated sampling pumps. Samples were taken only during times when the machines were operating and, for this reason, the pumps were shut off during the lunch break and other non-production times. General area samples were taken by placing pumps on tripods and on available structures such as noise barriers in front of the grinders. A description of the sampling equipment and the general procedures followed are presented in the Methods section of this report. In-plant measurements of humidity were made with a Bendix Model 566 Psychrometer.

Tracer Gas Study

A study was performed using a tracer gas to estimate two model parameters, k_R and k_{BZ}. These parameters will be fully discussed in the results section. A detailed description of the general procedure and set-up is discussed in the Methods section.

RESULTS OF SAMPLING PROGRAM

In-Duct Measurements

Particulate Measurements--
Three separate tests were conducted to assess collector performance. The

first test consisted of three outlet and three inlet sampling runs taken consecutively. These results were later invalidated because it was later found that the collector had been installed improperly resulting in the impellor rotating in the reverse direction and a reduction in the air flow. After the collector was repaired, a second test was performed in the outlet to verify that the collector was operating correctly. Since this test found that the outlet concentrations were significantly lower than original measurements, another test was scheduled. In the third test, three 1-hour sampling runs were simultaneously performed in the inlet and outlet to obtain a true representation of collector performance. The average collection efficiency in this test was 96.2%. The results of the second and third tests are presented in Table 3-2. A summary of the pertinent sampling data obtained during these tests is found in Table 3-3.

After the results were analyzed, it was theorized that the collector was not operating properly. As a result, the outlet concentrations measured in the third test are probably higher than would be normally found. During the third test, it is probable that the centrifugal outlet chamber in the scrubber was partially filled with water due to a clogged drain. This evidently caused some "carryover" of water droplets which contained dust particles. This conclusion was reached because of the following evidence:

1. Prior to the third test, a buildup of material on the impeller had been causing a vibration problem. The impeller was cleaned but some of the loosened material was carelessly discarded by the workers and probably resulted in partially clogging the centrifugal outlet drain.

2. During the third test, the sample probe was noticed to be covered with dirty water droplets. During the second test the probe was dry.

3. A humidity measurement during the third test showed the outlet exhaust stream to be saturated. During the second test, the humidity in the outlet was only 70%.

4. During the day following the third test, the centrifugal outlet completely filled with water and overflowed.

Since the outlet concentrations measured in the third test do not reflect typical values, the outlet concentrations in the second test are used to calculate an average collector efficiency which is more meaningful, but higher than the first estimate. As shown in Table 3-2, the efficiency calculated with this assumption is 97.9%.

Particle Sizing--
Particle size measurements indicated that the mass median diameter at the inlet was 19.0 micrometers, compared to 1.4 micrometers in the outlet. As expected, the collector removed larger particles at a higher efficiency than smaller particles. A summary of the sampling data appears in Table 3-4. Each particle size distribution is plotted in Figure 3-4 as aerodynamic diameter vs. the percent less than the indicated size.

3-8

Table 3-2. Summary of in-duct measurements.

| Test No. | Run No. | Location | Concentration, mg/m³ | | | |
			Total dust	Fe	Mn	Cr
2	1	Outlet	3.68	Not analyzed		
	2	Outlet	5.39	Not analyzed		
	3	Outlet	3.37	Not analyzed		
		Average outlet	4.15			
3	1	Inlet	318.6	164.5	26.40	1.30
		Outlet	8.42	2.87	0.320	0.031
	2	Inlet	62.2	31.20	5.48	0.524
		Outlet	3.67	1.01	0.940	0.004
	3	Inlet	264.7	145.5	23.38	1.19
		Outlet	7.45	2.16	0.203	0.025
		Average inlet	215.2			
		Average outlet	6.51			

——————————— Average particulate collection efficiency, percent ———————

Third test	Run 1	97.4
	Run 2	94.1
	Run 3	97.2
	Average	96.2
Using inlet values from third test and outlet values from second test	Average	97.9

Table 3-3. Summary of in-duct sampling data.

Test	Location	SP (avg), in. H$_2$O	$\sqrt{VP}$ (avg), in. H$_2$O	ΔH (avg), in. H$_2$O	V_m, sm^3	Weight on filter, mg	Backwash weight, mg	Concentration, mg/m^3
No. 2-Run 1	Outlet	--	--	--	15.95	58.78	--	3.68
No. 2-Run 2	Outlet	--	--	--	9.73	52.49	--	5.39
No. 2-Run 3	Outlet	--	--	--	10.58	34.97	--	3.31
No. 3-Run 1	Inlet	2.70	1.35	0.82	0.921	44.23	249.07	318.60
No. 3-Run 1	Outlet	--	--	--	10.62	89.35	--	8.416
No. 3-Run 2	Inlet	2.75	1.27	0.74	0.805	7.05	42.98	62.17
No. 3-Run 2	Outlet	--	--	--	15.35	56.27	--	3.667
No. 3-Run 3	Inlet	2.60	1.28	0.73	0.804	27.57	185.37	264.74
No. 3-Run 3	Outlet	--	--	--	11.311	84.24	--	7.448

Table 3-4. Particle size measurements – data summary.

Location	Stage	micrometers	Iron content		Manganese content	
			mg	Cumulative percent*	mg	Cumulative percent*
Inlet to collector	1	>15.0	0.475	44.5	0.075	69.1
	2	9.2 – 15.0	0.088	33.1	0.109	24.6
	3	3.7 – 9.2	0.033	28.9	0.045	6.1
	4	2.2 – 3.7	0.088	17.6	0.003	4.9
	5	1.4 – 2.2	0.038	12.9	0.001	4.5
	6	0.76 – 1.4	0.023	9.8	0.001	4.1
	7	0.42 – 0.76	0.005	3.8	0.001	3.7
	Back-up	<0.42	0.030	0	0.008	0
	Total		0.780		0.243	
Outlet of collector	1	>15.0	--	100.0	--	100.0
	2	9.2 – 15.0	--	100.0	--	100.0
	3	3.7 – 9.2	0.005	98.0	--	100.0
	4	2.2 – 3.7	0.041	82.5	0.001	97.0
	5	1.4 – 2.2	0.060	59.8	0.002	92.0
	6	0.76 – 1.4	0.050	40.9	0.003	84.0
	7	0.42 – 0.76	--	40.9	0.001	81
	Back-up	<0.42	0.108	0	0.030	0
	Total		0.264		0.037	

* Cumulative percent less than the lower limit of the size range.
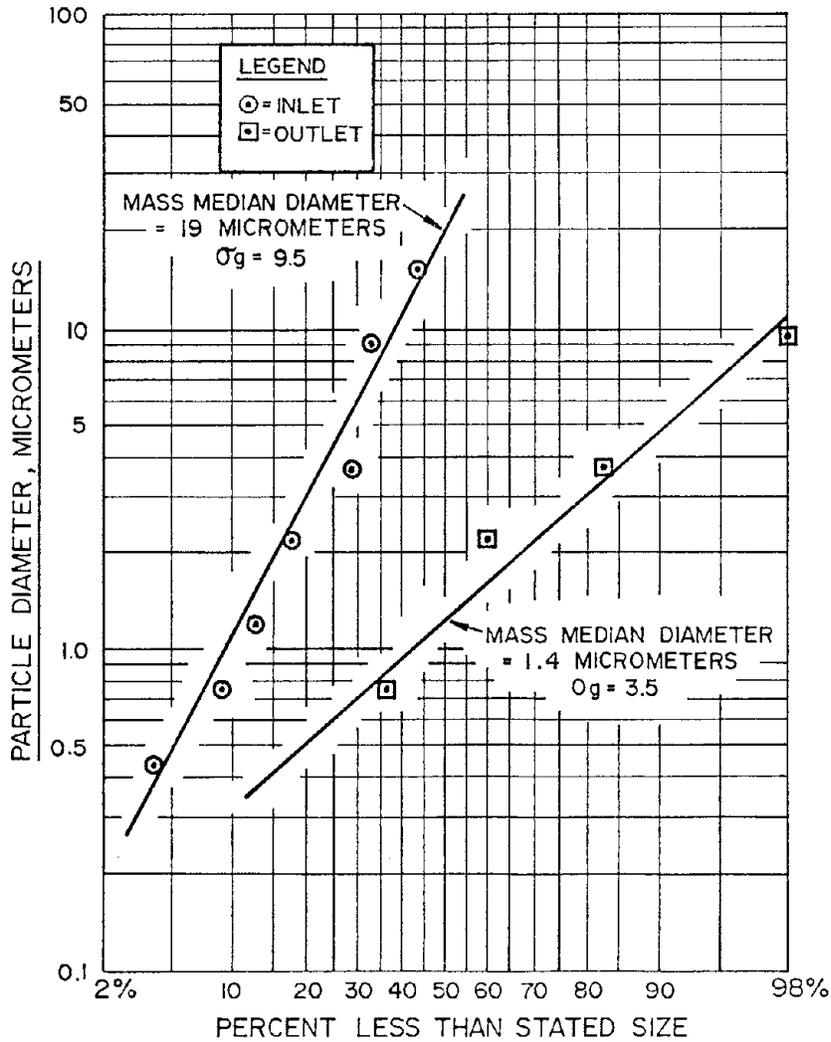
Figure 3-4. Particle size distribution plots.

In-Plant Measurements

General Area and Breathing Zone Measurements--
Since in-plant samples were taken after the collector had been repaired
measurements are believed to be representative of normal operating
conditions. During the survey, an attempt was made to assess the impact of
recirculation by measuring workroom contaminant levels in two conditions.
First, measurements were made with the exhaust air returning to the room-
the "after" condition. Second, measurements were made with the exhaust
system in the bypass mode in an attempt to create a "before" condition.

During both sample conditions, attempts were made to maintain similar process
and ventilation conditions. All doors and windows were closed in the high
bay area to avoid interferences from cross-drafts and to simulate the closed
conditions of winter. Five general area samples and two personal samples
were taken on each day to document the difference between the two conditions.

A summary of workplace and breathing zone measurements is presented in Table 3-5. As noted, both samples indicated a significant increase in total dust after recirculation. A substantial amount of the contaminant was found to be iron, while manganese was present at very low levels. Chrome and nickel were below detectable limits.

Table 3-5. Summary of workplace measurements.

| Parameter | Statistic | Concentration, mg/m^3 | |
		"Before" recirculation	After recirculation
Total dust - personal samples	Average	1.60	2.41
	Standard deviation	0.52	0.90
Total dust - fixed samples	Average	1.97	3.40
	Standard deviation	1.03	1.05
Iron (all)	Average	0.625	1.022
	Standard deviation	0.360	0.259
Manganese (all)	Average	0.076	0.127
	Standard deviation	0.030	0.031

Concentrations measured in the "before" condition would have been even lower than measurements indicate if complete, rather than partial, bypass of the cleaned air was being achieved with the damper in the "bypass" position. Complete bypass was not possible because 10% of the exhaust flow was recirculated back to the workplace at all times from the expansion chamber. Furthermore, the bypass damper was noticed to leak air into the room in the bypass mode. The total amount air returned to the room from these sources was estimated to be 142 m^3/min (5000 cfm).

A tabulation of all workplace measurements is presented in Table 3-6. As shown, these measurements exhibit a wide variability. This spread is due to the combined effect of process variations and sampler placement. Variations in measurements between sampling days resulted from differing numbers of machines being operated, varying sizes of castings being ground, and varying grinding times. Similarly, on a particular sampling day, the location of the sampler greatly influenced the measurement obtained. For example, the highest measurements were usually obtained by fixed samples which were situated directly in front of an operating machine. Since the sampling locations didn't vary, the levels measured by the samplers depended on which machines operated on a particular day. For most of the survey, the same machines were usually operated.

When considering sampler placement, it was desired to measure the highest contaminant levels likely to be found as well as typical measurements. Hence, locations F1, F2, and F3 in Figure 3-5 were placed very close to the grinding machines. In contrast, more typical contaminant levels were measured by locating F4 on top of a 1.9m (6 ft) platform in the center of

Table 3-6. Tabulation of workplace measurements.

Date	Location in Figure 3-4	Type of sample	Concentration, mg/m^3		
			Total dust	Fe	Mn
		"Before" recirculation			
9/14	F1	Fixed	1.24	0.480	0.076
	F2	Fixed	1.98	0.426	0.048
	F3	Fixed	1.11	0.428	0.046
	F4	Fixed	2.14	0.543	0.100
	F5	Fixed	0.82	0.263	0.028
	WS No. 1	Personal	1.28	0.398	0.033
	WS No. 3	Personal	1.09	0.309	01077
9/22	F1	Fixed	4.36	1.63	0.147
	F2	Fixed	1.90	0.620	0.070
	F3	Fixed	2.74	0.988	0.090
	F4	Fixed	1.21	0.559	0.056
	F5	Fixed	2.19	0.720	0.078
	WS No. 1	Personal	1.78	0.652	01077
	WS No. 3	Personal	2.23	0.729	0.092
		After recirculation			
9/12	F1	Fixed	2.02	0.754	0.100
	F2	Fixed	4.16	1.02	0.132
	F3	Fixed	4.92	1.15	0.136
	F4	Fixed	4.30	1.00	0.133
	F5	Fixed	1.99	0.875	0.122
	WS No. 1	Personal	2.96	0.929	0.121
	WS No. 3	Personal	3.05	1.11	0.144
9/13	F1	Fixed	3.89	0.923	0.107
	F2	Fixed	4.38	1.80	0.220
	F3	Fixed	2.92	1.23	0.138
	F4	Fixed	2.96	0.950	0.116
	F5	Fixed	2.55	0.818	0.095
	WS No. 1	Personal	2.53	0.929	0.112
	WS No. 3	Personal	1.10	0.830	0.104

the room; and by F5 situated on top of a noise barrier with the filter hanging away from the machines. Measurements at these locations were not under the direct influence of a grinding machine and are more representative of background air quality changes.
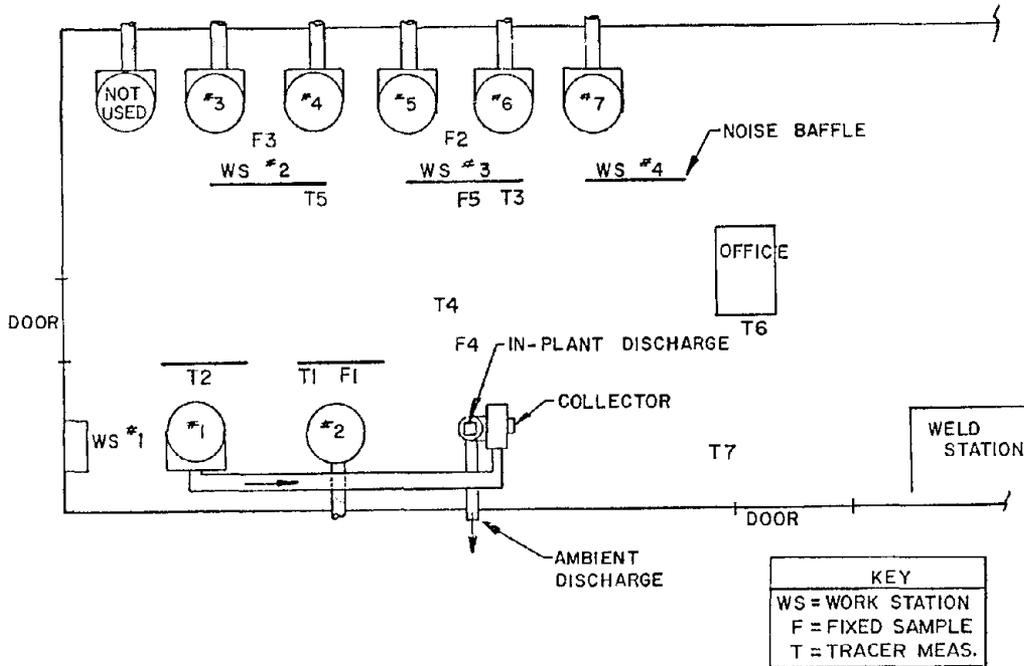
Figure 3-5. Area sampling locations.

Breathing Zone Measurements--
Personal samples WS1 and WS3 were made by instrumenting workers who were assigned to work station no. 1 and no. 3, respectively. Although much of their time was spent at these stations, workers also wandered throughout the room and sometimes entered other plant areas. This may account for the fact that breathing zone samples were, on the average, lower than area samples. No sampling was performed during lunch breaks since the grinding mills were shut down during this period. On one occasion, when the machine connected to the dust collector became inoperable, sampling was halted for an hour until the machine started up again. For these reasons, none of the samples can be considered 8-hour time - weighted averages, but the values do represent a comparison of similar working conditions that existed prior to and after recirculation was implemented.

Humidity Measurements--
After the collector was repaired, humidity measurements taken in the inlet and outlet ducts showed that the collector increased the relative humidity of the exhaust air from grinder no. 1 from 63% to 70%. This measurement is sharply contrasted to the saturated outlet levels which were measured when the collector malfunctioned.

Tracer Gas Study

An estimate of two parameters which are used in the recirculation model, k_{BZ} and k_R, was made using sulfur hexafluoride (SF_6) as a tracer gas. To assess k_{BZ}, the fraction of return air entering the breathing zone of the worker, the tracer gas was injected into the inlet to the collector, then measured in the outlet and in various locations within the room (Figure 3-4). The parameter k_R, the fraction of return air re-entering the local exhaust hood which is recirculated, was assessed by injecting gas prior to the collector, measuring the outlet concentration, then measuring the concentration in the inlet to the collector upstream of the injection point. Using this procedure, the following formulae were used to estimate the two parameters:

$$k_{BZ}(average) = \frac{Average\ concentration\ in\ room}{Concentration\ at\ collector\ outlet}$$

$$k_R = \frac{Concentration\ at\ collector\ inlet}{Concentration\ at\ collector\ outlet}$$

A peak value of k_{BZ} was also calculated using the peak room concentration in the first equation's numerator. The measurements and results of the tracer gas study are summarized in Table 3-7. From this procedure, k_{BZ} was assigned a value of 0.20 and k_R was estimated to be 0.23. A peak k_{BZ} value was estimated to be 0.25. A 3.3 ppm/min empirical "rise time" was calculated from the observation that the room concentration at sampling location T4 rose from 0 to 6.6 ppm in a 2-minute period following injection of the tracer gas. After two minutes, the tracer gas concentration neared steady state.

The low tracer gas estimates for k_R and k_{BZ} indicate that considerable dilution of the recirculated air flow is being achieved. As shown in Figure 3-6, the exhaust from the non-recirculated grinders are causing air to migrate from neighboring plant areas. Fortunately, the area of the plant providing this dilution ventilation contains only assembly processes, hence the quality of this "make-up" air is quite good.

Monitor Evaluation

During this survey, an opportunity was presented to evaluate a continuous particulate monitor, called a nephelometer, for possible use in a failure response strategy. Although the results of the evaluation are not conclusive, the instrument was able to provide a real time output of the outlet particulate concentration which vividly showed the variability of the process. An example of the output taken from the strip chart recorder (Figure 3-7) shows that there is a marked difference between contaminant generation rates and the number of grinding wheels contacting the piece. The monitor's output also reveals that the outlet concentration fluctuated as the inlet loading changed, indicating that the collection efficiency may have been nearly constant. Each peak on the plot corresponds to a slug of material generated by each contact of the grinding stone and the

Table 3-7. Tracer gas study results.

Measurement no.	Location in Figure 3	Description	Concentration ppm	Fraction of average outlet concentration
1	T1	Near grinder No. 2	6.0	0.19
2	T2	Near grinder No. 1	6.0	0.19
3	T3	Near grinder No. 6	6.0	0.19
4	T4	Near base of the cleaner	7.8	0.25
5	T5	Near grinder No. 4	6.0	0.19
6	T6	10.7 m (35 ft) W of collector	6.3	0.20
7	T7	9.1 m (30 ft) NW of collector	7.0	0.22
8	T8	Measured in inlet	8.0	--
9	T9	Initial outlet concentration	29.0	--
10	T10	Final outlet concentration	35.0	--

k_{BZ} estimate (average):

$$\frac{\text{Average concentration in room}}{\text{Average outlet concentration}} = \frac{6.44 \text{ ppm}}{32 \text{ ppm}} = 0.20$$

k_{BZ} estimate (peak):

$$\frac{\text{Peak concentration in room}}{\text{Average outlet concentration}} = \frac{7.8 \text{ ppm}}{32 \text{ ppm}} = 0.25$$

k_R estimate:

$$\frac{\text{Inlet concentration}}{\text{Final outlet concentration}} = \frac{8.0 \text{ ppm}}{35 \text{ ppm}} = 0.23$$

Rise time:

The room concentration at location T4 rose from 0 to 6.6 ppm in 2 minutes.
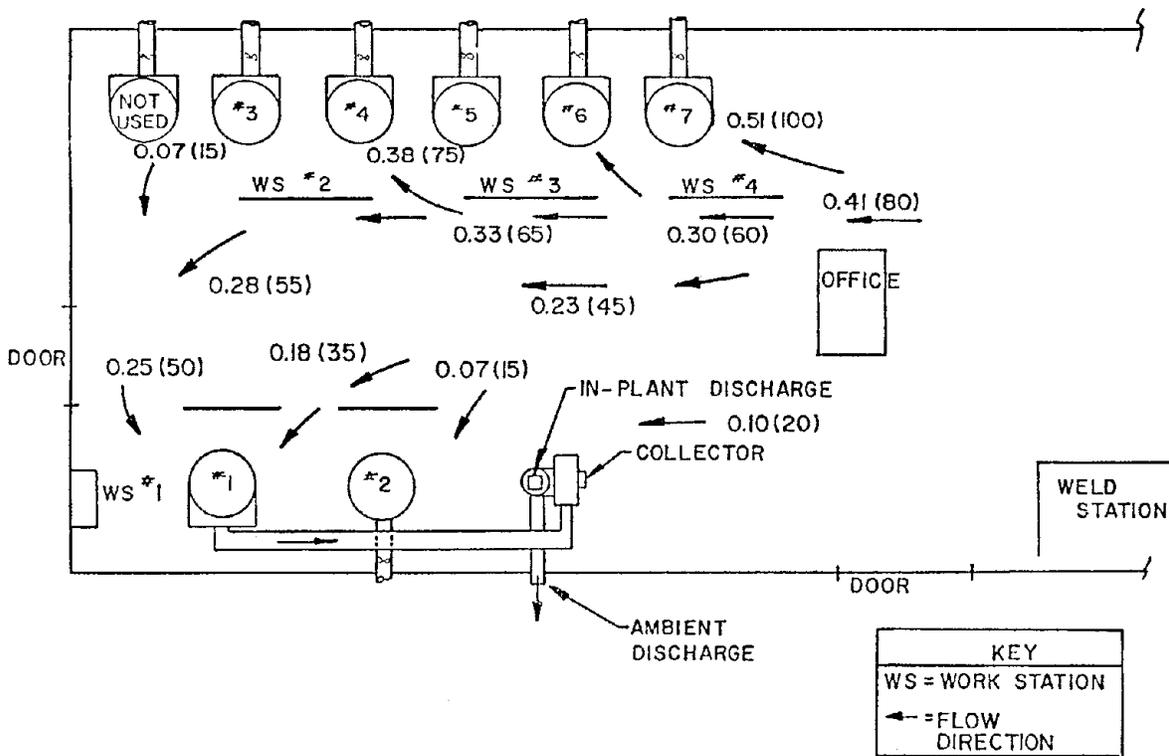
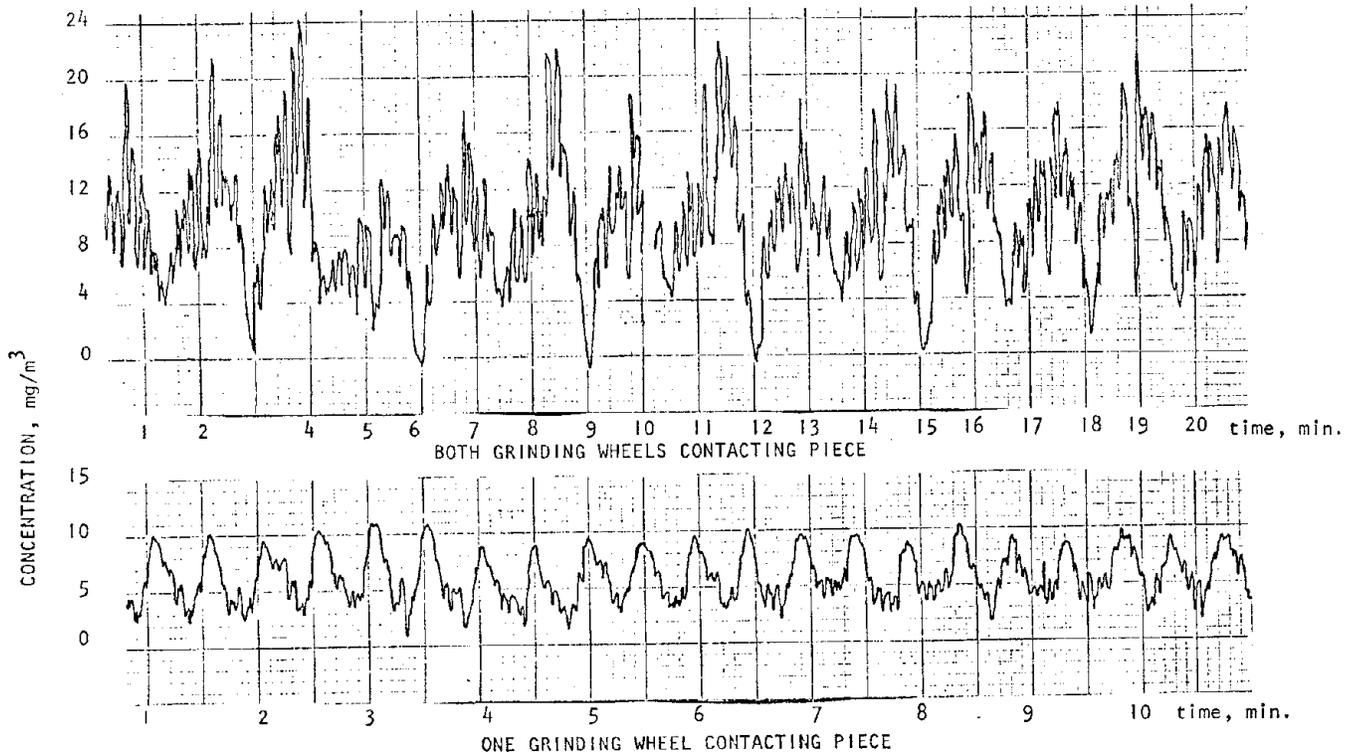Figure 3-6.   Air velocity patterns, m/sec (ft/min).

Figure 3-7.   Typical outlet concentration plots.

wheel(s). The lowest points represent "baseline" particulate measurements. The monitor's output was calibrated by taking a series of 10-minute in-stack filter measurements while the monitor's output was recorded.

It is to be additionally noted that the concentrations measured in this test are higher than the concentrations reported earlier because the monitor calibration was performed during the time period in which the collector was not operating properly.

Summary of Sampling Program

1. The particulate removal efficiency of the wet scrubber was initially measured at 96.2%. Results of another test indicated that the efficiency may be as high as 97.9%, however.

2. Particle sizing showed that, as expected, the collector selectively removed larger particles more efficiently than those in the respirable range.

3. Workplace samples showed a significant increase in area and breathing zone contaminant rates as a result of recirculation.

4. Iron was present in the measured particulate in significant percentage, while manganese was present in very low concentrations.

5. The wet scrubber did not appear to be humidifying plant air a significant amount.

6. An evaluation of a continuous particulate monitor showed that the contaminant generation rate was highly variable and depended on the number of wheels contacting the workpiece.

RETROACTIVE ASSESSMENT OF DESIGN APPROACH

Introduction

The preceding evaluation described the characteristics of the process, ventilation, and contaminant concentration levels, but it did not address all of the issues which a design team must face when considering recircula-tion, nor did it address the methodology presented in Reference One. There-fore, to evaluate the usefulness of the design approach recommended by Reference One, a retroactive assessment of this plant situation will be made using the criteria provided by Reference One. As a first step, an initial feasibility assessment will be performed utilizing the criteria presented in Chapter 2 of that document.

Initial Feasibility Assessment

The purpose of the initial feasibility assessment is to pre-screen major issues which will likely affect the chances of the design's success in an attempt to uncover insurmountable aspects of the program which may prevent recirculation. Through this step, unnecessary efforts and expenses for

field sampling, hardware evaluation, and design optimization can be prevented. Following this preliminary assessment, a more in-depth evaluation of contaminants, air cleaners, and monitors would be performed. After key aspects of the design are understood, the modeling approach presented in Reference One would then be used to determine the required efficiency of a collector, and to finalize a system configuration which would achieve acceptable breathing zone concentrations.

Legal Issues--
There are no legal restrictions which prohibit recirculation, however, there is implied in the law a restriction on the recirculation of air streams containing substances which are known or suspected carcinogens. The importance of this restriction relates to the possibility of the coolant used in the scrubber containing nitrosamines, substances suspected of having carcinogenic potential for man. Nitrosamines are believed to be formed from the reaction of sodium nitrite with amine compounds in the cutting oil (15). Because there are safe substitutes for the cutting oil the plant is presently using, the plant should proceed with the substitution before continuing the feasibility assessment.

Energy Consumption--
Because of the absence of make-up air supply units, the plant under study has such a high negative pressure that fans are probably operated at reduced capacities, and cold air infiltrating into workspaces chills the workers, even with the unit heaters operating. The recirculation system, then, can save energy by reducing the quantity of energy necessary for the unit heaters while improving the operation of existing fans and achieving a better distribution of tempered air. The potential cost savings for tempering air to replace that exhausted by grinder no. 1 may be calculated by computing the costing of supplying an equivalent amount of tempered air. Using the procedure in Reference 4, the yearly cost savings is $4325. If all seven grinders are ultimately fitted with similar systems, the net savings would be approximately $70,630 per year using this method. This make-up air cost offers a considerable "cost savings" toward the total project cost of $180,000.

Contaminant Classification--
From knowledge of the process, it is known that only a particulate contaminant is generated by the grinding operation, and that the greatest percentage of the material is iron. Manganese is also present in appreciable quantities, perhaps 10-14 percent. Additionally, there is a potential for nitrosamines to be present in the process.

In the in-depth evaluation, a stack test will be needed to quantify the peak emission levels because manganese is regulated by a ceiling standard. Knowledge of peak manganese levels may be necessary when specifying a collector and selecting an appropriate surveillance system.

Air Quality Regulations--
The motivation for recirculation was a desire to reduce the ambient emission levels from seven uncontrolled grinding operations. The aspect of recirculation was introduced as a cost saving feature to help sell the

idea to management. Hence, the need to comply with air quality regulations provided the major impetus for the project, although energy conservation reasons sparked the feasibility assessment of recirculating the cleaned exhaust.

Air Cleaner Availability--
The wet grinding operation produces a wet particulate which would be able to be removed by wet collection and possibly by filtration, depending on the collection properties of the dust. In the assessment of wet collection, however, consideration must be given to humidification of the workplace. Additionally, the liklihood of an odor being present should be considered because the machine coolant which is proposed to be used in the wet collector has a distinctive and somewhat disagreeable odor.

Monitor Availability--
Monitoring methods are available for continuously sampling particulates from air stream, however, the effect of moisture in the air stream on the monitoring device may complicate its use. Another consideration for the design team concerns the large number of collectors planned to be recirculated. Should automatic monitors be necessary, an assessment should be made of the feasibility and costs of monitoring each return air duct compared to area monitors. Consideration could also be given to the possibility of combining all return air flows to ease the complexity of monitoring.

Finally, the selection of monitors may also be complicated by the presence of manganese if concentrations are high enough to warrant the continuous detection of a ceiling concentration.

Process Emission Profile--
From visual observations of the grinding operation, it is evident that the emissions are highly variable with time. Extreme fluctuations in the contaminant generation rate will increase the difficulty of sizing air cleaning equipment and specifying an appropriate surveillance procedure.

Ventilation System Design--
The planned recirculation system will involve the installation of a new collection system at a substantially increased flow rate. There should be no difficulties in the proposed design because the basic exhaust hood arrangement will remain the same, and ducting will be run to a new indoor collector.

Summary of Initial Feasibility Assessment--
The assessment of eight key issues faced by the system designer resulted in the identification of several factos which must be addressed by further evaluations. Among these are:

1. The examination of legal issues indicated that the presence of nitrosamines in the recirculated exhaust should be eliminated by the substitution of a coolant which does not contain sodium nitrite.

2. The presence of manganese in the exhaust forces the designer
   to recognize that a regulated ceiling limit may influence the
   selection of an air cleaner and adequate monitoring strategies.

3. Both wet and dry types of air cleaners are feasible in the design.
   Wet collectors, although better suited to collect a moist air
   stream, must be further evaluated for possible odor and humidity
   problems.

4. The selection of appropriate monitoring strategies may be complicated
   by moisture levels in the exhaust stream and by the presence of a
   substance with a regulated ceiling unit. Furthermore, if unit
   collectors are planned, the possibility exists that many monitors,
   perhaps one per collector, may be required in the final design.

5. The highly fluctuating process operation rate may have an impact
   on the type of collector chosen and the ability to monitor a
   substance with a ceiling level in conjunction with a time-weighted
   average.

In-Depth Design Evaluation

Following the initial assessment, an in-depth evaluation of contaminants,
collectors, and monitoring approaches is conducted as part of the design
process to eliminate uncertainties raised by the preliminary feasibility
assessment.

Contaminant Characteristics--
A discussion with the process engineer would reveal that high manganese steel
with the following composition was being ground:

Constituent	Average composition, percent
Iron	82.8
Manganese	13.5
Silicon	1.0
Carbon	1.19
Phosphorus	Trace
Chromium	1.5

In addition to the dust originating from the casting, some material from
the grinding wheel is also liberated by the process. A contact with the
grinding wheel manufacturer would reveal that the wheel is composed of a
resin-bonded aluminum oxide. The exact composition of the resin material
is proprietary, but the bonding agent is reported to be an inert compound.
There are no gases known to be generated in this process.

As noted previously, a good possibility exists that the coolant may contain
a nitrosamines, a class of substances suspected of causing cancer in man.
Their formation is thought to result from the reaction with sodium nitrite
with amines present in the cutting fluid.

It was also learned that the fungicide contained phenolic compounds. It is not believed that the aerosol emitted from wet collector contained appreciable amounts of phenolic compounds because the fungicide was added infrequently in very small quantities.

Prior to the installation of the new collection system, the plant conducted a source test on the exhaust from grinder no. 1. However, the results from the tests were inconclusive because the person conducting the test noted a low carrying velocity in the duct caused a substantial settling problem. In the absence of other data, however, the plant doubled the estimate for the contaminant generation rate as a basis for their design.

To accurately estimate the quantity of particulates exhausted from the process, one would have to perform a source test in the exhaust duct of the new collector. Since the process is intermittent, several short duration tests would be necessary to assess the peak, as well as average inlet loading. Had this been done, results could be obtained similar to those presented in Table 3-8 (these are the actual measurements which were presented earlier).

An evaluation of the feasibility to recirculate must also include knowledge of pre-recirculation worker exposures. The plant did not have any such data, making it necessary to measure in-plant concentrations in a condition which simulated worker exposures without recirculation. Without pre-recirculation data, there could have been an overexposure problem that the plant would not have perceived until after the new system was installed.

The toxicity of each important contaminant should be understood to define what levels are acceptable in the employee breathing zones. Table 3-9 summarizes the current applicable standards for the contaminants which are hygienically significant.

Of the remaining materials, iron and aluminum oxide dust would be considered as nuisance dust for regulation purposes.

Selection of Air Cleaning Equipment--
Due to the wet nature of the process, the collection of a wet dust by fabric filtration may be difficult. Consequently, the company chose a centrifugal wet collector which had the advantage of utilizing the coolant water system for nozzle spray water.

Many different efficiency levels are possible with wet collectors. Since typical efficiency curves are available from the dust collector manufacturer for the type of collector used in the design, it becomes possible to use the inlet data from Table 3-7 to calculate an expected outlet concentration for the chosen collector. The efficiency curve pertaining to the general type of wet scrubber intended for use in the design is shown as Curve A in Figure 3-8. Utilizing this curve, the outlet predictions for the various particle size ranges are presented in Table 3-10. The overall collection efficiency calculated on this basis is 95.2% for total dust and 97.4% for

Table 3-8. Inlet concentrations vs. particle size.

| Peak loading vs. particle size | | Concentrations, mg/m^3 | | |
Size range, micrometers	Percent in size range	Total dust Peak	Average	Manganese
>15.0	60.9	194.0	131.0	8.10
9.2 - 15.0	11.4	36.3	24.5	11.80
3.7 - 9.2	4.2	13.4	9.0	4.90
2.2 - 3.7	11.3	36.0	24.3	0.32
1.4 - 2.2	4.9	15.6	10.5	0.11
0.76 - 1.4	2.9	9.2	6.2	0.11
0.42 - 0.70	0.6	1.91	1.3	0.11
<0.42	3.8	12.1	8.2	0.87
Inlet loading - total		313.6	215.2	26.32
Inlet loading - respirable (<5.0µ)		86.0	58.1	--

Table 3-9. OSHA breathing zone standards and ACGIH recommended levels.

	TWA TLV (8) mg/m^3	STEL(8), mg/m^3	OHSA 8-hr TLV(7), mg/m^3	OSHA ceiling(7), mg/m^3
Total nuisance dust	10.0		15.0	
Respirable nuisance dust	5.0		5.0	
Manganese	5.0*	5.0	5.0	5.0
Chromium			1.0**	

* Also the ceiling level.
** Metal and insoluble salts.

manganese. The collection efficiency predicted for respirable dust is only 80.5%. During the process of evaluating the wet collector, it is necessary to be aware of two potential problems which were alluded to previously:

1. The dust collector could contribute undesirable humidification to room air, an effect which may increase equipment deteriation and reduce the comfort level of employees. The sales literature explains that the "humidifying efficiency" for this type of collector is 56% at an inlet velocity of 1067 m^3/min (3500 fpm). This implies that, for example, when the inlet humidity is 50%, the collection system

will increase the humidity by 56%, resulting in an outlet humidity of 78%. The potential for a moisture problem may be more severe in winter when water vapor leaving the collector would quickly condense on cold surfaces such as windows. This might be offset, however, by lower ambient humidities which are experienced in winter.
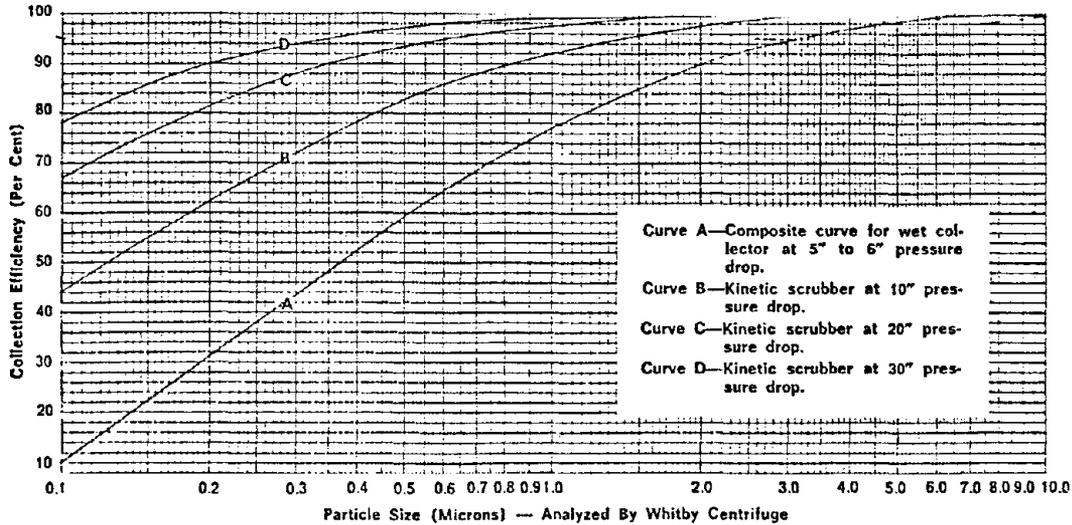
Figure 3-8. Published efficiency curve for wet collector (13).

Table 3-10. Predicted outlet concentrations vs. particle sizes.

micrometers	Efficiency at size range midpoint, percent	Outlet concentrations, mg/m^3		
		Dust		
		Peak	Average	Manganese
>15.0	99.8	0.39	0.26	0
9.2 - 15.0	99.5	0.18	0.12	0
3.7 - 9.2	99	0.13	0.09	0.05
2.2 - 3.7	94	2.16	1.45	0.02
1.4 - 2.2	86	2.18	1.47	0.02
0.76 - 1.4	78	2.03	1.36	0.02
0.42 - 0.76	64	0.69	0.47	0.04
0.1 - 0.42	38	7.50	5.08	0.54
·Total	Total	15.26	10.30	0.69
Respirable (<5.0μ)		14.59	9.85	--
Predicted collection efficiency total		95.21	95.2	97.4
Predicted collection efficiency - respirable		83.0	83.0	--

2. A second disadvantage of a wet collection system is the possible adverse affect of the coolant on room odor levels. Since the coolant has a distinct odor, working conditions could become intolerable if odor levels significantly increased. This problem can only be estimated after the system is installed, however.

In summary, use of a wet collector has several economic advnatages, but problems concerning efficiency, humidity, and odor must be carefully considered by the design team in the selection process.

Evaluation of Monitoring Strategies--
A failure detection strategy should address the principal failure modes and have a response which adequately protects the worker from overexposure. In this discussion, the pertinent failure modes will be identified, then several possible failure response strategies, including the one specified by the company, will be evaluated.

Failure Modes--
The principal means by which the present system could fail are listed in Table 3-11. Failure modes may be classified under two headings: failure of the air cleaner, and failures of the remaining exhaust system components. Unlike most systems, the fan in this system is part of the air cleaner.

The most common failure of this type of wet scrubber is disruption of the spray of finely divided water particles which permits the impaction and capture of particulate matter. The chief methods of disrupting the spray are the clogging of nozzles and pump failures; however, failures of any of the fluid system components, e.g., pipe plugging and microscreen blinding, will also cause failures to occur. Another type of failure, an overloaded impellor, may result in decreased efficiency of the scrubber, but its primary effect would be to cause severe vibrations leading to bearing failure or rupturing of fan or duct welds.

Although not considered a principal mode of failure, there is another failure which was experienced during the system evaluation which can cause the release of water droplets containing particulates. This is the previously noted drain blockage of the water mist separator. This "failure" will not be discussed further because the "dirty" water droplets would not likely result in increased breathing zone concentrations. Failures of the other exhaust system components include:

1. Breakdown of the fan/drive system.

2. Increased restrictions to flow, e.g., blockages in the hood inlet or recirculation outlet plenum.

On the chart, major failure effects are identified (underlined) as those which may cause overexposure of the grinding machine operator due to either:

1. Recirculation of excessive amounts of particulate.

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Table 3-11. Principal modes of failure and effects.

Failure type	System parameter failure effect			
	Water flow rate	Motor relay switch	Outlet concentration	Hood capture efficiency
Air cleaner failures				
Failure 1 - Water spray failure, i.e. pump failure, plugged nozzle	↓	no change	↑ (major)	no change
Failure 2 - Impeller becomes overloaded with process dust	no change	no change	↑	no change
Exhaust system failures				
Failure 3 - Drive failure	no change	trip	↑ (major)	↓ (major)
Failure 4 - Hood or duct blockage	no change	no change	↓	↓ (major)

↓ or ↑ denotes deviation from steady state performance.
—— denoted major failure effect

2. Decrease in the exhaust flow rate to the point that the hood is only partially effective and dust escapes directly from the process into the breathing zone.

Present Monitoring Method--
The monitoring method implemented by the company consisted of a sensor to detect decreased water pressure to the nozzle and a relay to indicate when the impellor was not rotating. Additionally, a lockout mechanism was provided to make the grinding machine inoperable if the collector had malfunctioned. The plant manager also indicated that he considered the visual surveillance of the return air duct as a part of their failure detection strategy. As a note of interest, it was observed that the workers made frequent comments about the visible mist "plume" emanating from the collector exhaust. Several of the comments indicated a mistrust and fear on the part of the employees.

As noted in Table 3-11, the failure response strategy installed by the company would provide response to only two of the four failure types (failures 1 and 3). It must also be noted that a water pressure sensor can indicate flow through the nozzle only when the flow through the nozzle is unimpeded. If a nozzle clogs, the water pressure will relate to both the amount of restriction of the nozzle, as well as the flow through it. In the extreme, a completely clogged nozzle could produce a pressure signal almost equivalent to a full flow condition.

An automatic monitoring device such as the nephelometer could provide response to failure 1 and, perhaps a response to failure 2. Although none of the response methods discussed can sense decreased air flows (a type 4 failure), there are commercially available "hood velocity alarms" which may be utilized for this purpose.

Design Optimization Using the Modeling Approach

Choosing an Appropriate Model--
The process of optimizing a design involves a carefully controlled balance of variables which may affect the outcome. The approach taken in Reference One is to balance pertinent factors by use of a series of equations defined as a "model". From a generalized modeling approach presented in Reference One, the authors have developed a number of simplifications to provide modeling equations for several types of recirculation systems commonly found. The situation in this case history could be described by configuration no. 2, which is presented in Appendix B in Reference One and Figure 3-9 in this report.

Actually, either system configuration no. 1 or no. 2 would be appropriate, because both depict systems where local exhaust streams are recirculated. Of these two, configuration no. 2 was chosen because this model depicts a case where no fresh air is added to the return air stream. It would be prohibitive to introduce a make-up air supply into the individual return air streams for all seven unit collectors.
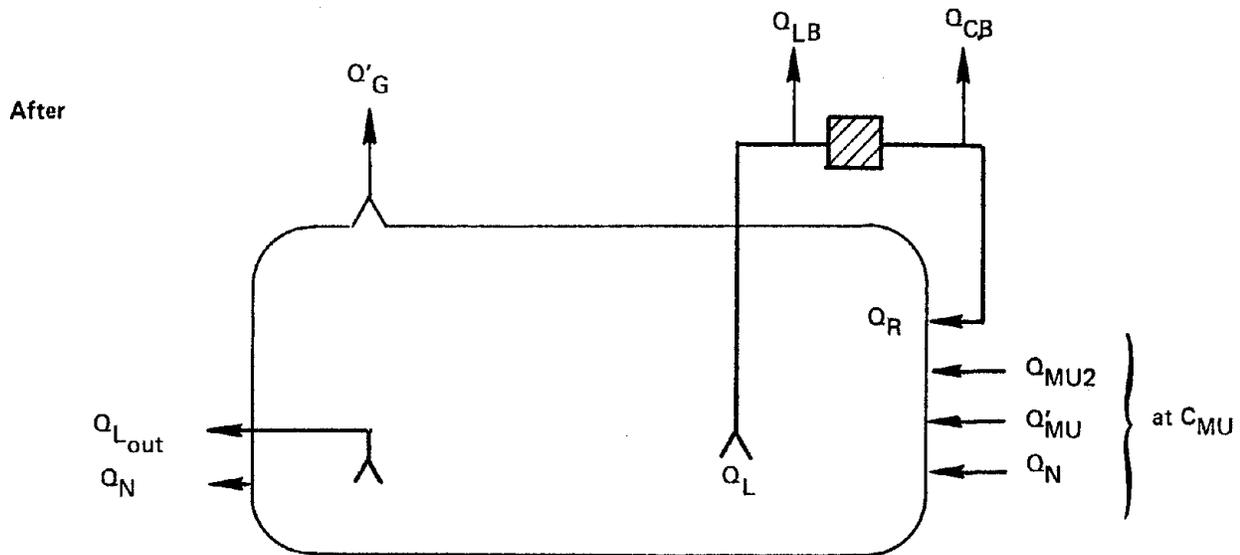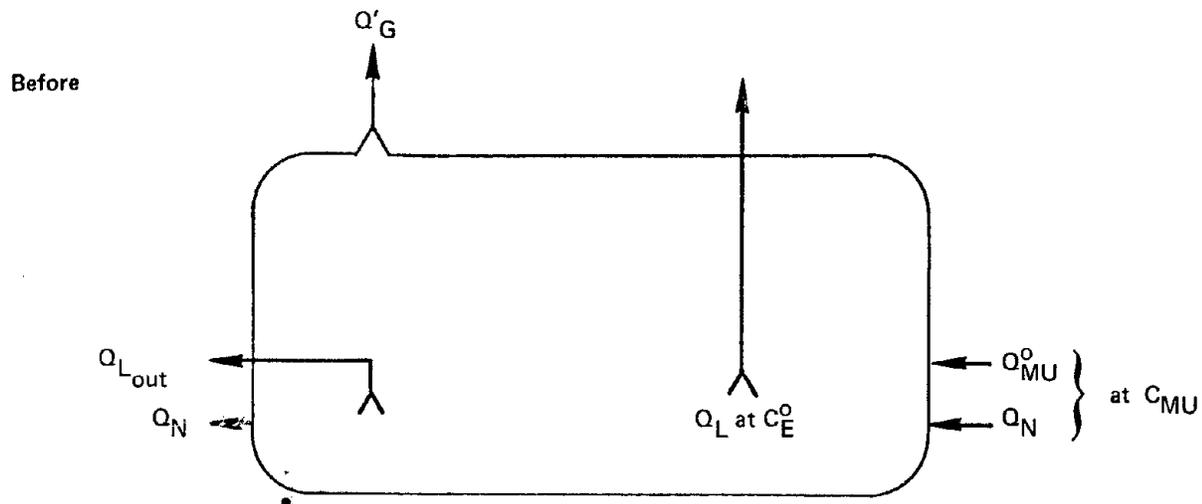
Before

After

See Discussion For Proper Design Procedure. Useful Equations are:

$$Q_R = Q_L - Q_{LB} - Q_{CB}$$

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

$$C_R = \frac{1}{k_{BZ}} \left[C_{BZ}^D - (1-f)\frac{Q_T^o}{Q_T} \ (C^o_{BZG} - C_{MU}) - f\,(C^o_{BZL} - C_{MU}) - (1-k_{BZ})\,C_{MU} \right]$$

$$\eta = 1 - \left[\frac{C_R}{C_E^o - k_R C_{MU} + k_R C_R} \right]$$

Figure 3-9. System configuration no. 2.

Several differences between the system actually studied and the configuration represented by Figure 3-9 should be noted:

1. The system boundary is defined as just the east end of the large bay in which the grinders are located, rather than the entire plant or high bay, because this area is far enough removed from other exhaust sources to be considered separately. The effect of the reduced system boundary affects the estimates for the values assigned to various air volumes in the room. For example, the volume of air locally exhausted excludes the volume of air exhausted from the plant spray booth at the far end of the high bay, resulting in a lower tabulation of the negative air pressure.

2. Because this assessment can only be made retroactively, the "before" condition is assumed to be when the new exhaust system (grinder no. 1 only) has been installed and is operating, but without cleaned exhaust air returning to the building.

3. Due to the air imbalance which existed in the room prior to recirculation, all of the model equations cannot be directly applied without some modifications. The negative pressure in the room "before" recirculation caused air to infiltrate from other plant areas. This air imbalance violates one of the assumptions of the model: that air mechanically extracted is mechanically made up. To account for this incongruity, a new meaning will be assigned to the term describing the natural ventilation rate, Q_N. In Reference One, Q_N describes the natural ventilation due to natural factors i.e., wind forces and heat sources within the rooms which are absent in the present case. The air imbalance before recirculation will be described by a new term, Q_N^O, while the air imbalance after recirculation will be assigned to Q_N.

Design Approach--
The Reference One design approach associated with configuration no. 2 is shown in Figure 3-9.

Assigning Parameter Values--
Model parameters are assigned values in Table 3-12.

Modeling Results--
Calculation of the amount of air to be returned, Q_R--Equation no. 1 in Table 3-12 shows that when there is no bypass of recirculated air (Q_{LB} = Q_{CB} = 0), the rate of return air, Q_R, is equivalent to the rate exhausted by the process, Q_L.

Calculation of the amount of make-up air required after recirculation, Q_{MU2}--Equation no. 2 calculates a dependent design variable, Q_{MU2}, a parameter which specifies the amount of fresh air which should be brought into the room to achieve an air balance. As calculated, approximately 1603 m^3/min should be brought into the room to offset the amount exhausted.

Table 3-12. Model parameter values.

Para-meter	Description	Value	Rationale
Q_{LB}	Exhaust volume bypassed before collector.	0	As a first approximation, assume all exhausted air returns to room.
Q_{CB}	Exhaust volume bypassed after after collector	0	As a first approximation, assume all exhausted air returns to room.
$Q_{L_{out}}$	Local exhausts other than what is recirculated	810 m^3/min	From Table 3-1, this is the total exhaust rate at the east end of the room. It includes local grinder exhausts not recirculated and a small welding exhaust.
Q_L	Initial volume of local exhaust stream	425 m^3/min	This is the design flow rate of the collector exhausting grinder No. 1.
Q_{MU}^O	Make-up rate for conventional systems	0	There is no source of mechanically made-up air in the room.
Q_{MU}'	Fixed make-up supply rate	0	There are no "fixed" sources of make-up air in the room, i.e., from heat recovery sources.
k_{BZ}	Contribution factor of return air to breathing zones	1.0	As a conservative first estimate, a value of 1.0 is assigned.
k_R	Contribution factor of return air to local exhaust systems	1.0	As a conservative first estimate, a value of 1.0 is assigned.
Q_G'	General exhaust rate not recirculated	793 m^3/min	From Table 3-1, this is the volume exhausted by the overhead roof ventilator.
Q_N^O	Natural ventilation rate (in this case, infiltration) prior to recirculation	1603 m^3/min	The amount infiltrating is equivalent to the amount exhausted: $$Q_N = Q_{L_{out}} + Q_G'$$ $$Q_N = 810 + 793 = 1603$$

Table 3-12 (continued).

Para-meter	Description	Value	Rationale
Q_T^O	Total ventilation rate before recirculation	1603 m^3/min	In a negative pressure condition, Q_T^O is equal to the amount of mechanically made up air and the infiltration rate.
Q_R	Amount of exhaust returned to the building.	425 m^3/min	Equivalent to the recirculated air flow since there are no bypass volumes.
Q_N	Natural ventilation rate after recirculation	1178 m^3/min	Recirculation will decrease the amount of infiltration by the amount recirculated: $$Q_N = Q_N^O - Q_L$$ $$Q_N = 1603 - 425 = 1178$$
Q_T	Total ventilation rate after recirculation	1603 m^3/min	In a negative pressure condition, Q_N^O is equal to the recirculated air flow, the amount of make-up air, and the infiltration rate. $$Q_T = Q_R + Q_{MU} + Q_N$$ $$Q_T = 425 + 0 + 1178 = 1603$$
C_{MU}	Make-up air concentration	~ 0	There is no mechanically made up air. Infiltration air originates from clean plant areas.
C_{BZG}^O	Initial breathing zone concentration in general plant areas	2.23 mg/m^3	This is the highest breathing zone measurement made prior to recirculation.
C_{BZL}^O	Initial breathing zone concentration is the influence of large volume exhaust systems	0	No large volume local exhaust hoods are present in the area of interest.
f	Local exhaust system influence factor	0	No large volume local exhaust hoods are present in the area of interest.

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Table 3-12 (continued).

Para-meter	Description	Value	Rationale
c_E^O	Initial concentration of local exhaust stream	215.2 mg/m^3	From Table 3-2 the average inlet concentration is used for this value because the average value is more appropriate for calculating outlet concentrations which are to be compared to 8 hour time-weighted average.
c_{BZ}^D	Desired breathing zone concentration	1.0 mg/m^3	As a first estimate, a value which is 20% of the OSHA PEL for respirable dust is chosen.

Without this additional amount of make-up air the design team would be faced with a negative pressure problem both before and after recirculation. In a plant with a balanced air condition before recirculation, the effect of recirculation would be to increase the total ventilation rate by the amount recirculated if there are no changes in the make-up supply rate or other ventilation parameters. But since no make-up air was brought into the room and there were no other ventilation changes, recirculation will only have the affect of reducing the amount of infiltration, with no resultant change in the total ventilation rate. Since the total ventilation rate will remain the same, there will be no contaminant concentration reduction due to the additional dilution ventilation provided by the recirculation. This dilution manifests itself by the reduced Q_η^O/Q_m term which is multiplied by the initial breathing zone concentration, c_{BZG}^O, in the simplified form of equation no. 3 in Table 3-13.

One additional comment should be made about the problem of infiltrating air. Presently, the negative pressure from the grinder exhausts causes a high infiltration rate throughout the plant, including areas remote from the grinder area. If the plant decides to recirculate all of the grinding exhausts, then the reduction is infiltration will cause a reduction in the total ventilation rate through adjacent plant areas. This could increase contaminant concentrations in those areas if they contained contaminant-producing operations. The solution to this problem is to provide additional make-up air in those plant areas to replace the air which was infiltrating.

Calculation of required return air concentration, C_R, and required efficiency, η--In the design optimization process, the design team should determine what the return air concentration must be to achieve a desired concentration in the breathing zone. Knowing the necessary contaminant level in the return air stream, a required collector efficiency can be calculated.

Table 3-13. Model application calculations.

1. <u>Equation No. 1</u>

$$Q_R = Q_L - Q_{LB} - Q_{CB}$$

$$Q_R = 425 - 0 - 0$$

$$Q_R = 425 \ m^3/min$$

2. <u>Equation No. 2</u>

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

$$Q_{MU2} = 0 + 0 + 810 + 793 - 0$$

$$Q_{MU2} = 1603 \ m^3/min$$

3. <u>Equation No. 3</u>

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

$$\left. f \ (C^o_{BZL} - C_{MU}) - (1-k_{BZ}) \ C_{MU} \right]$$

Simplification: $f = C^o_{BZL} = C_{MU} = 0$

$$C_R = \frac{1}{k_{BZ}} \left[C^D_{BZ} - \frac{Q^o_T}{Q_T} \ (C^o_{BZG}) \right]$$

a. First estimate

$(k_{BZ} = 1.0, \ C^D_{BZ} \ (resp) = 1.0 \ mg/m^3, \ C^o_{BZG} \ (resp) = 0.60)$

$$C_R \ (resp) = \frac{1}{1.0} \left[1.0 - \frac{1603}{1603} \ (0.60) \right]$$

$$C_R \ (resp) = 0.40 \ mg/m^3$$

Table 3-13 (continued).

___

b.   Second estimate

   (k_{BZ} = 0.54, remaining parameters the same as above)

   C_R (resp) = 0.74 mg/m^3

c.   Third estimate

   (k_{BZ} = 0.27, Q_T^O = 1603 m^3/min, Q_T = 2028 m^3/min)

$$C_R \text{ (resp)} = \frac{1}{0.27} \left[1.0 - \frac{1603}{2028} \ (0.60) \right]$$

   C_R (resp) = 2.50 mg/m^3

4.   Equation No. 4

$$\eta = 1 - \left[\frac{C_R \text{ (resp)}}{C_E^O \text{ (resp)} - k_R \ C_{MU} + k_R \ C_R \text{ (resp)}} \right]$$

a.   First estimate

   (C_R (resp) = 0.40 mg/m^3 k_R = 1.0, C_E^O (resp) = 58.1 mg/m^3

$$\eta = 1 - \left[\frac{0.40}{58.1 - 0 + 1.0 \ (0.40)} \right]$$

   η = 0.9930

b.   Second estimate

   (C_R (resp) = 0.74 mg/m^3, k_R = 0.54, C_E^O (resp) = 58.1 mg/m^3)

   η (resp) = 0.9871

Table 3-13 (continued).

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c. Third estimate

$(C_R \text{ (resp) } = 2.50 \text{ mg/m}^3, \; k_R = 0.21, \; C_E^o \text{ (resp) } = 58.1 \text{ mg/m}^3)$

$\eta \text{ (resp) } = 0.9573$

If the computed efficiency is unsuitable, then model parameters can be adjusted and refined as necessary until a required efficiency is calculated which is acceptable.

Two contaminants were identified in the initial evaluation which should be utilized in the design process: nuisance dust and manganese. Although manganese has the same regulated level as respirable nuisance dust and is present in much smaller quantities, it must be considered separately in the design because it is regulated by a ceiling concentration. In the modeling approach, nuisance dust will first be used to estimate a required collection efficiency. This level of efficiency will then be checked for possible excursions of the manganese standard using peak estimates of model parameters.

After making in-plant measurements of total dust and reviewing the particle size measurements in the outlet exhaust, it was realized that the level of respirable dust in the workplace probably has more of an impact on the design than total dust levels. Not having initially realized this, no measurements of respirable dust were made in the survey. However, enough is known about the process from the measurements which were made to make good estimates of respirable dust concentrations in the workroom. This is an essential pre-requisite before assigning parameters the respective values based on respirable dust levels.

Particulate contaminants in the workroom results primarily from two sources: dust generated by the process which escapes capture by the hoods, and dust which re-enters the room in the recirculated exhaust. Assuming that the room contaminant levels nearly represent the results of the particle size tests in the collector inlet, the respirable dust content of the process-generated dust is approximately 27% (from Figure 3-4). Similarly, the respirable dust content of the outlet air stream is approximately 92% as measured by particle size tests in the outlet. In this discussion, it is assumed that the respirable fraction is the percentage of particles below 5.0 micrometers.

The values assigned to several model parameters previously assigned may now be reassessed. The following table presents a new estimate of several pertinent model parameters: A required return air concentration may be calculated after the remaining parameters in equation no. 3 are assigned appropriate values. The equation may be initially simplified by noting that there are no large volume local exhaust hoods in the plant area of interest $(f = C_{BZL}^o = 0)$, and that the concentration in the air make-up supply can

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be assumed to be insignificant ($C_{MU} \cong 0$). The values of several of the
parameters, i.e., k_{BZ}, Q_T^O, Q_T and C_{BZG}^O, are presented and supported in
Table 3-14.

Table 3-14. Respirable dust fraction of several model parameters.

Old parameter	Total dust measurement, mg/m^3	Respirable dust fraction, mg/m^3	New parameter name
C_{BZG}^O	2.23	0.60	C_{BZG}^O (resp.)
C_R	4.15	3.82	C_R (resp.)
C_E^O (avg.)	215.2	58.1	C_E^O (resp.)
C_{BZG}	2.41	2.21	C_{BZG} (resp.)

A final important model parameter must be specified before a calculation can
be made: C_{BZ}^D, the desired return air concentration. Knowing that C_{BZG} (resp.)
before recirculation is 0.60 mg/m^3, and that recirculation will cause some
increase in the breathing zone concentration, a slightly higher level of
1.0 mg/m^3 could be chosen by the designer as a first estimate. This level
represents an increase in the breathing zone level of respirable dust from
12% to 20% of the OSHA PEL for respirable nuisance dust.

Efficiency estimates may now be made. As noted in the calculation in
Table 3-13, the first estimate of equation no. 3 for the return air concentra-
tion is 0.40 mg/m^3. With this return air dust level, the first estimate of
equation no. 4 predicts a required collector efficiency of 99.30%. Realizing
that this efficiency is much higher than the 10% scrubber efficiency which
is expected for respirable dust (see Table 3-9) the design team may want
to investigate the refinement of some of the conservative model parameters,
such as k_R and k_{BZ}.

As Reference One suggests (p. 134), these parameters may be reasonably
estimated by knowing the magnitudes and expected distribution of the return
air stream and the source of "make-up" air (in this case due to infiltration).
For example, a maximum value for k_R might be estimated by noting that the
amount of return air reentering the exhaust hood, if properly mixed, can be
approximated by the following ratio:

$$\frac{Q_T}{Q_T} = \frac{425 \text{ m}^3/\text{min}}{1603 \text{ m3/min}} = 0.27$$

However, more realistic estimates should be made for k_R because this result is an ideal value which assumes that all infiltrating air is perfectly mixed with return air. Since the return air location is located in the middle of the room at an elevation of 7.6 m (25 ft), good mixing will occur, but it will certainly not be ideal. As a somewhat conservative estimate, it will be assumed that k_R is 0.54, a value which is twice the calculated ideal value. This value could also be assigned to k_{BZ} because the mixed air which reaches the recirculated exhaust hood will also reach the breathing zone of the worker who is located nearby.

With these estimates, Table 3-13 presents the calculated values of C_R and η which were obtained (second estimates). As noted, C_R was computed to be 0.74 mg/m^3, resulting in a required collection efficiency for respirable dust of 98.71%.

At this point, the design team should realize that, with the present design, breathing zone levels after recirculation are not acceptable. As a consequence, further explanation should consider alternatives to the percent conditions. As an example, alternate configurations, improved collection methods, or perhaps a re-evaluation of important parameters (such as C_{BZ}^D) should be considered.

Assessment of design alternatives--Realizing that the collection efficiency of the specified collector is not adequate, several options are available which may result in a suitable design. First, a collector with a higher efficiency could be specified, although the increased efficiency would require higher pressures and increase in operating costs. As shown in Figure 3-7, the collectors denoted by curves B, C, and D operate at approximately 2, 4 and 6 times the operating pressure drop as the collector first specified (curve A), with correspondingly higher initial capital outlays and operating costs for each. Since operating cost increases are roughly proportional to the square of the increase in pressure drop, the additional costs will result in making recirculation much less cost-effective and perhaps uneconomical. The economic feasibility of this alternative should be further evaluated in a detailed economic analysis of the final resolution, however.

As a second alternative, the use of secondary filters following the specified collector could be investigated. These filters would primarily remove smaller particles which the first collector did not remove. Several problems may be encountered with secondary filters, however. Using throw-away filters, filter life may be short because a relatively large amount of particulates escape the first collector. For example, a secondary collector with an overall efficiency of 80% would collect 1520 gm (3.3 lb) in a 24-hour period, assuming that the grinder operated 75% of the time.

Another problem that may have to be dealt with is the possibility of blinding the secondary filter with moisture. Usually, the effect of the humidity of the outlet stream is not significant because the humidifying effect of the air cleaner is not that great. But on days with high ambient humidity, the increase in humidity levels in the inlet may result in a saturated outlet stream and possible blinding of the secondary filter.

Assuming that the two previous options are rejected, a third alternative adding sufficient make-up air to the room should be considered.

Assessment of configuration alternatives--The introduction of increased amounts of make-up air would have the beneficial effect of attaining an air balance in the room with the resulting elimination of infiltration. Additionally, this would cause further contaminant reductions by providing properly placed dilution ventilation. In the model analysis, the increased levels of dilution is evidenced by a reduction in the estimates of the terms Q_T, k_R and k_{BZ}. Thus, these parameters will be re-estimated to calculate the effect of providing make-up air on the required collection efficiency.

With the addition of make-up air to the room, the total ventilation rate will increase by the rate of make-up air being introduced. The amount of make-up air required to attain an air balance was previously calculated in the computation of the term Q_{MU2}. Following recirculation, the total ventilation rate is computed to be the sum of the amount recirculated plus the necessary amount of make-up air provided:

$$Q_T = Q_R + Q_{MU2}$$

$$Q_T = 425 \text{ m}^3/\text{min} + 1603 \text{ m}^3/\text{min}$$

$$Q_T = 2208 \text{ m}^3/\text{min}$$

The parameters k_R and k_{BZ} can be estimated as before, by noting the magnitudes of Q_R and Q_T and the expected distribution (or mixing) of each. For this calculation, the assumption of good mixing could again be made because it is possible to design the air make-up to achieve a high degree of mixing. Thus, k_R and k_{BZ} can be approximated by the following ratio:

$$\frac{Q_R}{Q_T} = \frac{425 \text{ m}^3/\text{min}}{2028 \text{ m}^3/\text{min}} = 0.21$$

The overall effect of the addition of make-up air is shown by the third estimate of equation no. 3 and no. 4 in Table 3-12. A calculated return air concentration of 2.50 mg/m^3 (respirable dust) results in a required collection efficiency of 95.73%.

The efficiency required for respirable dust removal is still much above the efficiency of the collector intended for use (83.03%). The designer could now reassess other model parameters to discern where further refinements could be made. Since the parameter C_{BZ}^D, the desired breathing zone level, has such an important effect on the design it will be further discussed in the next section.

Evaluation of C_{BZ}^D, desired breathing zone concentration--In this discussion the effect of increasing values of C_{BZ}^D are investigated for two configurations: one without an air balance (no. 1) and the other with the provision for an adequate make-up air supply (no. 2). The values of parameters pertaining

to the first configuration are listed in Table 3-13 in the calculation of
the second estimates of equations no. 3 and no. 4. The values of parameters
in the second configuration are shown in the third estimates of equation
no. 3 and no. 4 in the same table. Table 3-15 summarizes the
findings.

The high efficiency estimates in configuration no. 1 indicate that without
the addition of make-up air to the plant (within the given constraints of this
calculation), the collector which has been previously specified for use
would not be suitable. However, with the addition of make-up air in
configuration no. 2, the required collection efficiency meets the anticipated
collection efficiency, 83.03% at a desired breathing zone concentration of
2.47 mg/m^3 (by interpolation). Of course, a lower C_{BZ}^D can be achieved
by specifying a more efficient collector.

Calculation of peak manganese levels--Assuming that the designer chose
configuration no. 2, a calculation can be made of the anticipated peak
manganese levels to determine possible excursions of the ceiling limit.
Table 3-16 below assigns appropriate values to the model parameters: Note
that peak values are used for C_E^O and C_{BZG} because a maximum concentration
is desired to be calculated.

The predicted return air concentration is calculated from the simplified
equation no. 3:

$$C_R \text{ (Mn)} = \frac{1}{0.21} \left[(0.50 - \frac{1603}{2028} (0.092) \right]$$

$$C_R \text{ (Mn)} = 2.03 \text{ mg/m}^3$$

The required efficiency is given by equation no. 4:

$$\eta = 1 - \left[\frac{2.03}{26.4 - 0 - 0.21 (2.03)} \right]$$

$$\eta = 0.9218$$

The required value is well below the anticipated collection efficiency for
manganese, 97.4% (Table 3-10) indicating that the specified collector is
also suitable for the removal of manganese to acceptable levels.

Failure Analysis of Chosen Configuration

A failure analysis is performed by the design team to allow the comparison
of the critical required response time to the response of the monitoring
system chosen for use. The critical response time is defined as the
shortest time in which any employee is exposed to unacceptable concentration
levels. A complete explanation of the analysis of failures is given in
Appendix F of Reference One.

Calculation of Steady-State Concentration After Failure--
A steady-state breathing zone concentration is calculated by setting the
collector efficiency to zero in a breathing zone equation. The following
expression results:

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Table 3-15. Effect of increasing C_{BZ}^D in two configurations.

C_{BZ}^D (resp)	Configuration No. 1 no make-up air		Configuration No. 2 with additional make-up air	
	C_R (resp)	η, percent	C_R (resp)	η, percent
1.0	0.74	0.9871	2.50	0.9569
2.0	2.59	0.9543	7.27	0.8715
3.0	4.44	0.9202	12.03	0.7835
4.0	6.30	0.8849	16.79	0.6923
5.0	8.15	0.8482	21.55	0.5362

Table 3-16. Model parameter values (manganese).

Parameter	Value	Rationale
C_E^O (Mn)	26.4 mg/m^3	The peak concentration estimated earlier in this section
C_{BZG}^O (Mn)	0.092 mg/m^3	The highest personal sample taken before recirculation. (Table 3-6)
k_{BZ}, k_R	0.21	This value which was calculated earlier in the discussion reflects the addition of make-up air.
C_{BZ}^D (Mn)	0.50 mg/m^3	As a first estimate, assume 10% of the OSHA PEL as the desired level.

$$C_{BZ}^{FS} = C_{BZ}^O + C_E^O \left[\frac{k_{BZ}}{1 - k_R} \right]$$

The superscript F in the first term denotes "failure", while S indicates that this is the steady-state concentration after failure. In this study, the post-failure concentrations of manganese and respirable nuisance dust are most important. For manganese, the value for C_{BZ}^{FS} would be calculated as follows: (with tracer gas estimates for k_R and k_{BZ}):

$$C_{BZ}^{FS} = 0.092 + 26.4 \left[\frac{0.25}{1-0.23} \right]$$

$$C_{BZ}^{FS} = 8.66 \text{ mg/m}^3$$

The following post-failure concentration is calculated for respirable dust:

$$C_{BZ}^{FS} = 0.60 + 180.0 \left[\frac{0.25}{1 - 0.23} \right]$$

$$C_{BZ}^{FS} = 59.0 \text{ mg/m}^3$$

Measuring Rise Time, t_o --
The time to reach steady-state is defined as the "rise time". It may be measured by means of a tracer gas study (see Table 3-6). The tracer gas measurements of rise time which were made, are summarized below (Table 3-17).

Table 3-17. Tracer gas rise time measurements.

Variable	Time of measurement, min	Concentration in breathing zone at time, t_n, ppm
$C_{BZ}(t_o)$	0	0
$C_{BZ}(t_1)$	1.0	2.2
$C_{BZ}(t_2)$	2.0	4.4
$C_{BZ}(t_3)$ *	4.0	6.0

* Concentration at steady-state.

The rise time equation in Reference One can now be used to calculate the empirical rise time for a one minute (0.0167 hr) rise:

$$t_o = \frac{t_1}{\ln \dfrac{C_{BZ}(t_1)}{C_{BZ}(t_2) - C_{BZ}(t_1)}}$$

$$t_o = \frac{0.0167}{\ln \dfrac{2.2}{4.4 - 2.2}}$$

$$t_o = \infty$$

An answer of infinity is obtained because the natural log of one is zero, and the division by zero is undefined. This suggests that the tracer gas measurement used in this calculation did not encompass a segment of the concentration vs. time curve which exhibits a exponential behavior. This indicates that the accuracy of the tracer gas measurement is critical within the first few minutes of a tracer gas survey. A more meaningful answer could be obtained by using data from another part of the rise curve, such as was indicated from t_2 to t_3:

$$t_o = \frac{0.0167}{\ln \frac{4.4}{6.0 - 4.4}}$$

$$t_o = 0.0165 \text{ hr} = 1.0 \text{ minute}$$

A one minute rise time means that workers will quickly experience high concentrations following after a failure.

Calculation of Critical Response Time--
The critical response time should be calculated for manganese and respirable nuisance dust because the response time will be different for a substance regulated by ceiling levels compared to substances regulated by time weighted averages. In Reference One, the critical response time of substances regulated by ceiling concentrations is defined as the smaller of the quantities defined by the following two statements:

1. The time for $c_{BZ}^F(t)$ to reach the ceiling, should one exist; this is denoted by T_{C1};

2. The time for the 8-hour time-weighted average to reach the PEL, denoted by T_{C2}.

Using the first expression, the critical response time for manganese would be calculated as follows:

Equation 1: $\quad T_{C1} = t_o \ln \left[\dfrac{c_{BZ}^{FS} - c_{BZ}}{c_{BZ}^{FS} - c_{ceiling}} \right]$

Where:

T_{C1} = Time after failure to reach ceiling level

$C_{ceiling}$ = Ceiling concentration = 5.0 mg/m^3 for manganese

c_{BZ}^{FS} = Steady-state post-failure breathing zone concentration

= 8.66 mg/m^3

C_{BZ} = Pre-failure breathing zone concentration

= 0.092 mg/m^3 (Mn)

t_o = Estimate from tracer gas measurements

= 0.0165 hr

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Substituting, a critical response is calculated:

$$T_{Cl} = 0.0165 \ \ln \left[\frac{8.66 - 0.092}{8.66 - 5.0} \right]$$

$$T_{Cl} = 0.0142 \ hr. = 51 \ seconds$$

The above result indicates that a manganese level of 5.0 mg/m^3 could be reached in 51 seconds following a failure. This short time period has serious implications on the dependability and response time of the failure response strategy which is chosen.

Merely as a check, the critical response time of a nuisance dust will be made the appropriate equation presented in Reference One (equation 2):

$$\text{Equation 2:} \quad T^* = \frac{8}{t_o} \left[\frac{TLV - C_{BZ} - (C_{BZ}^{FS} - C_{BZ}) \frac{t_o}{8}}{C_{BZ}^{FS} - C_{BZ}} \right]$$

Where:

$$PEL = 5.0 \ mg/m^3 \ for \ respirable \ dust$$

$$C_{BZ} = 0.60 \ mg/m^3 \ (Table \ 3-13)$$

$$C_{BZ}^{FS} = 59.0 \ mg/m^3 \ (calculated \ earlier \ in \ this \ section)$$

$$t_o = 0.0165 \ hr$$

Substituting,

$$T^* = \frac{8}{0.0165} \left[\frac{5.0 - 0.60 - (59.0 - 0.60)\frac{0.0165}{8}}{59.0 - 0.60} \right]$$

$$T^* = 35.4$$

As stated in Reference One, for values of T* above 4.0, the critical response time is some value greater than four minutes. Comparing this result to the critical response time for manganese, it is apparent that the presence of manganese will dictate that the failure strategy have a quick response time and have a high degree of reliability.

System Performance Validation

Once a recirculation system is designed and installed, Reference One suggests that a system should be checked prior to actual production to protect the worker from overexposure if the system is not adequately designed or installed. A calculation will be made to check the air cleaner's performance using the approach in Reference One.

Checking Air Cleaner Performance--
Once a recirculation system is designed and installed, the system should
be checked to ensure that its performance meets design specifications.
Since a 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.
Reference One gives the following equation to calculate a C_R which the
actual system must not exceed:

$$C_R \leq \frac{1}{k_{BZ}} \left[C_{BZG}^D - C_{BZ}^O \left(\frac{Q_T^O}{Q_T}\right) \right] + C_{MU}$$

Assuming that the design team chose to introduce additional make-up air
into the room (see third estimate, equation no. 3, Table 3-13, the planned
return air concentration calculated below should not be exceeded by the
new collector:

$$C_R \text{ (resp)} \leq \frac{1}{0.21} \left[1.0 - \frac{1603}{2028} (0.60) \right] + 0$$

$$C_R \text{ (resp)} \leq 2.50 \text{ mg/m}^3$$

The manganese concentration should also not exceed the following calculated
value (see Table 3-16) for explanation of value assignments).

$$C_R \text{ (Mn)} \leq \frac{1}{0.21} \left[0.5 - \frac{1603}{2028} (0.092) \right] + 0$$

$$C_R \text{ (Mn)} \leq 2.03 \text{ mg/m}^3$$

This is the value one would expect by taking into consideration all of the
assumptions which have been made in this analysis, i.e., $C_{BZ}^D = 1.0 \text{ mg/m}^3$,
$k_{BZ} = 0.21$, etc. These assumptions were all made in the context of the
retroactive assessment because the guidelines of Reference One were being
followed. Thus, one must be careful when comparing this required "return"
air concentration of respirable dust to the concentration actually measured:

$$C_R \text{ (resp)} = \text{(fraction of respirable dust)} \ C_R$$
$$C_R \text{ (resp)} = (0.92) (6.51 \text{ mg/m}^3)$$
$$C_R \text{ (resp)} = 5.98 \text{ mg/m}^3$$

The reason that this actual value is higher than the required value lies in
the difference between the assumptions underlying the required value and
actual conditions. Obviously, a major factor in the low required estimate
is a desired breathing zone concentration of 1.0 mg/m^3, compared to an
actual breathing zone concentration of approximately 2.21 mg/m^3 of respirable
dust (Table 3-14).

Comparison of Model Estimates to Actual Concentrations

The large number of workplace measurements and the tracer gas analysis provides a good opportunity to compare model predictions to concentrations actually measured. A simplified breathing zone concentration presented in Appendix A of Reference One may be used for this purpose:

$$C_{BZ} = \frac{Q_T^O}{Q_T} (C_{BZG}^O) + k_{BZ}C_R$$

<u>Where:</u>

C_{BZ} = The predicted breathing zone concentrations, mg/m^3

Q_T^O = The total ventilation rate before recirculation

= 1603 m^3/min (from Table 3-12)

Q_T = The total ventilation rate after recirculation

= 1603 m^3/min (from Table 3-12)

C_{BZG}^O = The initial breathing zone concentration

= 1.60 mg/m^3 (average of personal measurements - Table 3-5)

k_{BZ} = The contribution factor of return air to breathing zones

= 0.20 (Table 3-7)

C_R = The return air concentration

= 4.15 mg/m^3 (Table 3-2)

Substituting,

$$C_{BZ} = \frac{1603}{1603} (1.60) + 0.20 (4.15)$$

$$C_{BZ} = 2.43 \ mg/m^3$$

This prediction compares well to the average concentration measured after recirculation, 2.41 mg/m^3, implying that the modeling equations are based upon sound concepts.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions which can be made from this case study support the conclusions and recommendations of Reference One:

1. As identified in Chapter 4 of Reference One, the evaluation of wet scrubbers must include an assessment of the effect of increased humidity levels on the deterioration of equipment and the comfort of workers within the work area.

2. The fact that the plant did not have knowledge of pre-recirculation breathing zone concentrations presents serious difficulties in the selection of suitable air cleaners and the design process in general.

3. The collection malfunctions experienced in the survey suggest that plants should thoroughly debug a new system before attempting to recirculate.

4. In general, the modeling approach was a useful tool for evaluating a host of possible configuration alternatives.

5. The observed mistrust and fear of the recirculation system on the part of the employees emphasizes the need for a safe design and supports Reference One's recommendation for the implementation of an adequate education and training program following system installation.

6. The likely presence of nitrosamines, a class of suspected carcinogens, in the return air stream forced the designer to seek safer substitutions for the cutting oil presently used in the scrubber water. Reference One recommends that known or suspected carcinogens not be recirculated.

7. The close agreement of the breathing zone concentration predicted by the modeling approach and the average value actually measured implies that the modeling equations are based on sound concepts.

The following conclusions did not fully support the conclusions and recommendations of Reference One.

8. The early recognition of the potential for the return air stream to be odorous was an observation which Reference One did not suggest in the discussion of the initial feasibility assessment (Chapter 2).

9. The presence of a substance which is regulated by a ceiling concentration complicates the evaluation of monitoring strategies and devices. This difficulty was not specifically mentioned in Chapter 6 of Reference One which deals with the topic of surveillance.

10. The evaluation of contaminants discussed in Chapter 4 of Reference One does not suggest that the collection medium (scrubber water) could be the source of harmful contaminants, i.e., nitrosamines, which should not be overlooked in the evaluation.

11. If the segment of the measured tracer gas rise exhibits linear instead of exponential behavior, the equation in Appendix F of Reference One which is used to calculate the rise time will give meaningless results.

12. The respirable dust content of the workroom air may significantly increase after recirculation due to the selective nature of air cleaning devices. The rise of the respirable dust fraction has important implications in the evaluation of workplace contaminant concentrations.

RECOMMENDATIONS

The following recommendations emanate from the conclusions:

1. The possibility of objectionable odors being present in the return air stream should be considered in the initial feasibility assessment.

2. It should be realized that the presence of a substance which has a regulated ceiling concentration may complicate the selection of suitable monitoring devices.

3. The possibility that scrubber water could contain harmful substances should be investigated when evaluating wet air cleaning devices.

4. When using the rise time equation in Appendix F of Reference One, it should be realized that the equation will give erroneous results when an improper segment of the tracer gas rise measurement is chosen.

5. It should be emphasized that since recirculation systems have a greater for potential for emitting respirable size particles, the toxic hazard from respirable dust should be evaluated after system installation.

CASE STUDY NO. 4
EVALUATION OF AN ENAMEL BLENDING PROCESS
OCTOBER 1978

CONTENTS

FIGURES

TABLES

INTRODUCTION

This case study contains the results of a survey of an air recirculation
system which had been recently installed on a process which produced a dry
enamel powder. New total enclosure hoods and an improved dust collection
system replaced an inadequate ventilation system which had smaller hoods
and operated at a much lower flow rate. The purpose of the new system was
to improve breathing zone control while the concept of recirculation was
added primarily to save energy.

PLANT DESCRIPTION

Various colors of powdered enamel mixtures were prepared on the first floor
of a building for later use in enamel-coated cast iron products. As shown
in Figure 4-1, the first floor consisted of two rooms, the "white room" and
the "color room". Because the recirculation system returned air only to
the east end of the color room, the west end of the room is not shown. The
white
m
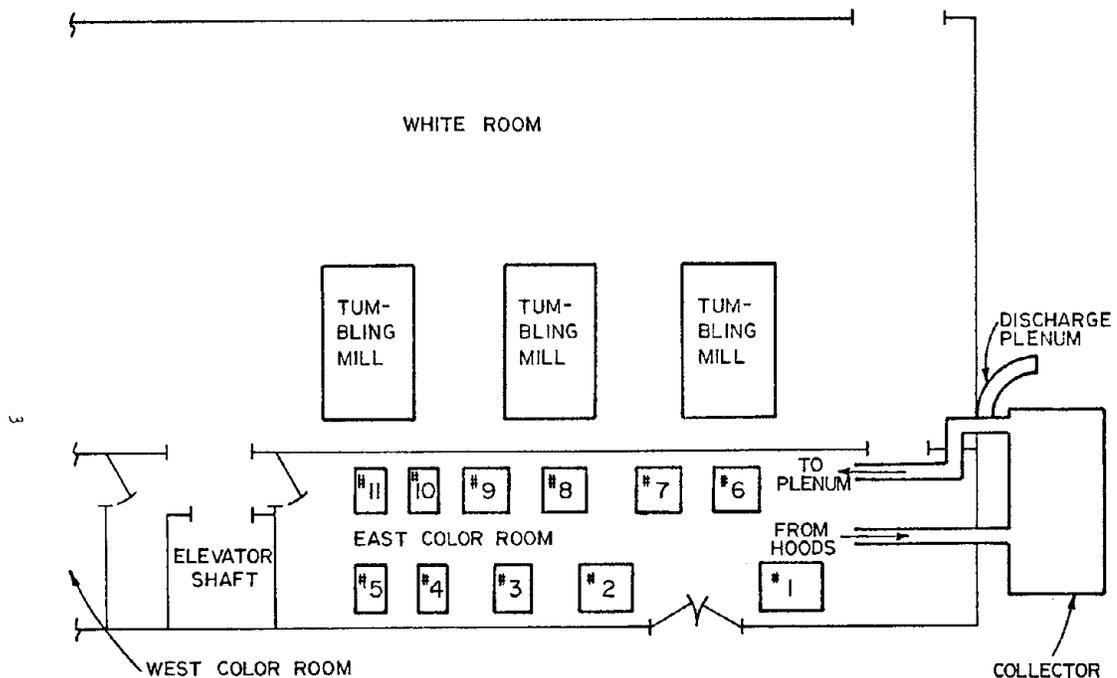
Figure 4-1. Plant layout.

PROCESS DESCRIPTION

Process Flow and Layout

The five large tumbling mills in the white room produced an enamel powder by
grinding smelted glass frit into a fine powder (three mills are shown in
Figure 4-1). A portion of this powder was manually conveyed to the color

room where it was combined with small amounts of pigments in the smaller mills. Both the large tumbling mills and the smaller mills in the color rooms operated on a batch basis on three shifts.

Two types of mills were employed in the color room. The first type of mill was called a blender (no. 1 and no. 2 in the east color room in Figure 4-1) because it used the action of a spinning blade to blend the ingredients. Blenders had capacities of 227 kg (500 lb) and could blend one batch in 25 minutes. The remaining 19 mills were porcelain-lined ball mills (no. 3-no. 11 in the east color room in Figure 4-1) which rotated to provide the mixing action. The capacity of these mills ranged from 36-227 kg (80-500 lb), and the duration of their cycle was typically 1/2 to five hours. A typical ball mill is shown with the hood enclosure in Figure 4-2.
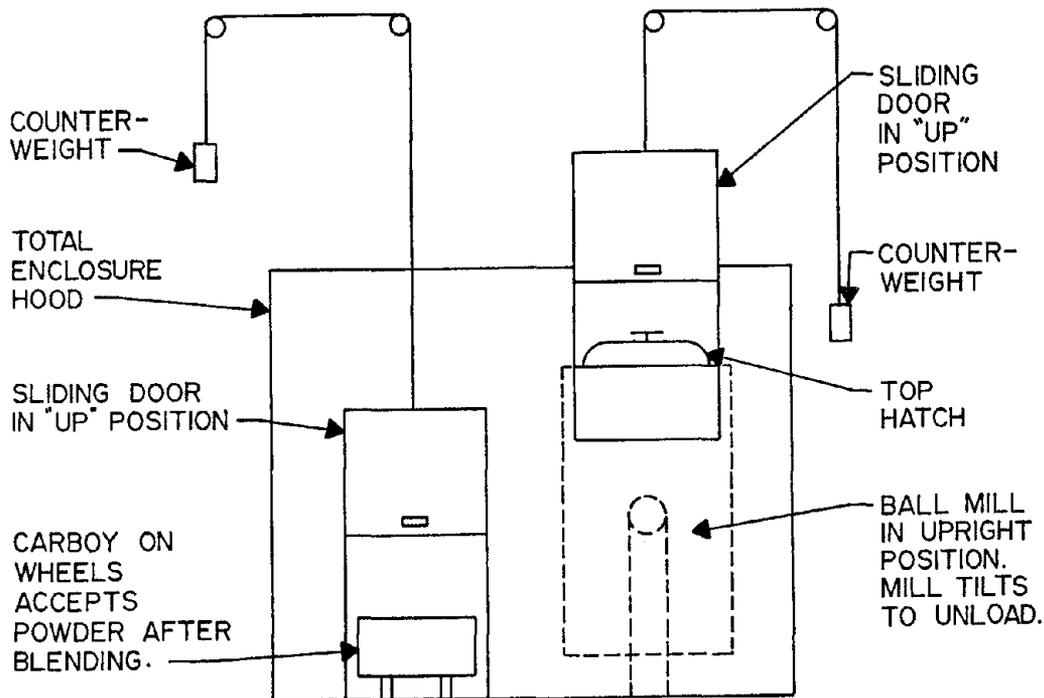
Figure 4-2. Front view of typical ball mill and hood enclosure.

Process Constituents

The white enamel powder consisted of a glass frit containing 16% lead and lead compounds and less than 0.1% free silica. The remainder was inert compounds. The pigments were composed of various proprietary inorganic coloring compounds. Three of the sixteen pigments contained cadmium and several others contained zinc.

Process Operation

All of the mills in the color room were surrounded by new, totally enclosing exhaust hoods with sliding doors for manual loading and unloading. To

initiate a work cycle, a worker first entered the white room and retrieved carboys on wheels filled with the white powder. Once at the mill, he opened the upper sliding door and dumped the carboys into the top of the mill through a hatch. Sacks containing pre-measured amounts of pigments were next emptied into the mill. The mill was then closed and the mixer was started. Near the end of the cycle, the worker stopped the mixer and retrieved a small sample for a quality control test. At the end of the cycle, a lower sliding door was opened and the contents of the mill were discharged into a carboy by rotating the top of the mill downward. Following each cycle, the mixers and the enclosed hood were thoroughly cleaned with an air nozzle to remove loose material clinging to the mill and cabinet surfaces. During the shift, workers also periodically swept spillage from in and around the machines.

VENTILATION SYSTEM

Exhaust System

All of the hooded mills were exhausted by a common ductwork system leading to a reverse-air fabric dust collector. The design capacity of the new collector was 651 m^3/min (23,000 cfm). This flow rate represented a significant increase over the previous collector's capacity of 184 m^3/min (6500 cfm).

The new exhaust system was designed to induce a 1.5 m/sec (300 fpm) in-draft velocity into each of seven open hoods, the maximum number assumed to be opened at once. Normally, five hoods might be opened at once, and at most, seven hoods might be open. When all of the hoods were closed, the system's static pressure would normally increase with a decrease in air flow. To compensate for this, a barometric damper was installed at the far end of the system (in the west color room). The damper was designed to open as the static pressure increased. This maintained a nearly constant air flow rate into the collector even though the number of open and closed hoods varied during the operation.

Recirculation System

Exhaust air from both the east and west color rooms was transported to the collector, cleaned, then returned to the workroom through an air plenum which distributed it along the entire length of the east color room (Figure 4-1). Since more air was returned to the east color room than was exhausted, the room was under positive pressure. This pressure had the beneficial effect of preventing infiltration of airborne dust from uncontrolled processes in the white room. The recirculation system was operated in this mode all year to assure continuous protection against infiltration. Excess air left the east color room by one of two interior doors (Figure 4-1) or entered the west room through a connecting duct above the walkway joining the two rooms. When the small air make-up unit was operating during winter months, the additional incoming air caused an even greater positive pressure in the east color room.

4-4

Through the improved exhaust system, the company sought to accomplish two objectives:

1. To improve the capture effectiveness of the hoods on the mills and blenders by totally enclosing the process and increasing the exhaust rate almost fourfold.

2. To eliminate infiltration of dusty air from the white room by placing the east color room under positive pressure.

If the company had increased the exhaust rate without recirculation, it would have meant increased energy costs from the make-up air to prevent infiltration. Thus, recirculation was seen as a feasible and economical approach toward reducing the energy penalty associated with increasing the exhaust rate.

Realizing the need to monitor the exhaust stream, the company addressed the issue of surveillance by selecting two in-duct monitoring devices: a differential pressure sensor across the fabric collector, and a nephelometer in the return air duct. The differential pressure sensor was designed to detect increased pressures from the normal, steady-state pressure drop across the baghouse of 5.1 cm (2 in.). In the design, the sensor was set to trip if the pressure dropped below 2.5 cm (1 in.) or exceeded 7.6 cm (3 in.). In addition, the switch was set to trip if the pressure across the baghouse rapidly changed. The nephelometer which was selected was a prototype monitor which will be tested soon at the plant as part of a demonstration program. If the test is successful, the company will incorporate the monitor into the present design. The projected cost of the monitor is approximately $3500 (not including installation costs).

Following a failure, a signal from the pressure sensor or the nephelometer was designed to cause a buzzer and a warning light to activate on a control panel located inside the room. Workers were supposed to respond to the signal by shutting down the process and bypassing the exhaust by activating a manual damper.

Air Make-Up

Fresh make-up air was provided by a 142 m^3/min (5,000 cfm) air make-up unit which was located in the east color room. During the survey, the air make-up unit in the color room did not operate in conjunction with the exhaust system. In colder months, both systems normally would operate simultaneously.

METHODS

In-Duct Sampling

Inlet and outlet particulate measurements were taken simultaneously to allow calculation of the actual collector efficiency for each test. Samples were extracted from the collector inlet with an EPA Method 5 particulate sampling train and approved procedures. Because low concentrations were anticipated in the outlet, samples were extracted with a high-volume

sampling train operating at a flow rate of 0.46 - 0.52 m^3/min (16.2 - 18.5 cfm). This rate is about 25 times the flow rate that the EPA Method 5 stack sampling apparatus would have sampled. A particle size analysis of the inlet and outlet was performed with a Sierra Series 228 multi-stage in-stack impactor. All sampling methods and procedures are discussed in detail in the Methods section of the main report.

In-Plant Sampling

Breathing zone and workplace measurements were made with battery-operated sampling pumps. Area samples were collected by placing sampling pumps on tripods in the room, or in one instance, by attaching a sampler under the eave of a doorway. The general procedure followed while taking and analyzing in-plant samples is summarized in the Methods section.

Tracer Gas Study

A study was performed to assess two parameters, k_R and k_{BZ}. A detailed description of the general procedure and set-up is presented in the Methods section.

RESULTS OF SAMPLING PROGRAM

In-Duct Measurements

Particulate Measurements--
The in-duct measurements revealed that the dust collector was performing at its rated high efficiency (99.83%). The results of the in-duct particulate sampling in the inlet and outlet to the collector are presented in Table 4-1. The raw data obtained during these tests is summarized in Table 4-2.

To be noted in Table 4-1 were the small percentages of lead and cadmium which were found to be present. Zinc measurements were invalidated because high background levels in the Type A glass fiber filters obscured the results.

The percentages of lead appears to be much smaller than the amount previously thought. One reason for the lowered measured value was that the lead level in the process, 16%, includes the weight of lead compounds, whereas the analysis of the samples measured only lead.

Particle Sizing--
The results of particle size tests appear in Table 4-3 and Figure 4-3. The mass median diameters measured in two inlet tests were 19 and 30 micrometers, respectively. Although it was desired to obtain a particle size measurement in the outlet, the time necessary to obtain sufficient sample for analysis was prohibitive because of the low concentration of contaminants present in the outlet air stream.

Table 4-1. In-duct sampling results.

Run	Location	Sample volume, m³	Concentration, mg/m³		
			Total dust	Pb	Cd
1	Inlet	3.40	20.9	0.338	0.013
	Outlet	85.63	0.038	0.001	BDL†
2	Inlet	3.38	31.96	0.875	0.096
	Outlet	82.36	0.023	0.003	BDL
3	Inlet *	3.47	26.11	0.729	0.026
	Outlet	83.37	0.074	0.002	BDL
Avg.	Inlet	3.42	26.32	0.647	0.045
	Outlet	87.79	0.045	0.002	BDL

——————— Summary--particulate collection efficiency, percent ———————

Run 1	99.82
Run 2	99.93
Run 3	99.72
Average	99.82

* The backwash to this run was lost. The numbers which are presented were calculated by assuming that the relationship between the filter and backwash samples for runs No. 1 and 2 is applicable to this run. Thus, in Table 4-2, the backwash catch in run No. 3 of 3.55 mg was calculated by multiplying the average backwash/filter weight ratio (1.41) from runs No. 1 and 2 by run No. 3's filter catch (2.52 mg). The outlet concentrations for lead and cadmium were calculated in a similar manner.

†BDL denotes the levels were below the detectable limit of 0.001 mg/m³.

Table 4-2. Summary of in-duct sampling data.

Run	Location	SP(avg) in.H₂O	√vp(avg), in.H₂O	ΔH(avg) in.H₂O	Vm std. m³	Filter weight, mg	Backwash weight, mg	concentration mg/m³
1	Inlet	-4.0	1.81	1.52	3.40	18.40	52.65	20.90
	Outlet	-38.1	--	--	85.63	1.21	2.04	0.038
2	Inlet	-4.1	1.79	1.49	3.38	31.97	76.06	31.96
	Outlet	-38.1	--	--	82.36	0.89	1.01	0.023
3	Inlet	-4.7	1.87	1.01	3.47	39.13	51.46	26.11
	Outlet	-38.1	--	--	83.37	2.52	3.55	0.074
PS 1*	Inlet	-4.1	4.2	0.40	0.299	--	--	--
PS 2*	Inlet	-4.1	4.2	0.40	0.303	--	--	--

* Denotes particle sizing test.

Table 4-3. Particle size measurements - data summary.

Location	Stage	Size range, micrometers	Weight, mg	Percent in size range	Cumulative percent less than stated size
Inlet, run No. 1	Backwash	>15	17.8	63	37
	1	15	1.61	6	31
	2	9.2	1.23	4	27
	3	3.7	2.37	9	18
	4	2.2	2.65	10	8
	5	1.4	1.58	6	2
	6	0.76	0.45	2	0
	7	<0.42	0.	0	0
	Back-up	0.42	0	0	0
	TOTAL		27.69	100	
Inlet, run No. 2	Backwash	>15	9.39	55	45
	1	15	0.94	5	40
	2	9.2	0.79	4	36
	3	3.7	2.07	12	24
	4	2.2	2.66	15	9
	5	1.4	1.45	8	1
	6	0.76	0.26	1	0
	7	<0.42	0	0	0
	Back-up	0.42	0	0	0
	TOTAL		17.56	100	
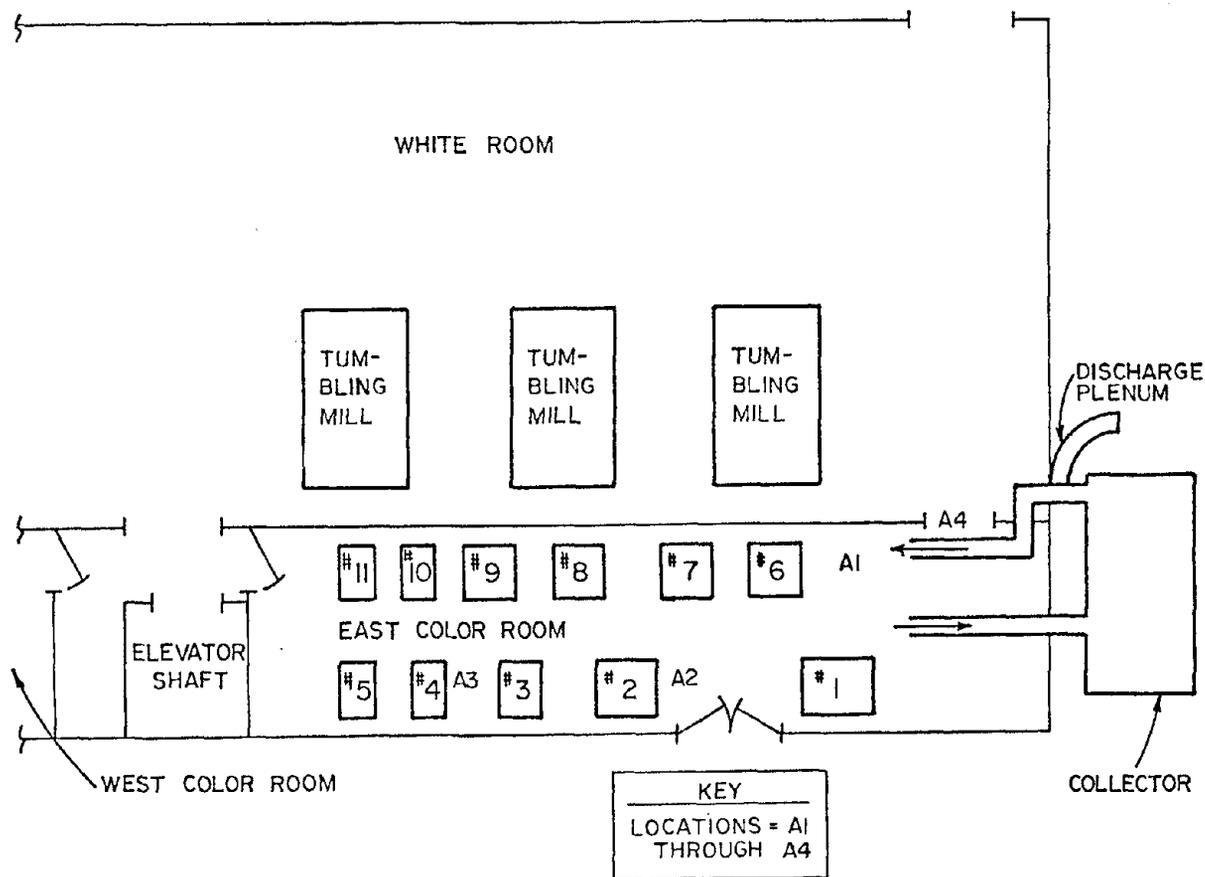
Figure 4-3. Area sampling locations.

In-Plant Measurements

Breathing zone and general area samples were taken under two different
conditions in an attempt to evaluate the effect of recirculating the cleaned
collector exhaust. Measurements indicative of post-recirculation conditions
were made by returning the air to the room without the air make-up unit
operating. Air make-up was not provided because it was learned that the
unit did not operate continuously throughout the winter, indicating that the
desired "worst case" conditions would be represented by the times it was
not operating.

Pre-recirculation conditions were attempted to be simulated by exhausting
the collector exhaust to the outdoors. However, it was not initially
realized that infiltrating dust from the white room would obscure the
measurements made in this mode. Hence, several days of samples were taken
before it was realized what was occurring.

General Area Measurements--
Measurements of area dust concentrations generally consisted of total dust
samples and respirable dust samples taken side-by-side at three or four
room locations (Figure 4-3). Location A1, A1 and A3 were very close to the
mills, while A4 was in the doorway leading to the white room. This latter

sampling location was chosen in the simulated "before" condition to confirm suspicions that dust was infiltrating from the white room. Thus, location A4 is an indication of dust levels in the infiltrating air. Measurements of the before and after conditions consisted of respirable and total measurements taken for three days. The results of the total and respirable dust measurements are presented in Tables 4-4 and 4-5, respectively.

As discussed previously, the "before" measurements are not meaningful because they were affected by the infiltration of dust from the white room. The only samples which were free from the white room's effects were the samples taken "after recirculation".

These samples are not indicative of the quality of the return air, rather, they are more indicative of the dust which escapes the hoods or which is made airborne from sweeping. The effect of the recirculated air was observed to cause a high rate of turnover in the room because the exhaust rate was so high and the room was so small. The air movement undoubtedly helped airborne dust to be quickly swept toward the nearest exhaust hood. The prevailing air patterns shown in Figure 4-4 confirms the high velocity air currents.

Free silica measurements indicated that this toxic substance was not present in sufficient quantities to be a potential hazard.

Breathing Zone Measurements--
Breathing zone samples were taken during the study, but because of interferring factors, their results were not meaningful and thus are not presented. The breathing zone samples could not be used to make comparisons of the conditions before and after recirculation because measurements were adversely affected by contamination received when workers entered the white room to retrieve carboys of powder, and by several work practices which were observed to contaminate breathing zones. Workers spent up to 30-40% of their time in the white room, causing their breathing zone samples to be contaminated. Workers also experienced excessive dust exposures from poor work practices such as inserting their heads through the cabinet doors, blowing dust off clothes with air nozzles, shoveling loose dust into open barrels, and sweeping the floor with brooms.

Tracer Gas Study

An estimate of two parameters which are used in the recirculation model was made using sulfur hexafluoride (SF_6) as a tracer gas. To assess k_{BZ}, the fraction of return air entering the breathing zone of the worker, the tracer gas was injected into the inlet to the collector, then measured in the outlet and in various locations within the room (shown in Figure 4-3). The parameter, k_R, the fraction of return air re-entering the local exhaust hoods, was also assessed by injecting tracer gas prior to the collector, measuring the outlet concentration, then measuring the concentration in the inlet to the collector upstream of the injection point. The two

Table 4-4. Area sampling results - total dust and metals.

Date	Location	Concentration, mg/m^3			
		Total dust	Pb	Zn	Cd
"Before recirculation"					
10/5	A1	19.56	2.30	0.100	0.010
	A2	19.70	2.34	0.094	0.009
	A3	11.01	1.22	0.054	0.012
	A4	23.19	2.33	0.089	0.008
	Average	18.37	2.05	0.084	0.010
10/6	A1	11.24	1.38	0.056	0.007
	A2	9.80	0.90	0.036	0.005
	A3	13.25	1.48	0.056	0.018
	A4	8.75	0.88	0.035	0.005
	Average	10.76	1.16	0.613	0.009
10/12	A1	25.68	1.81	0.078	0.008
	A2	31.40	1.58	0.138	0.032
	A3	13.40	1.10	0.049	0.003
	A4	35.78	1.22	0.057	0.007
	Average	26.56	1.43	0.081	0.013
	Overall average	17.73	1.54	0.070	0.010
	Overall std. dev.	9.27	0.54	0.030	0.008
"After recirculation"					
9/19	A1	0.827	0.087	0.005	0.007
	A2	0.605	0.070	0.006	0.007
	A3	0.418	0.044	0.005	0.001
	Average	0.637	0.067	0.005	0.005
9/20	A1	1.17	0.120	0.012	0.088
	A2	0.712	0.073	0.009	0.053
	A3	0.595	0.061	0.009	0.037
	Average	0.826	0.085	0.010	0.059
9/21	A1	1.41	0.148	0.011	0.004
	A2	1.15	0.121	0.008	0.004
	Average	1.28	0.134	0.015	0.004
	Overall average	0.868	0.091	0.008	0.025
	Overall std. dev.	0.340	0.036	0.003	0.032

Table 4-5. Area sampling results - respirable dust.

Date	Location	Respirable dust, mg/m^3	Percent free silica
		"Before recirculation"	
10/5	A1	6.00	na
	A2	8.10	*
	A3	3.85	na
	A4	6.91	na
	Average	6.22	--
10/6	A1	3.62	na
	A2	3.10	<1.0
	A3	4.86	na
	A4	4.88	na
	Average	4.12	--
10/12	A1	7.76	na
	A2	8.90	*
	A3	5.37	na
	A4	7.99	na
	Average	7.51	--
	Overall average	5.95	--
	Overall std. dev.	1.96	--
		"After recirculation"	
9/19	A1	0.107	na
	A2	0.084	†
	A3	0.355	na
	Average	0.182	--
9/21	A1	0.926	na
	A2	0.300	3.0
	Average	0.613	--
8/14	A1	0.418	na
	A2	0.250	†
	A3	0.931	na
	Average	0.334	--
	Overall average	0.421	--
	Overall std. dev.	0.333	--

na = not analyzed. * Samples in range of blank. Answer unobtainable.
† Sample weight too low to analyze for free silica.

parameters were estimated as follows:

$$k_{BZ} = \frac{\text{Average concentration in room}}{\text{Concentration at collector outlet}}$$

$$k_{R} = \frac{\text{Concentration at collector inlet}}{\text{Concentration at collector outlet}}$$
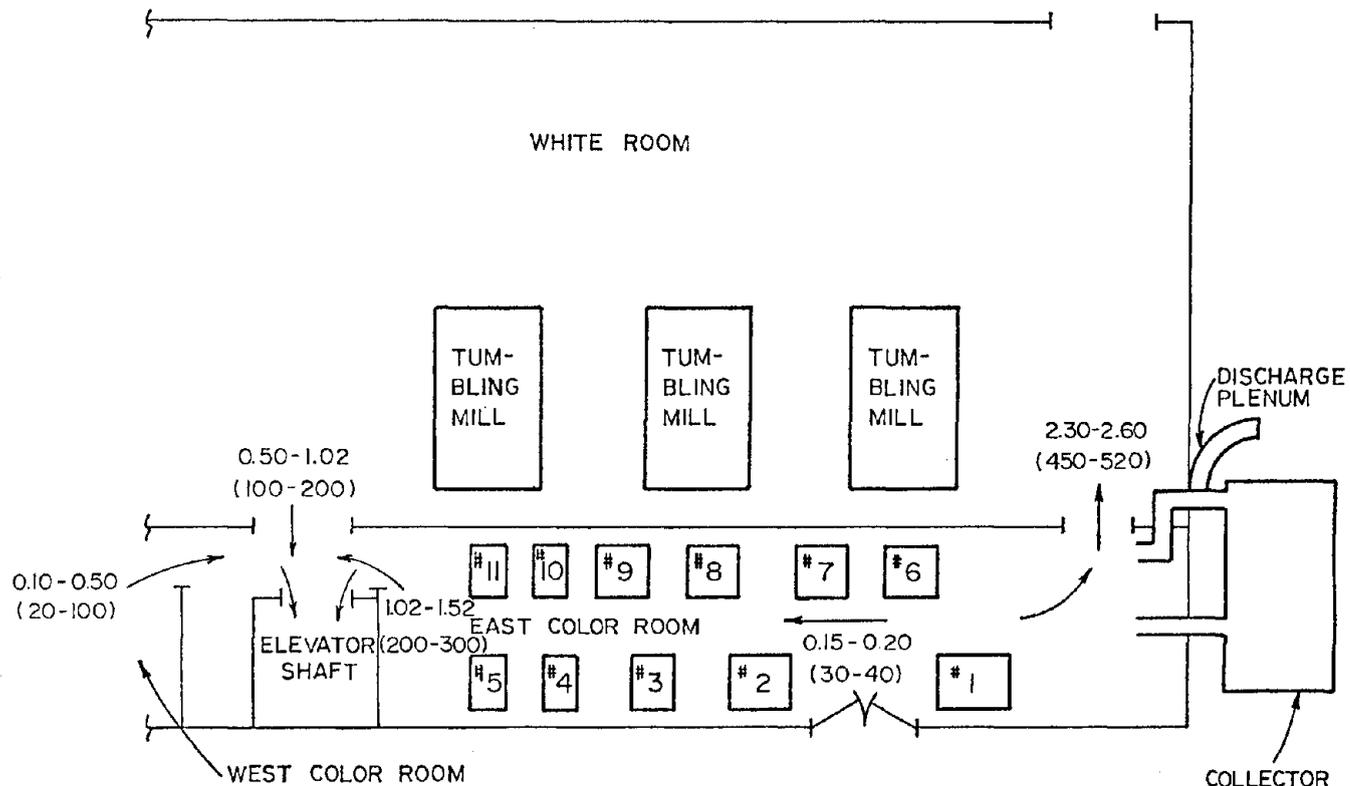

Figure 4-4. Air velocity patterns after recirculation, m/sec (ft/min).

The tracer gas measurements and results of the study are summarized in Table 4-6. Because of dilution, the average estimate for k_{BZ} in the east room was low when doors and windows were open (0.53), but under closed conditions the estimate approached 1.0 (0.96). THe low 0.53 value obtained for k_{BZ} was affected by dilution air even though the room was mostly under positive pressure. Apparently, when all doors and windows are opened, wind forces are strong enough to overcome thepositive pressure, thus resulting in some dilution ventilation.

The parameter k_{R} was assigned a value of 0.22 because the concentration of tracer gas in the collector inlet (prior to the injection point) was 22% of the value of gas in the collector outlet (after the injection point). The estimate for k_{R} was surprisingly low because it would be expected that the concentration in the return air duct should be somewhat close to the concentrations found in the room. One possible explanation for the low value is that during the measurement most of the hood doors in the east

Table 4-6. Tracer gas results and analysis.

Measurement number	Location in figure	Description of ventilation change	Concentration ppm	Fraction of inlet concentration
		Results		
1	1	Door and windows open	10.0	0.15
2	2	Doors and windows open	24.0	0.60
3	3	Door and windows open	12.0	0.30
4	4	Door and windows open	22.5	0.56
5	5	Door and windows open	22.5	0.56
6	6	Door and windows open	23.5	0.59
7	7	Door and windows open	22.5	0.56
8	8	Door closed	32.5	0.81
9	9	Door closed	32.5	0.81
10	10	Door and windows closed	40.0	1.00
11	11	Door and windows closed	40.0	1.00
12	9	Door and windows closed	37.0	0.92
13	8	Door and windows closed	37.0	0.92
14	West room	Door and windows closed	9.0	0.22
15	Outlet*	Door and windows closed	10.0	0.26
16	Inlet	Door and windows closed	40.0	1.00

* Prior to injection point.

Parameter	Method of calculation	Value assigned
	Analysis	
Lower estimate of k_{BZ} (east room)	Average all east room measurements made with room open (No. 1-No. 7)	0.53
Upper estimate of k_{BZ} (east room)	Average all east room measurements made with room shut (No. 10-No. 13)	0.96
k_{BZ} (west room)	Measurement No. 14	0.22
k_R	Measurement No. 15	0.26

color room were shut, resulting in the drawing of the majority of the exhaust from the west color room through the barometric damper. Since air in the west color room also originates from other plant areas, the air drawn through the damper did not contain the tracer gas in the recirculated air.

Summary of Sampling Program

1. The in-duct measurements revealed that the dust collector was performing at its rated high efficiency. This resulted in very low levels of total dust and lead in the recirculated air. Cadmium, although present in the collector influent, was below detectable limits in the return air.

2. A positive benefit of recirculation was evident in the significant difference in the total dust measured in the color room compared to the condition with air being bypassed. This difference can be attributed to the quality of the recirculated air, as well as reduction in cross-contamination from the adjacent tumbling mills in the white room.

3. Breathing zone samples of mill workers were not meaningful because of several interferring factors. Worker exposures were elevated because of work practices such as cleaning out mills with short air nozzles, sweeping and shovelling, and because the workers spent 30-40% of their time in an uncontrolled plant area, the white room.

4. The tracer gas study showed that the fraction of return air entering the breathing zones of workers, k_{BZ}, approached 1.0 when doors and windows were closed and the workers breathed only recirculated air. When the doors and windows were opened, natural ventilation reduced k_{BZ} to one-half. The fraction of return air re-entering the local exhaust hoods, k_R, was surprisingly low (0.22), probably because non-recirculated air from other plant areas entered the barametric damper during the test.

RETROACTIVE ASSESSMENT OF DESIGN APPROACH

In the following section, a retroactive assessment of the recirculation system design is presented using the evaluation criteria presented in Reference One. The discussion will begin at the point at which the company realized that improved breathing zone control was needed in the east color room.

As the design team considers recirculation, a preliminary feasibility assessment is first performed. The purpose of this preliminary step is to pre-screen a series of eight factors affecting the likelihood of success in an attempt to uncover aspects of the program which may prevent recirculation. Thus, unnecessary efforts and expenses for field sampling, hardware evaluation, and design optimization can be prevented. Following the preliminary assessment, the initial findings are summarized. Then, a more in-depth investigation of contaminants, air cleaners, and monitors is presented.

Preliminary Feasibility Assessment

Legal Issues--
No legal considerations now exist which would restrict recirculation in the
present case. However, at the time of the survey OSHA had proposed a
regulation prohibiting the recirculation of an exhaust stream containing
residual amounts of lead (2)*. The possibility of this proposed standard
becoming law must be considered by the company when they address the
feasibility of recirculation.

Energy Consumption--
With the increased exhaust flow of the new system, without recirculation
the company would have to provide more make-up air to prevent contaminant
infiltration into the color room from the white room. However, with recirculation
the company does not have to temper an amount of fresh air equivalent to
exhaust rate of 651 m^3/min (23,000 cfm). Since the cost to heat this amount
of make-up air with natural gas is approximately $6,000 per year (from
methods in Reference 4), recirculation will represent a considerable cost
savings to the company.

Contaminant Classification--
The type and quantity of contaminants can be determined from knowledge of
the process and previous collection system. The contaminant generated in
the process is a dry, particulate dust. A particle size analysis of the
process dust by the company indicated that 99.5% of the particles were between
1.5 - 100 micrometers. The dust was known to contain about 16% lead and lead
compounds (maximum, by weight), and less than 0.1% free silica. The
addition of pigments added small amounts of zinc, cadmium and other less
toxic compounds.

The company first estimated the inlet concentration of the new system based
on the amount of material caught in the old collection system. Knowing
that the new system was expected to collect more dust due to better hood
efficiencies, and that the previous collector caught approximately
136 kg (300 lb) in a 24-hr period, the company designer made a preliminary
estimate of the new collector catch of 182 kg (400 lb) for a 24-hr period.
On this basis, it was calculated that a 651 m^3/min (23,000 cfm) collector
would experience an inlet concentration of approximately 200 mg/m^3 of total
particulate. With the assumed percentage of lead, the expected inlet
concentration would be approximately 32 mg/m^3.

In addition to the concentration of the dust, the toxicity of the
contaminants generated in the process should be a major concern in the
initial feasibility decision assessment. Reference One suggests that the
recirculation of less toxic contaminants is preferable to highly toxic
contaminants especially when the toxic effects are acute. Consequently,
the designers should realize that the expected concentration of lead and

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*As of the date of this writing, the new lead standard, effective March 1,
1979, does not prohibit the recirculation of exhaust streams containing
lead (3). However, since the proposed standard with the clause prohibiting
recirculation was in effect at the time this retroactive assessment was
assumed to begin, it will be assumed valid in the remainder of this discussion.

its highly toxic nature probably mandates that a highly efficient collector will be required, and that the system performance will have to be adequately monitored to protect workers from being overexposed following a malfunction.

Air Quality Regulations--
The exhaust stream is required to be cleaned for air pollution purposes because of emission restrictions imposed by the ambient lead standard and process emission regulations. Because of this requirement, a highly efficient collection method such as fabric filtration would be an effective control measure for the dry particulate contaminant. Similarly, the efficiency demands imposed by recirculation would also indicate that a cleaning method such as fabric filtration be chosen. Therefore, the existence of strict air quality regulations provides incentives for selecting a collector which would also be suitable for use in a recirculation system.

Air Cleaner Availability--
Knowing that a dry particulate dust is being generated, the design team would evaluate some highly efficient collection method such as filtration or electrostatic precipitation, because such methods would likely provide the high degree of efficiency required. Among their options, they would find a number of collectors available:

        Fabric filters
        Cartridge-type filters
        Double HEPA filters
        2-Stage electrostatic precipitators

Having identified that suitable methods are probably available, a more thorough evaluation should be made of the suitability of each particular collector in terms of size, cost, required maintenance, reliability and energy requirements.

Monitor Availability--
Adequate detection of reduced system performance is also crucial because of the toxic nature of lead. Consequently, the failure response mode should be automatic and the response should result in an action which will immediately protect the worker. Process shutdown and/or exhaust bypass are acceptable failure response strategies, but the exact method for detecting failures needs further investigation.

There are several monitoring techniques which are good potential candidates, but actual field testing of the devices should be undertaken before final selection. As noted previously, pressure sensing devices are able to detect certain failures of filtration collectors, while several automatic monitors can detect increased outlet concentrations of particulates.

Process Emission Profile--
The enamel powder production process generates dust levels which are intermittent and thus variable in concentration. Dust levels are particularly high when the mills are loaded and unloaded. The variability of the inlet loadings undoubtedly will result in some variability in outlet concentrations, but these fluctuations should not adversely impact on the design if

filtration collection methods are chosen because such methods will usually dampen the variations considerably.

Ventilation System Design--
There are no apparent difficulties in the design of the ventilation system which will impact on the feasibility of the final system.

Summary of Preliminary Feasibility Assessment--
Although none of the eight factors presented obvious barriers to recirculation, the preliminary assessment was useful in that several issues were raised which should be addressed by further evaluations. Among these are:

1. Because of the existence of a proposed standard prohibiting recirculation of lead, the company must be willing to accept the risks of going ahead with the recirculation evaluation at this time.

2. Highly efficient collectors are available, but further evaluations are needed to determine other pertinent factors such as size, cost, maintenance, reliability, and energy requirements.

3. Several monitors are capable of detecting failures, although further study is needed to evaluate such important factors as cost, reliability and sensitivity.

In-Depth Design Evaluation

Following the preliminary assessment, an in-depth evaluation of contaminants, collectors and monitoring approaches is conducted as part of the design process to eliminate uncertainties raised by the preliminary feasibility assessment. These topics are further discussed in the following three sections.

Contaminant Characteristics--
The design team should initially define the physical and chemical properties of the contaminants to provide a basis for selecting appropriate collection methods and monitoring strategies. The most important contaminant properties are the inlet concentration of particulates, the size of particles, the composition, and the potential adverse health effects of the constituents. In the preliminary assessment, a crude estimate of the concentration was made and a particle size analysis was obtained. From the survey, it was found that the estimate provided by the company grossly overestimated the actual lead content of the exhaust stream. Designers should note that without accurate knowledge of the contaminant generation rate, the ability to formulate an adequate design is severely hampered.

Regarding health efforts, the toxic hazard from dust generated in this process is due principally to lead. Although cadmium exhibits a similar toxicity, it is present only in minute quantities whereas lead comprised an appreciable amount of the dust. Because respirable silica is thought to be a minor constituent of the dust, it does not constitute a toxic health hazard. As a precaution, its concentration level should at least be

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checked by the design team. The toxic hazard of each constituent can be judged from the restrictiveness of the applicable OSHA PEL's and ACGIH recommended levels presented in the following table. Other metallic dusts in the pigments which are not included in the table would be regulated by the PEL for nuisance dust.

Table 4-7. OSHA PEL's and ACGIH and NIOSH recommended levels.

	Time-weighted concentration, mg/m^3		
	8-hour OSHA PEL, 1977 (7)	ACGIH TLV, 1977 (8)	NIOSH Level 1977 (18)
Lead	0.20*	0.15	<0.05
Cadmium (dust)	0.20	0.05	0.04
Zinc	5.0†	5.0	5.0†
Crystalline silica	10.0	10.0	0.05
Nuisance dust	2+% S_iO_2	2+% S_iO_2	
Nuisance dust:			
Total	15.0	10.0	–
Respirable	15.0	5.0	–

* The standard which applied at the outset of the survey.
† The standard applies to zinc oxide fume.

In some cases, an "additive mixture" TLV or standard may need to be assessed when more than one toxic substance is present in appreciable amounts. However, in this case, the toxic hazard is clearly due to lead while the other toxic substances are not present in high enough quantities to merit determination of additive standards. For the same reason, the liklihood of one contaminant having a synergistic effect on another contaminant is small.

Selection of Air Cleaning Equipment--
The type of dust generated does not present difficulties in selecting a suitable collection method, except that a highly efficient collector will be required because of the highly toxic nature of the dust.

Fabric filtration is a good choice of collection because a dry particulate contaminant is generated which has no unusual properties which might make fabric cleaning difficult. Recognizing this, it will be assumed that the company chose a fabric filter which utilized a reverse air cleaning method. Reverse air cleaning is more desirable, in this case, than pulse jet cleaning because reverse cleaning utilizes a gentle cleaning action which tends to leave a good filter cake on the bags between each cleaning pass. In contrast, the pulse jet cleaning method produces a more uneven outlet concentration profile because the violent nature of this form of cleaning can remove a

substantial portion of the accumulated dust cake, resulting in a drop in filtering efficiency through the bags for a short period after cleaning.

It is interesting to note that, in the actual design, the company designer obtained an "efficiency guarantee" of 99.9% from the manufacturer. A guarantee was sought as an added assurance that the collector would provide the level of removal efficiency specified by the manufacturer.

Evaluation of Monitoring Strategies--
Reduced performance of the collector should be addressed by the designer by first evaluating the possible failure modes and then selecting a strategy which will adequately protect the worker's breathing zone. In this discussion, the identification of possible modes of system failure will be followed by a discussion of several monitoring strategies, including the one chosen by the company.

Failure modes--The general types of failure modes and their effects on the collector differential pressure, air flow, outlet concentration, and hood capture velocity have been summarized in Table 4-8. Four failure modes are identified which can significantly increase breathing zone concentrations. The major failure effect in three of the four modes is caused by decreased hood capture efficiency, while only one of the failure modes directly affects recirculated air quality. A failure mode may also cause either an increase or decrease in collector differential pressure or exhaust flow rate.

After thoroughly reviewing the failure modes and effects, a monitoring strategy should be selected which detects these major failure effects. It is apparent from the Table 4-8 that two different methods are probably necessary to detect all major failure effects, because the effect of major failures is both increased outlet concentrations and reduced hood capture efficiency.

Monitoring strategy selection--As recommended by Reference One, the surveillance strategy should be assessed by addressing all the possible types of monitors (or methodologies) and then choosing an appropriate response strategy. As identified in the failure mode analysis, the strategy must be capable of detecting decreased collector efficiencies, and decreased hood effectiveness. In addition, Reference One suggests that an evaluation be made as to whether the scheme should be manual or automatic, in-duct or area, or specific or non-specific. Each of these factors will be briefly discussed in the selection process.

From an examination of possible monitors, it should be evident that reduced air cleaner efficiencies resulting in increased outlet concentrations may be detected by a particulate monitor, while a decreased air flow rate and the resultant decrease in hood capture efficiency may be detected by a velocity pressure sensor.

When selecting a monitor, it should be realized that it must be sensitive enough to measure small increases in the outlet concentration, and yet not be affected by normal process fluctuations. Because the normal variation is room dust levels are expected, in-duct monitoring is more suitable in this application than monitors which only measure area concentrations.

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Table 4-8. Principal modes of failure and effects.

Failure type	Collector, ΔP	Failure effect	
		Outlet concentration	Hood capture efficiency
Air Cleaner Failure			
Failure 1 - Blinding, e.g. excessive loading, reverse air failure	↑	↓	↓
Failure 2 - Breakthrough, e.g., bag tear, burn holes, bag unhooking, seal failures	↓	↑	↑
System Failure (hoods, ductwork, fan, drive)			
Failure 3 - Duct blockage	↓	↓	↓
Failure 4 - Slipping belts	↓	↓	↓

↑ or ↓ denotes deviation from steady-state performance.

___ = major failure effect.

Ideally, particulate monitors which determine specific contaminant concentrations, i.e., lead levels, would obviously be the most desirable type of in-duct monitoring methods, but unfortunately such devices are not presently available. However, non-specific devices are available which can measure a parameter such as mass concentration of particulate. These devices may provide an acceptable measure of the outlet concentrations of total particulate and, because the percentage of lead can be determined, the device may also provide an indirect indication of approximate lead concentrations.

Regarding the response to a failure, an appropriate course of action following a failure should be a combination of process and control system shutdown. From earlier discussions, it was seen that the bypass of the collector effluent to the outdoors is unacceptable because this would result in the infiltration of dusty air from the white room. Since the workers cannot safely operate the process without the dust collector operating, both the process and collector must be shut down to prevent overexposures.

With a highly toxic substance such as lead, an automatic system is most desirable, although a manual system could work if the employees were well instructed on the proper response strategy. There is always the chance with a manual monitoring method, however, that there will be no response to a potentially serious health hazard. Automatic monitoring offers the most conservative approach because it reduces the element of human intervention. There is a very serious question as to whether a manual response is reliable enough to provide sufficient worker protection when recirculating a highly toxic dust.

Present design--The system evaluated in the survey contained a differential pressure sensor across the baghouse to detect filter media failures. This monitoring method is attractive because the differential pressure sensor is a low cost, readily available item with a simple design. It essentially consists of pressure taps on either side of the baghouse and a switching circuit which actuates above and below pre-set limits. The major drawback to this method is that it is not sensitive enough to detect small, but significant, breakthroughs which could adversely affect the return air quality. It is generally a suitable method for detecting bag blinding, large breakthroughs, etc. However, realizing this, the company is also evaluating the possible use of a continuous particulate monitor called a nephelometer. Initial indications are that the device will be economically and technically feasible in the design.

In the present design, a failure which is detected by the differential pressure sensor will activate a buzzer and alarm. Following a failure, the employees have been instructed to inform a designated person in the maintenance department who has the responsibility of bypassing the exhaust until the collector is repaired. The buzzer and alarm can be manually over-ridden while repairs are being made.

One disadvantage of the manual override is that since the switch is accessible to workers, there is a potential for its abuse in the event of a failure. As a safety measure, the override switch should be controlled only by persons with proper authority.

Another problem noted with the present design was a periodic "false" signal from the pressure sensor due to vibrations from the operation of the failure filter. After noting the problem, the engineer in charge made arrangements for the sensor to be mounted on a wall near the fabric filter which did not vibrate.

Design Optimization Using the Modeling Approach

Introduction--
To determine the impact of recirculation on the proposed system, it is desirable to apply a modeling approach to determine the resultant worker exposure levels that will exist after the system is installed. The modeling approach presented in Reference One requires that the breathing zone levels of the workers be either measured or estimated in the condition prior to recirculation. The levels which could be measured before the proposed changes are undertaken would not be representative of a "before" recirculation condition because a significant reduction in exposure levels is anticipated as a result of the proposed dust capture improvements. Therefore, the model cannot be used to make predictions of the effects of recirculation on existing breathing zone levels. However, the modeling approach can be a useful tool to the design team if some assumptions are first made.

In the following section, the model is first used to predict what collector efficiencies the designer might specify in his initial assessment, with the assumption that breathing zone control had been achieved before recirculation. The model is then applied using values actually measured to calculate what breathing zone level might be required prior to recirculation to meet applicable standards after recirculation.

The "before" condition in this discussion will be the point in time where the new collector is installed and operating, and an air make-up unit with enough capacity to replace the exhausted air is also operating. The capacity of the air make-up unit would be 651 m^3/min. After recirculation, the actual conditions now existing in the plant will be assumed.

Choosing an Approach Model--
Referring to Appendix B of Reference One, the design team would recognize that several modeling simplifications called "configurations" would be applicable to the present situation. Realizing that several configurations pertain to locally exhausted recirculation systems, configuration no. 2 might be chosen because in that configuration, make-up air is introduced into the room instead of the return air stream. This configuration better represents this plant situation because the recirculated air plenum and air make-up plenum are physically separated in the east color room. Configuration no. 2 is reproduced as Figure 4-5 in this report.

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Assigning Parameter Values--
In the modeling approach, values must first be assigned to the appropriate
parameters. Each parameter discussed in this section is more completely
explained in Appendix A of Reference One. The reader is advised to be
familiarized with the modeling approach before reading further.

A summary of the parameters, their assigned value, and a brief rationale
of the value given is presented in Table 4-9.

Design Approach--
Beneath the diagram in Figure 4-5, three equations are given which may be
used to predict the effects of recirculation. These equations will be
used according to the design procedure outlined in Appendix B of Reference
One:

1. Choose a value for Q_{CB} or Q_{LB}.

2. Compute values for Q_{MU2} and Q_R.

3. Based upon the magnitudes and expected distribution of Q_{MU2} and
   Q_R, estimate values for k_{BZ} and k_R.

4. Compute the necessary C_R and the necessary fractional air cleaner
   efficiency η from the equation provided.

5. 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.

Modeling Results--
Since the concentration of lead in the workplace is the overriding considera-
tion in this evaluation, all concentrations will refer to lead levels in the
following discussions.

Calculation of the amount of air returned to the room, Q_R--The first equation
in Figure 4-5 calculates the amount of air returned to the room. This
quantity depends on the amount of cleaned (Q_{CB}) or uncleaned (Q_{LB}) air which
is bypassed. In Table 4-10 the result of the calculation indicates that
the amount returned, Q_R, is equal to the amount exhausted, Q_L, when the
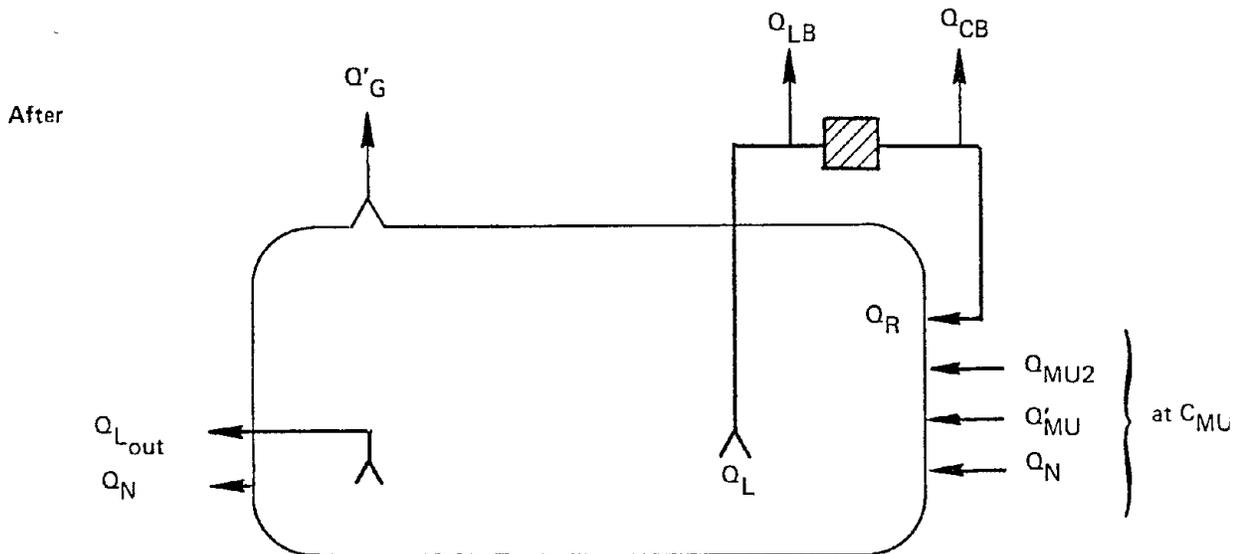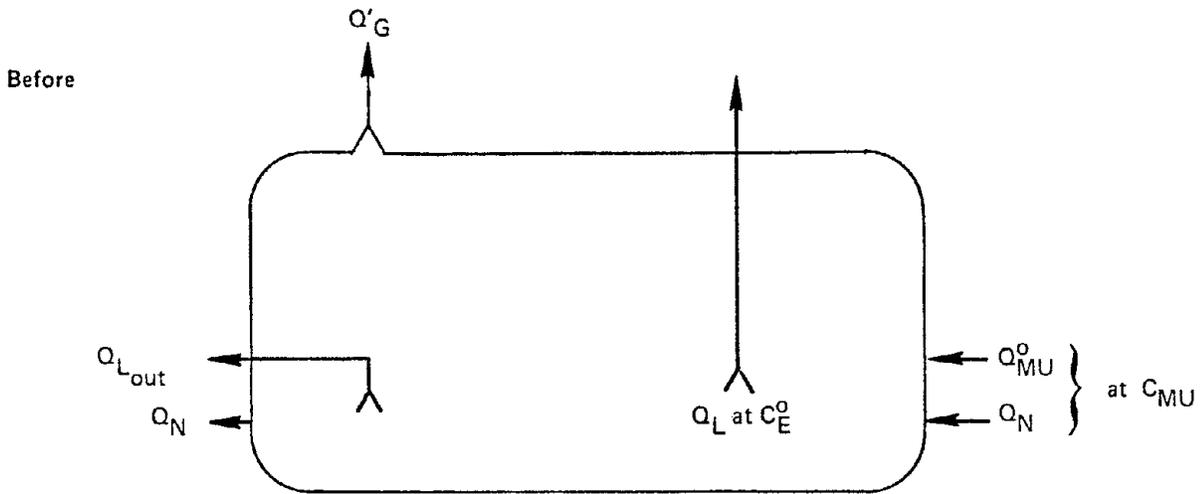bypass volumes Q_{LB} and Q_{CB} are set equal to zero.

Calculation of required make-up supply, Q_{MU2}--Equation no. 2 in Figure 4-5
allows calculation of Q_{MU2}, the dependent design variable referring to the
amount of make-up air supply not mixed with recirculated air which is
required after recirculation. As shown in Table 4-10, the value of Q_{MU2} is
zero, implying that no additional make-up air is necessary to obtain a flow
balance since the recirculated air flow rate is, by itself, adequate to
maintain the air balance. In the actual system, the east color room actually
will be under positive pressure after recirculation because of the additional
supply air provided by a small air make-up unit. Therefore, the actual
value for this term is equivalent to the air make-up unit capacity, 142 m^3/min.

Table 4-9. Model parameter values.

Para-meter	Description	Value	Rationale
Q_{LB}	"Dirty" bypass exhaust volume	0	Set initially at 0 since all exhaust is planned to be recirculated.
Q_{CB}	"Clean" bypass exhaust volume	0	Set initially at 0 since all exhaust is planned to be recirculated.
C_{MU}	Make-up air concentration	0	Assume air make-up unit is providing only fresh air, and that the amount of infiltrating contaminated air is negligible.
C_E^o	Initial concentration of local exhaust stream	32 mg/m^3	Sixteen percent of the inlet concentration originally estimated (200 mg/m^3) may be lead. This assumption is made purely for demonstration purpose. The actual measured volume will later be used in the calculation.
C_{BZG}^o	Initial breathing zone concentration	0.05 mg/m^3	Assume that breathing zone concentrations of lead have been controlled at this level prior to recirculation.
k_{BZ}	Contribution factor of return air to breathing zones	1.0	Assuming workers will often be in the direct influence of the return air, a conservative value is chosen.
k_R	Contribution factor of return air to local exhaust systems	1.0	As a conservative estimate, assume that only return air enters hoods.
C_{BZL}^o	Initial breathing zone concentration in the influence of large volume exhaust system	0	No large volume exhaust hoods are present in the area of interest.
Q_L	Initial volume of local exhaust streams	651 m^3/min	The design flow rate of the collector.

Table 4-9 (continued).

Parameter	Description	Value	Rationale
$Q_{L_{out}}$	Local exhausts other than other than what is recirculated	0	There are no local exhausts other than the recirculated exhaust
Q_G'	General exhaust volumes	0	There are no general exhausts in the plant area of interest.
Q_{MU}^O	Make-up air rate for conventional systems prior to recirculation	142 m^3/min	Capacity of air make-up unit.
Q_{MU}'	Fixed make-up supply rate	0	There are no sources of fixed make-up air in the plant area of interest.
f	Local exhaust system influence factor	0	No large volume exhaust hoods are present in the area of interest.
Q_T^O	Total ventilation rate before recirculation	651 m^3/min	It is assumed that the new collection system is installed, and an air make-up unit is operating with enough capacity to replace the exhausted air. In an air balance, the total ventilation rate is the amount supplied or exhausted. $$Q_T^O = Q_L$$ $$Q_T^O = 651 \ m^3/min$$
Q_T	Total ventilation rate after recirculation	793 m^3/min	Total volume rate of the make-up unit and the exhaust rate. $$Q_T = Q_R + Q_{MU2}$$ $$Q_T = 651 + 142$$ $$Q_T = 793 \ m^3/min$$

Before

Q'_G

$Q_{L_{out}}$

Q_N

Q_L at C_E^o

Q_{MU}^o

Q_N

at C_{MU}

After

Q_{LB}

Q_{CB}

Q'_G

Q_R

Q_{MU2}

Q'_{MU}

Q_N

at C_{MU}

$Q_{L_{out}}$

Q_N

Q_L

See Discussion For Proper Design Procedure. Useful Equations are:

$$Q_R = Q_L - Q_{LB} - Q_{CB}$$

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

$$C_R = \frac{1}{k_{BZ}} \left[C_{BZ}^D - (1-f)\frac{Q_T^o}{Q_T} (C_{BZG}^o - C_{MU}) - f(C_{BZL}^o - C_{MU}) - (1-k_{BZ}) C_{MU} \right]$$

$$\eta = 1 - \left[\frac{C_R}{C_E^o - k_R C_{MU} + k_R C_R} \right]$$

Figure 4-5. System configuration.

Table 4-10. Model application calculations.

Note: All concentrations are lead.

1. <u>Equation No. 1</u>

$$Q_R = Q_L - Q_{LB} - Q_{CB}$$

$$Q_R = 651 - 0 - 0 = 651 \ m^3/min$$

2. <u>Equation No. 2</u>

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

$$Q_{MU2} = 0 + 0 + 0 + 0 - 0 = 0$$

But actually is equal to capacity of air make-up unit, $142 \ m^3/min$ (see text).

3. <u>Equation No. 3</u>

$$C_R = \frac{1}{k_{BZ}} \left[C_{BZ}^D - (1-f) \frac{Q_T^o}{Q_T} \ (C_{BZG}^o - C_{MU}) - f(C_{BZL}^o - C_{MU}) - (1-k_{BZ}) \ C_{MU} \right]$$

Simplification: $(f = C_{BZL}^o = C_{MU} = 0)$

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

a. First estimate $(C_{BZ}^D = 0.05 \ mg/m^3)$

$$C_R = \frac{1}{1.0} \left[0.05 - \frac{651}{792} (0.05) \right] = 0.009 \ mg/m^3$$

4. <u>Equation No. 4</u>

$$\eta = 1 - \frac{C_R}{C_E^o - k_R C_{MU} + k_R C_R}$$

Table 4-10 (continued).

Simplification: $(C_{MU} = 0)$

$$\eta = 1 - \left[\frac{C_R}{C_E^O + k_R C_R} \right]$$

a. First estimate: $(C_R = 0.009 \text{ mg/m}^3, C_E^O = 32 \text{ mg/m}^3$

$$\eta = 1 - \left[\frac{0.009}{32 + 1.0 \ (0.009)} \right]$$

$$\eta = 0.9997$$

b. Second estimate: $(C_R = 0.009 \text{ mg/m}^3, C_E^O = 0.875 \text{ mg/m}^3$

$$\eta = 1 - \frac{0.009}{0.875 + 1.0 \ (0.009)}$$

$$\eta = 0.9898$$

Calculation of the required return air concentration, C_R and required collector efficiency, η--The third equation in Figure 4-5 calculates a return air concentration which will be utilized in equation no. 4 to determine a required collection efficiency. As shown in Table 4-10, the equation can be simplified by noting that there are no large volume exhaust hoods in the plant area of interest $(f = C_{BZL}^O = 0)$, and that the contaminant concentration in the make-up air is negligible $(C_{MU} = 0)$.

The return air concentration can now be calculated by choosing a desired breathing zone concentration, C_{BZ}^D. Remember, it is being assumed that safe level of control has been achieved after system installation but before recirculation. Because of the presence of a highly toxic substance, lead, the desired breathing zone concentration should significantly be lower than the OSHA standard of 0.20* to provide an adequate margin of safety in the design. Assuming that the design team chose a C_{BZ}^D of 0.05 mg/m^3, the pre-recirculation "controlled" level should be about the same or slightly lower than the level after recirculation.

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*Effective March 1, 1979, the new OSHA limit for lead is 0.05 mg/m^3(3). The new standard is not considered in this discussion because the higher standard was in effect at the time the retroactive assessment was assumed to begin.

As a first estimate, the modeling equation will be used to calculate a return air efficiency which does not increase breathing zone levels above a pre-recirculation level of 0.05 mg/m^3. It is possible to not have an increase because the reduction in concentrations due to the dilutory effect of an increased total ventilation rate may be used to offset the small level of contaminants added to the breathing zone as a result of recirculation. With this strategy, equation no. 3 in Table 4-10 computes a required return air concentration of 0.009 mg/m^3. Equation no. 4 shows that a collector with an efficiency of 99.97% would be required to achieve this level.

The efficiency level calculated is the upper level of most fabric filters. It is too high a level for a fabric collector to be expected to achieve at all times because, following cleaning, efficiency levels will usually drop slightly. Reference One discusses this specific topic in detail in Chapter 5.

At this point in the design process, the designer may want to consider one of the following alternatives which will enable the design process to continue:

    1. Increase the desired breathing zone concentration.
    2. Select a more highly efficient primary collector.
    3. Select a secondary collector.
    4. Introduce more fresh air into the color room.

Not wishing to decrease the safety margin, or to increase the cost of the design through additional collectors or make-up air, the design process would stop at this point. The design team should now review all of the parameters to investigate if the predictions are reasonable.

After some review, the design team should realize that it would be wise to obtain a better estimate of the inlet concentration of lead because the highest concentration level of lead actually measured in the inlet to recirculation system, 0.875 mg/m^3, was much lower than the previous estimate of 32 mg/m^3. Assuming that a more accurate estimate of the inlet concentration was made, a better estimate of the collection efficiency could be calculated. The second estimate of equation no. 4 in Table 4-10 shows that the required efficiency is approximately 99.0% when the highest lead concentration measured is assigned to C_E^O. This efficiency is well within the range expected by the air cleaner.

System Performance Validation

Air Cleaner Performance--
Since the system design is liable to be based on relatively imprecise estimates of air cleaner efficiency, Reference One gives the following equation to calculate a C_R which the actual system must not exceed.

$$C_R \le \frac{1}{k_{BZ}} \left[C_{BZG}^D - C_{BZ}^O \frac{Q_T^O}{Q_T} \right] + C_{MU}$$

Using the same parameters which were inserted in equation no. 3 in Table 4-10, the following planned return air concentration which is calculated should not be exceeded by the new collector:

$$C_R \leq \frac{1}{1.0} \left[0.05 - \frac{651}{792} (0.05) \right]$$

$$C_R \leq 0.009 \ mg/m^3$$

The actual collector outlet concentration of lead was 0.002 mg/m^3, implying that the collector which was specified in the actual system was adequately designed.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions from the valuation reinforced conclusions and recommendations in Reference One.

1. The use of inaccurate estimates of the inlet contaminant concentration in the design may lead to the specification of a collection efficiency which is overly conservative and perhaps unobtainable.

2. The dilutory effect of an increased total ventilation rate may be used in the modeling approach to follow a Reference One suggestion that, wherever possible, the breathing zone concentration should be maintained or lowered (especially when dealing with toxic substances).

3. Because the plant implemented a major improvement in their ventilation system in conjunction with the concept of recirculation, it is difficult, if not impossible, to utilize the modeling approach to assess and predict the combined affects of both ventilation changes. This agrees and expands upon the concept presented in the preliminary feasibility assessment that existing in-plant systems should be optimized prior to the assessment of the feasibility of recirculation.

4. The existence of strict air quality regulations for lead emissions provided incentives for the plant to specify a highly efficient air cleaner which would also be useful for recirculation.

5. Although an "efficiency guarantee" on the manufacturer-stated collection efficiency may offer some assurance that the collector will perform as claimed, they should not be considered as an "absolute" number. The actual collection efficiency should be verified by measurements after system installation. This essentially agrees with suggestion in Reference One that the air cleaner performance be checked as part of an overall system performance validation.

The following conclusions from the evaluation expanded on the conclusions and recommendations in Reference One.

6. In this case study, the recommended failure response of bypassing the exhaust air to the outdoors following a collector failure would be, by itself, an unacceptable alternative because this action causes contaminated air to enter from an adjacent working area.

7. One benefit of recirculation not discussed in Reference One was the pressurization of one work area to prevent contamination from an adjacent area.

8. There are unique sampling problems associated with the clean nature of recirculated return air streams which relate to the difficulties in obtaining a sufficient sample in particulate and particle size tests with conventional in-stack sampling methods and impactors.

RECOMMENDATIONS

1. When the failure response of bypassing the collector exhaust results in unacceptable condition, then another suitable strategy such as process shutdown should be implemented following a failure.

2. When extremely low particulate concentrations in return air stream are to be measured, consideration should be given to using the high volume extraction technique described in this report. A convenient method still needs to be developed for measuring the particle size distribution in air streams containing extremely low particulate concentrations.

GLOSSARY

C_{BZ} The predicted breathing zone concentration, mg/m^3

C_{BZ}^D The desired breathing zone concentration, mg/m^3

C_{BZG}^O Initial breathing zone concentration (TWA), in open plant areas, mg/m^3

C_{BZL}^O Initial breathing zone concentration (TWA), under the influence of large volume exhaust systems, mg/m^3

C_E^O The initial concentration of local exhaust streams, mg/m^3

C_{MU} The concentration in make-up air, mg/m^3

C_R Return air concentration, mg/m^3

f Local exhaust system influence factor

ΔH Control case orifice pressure drop, $cm\ H_2O$ (in. H_2O)

k_{BZ} Contribution factor of return air to breathing zones

k_R Contribution factor of return air to local exhaust systems

η Air cleaner efficiency

Q_{BZ} "Clean" exhaust bypass rate, m^3/min

Q_G' General exhaust rate not recirculated, m^3/min

Q_L The initial rate of local exhaust streams, m^3/min

Q_{LB} "Dirty" exhaust bypass rate, m^3/min

Q_{MU}^O Make-up for conventional systems, m^3/min

Q_{MU}' Fixed make-up supply rate, m^3/min

Q_{MU1} Make-up air supply for air mixed with recirculated air, m^3/min

Q_{MU2} Make-up air supply rate for air not mixed with recirculated air, m^3/min

Q_N Natural ventilation rate, m^3/min

Q_R Return air volume rate, m^3/min

Q_T^O Total ventilation rate before recirculation, m^3/min

Q_T Total ventilation rate after recirculation, m^3/min

STEL   Short term exposure limit - ACGIH, mg/m^3

SP   Static pressure, cm H_2O (in. H_2O)

TLV   Threshold limit value - ACGIH, mg/m^3

T_S Stack temperature, ^OC (^OF)

TWA   Time-weighted average, mg/m^3

V_m Dry gas meter volume, m^3 (ft^3)

VP   Velocity pressure, cm H_2O (in. H_2O)

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