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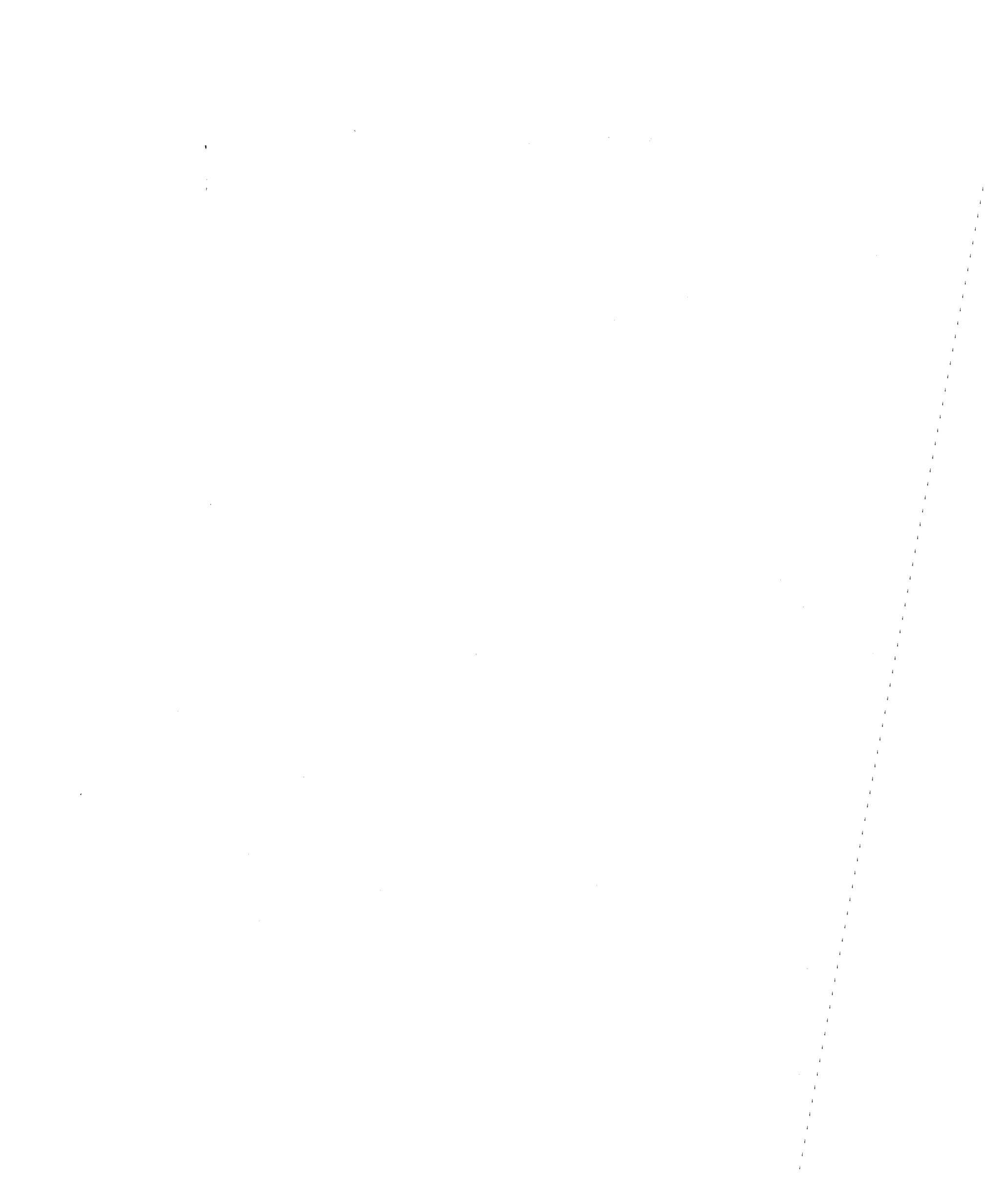
RESEARCH REPORT

VALIDATION OF A RECOMMENDED APPROACH TO RECIRCULATION OF INDUSTRIAL EXHAUST AIR

VOLUME I

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. d-210-77-0154	2.	3. Recipient's Accession No. PB80-161474

4. Title and Subtitle	5. Report Date
Validation of A Recommended Approach to Recirculation of Industrial Exhaust Air—Volume I (Spring Grinding, Chrome Plating, Dry Cleaning, Welding, and Vapor Degreasing Operations)	August 1979
	6.

7. Author(s) Hagopian, J. H.	8. Performing Organization Rept. No.

9. Performing Organization Name and Address	10. Project/Task/Work Unit No.
Division of Physical Sciences and Engineering, Cincinnati, Ohio NIOSH, NIOSH Publication No. 79-143A, NIOSH Contract No. 210-77-0154	
	11. Contract(C) or Grant(G) No. (C) 210-77-0154 (G)

12. Sponsoring Organization Name and Address	13. Type of Report & Period Covered
Same as box 9	
	14.

15. Supplementary Notes

NIOSHTIC 00091894

16. Abstract (Limit: 200 words)

A recommended approach to the recirculation of industrial exhaust air was investigated for possible verification based on field studies. Exhaust systems in a spring grinding factor, two hard chrome factories, a dry cleaning establishment, a welding operation, and a degreasing facility were evaluated. Legal issues, energy consumption statistics for each industrial facility, contaminant classifications, air cleaner and monitor availabilities, process emission profiles, and ventilation system designs were considered. Predictive equations were devised for breathing zone and return air concentrations and failure analysis. The author concludes that the approach provides a framework for the design process, is aimed specifically at health and study issues and presumes availability of certain design data, and demonstrates useful and valid design procedures. A re-circulating exhaust system should undergo frequent maintenance and inspection. Inform-ation is needed about the efficiency of air cleaning devices that are installed and operating under field use conditions. The development of a NIOSH recirculation system design criteria directed toward common industrial operations is recommended by the author

17. Document Analysis   a. Descriptors

KEYWORDS: NIOSH-Publication   Ventilation-systems   Air-sampling
           NIOSH-Author   Ventilation-equipment   Air-quality-measurement
           NIOSH-Contract   Industrial-environment   Air-circulation
           Contract-210-77-0154 Air-contaminants   Industrial-health
   b. Identifiers/Open-Ended Terms   Regulations
                                                          Legislation

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) unclassified	21. No. of Pages
Available to the Public	20. Security Class (This Page) unclassified	22. Price

(See ANSI–Z39.18)   See Instructions on Reverse   OPTIONAL FORM 272 (4–77)
                                                                (Formerly NTIS–35)
                                                                Department of Commerce

VALIDATION OF A RECOMMENDED APPROACH
TO RECIRCULATION OF INDUSTRIAL EXHAUST AIR -- VOLUME I
(Spring Grinding, Chrome Plating, Dry Cleaning,
Welding, and Vapor Degreasing Operations)

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Contract No. 210-77-0154

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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 docu-
ment requires familiarity with the contents of that
previous report.

ii

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

The National Institute for Occupational Safety and Health (NIOSH) sponsored development of a report entitled "A Recommended Approach to Recirculation of Exhaust Air" under Contract No. 210-76-0129. That report (DHEW(NIOSH) Publication No. 78-124) provides a methodology by which the design, installation, and operation of recirculating systems can be undertaken and completed in a manner which ensures the health of employees within the work place.

The validity of the recommended approach to recirculation of exhaust air was evaluated in this program by studying its application in the design of new recirculation systems and in retroactive applications to existing systems. Wherever possible, the conditions under which the recommended approach may not be fully appropriate were determined and recommendations for improvements to the approach developed.

The study results indicate that the recommended approach provides an appropriate framework for the design of recirculation systems and is of value in identifying and resolving problems of health and safety. Additionally, it identifies various limitations of the approach and discusses potential approaches to their resolution.

This report was submitted in fulfillment of Contract No. 210-77-0154 by Arthur D. Little, Inc. under the sponsorship of the National Institute for Occupational Safety and Health.

CONTENTS

ACKNOWLEDGMENTS

INTRODUCTION

A common and effective engineering approach to control of airborne contaminants in the working environment is the use of exhaust ventilation systems. Such systems serve to continually remove contaminated air volumes from the work place, and discharge them outdoors. They are usually complemented by an air supply system designed to replace (i.e., make-up) exhaust volumes with fresh outdoor air volumes; these latter supplies being heated or conditioned as necessary for worker comfort.

The cost of heating or conditioning large volumes of make-up air has increasingly become of concern to numerous sectors of industry, especially as fuel costs rise and there are threats of shortages. In consequence, there has been considerable interest in methodologies which allow reductions in make-up air supply rates and attendant reductions in energy requirements. A strong contender among these is the practice of exhaust air recirculation, most commonly through the use of sophisticated air cleaning devices and return air distribution systems.

Since few air cleaning equipment trains are 100-percent effective in removing all contaminants from air streams, the practice of recirculation has the potential to adversely impact the health of employees by increasing internal contaminant levels. Indeed, the implementation of such systems has generally been discouraged in the past whenever the contaminants involved were considered toxic, mostly due to the fact that there has not been a practical and reliable methodology by which the effect of recirculation upon a work place can be adequately assessed before recirculation is implemented.

Since 1974, the National Institute for Occupational Safety and Health (NIOSH) has sponsored a number of research programs aimed at resolving the various health and safety issues associated with recirculation. Its goal has been to provide industry with a comprehensive approach to the design of recirculation systems which ensure the acceptability of the working environment. Although these programs have not addressed all practical engineering problems associated with this task, they have nevertheless provided industry with the framework for a successful design and implementation effort. One of the latest products of NIOSH's activities is a report entitled, "A Recommended Approach to Recirculation of Exhaust Air."* Published in early 1978, this report (called Reference 1 throughout this document) discusses issues of importance, and represents a first attempt at developing a practical and comprehensive approach to recirculation system design. Topics include legal issues, energy consumption, air quality regulations, contaminant characteristics, air cleaning, system surveillance, analytical design procedures, performance validation, maintenance, failure analysis, and others.

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*Partridge, L. J., Nayak, P. R., Stricoff, R. S., and Hagopian, J. H., 1978. A Recommended Approach to Recirculation of Exhaust Air. DHEW(NIOSH) Publication No. 78-124. U.S. Government Printing Office, Washington, D. C. 20402.

STUDY OBJECTIVES AND APPROACH

The basic objective of the current study was to investigate the validity of the qualitative recommendations and analytical design procedures (i.e., models) of Reference 1 under real-world operating conditions. This was usually to be accomplished by the performance of field surveys in plants which currently recirculate exhaust air, followed by retroactive application of Reference 1's methodology to identify and evaluate how its use may have altered the design process. Additionally, if the opportunity presented itself, it was desired to apply the methodology to plants which are considering recirculation, with the purpose of designing and implementing a recirculation system and evaluating its overall performance and acceptability.

To achieve study goals, detailed field surveys were conducted at four plants which currently recirculate exhaust air and at two plants which would consider the practice. Additionally, walk-through surveys were performed at plants which currently recirculate to gain a broader perspective of the numerous types of successful recirculation systems in operation in industry, and to further define and/or resolve the difficulties associated with recirculation system design.

A subsequent section of this document contains a series of individual case study reports detailing the scope of study activities and findings. These first describe the plant and its pertinent processes, the sampling strategy and methodology utilized, and sampling results. They then proceed to apply Reference 1's methodology to the system being studied. This is accomplished in a step-by-step fashion with attendant discussions concerning the validity of Reference 1's recommendations. Finally, each case study report provides various conclusions and recommendations which evolve from the investigation.

It must be noted that Reference 1 is a very detailed document which discusses a great many topics qualitatively. Additionally, it devotes on the order of 100 pages to presenting and explaining details of quantitative models for assisting recirculation system design efforts. This document does not attempt to reiterate every facet of every issue addressed by Reference 1. Rather, it presumes that readers will be sufficiently familiar with the contents of that work to appreciate the implications and ramifications of findings in this report with a limited degree of prompting. Indeed, it must be stressed that this report is intended to supplement and expand upon Reference 1. It is not intended to stand alone as any sort of guide to recirculation system design and implementation.

GUIDING PHILOSOPHY

The principal investigator of this study was intimately involved with the development and preparation of Reference 1, and was fully knowledgeable of the various discussions, arguments, and other factors which led to the final form of that document. It therefore serves well to comment upon the philosophy of the approach taken for evaluating the validity of Reference 1's recommendations and analytical design procedures.

It was not desired to apply Reference 1's recommendations verbatim in this study solely to determine whether they are right, wrong, or somewhere in between, although that was one objective of the program. Instead, based upon a knowledge of the various pro's and con's associated with each aspect of Reference 1, and a knowledge of the degree of uncertainty associated with each element of its approach, it was also desired to simultaneously further investigate issues which were felt to be significant and in need of closer inspection.

The reader will, therefore, note that the various case study reports do not give equal weight to considering all issues associated with recirculation system design. Rather, they sometimes superficially address issues which were not considered controversial or otherwise worthy of lengthy discussion, and often dwell upon exceptions to Reference 1's recommendations which were judged important for distinction. It was through this route that it was hoped to not only "validate" previous design guidelines, but to take the next step in enhancing the basic understanding of issues associated with recirculation.

STUDY LIMITATIONS

The nature of this study resulted in circumstances which served to limit the degree to which some study objectives were fulfilled. These limitations are generally discussed below.

Retroactive Assessments

To fully test all the elements of Reference 1's methodology in a single design effort, it would have been necessary to identify a plant that would have been willing to pay for the acquisition and installation of all necessary recirculation system components. Additionally, it would have been necessary for Reference 1's methodology to have indicated that recirculation is feasible in such a plant.

Unfortunately, neither of the plants surveyed without recirculation provided the proper circumstances for installation of a recirculation system. Thus, all case studies involved partial application of the methodology, or involved its retroactive application to an existing system.

Such retroactive evaluations served well to assess the applicability and validity of Reference 1's qualitative recommendations. They did not, however, allow complete evaluation of the various recirculation system design models. The problem stemmed from the fact that the models have the basic purpose of predicting post-recirculation worker exposures based upon pre-recirculation conditions. When only post-recirculation conditions are available for characterization, it is possible to back calculate pre-recirculation conditions, but not possible to compare them with actual pre-existing conditions.

Sampling Problems

The proper evaluation of the operating performance of a recirculating exhaust system requires the taking of air samples at various points in the work place

3

and in ductwork. Ideally, such activities will encompass the full range of operating conditions to which the recirculation system may be subjected.

The scope of sampling activities in the six plants surveyed in depth was often limited and not always as comprehensive as was desired. Reasons involved limitations in resources and time, limitations imposed by job-shop environments, and others imposed by plant managements. Generally, survey teams were allowed to obtain data only during time periods specified at the convenience of plant managements. Additionally, they were required to accept whatever operating conditions were prevalent during these time periods, with no opportunity to investigate the effects of varying process parameters.

Yet other problems derived from equipment malfunctions. Indeed, three of the six air cleaning devices available for study were found to have serious deficiencies which prevented their optimal performance, and the meaningful characterization of their efficiency.

Tracer Gas Studies

As the study progressed, it became increasingly evident that proper evaluation of recirculation system design models requires accurate knowledge of the fraction of air in recirculating exhaust systems and in pertinent breathing zones which originates in a return air stream. Reference 1 suggests that the necessary data can be obtained through the performance of tracer gas studies.

In practice, it was found difficult to perform tracer gas studies in the plants surveyed in depth. Although such a study was conducted in one plant, the conditions at others were not conducive to such efforts. At one plant there were nine separate recirculation systems within a relatively small working area, each with radically different operating characteristics. At two others that do not currently recirculate exhaust air, it was not practical to design and install mock-ups of envisioned return air distribution systems. Similarly, either a tracer gas study was not warranted in other plants, or there were factors in evidence which would not allow the performance of a useful study under observed operating conditions.

Access to Plants

Some sectors of industry do not participate in any study that is sponsored by the government, that involves air sampling studies, and/or that may involve outside personnel touring a facility. In the current study, this philosophy hampered efforts to identify and study plants best suited for evaluation and, therefore, limited a study with the basic purpose of helping plants to safely reduce energy expenditures.

The case studies discussed in this report involve a wide variety of contaminant types (dry particulate, acid mists, solvent vapors, and metal fumes), as well

4

as a variety of air cleaning technologies (fabric filtration, wet scrubbing, carbon adsorption, and electrostatic precipitation). Much valuable information will, therefore, be seen to have evolved from the overall program even though the surveys generally involved plants willing to cooperate in the survey, but not always the best to serve study objectives.

OVERVIEW OF CASE STUDIES

INTRODUCTION

The following sections introduce the contents of the various case studies and briefly discuss how these studies validated and/or demonstrated deficiencies in the approach to recirculation recommended by Reference 1. Initially, discussions are confined to the qualitative recommendations provided therein. A separate discussion then addresses various aspects of the recirculation system design models.

The case studies are purposely discussed in the chronological order in which they were performed. This allows demonstration of how certain recommendations and conclusions not immediately evident from the results of any single case study evolved from a broader perspective of study findings.

SPRING GRINDING

The first study involved a large modern plant which manufactures coil springs and then grinds their ends to square and flatten them. This dry process is accomplished with specially designed grinding machines for which the shop has designed and installed integral local exhaust hoods. Exhaust air from eight groups of these machines is ducted to one of eight bag filter units which are located on the plant floor, and which clean and return air directly to the working environment. No monitoring devices or exhaust air bypass ducts to the outdoors are provided.

A close study of one recirculation system indicated that the return air stream was contaminated with approximately 1.4 mg/m^3 (time-weighted-average during work periods) of particulate matter under the operating conditions observed. From results of tracer gas studies, it was evident that this discharge was incrementally increasing pertinent breathing zone concentrations by roughly 0.4 to 0.6 mg/m^3 in the immediate vicinity of the bag filter. When nuisance materials were being handled, the overall worker exposure on the order of 1 to 2 mg/m^3 was well below permissible limits. It was estimated, however, that conditions would be borderline, if not in violation of limits, if more toxic metals were processed for a large fraction of a shift.

For nuisance materials, the system was designed in accordance with recommendations of Reference 1 and provided fully acceptable results. For toxic materials, the criteria would have suggested consideration of bypass ducts to the outside for use when toxic materials are processed and/or air quality monitoring devices to ensure full compliance with pertinent limits under all operating conditions. Given the clear possibility of bag breaks and excessive contaminant levels when toxic materials were processed, such measures must be considered warranted.

A further significant finding was that the recirculation systems in the plant were rather useless as an energy conservation measure, and were applied to poorly chosen exhaust streams. Both of these findings derived from an observation that at least 106.2 m^3/s (225,000 cfm) of barely contaminated general exhaust air were being discharged outdoors, while no more than 14.2 m^3/s (30,000 cfm) of sometimes highly contaminated local exhaust streams were being cleaned and recirculated. It was clear that the general mechanical ventilation rate could be lowered by much more than 14.2 m^3/s (30,000 cfm), with a greater degree of safety, if only all local exhaust streams were discharged outdoors.

Other findings were that:

- An initial feasibility assessment for recirculation must fully consider the presence of objectionable odors.
- A tracer gas study, under some circumstances, has the potential to provide conservative results when the contaminants of interest are aerosols and have a strong tendency to settle upon exposed room surface areas.
- There were no serious deficiencies in the recommendations of Reference 1 for the basic and straightforward system configuration investigated. Indeed, they provided the basis for the identification of probably safer and more beneficial measures for energy saving.

HARD CHROME PLATING PLANT #1

A job-shop which predominantly provides hard chrome plating services has been recirculating the exhaust air from plating tanks for approximately 20 years. At present, nine small and self-contained wet scrubbers are utilized to clean the exhaust air from 12 plating tanks. Each scrubber handles the effluent from one or two tanks, is sited in the immediate vicinity of its associated tanks, and returns air to the work place directly through an open exhaust port on its side. There are no bypass ducts to the outdoors or any sort of automatic or manual monitoring systems.

The inplant survey indicated that contaminant concentrations, primarily chromic and sulfuric acids, were at or below permissible exposure limits under observed operating conditions. It also indicated that this finding was purely a matter of luck and favorable circumstances because both of the air cleaners closely studied were found to have serious operating deficiencies, and most exhaust systems provided control velocities well below those minimally recommended.

One of the air cleaners did not have an inlet supply of water for air washing purposes. Although its internal mist eliminator was doing an admirable job of reducing contaminant levels in the exhaust air, the unit had been accumulating concentrated acid mists for quite some time. When a well-intentioned plant maintenance man learned of the deactivated water supply system, he quickly found a closed valve and opened it. This action caused a large amount of acid to literally spray and pour from the outlet port of the air cleaner, thereby severely contaminating the air quality in the plant and causing somewhat of an emergency situation.

This incident graphically demonstrated that a bypass duct to the outdoors is highly recommended for emergency and/or warm weather use. If such ducts had been provided, the emergency conditions could have been dealt with in a considerably more satisfactory manner than was possible. Additionally, the incident demonstrated: 1) the need for frequent maintenance and inspection; 2) the usefulness of monitoring devices for air cleaner performance parameters; and 3) the possibility that some types of air cleaners can accumulate and catastrophically discharge contaminants.

In regards to the recommendations of Reference 1, it was found that these would have strongly suggested the need for every precautionary measure that was obviously lacking and needed in this plant. Additionally, it became evident that recirculation of hard chrome plating exhaust volumes is generally feasible when: 1) high-efficiency scrubbers are used; 2) the increased humidity level in the plant is not of concern to plant management; 3) few other contaminant-producing operations are conducted in the plant; 4) frequent maintenance and inspection is provided; 5) bypass ducts to the outdoors are provided for emergency and/or warm weather use; 6) surfactants and/or floating plastic balls are used to reduce mist generation; and 7) the implementation of recirculation does not change the total ventilation rate through the plant.

HARD CHROME PLATING PLANT #2

A second metal finishing plant provides hard chrome plating services in a single large room housing a wide variety of contaminant-producing operations. Four large wet scrubbers situated on the roof clean all exhaust streams and discharge to the outdoors. Thus, the plant does not currently recirculate any amount of exhaust air.

This plant was chosen for review with the objective of applying the recirculation criteria to the task of designing a recirculating exhaust system for plating tank exhausts. Plant management was extremely concerned about the possible adverse effects of increased humidity levels, but was willing to cooperate and listen to resulting proposals.

After exploring numerous alternatives for recirculation system design configurations, it was concluded that none could presently be implemented in a cost-effective manner because of two major stumbling blocks. The first of these involved the presence of two fixed-capacity make-up air supply units; neither of which could be modified to provide a lower supply rate. The second involved a lack of sufficient data and the potential costs of additional sampling efforts.

Essentially, it was found that all feasible energy saving concepts involved a reduction in the total ventilation rate through the plant because: 1) there usually is an excess make-up air supply; 2) the most desirable concepts require deactivation of one of the make-up air supply units; and 3) it is not feasible to replace make-up air with recirculated air on a one-to-one basis. Thus, it would be necessary to assess the effects of a reduction in the total ventilation rate upon all plant operations, and not only those conducted in the hard chrome plating area. Such a program, however, would be sufficiently

expensive and time-consuming so as to be prohibitive. Simply stated, there were too many diverse contaminants present, too many radically different metal finishing operations conducted, and too many uncertainties caused by the job-shop nature of the working environment.

Numerous conclusions evolved from the study. The most significant of these were:

- Reference 1 generally provides a complete and adequate framework for the identification and treatment of all important factors in an analysis dealing with health and safety issues. It does not, however, provide any guidance on how to address the myriad of practical engineering problems which greatly complicated the assessment of recirculation feasibility.
- Significant uncertainties are introduced to the analysis when air-flow patterns in the plant will be significantly modified by the implementation of recirculation. The best case appears to be when a fresh air make-up air stream in an existing plant will be replaced by a return air stream entering at the same location and at the same volume rate.
- The presence of make-up air units of fixed capacity can complicate an analysis unless the amount of air to be recirculated is equal to the capacity of the make-up air unit(s) to be deactivated.
- Recirculation appears to be better suited at present for plant areas with only a few types of airborne contaminants with readily iden- tifiable sources.
- Wet scrubbers require frequent maintenance and inspection by know- ledgeable personnel to ensure their optimal performance. The unit closely studied in this investigation was rather useless for air cleaning purposes because of a lack of proper attention.
- Few plants have a perfect air balance before recirculation is imple- mented. The models' assumption that such a balance exists serves to complicate their application in many cases.

DRY CLEANING ESTABLISHMENTS

The majority of dry cleaning establishments in this country utilize perchloro- ethylene as the washing solvent. To recover this valuable substance from exhaust streams, most utilize activated carbon adsorption units, and a small- er subset allow the exhaust to reenter the work place directly through the normal exhaust ports of the air cleaning devices. Two plants which currently recirculate air in this fashion and one which does not were evaluated.

Reference 1's guidelines clearly indicated that recirculation can be safely implemented in such plants, but that the practice is not warranted in any of the plants surveyed. Major reasons were:

- The permissible exposure limits for perchloroethylene may be significantly lowered in the near future;

8

- The maximum amount of energy savings at any plant was on the order of $300 per year through recirculation; and
- The costs of designing or retrofitting such systems so that they will reliably maintain worker exposures at or below permissible limits were in excess of potential savings.

The first reason represents a substantial economic risk to continued recirculation. It was patently clear that recirculation could make the difference between compliance and non-compliance in some plants if the limits were significantly lowered in the near future. The second reason enhances the validity of this finding by suggesting that not much can be gained through recirculation, even if exposure limits are unchanged. Finally, the third point indicates that the potential savings would be overshadowed by costs of providing bypass ducts to the outdoors, return air distribution ductwork, and monitoring systems to warn of carbon bed breakthrough or malfunction.

WELDING OPERATION

A large automobile parts manufacturing company was in the process of designing and implementing a prototype recirculation system for welding fumes during the course of this study. A review of its design process in developing the system provided a unique opportunity to observe how others may design a recirculating system when they are aware of Reference 1's approach.

The design of the resulting system was based upon a virtually negligible amount of sampling data. Nevertheless, it was clear that there was practically no possibility that the prototype would provide an unacceptable working environment. The design incorporated a two-stage electrostatic precipitator of relatively high efficiency, the loading to the air cleaner was moderate, the return air stream entered a plant area without major contaminant-generating processes, and the system configuration included a bypass to the outdoors automatically controlled by an in-duct monitoring system for welding fumes.

The implementation of the system was not without problems, however. The lack of an adequate characterization of pre-recirculation conditions meant that there was considerable uncertainty associated with predictions of post-recirculation conditions. It also meant that the feasibility of recirculation on a widespread basis could not be evaluated until the expensive prototype system was thoroughly evaluated after its installation.

The lack of a complete economic analysis for the system before its major components were purchased led to the late realization that the planned system design was barely cost-effective. There were abnormally high costs associated with custom mounting platforms and sheet metal work which had not been considered.

Overall, the experience generally confirmed the appropriateness of the complete Reference 1 methodology. The difficulties and uncertainties occurred in this plant because "short-cuts" were taken with some of that document's recommendations. However, it was also noted that there are cases involving relatively low toxicity contaminants, high efficiency air cleaners, low to moderate air

9

cleaner loadings, and low pre-recirculation exposures which justify common sense approaches to assessing post-recirculation conditions. It is not always necessary in such circumstances to utilize the models of Reference 1 in a rigorous manner, and/or to obtain complete characterizations of pre-recirculation conditions.

DEGREASING OPERATIONS

A plant with a relatively large degreasing unit using the solvent trichloroethylene practiced a type of exhaust air recirculation which was not observed elsewhere. Essentially, the degreaser was completely enclosed with openings only for entering and exiting parts. Exhaust air from the enclosure would pass through a dual-bed carbon adsorption unit which reduced the contaminant concentration to a level below 50 ppm. A continuous monitoring system ensured this, and served to switch the exhaust air from one bed to the other when contaminant levels approached 50 ppm. The cleaned air was then directly returned to the degreaser casing.

Because of the enclosed nature of the process, trichloroethylene concentrations in the general area of the system were below 5 ppm, and there was virtually no solvent loss. In consequence, this arrangement of equipment was seen to incorporate all the benefits of recirculation with few, if any, attendant risks.

OVERVIEW OF MODEL VALIDATION EFFORTS

The purpose of the models in Reference 1 is to allow a user to analytically evaluate the effect of recirculation upon worker exposures to airborne contaminants before a system is actually installed. Their primary value, therefore, is to reduce uncertainties associated with implementation of the practice. This is accomplished by focusing attention upon all physical factors which can adversely influence the acceptability of the resulting system.

Each model in Reference 1 essentially contains three elements. The first of these involves a series of equations which describe the overall air flow balance in a plant and the flow at various points in ventilation and recirculation systems. These involve simple additions and subtractions of various inflow and outflow volume rates. There is no theoretical uncertainty associated with the concept upon which they are based, but only a need to determine whether the sets of these equations presented in Reference 1 can be applied to the range of conditions observed in industry.

A second element involves two equations for predicting the levels of contaminants in return air streams. These utilize data for pre-recirculation contaminant concentrations in the exhaust volume to be recirculated, concentrations in make-up air supply volumes (if any), air cleaner efficiencies, and a factor (k_R) which indicates the volume fraction of air entering a recirculation system which itself originated in a return air stream. Theoretically, these equations also have few attributes that are questionable.

Finally, each model contains a breathing zone concentration prediction equation which attempts to forecast the effect of recirculation upon particular breathing zones of interest. This equation incorporates novel concepts, has the greatest degree of associated uncertainty, and therefore merits close scrutiny.

Spring Grinding

In the spring manufacturing plant it was possible to perform a tracer gas study to characterize how recirculated air disperses throughout pertinent working areas. In consequence, it was feasible to retroactively apply the appropriate model in Reference 1 to test the consistency of its results and to determine if these results were reasonable when compared with intuitive estimates of pre-recirculation conditions.

No problems were experienced or envisionable with applying the air flow balance equations to this plant. The equations contained all elements necessary to characterize existing as well as pre-recirculation flow volumes, and were seen to provide logically correct answers. Similarly, the equations for predicting contaminant concentrations in return air volumes provided obviously correct results. Indeed, for this most simple of feasible recirculation system configurations, their accuracy was seen to be limited only by the accuracy of input data provided by the user.

Retroactive application of the breathing zone concentration prediction equation provided results judged to be consistent with observed post-recirculation conditions in the breathing zone of the machine operator. This worker was situated less than 4.6 m (15 feet) from the air cleaner discharge and was essentially directly in front of the outlet. The equation provided somewhat excessively conservative results, however, for areas more distant from the return air source. One possible explanation for this occurrence involved the manner in which a tracer gas was used to characterize the airborne path of particulate matter leaving the air cleaner discharge. It was surmised that grinding dust in the return air was settling out upon exposed room surface areas before reaching distant sampling points, while no such effect hampered the dispersion of the tracer gas. This led to the observation that one must use caution when attempting to study the dispersal of particulate matter with a gaseous simulant.

Hard Chrome Plating Plant #1

Application of the model in the spring plant was facilitated by the fact that most recirculation systems were generally widely separated in terms of distance, and that the system closest to the one studied was essentially unused during the survey. Thus, there was no practical need to investigate the interaction of effects of two or more recirculation systems upon any particular breathing zone.

In the first plating facility studied, the situation was radically different. Not only were there nine recirculating systems scattered randomly throughout the relatively small working area, but each of these systems was essentially unique in terms of air cleaner loading, air cleaner type and capacity, and nature of processes controlled. It was therefore necessary to consider the usefulness of models not only for evaluating the acceptability of individual recirculation systems, but also for considering the effect of recirculation upon the work place as a whole. This effort identified a number of problem areas associated with model application in such situations.

The plant in question has never had any sort of mechanical make-up air system. It has essentially relied upon natural ventilation through open garage doors (even in winter) to provide make-up air. Thus, recirculation served to reduce the natural ventilation rate by substantially increasing internal pressures relative to those provided by wind and other forces.

The air balance equations presented by Reference 1 all assume that it is a mechanically provided make-up air supply which will be replaced by a recirculated supply. Additionally, they assume that the natural ventilation rate in combination with the infiltration rate will not be affected by the implementation of recirculation. Thus, these equations are inappropriate and somewhat misleading for use in some situations. A review of the concepts upon which the equations are based indicated no deficiencies, however. The elements were there for proper treatment of this problem, but simply had not been applied to a situation similar to the case in hand.

The only problem identified for the equations dealing with concentrations in return air supplies involved definition of a value for the parameter k_R; the fraction of air entering a recirculating exhaust system which originates in the return air stream of such a system, i.e., the fraction of air recycled more than once. Since the air volumes entering the various air cleaners could have originated in any of the nine recirculation systems or in fresh air supplies, it was impossible to estimate an accurate value for this parameter. In consequence, k_R must be assigned its maximum possible value of 1.0 in such a situation. Where air cleaner efficiencies are high and/or contaminant concentrations in fresh air supplies are low, such an estimate would have little effect upon the validity of results. In other circumstances, which are admittedly more unusual, such action could lead to results which are overly conservative.

The presence of nine different and interacting recirculation systems also caused difficulties in applying the breathing zone equation. Since this expression was derived with the expectation that only the return air from a single recirculation system would interact with any particular breathing zone, or that the interactions of more than one system would involve systems which are reasonably similar, it was necessary to deliberate on how to assign values to two important parameters.

The first of these is the parameter designated as C_R, the contaminant concentration(s) in the return air stream affecting breathing zones of interest. It was clear that there was no practical methodology by which an accurate value for this parameter could be predicted for any given location in the work place before recirculation is implemented. Hence, it became necessary to consider use of the highest C_R value for each contaminant, as determined by estimating the C_R values associated with each of the nine recirculation systems. This was concluded to be a conservative approach, albeit one which can also produce overly conservative results on occasion.

Completely analogous difficulties involved the parameter k_{BZ}, the fraction of air in a breathing zone of interest which originates in a return air stream. It became necessary to consider using the maximum possible value of 1.0 for this parameter, although this action would further compound the conservativeness of results.

12

If breathing zone concentration predictions are found to be acceptable when these conservative values are utilized in equations, it can be assured that the recirculation system will provide an acceptable working environment. If such predictions are not acceptable, however, the situation becomes some-what uncertain. It becomes unclear whether undesirable results are caused by excessive conservativeness in parameter value assignment, or whether the system might actually provide unacceptable working conditions.

Hard Chrome Plating Plant #2

This case study involved use of the models to assess the feasibility of recir-culation in a plant which does not currently recirculate. In consequence, the models were applied for a number of potentially feasible system configurations.

The assumption of a perfect mechanically provided air balance before recir-culation is implemented again caused difficulties in applying the air balance equations. This was due to the fact that the plant had an excess make-up air supply. This excess was leaving the plant through exfiltration, as well as by the action of boosting the exhaust volume rates of individual local exhaust systems throughout the plant. To account for these circumstances, it was neces-sary to ignore the air flow balance equations presented in Reference 1, and to simply estimate air flow rates for each desired point in the system by more straightforward means. This was not difficult, but did digress from Reference 1's stated procedures.

The return air contaminant concentration prediction equations were found to be completely appropriate for the various system configurations considered. Dif-ficulties encountered simply involved estimation of parameter values for use.

The plant was surveyed under what were said to be typical operating conditions. However, the person in charge of the plating operation indicated that the tanks may be "cranked up" during particularly busy periods. This was cause for concern because there was no possibility of returning to the plant on some future date when worst case operating conditions might be prevalent. Thus, it became neces-sary to utilize somewhat arbitrary safety factors in assessing return air con-centrations. Of interest is that Reference 1 notes the need for comprehensive sampling data which represent worst case as well as more typical conditions. Difficulties encountered in this evaluation derived from an inability to meet this requirement rather than any deficiency on the part of Reference 1.

Application of the breathing zone concentration prediction equation was also straightforward, but again required the use of a safety factor upon concentra-tions actually measured in the plant. Additionally, it required the estimate of a conservative k_{BZ} value of 1.0 because there was no practical way to per-form a tracer gas study in this plant.

Overall, it was found that the models were extremely useful for the needed analysis. They forced attention upon all factors which can influence worker exposures throughout the plant, allowed investigation of the effects of any errors in assignment of values to various parameters, and more importantly, clearly indicated that recirculation in this plant could not be safely accom-plished without a considerably more complex sampling and analysis program for

contaminant producing operations in the plant. Conversely, it was noted that
the scope of the models should be increased to allow consideration of plants
with imperfect air balances.

Dry Cleaning Establishments

Model evaluation for dry cleaning establishments studied involved a somewhat
unusual approach. Since the recirculation system configurations utilized
were similar to those in the spring manufacturing plant and hard chrome plating
plant #1, there was no attempt to numerically apply the pertinent model in
retrospect. Rather, the derivation of the model was reviewed to investigate
whether it contained the elements necessary to perform the needed analysis.
This led to identification of two weaknesses in the equations caused by simpli-
fying assumptions.

The first involved the assumption that any contaminant concentrations (C_{MU}) in
make-up air supplies to the plant area of interest would remain constant before
and after recirculation. This assumption was found to be somewhat conserva-
tive and acceptable when the make-up air entering the plant area of concern was
from the outdoors. In one of the dry cleaning plants, however, a situation was
encountered where the recirculation system discharged into a small room within
the plant, left the room through exhaust fans discharging into an adjacent
plant area, and then partially returned to the room through open doorways. This
was obviously a somewhat unusual situation, but pointed out the fact that some
systems may be implemented under circumstances where C_{MU} values can increase
when recirculation is implemented. In consequence, it was recommended that
the model be modified to account for such situations if and when they occur.

A second weakness again evolved from consideration of the effects of changes
in natural ventilation and infiltration rates when recirculation is implemen-
ted. It led to a recommendation that the combined rate of these effects (Q_N)
not always be considered a constant in equations, but be allowed to have
separate before and after values.

Other Case Studies

Other plant visits involved walk-through surveys and discussions with plant
personnel. In consequence, the case study reports for these do not include
detailed evaluations of model validity, although some qualitative observations
were formulated regarding model usefulness in similar applications of recir-
culation systems.

DISCUSSION AND SUMMARY OF FINDINGS

A broad-based view of program results allows an ordered evaluation of
Reference 1, as well as discussion of other issues discovered to be per-
tinent. In the following, important findings are summarized through
discussion of the individual design steps outlined by Reference 1. These
steps are listed in Chapter 2 of that document and are discussed in various
chapters and appendices.

INITIAL FEASIBILITY ASSESSMENT

Reference 1 suggests the performance of an initial feasibility assessment to provide an indication of whether recirculation is worthwhile or possible in a particular plant before detailed and expensive design efforts are initiated. The various steps of such an assessment are discussed below.

Legal Issues

There are few states which prohibit or otherwise explicitly regulate the practice of exhaust air recirculation. In addition, the Federal government has few if any regulations specifically concerning the subject. Nevertheless, it is apparent that Reference 1 is justified in recommending that all legal issues be investigated to determine if such factors can influence the decision to recirculate. A failure to do so would run the risk of violating one of the few regulations which do currently exist. Discussion in the case study entitled "Welding Operation" confirms this point.

Energy Consumption

An early assessment of current energy usage, costs, and availability can indicate in general terms whether there are any worthwhile savings to be realized by recirculation. Indeed, the finding that make-up air heating costs are rather insignificant in some dry cleaning establishments provided an important basis for concluding that the practice is not warranted in many such facilities. Reference 1's recommendations in this area are therefore clearly in order.

Contaminant Classification

Reference 1 suggests thorough consideration of the types of contaminants present in air volumes considered for recirculation. Additionally, it prompts evaluation of their toxicity, physical and chemical characteristics, and other attributes.

The only possible statement on this topic serves to expand and emphasize further the comment that the number and nature of contaminants can influence the decision to recirculate. Reference 1 indicates that such factors play major roles in assessing the technical feasibility and economics of cleaning air streams. It is found necessary to extend the scope of this statement to encompass the costs of sampling and analysis of contaminant concentrations before and after recirculation is implemented.

The potential cost of characterizing contaminant concentrations in a work place increases in almost direct proportion to the number of airborne contaminants present and the number of their physical forms (i.e., vapor, dust, mist, fume, etc.). In plant areas which have few airborne contaminants being generated from a few easily characterized processes, the costs of sampling and analysis can be quite moderate. However, if there are many important contaminants, and if each requires a unique sampling strategy, it is found that the potential costs of such efforts can adversely influence the economic justification for recirculation.

Air Quality Regulations

Reference 1's statements on this topic are quite logical and warranted. No deficiencies were identified in this subject area.

Air Cleaner Availability

As above, no deficiencies were identified in this subject area. It is, however, reiterated and stressed that the effect of the air cleaner upon the quality of recirculated air must be evaluated. In the study of Hard Chrome Plating Plant #2, plant management's concern with the effects of an increased humidity level in the plant was particularly impressive and warranted.

Monitor Availability

Reference 1's recommendations on this topic have merit and do not in themselves require comment. The availability of a suitable methodology for detecting reduced system performance should play an important part in the decision to recirculate. Indeed, this study's frequent finding that specific air cleaners were malfunctioning underscores the need for system surveillance.

Process Emission Profile

Reference 1 cautions in general terms that the task of recirculation system design is complicated by fluctuating process emission profiles. The results of the current study allow further discussion of the issue.

Generally, processes which fluctuate rapidly between known range limits can be successfully characterized in terms of time-weighted average concentrations. The only prerequisite is that the fluctuations be sufficiently rapid in exhaust streams to be recirculated that they cannot cause violation of ceiling or other short-term exposure limits if such are pertinent.

The greatest problem appears to involve processes with emission rates subject to increase in the long-term sense due to changes in work loads, process variables, production rates, etc. This is a particular problem in job-shop environments where sampling programs cannot concurrently be conducted with worst case operating conditions. The nature of difficulties is best demonstrated by the case study entitled "Hard Chrome Plating Plant #2." The system design procedures in that effort had to utilize somewhat arbitrarily estimated safety factors because there was no opportunity to study the plating processes when all tanks were operating at maximum capacity.

Ventilation System Design

Reference 1 clearly notes that difficulties associated with conversion of a conventional ventilation system to one which recirculates must be fully considered. In retrospect, its comments are found to be rather superficial

and lacking in emphasis. There appears to be a need to list some of the major difficulties which the implementation of a recirculation system may entail, and to stress that the extent of practical engineering problems must be evaluated.

In Hard Chrome Plating Plant #2, practical engineering problems involved:

- Heat losses due to outdoor air cleaner placement;
- Modification of an existing air cleaner to provide return air and bypass ducts in the necessary orientation;
- A means to route a new return air duct from the roof to the work place;
- A means to provide access to an air cleaner suspended under a high ceiling; and
- The definition of how and where to locate new air cleaners on the floor of a crowded work place.

In the Welding Operation case study, it was seen that the cost of the system greatly exceeded expectations because of difficulties in providing a structurally sound elevated platform around the air cleaner and in providing custom-fabricated diverging and converging sections.

These and similar issues require consideration on a case-by-case basis. Although they do not directly influence the health and safety aspects of the recirculation system design process, they do so indirectly by limiting the number and nature of system configurations which are feasible for installation.

Other Issues

Other issues that might best be addressed in an initial feasibility assessment involve equipment purchase and installation costs, water quality regulations, alternative energy conservation measures, employee relations, insurance considerations, current make-up air supply methodology, maintenance, and odors.

At present, Reference 1 suggests an overall economic analysis of recirculation during a late stage of the analysis procedure. For rather self-evident reasons, it is now suggested that a preliminary and crude assessment of the economic justification for recirculation be conducted during an initial feasibility assessment. It is only prudent to estimate whether any savings can be realized before detailed design activities are initiated.

Insurance companies which address the health and safety aspects of the work place are sure to be interested in any controversial measure with the potential to affect worker exposures. Additionally, they may have their own guidelines or restrictions on recirculation. Discussions with insurance company representatives are therefore in order during an initial feasibility assessment. Indeed, even local fire officials may have a say in the matter when flammable or explosive substances are involved.

Water quality regulations can be important if the effluent streams from wet collectors must be treated before disposal.

17

Recirculation is one of many energy conservation measures available to industry. Although Reference 1 does not address measures other than recirculation, it is recommended that the cost-benefit-risk aspects of every alternative be assessed before any particular one is chosen for implementation. In the spring manufacturing plant, a simple reduction in the general mechanical ventilation rate might have made more sense than the practice of recirculation.

Employee relations enter the analysis to the extent that problems are envisioned with worker acceptance of recirculation systems. Regardless of the technical aspects of ensuring the acceptability of system performance, it is felt that individual worker and union attitudes on the subject must be evaluated.

Energy saving through the practice of recirculation usually suggests a reduction in conditioned or tempered make-up air supplies. In Hard Chrome Plating Plant #2, significant problems in designing an acceptable recirculation system directly evolved from the fact that each make-up air supply unit was of substantially greater capacity than the capacity of the local exhaust system considered for recirculation. The effect of such imbalances upon the design process must therefore be considered at an early stage.

In many of the case studies, it was observed that air cleaning and ventilation system components required frequent inspection and maintenance. In consequence, it is strongly recommended that an initial feasibility assessment honestly consider the availability of skilled maintenance personnel and whether management is willing to make an irrevocable long-term commitment to frequent inspection and maintenance activities.

Finally, it is noted that the spring grinding assessment indicated the potential for accumulation of excessively objectionable odors with recirculation. The presence of odoriferous materials in exhaust streams should therefore be qualitatively evaluated during this stage of the analysis.

CONTAMINANT CHARACTERISTICS

The second major design step in Reference 1 entails a thorough characterization of airborne contaminants in the work place as well as in exhaust streams to be recirculated. Elements of the analysis include:

- Assessment of physical and chemical properties;
- Assessment of toxicological characteristics;
- Consideration of odor characteristics;
- Exclusion of human carcinogens;
- Selection of desired exposure levels;
- Concentration measurements in exhaust streams; and
- Exposure characterization in pertinent working areas.

Physical and chemical properties of contaminants are necessary for the selection and/or design of air cleaning equipment trains or sub-systems to detect reduced recirculation system performance. Reference 1 is quite

18

specific regarding the nature of properties commonly needed and provides lists of these for consideration. No deficiencies in its statements were identified in this study; however, it was noted that the level of detail called for by Reference 1 is rarely necessary. In most circumstances involving common industrial operations, the selection of a particular air cleaning device or surveillance system is more likely than not to be predicated upon its successful application elsewhere.

The recommendation that human carcinogens not be recirculated, as a general rule, is seen as appropriate, as is the observation that the decision to recirculate should favor exhaust streams with low toxicity contaminants. It is further recommended, however, that the recirculation of contaminants with high acute toxicity be discouraged when: 1) the air cleaning equipment train can accumulate contaminants; 2) the air cleaning equipment has the potential to catastrophically discharge accumulated materials into the work place; and 3) a reliable methodology does not exist for automatic bypass of the return air stream to the outdoors in the event of air cleaner malfunction. The value of such a recommendation is graphically demonstrated in the case study entitled "Hard Chrome Plating Plant #1," and is further supported by incidents occurring during the case study involving spring grinding.

The selection of a "desired breathing zone concentration" for use as a design specification has merit. In many cases, however, it was seen that a more common sense approach to designating a proper safety margin involves: 1) selection of a particular recirculation system design; 2) prediction of post-recirculation conditions using an appropriate model; 3) intensive review of the validity of input data to the analysis; and 4) decisions as to whether the difference between predicted levels and permissible limits constitutes an acceptable safety margin within the accuracy limitations of the overall analysis procedure.

The previous comments about emission profiles and fluctuating processes are also pertinent to the quantification of contaminant levels in pertinent working areas. Reference 1 is completely justified in recommending that worst case conditions be characterized. It also is considered justified in all other of its recommendations on this topic which are not discussed above.

WORK PLACE, PROCESS, AND VENTILATION SYSTEM CHARACTERISTICS

In general terms, Reference 1 suggests complete characterization of the work place, processes, and existing ventilation system (if any) to provide essential inputs to the recirculation system design process. Certain difficulties in assignment of values to model parameters will be discussed in a later section. It is appropriate here to stress simply that this characterization must be conducted under the worst case conditions expected when the recirculation system will be operational. It is not fully appropriate to survey a plant when windows and doors are open in warm weather, and then to apply resulting data to the task of predicting post-recirculation conditions for cold seasons. Not only might there be significant differences in natural ventilation and infiltration rates, but these differences will be virtually impossible to evaluate accurately.

SELECTION OF AIR CLEANING EQUIPMENT FOR FURTHER CONSIDERATION

Reference 1 does not attempt to provide detailed assistance for the
selection or design of an air cleaning section for use in any particular
situation. Instead, it presents an overview of the important factors that
a designer should consider. No deficiencies were identified in this study,
but it is important to stress a certain point which is not fully addressed
by Reference 1.

When a designer utilizes efficiency data published by an equipment manufacturer,
or otherwise derived from pilot plant studies conducted under laboratory con-
ditions, he unfortunately runs the risk of overestimating the long-term
efficiency of the air cleaning equipment train. Observations in most case
studies indicate that the actual efficiency of a unit is a sensitive para-
meter. It can be adversely affected by general wear and tear of equipment,
improper operating conditions, and lack of frequent inspection and mainte-
nance. Hence, a system designer should make every effort to review
independent literature pertaining to efficiencies measured in field situations,
and to utilize data which are determined to be most realistic.

SELECTION OF SURVEILLANCE EQUIPMENT FOR FURTHER CONSIDERATION

As above, Reference 1 provides an overview of factors to be considered
and leaves it to the system designer to decide how specifically to moni-
tor recirculation system performance. In general, no deficiencies were
identified in the approach, but some further thoughts on the subject were
formulated.

The recirculation system design procedure accounts for the benefits of all
factors influencing post-recirculation worker exposures. In consequence,
the continued acceptability of the system is not only contingent upon proper
performance of recirculation system components, but also depends upon the
performance of other plant systems. For example, a review of model equations
in various case studies indicated that exposures can be affected by changes
in total ventilation rates through pertinent plant areas, and that this
rate is a function not only of the return air supply rate. Thus, it is
necessary to note that an area monitoring methodology has certain advantages
which are not fully addressed in Reference 1.

A second thought on the subject derives from the two case studies involving
hard chrome plating operations. It was seen that the failure modes of wet
scrubbers can involve wash water quality and flow rate characteristics,
power usage, and other factors which indicate whether or not the air cleaner
is operational. In the absence of chemical-specific and even non-specific
measures to monitor air quality characteristics, surveillance of other air
cleaner operating characteristics can provide alternative, albeit less satis-
factory, techniques to be considered.

Finally, it is desirable to note that it is currently difficult to identify manufacturers of monitoring equipment for many types of airborne contaminants, and/or for unusual types of non-chemical-specific operating parameters. A future NIOSH-sponsored effort to catalog currently available instrumentation will do much to facilitate design efforts and, in doing so, should help promote the implementation of system surveillance measures.

DETERMINATION OF FEASIBLE SYSTEM CONFIGURATIONS

Reference 1 rightfully suggests consideration of all feasible approaches to energy saving based upon the recirculation concept. Evaluation of different system configurations in the spring plant, in the dry cleaning establishments, and in the plant with the welding operation may have led to more economical and/or safer designs.

DESIGN OPTIMIZATION FOR FEASIBLE CONFIGURATIONS

The design optimization process involves application of Reference 1's models and detailed economic analyses. The analytical procedures will be evaluated in detail in a subsequent section; the general description of economic factors for consideration does not need comment.

FAILURE ANALYSIS FOR FEASIBLE CONFIGURATIONS

A subsequent section dealing with the analytical design procedures will also discuss deficiencies in the failure analysis procedure. It is appropriate here to note simply that such a formal analysis is not always necessary when the recirculation system will incorporate a reliable continuous monitoring methodology with provision for automatic bypass of return air to the outdoors. Since the purpose of failure analysis is to estimate the elapsed time from system malfunction to excessive worker exposure, such an analysis is also not necessary when it is obvious that a malfunctioning air cleaner will cause unhealthy working conditions within seconds.

Additionally, it must be noted that the Reference 1 approach to this subject assumes that a worst case air cleaner malfunction will involve a zero cleaning efficiency. In a number of case studies, it was observed that this assumption does not hold when the air cleaner can accumulate contaminants and then discharge them all at once. The best example involves a fabric collector with a bag which bursts. Another involves the action of the wet scrubber at Hard Chrome Plating Plant #1.

SELECTION OF THE "BEST" CONFIGURATION

This and the next two steps of Reference 1's approach (Final Equipment Selection and Detailed System Design and Installation) do not require significant comment. It suffices to note that any digressions from general system performance specifications formulated in previous design steps must be evaluated in the context of their effect on work place air quality.

SYSTEM PERFORMANCE VALIDATION

Chapter 8 of Reference 1 outlines the procedure for ensuring that an
installed recirculation system is functioning within design specifications.
Elements of the task include a check of recirculated air quality, testing
of surveillance systems and alarms, a test of the designated failure response
strategy, and the recording of performance data.

It is recommended that this effort also entail a re-evaluation of employee
exposures in working areas affected by recirculated air supplies. This is
seen as absolutely necessary to ensure that the return air stream is mixing
with other air supplies at least to the extent estimated in the design process.

PLANNED MAINTENANCE AND INSPECTION

Chapter 9 of Reference 1 discusses the need for inspection and maintenance
of all recirculation system components, periodic air sampling studies,
record-keeping, and failure response planning. Without doubt, this study
has not only confirmed the validity of the recommendations in this chapter,
but has demonstrated that the continual safe operation of any recirculating
exhaust system is a direct function of the frequency and adequacy of main-
tenance activities. As noted previously, no plant should consider recirculation
unless its management makes an irrevocable commitment to such efforts.

MODEL APPLICATION

An overview of model evaluation efforts has generally described the
limitations and deficiencies which were identified during this study. The
following presents a systematic review of problem areas and, where necessary,
presents alternative approaches better suited to realistic conditions.

Model Use Necessity

There clearly are circumstances in which there is no need to apply
rigorously one of the models in Reference 1 to the task of predicting
post-recirculation conditions. It requires some amount of professional
judgment to determine if such circumstances apply to a particular situation,
but the effort required is rather minimal.

For example, consider the simple case when a local exhaust stream conveying
dry, non-toxic particulate matter is to be recirculated, a high-efficiency
fabric collector will be utilized, and recirculated air is to replace an
equivalent amount of fresh make-up air. In such a case (similar to that
described in "Spring Grinding"), the various air flow balance equations of
the models would not provide relevant information. They simply would indi-
cate that the total ventilation rate through the plant area of concern does
not change.

Equations for predicting contaminant concentrations in return air supplies would essentially simplify to the form:

$$C_R = (1 - \eta) \, C_E^\circ / \eta$$

where C_R is the total dust concentration in the return air stream;

η is the overall air cleaner efficiency; and

C_E° is the average total dust loading to the air cleaner.

The pre-recirculation exposure of any worker could then be summed with the C_R value to provide a worst case prediction of post-recirculation conditions. The appropriate equation is:

$$C_{BZ} = C^\circ_{BZG} + C_R$$

where C_{BZ} is the worst case post-recirculation exposure (total dust); and

C°_{BZG} is the associated pre-recirculation exposure (total dust).

If the predicted value for C_{BZ} is below the permissible respirable dust exposure limit, no further analysis is really necessary. Thus, it is suggested that this approach be attempted by system designers to indicate whether more rigorous analysis is warranted when circumstances are similar.

Air Flow Balance Equations

Each model contains one or more equations describing the air balance in the plant before recirculation is implemented, after its implementation, and at various points within the system. It is necessary for a model user to ensure that the results of such equations are consistent with the desired characteristics of the recirculation system configuration being studied. If they are not, then the mass balance basis for subsequent equations will be invalidated.

All such equations were formulated with the basic assumption that a perfect air balance is mechanically provided in the plant before recirculation, and that such a balance will be maintained. Since difficulties can be experienced when the equations are applied to a plant which initially has an excess or shortage of mechanically provided make-up air, it is advantageous to reformulate certain equations in Reference 1 to account for these possibilities.

Pre-Recirculation Total Ventilation Rate (Q_T°)--
With the exception of the model shown on page 135 of Reference 1 (Figure B3), all models contain an expression for estimating the total ventilation rate through the plant area of interest before recirculation is implemented.

The equation is:

$$Q^\circ_T = Q^\circ_{MU} + Q_N$$

where:

Q°_T is the pre-recirculation total ventilation rate;

Q°_{MU} is the total pre-recirculation rate of mechanically provided make-up air; and

Q_N is the combined rate of natural ventilation and infiltration.

The model presented on page 135 does not use this expression because it was formulated with the inherent assumption that the total ventilation rate will not change when air is recirculated. In other words, it assumes that recirculated air will replace make-up air on a one-to-one basis.

To simplify this discussion, it will be assumed that the designer is sufficiently knowledgeable to estimate a value for Q°_T without being provided a generalized and detailed mathematical expression for the parameter. Rather, qualitative reasoning will be used to demonstrate the appropriate procedure. This requires the realization that Q°_T is equivalent to both of the following two quantities.

1. The combined total rate of mechanically exhausted air volumes; outward flows through open windows, doors, and vents; and outward flows due to exfiltration to the outdoors or to other plant areas.
2. The combined total rate of mechanically provided make-up air supplies; inward flows through open windows, doors, and vents; and infiltration into the plant area of interest from outdoors or other plant areas.

The process of estimating the magnitude of natural ventilation, infiltration, and exfiltration rates is not as difficult as first impression may indicate. In the case where an excess of mechanically provided make-up air exists, the plant area will be under positive pressure relative to other locations, and the total make-up air rate will adequately serve as a slightly conservative value for Q°_T. If there is a shortage of make-up air, it is not unreasonable to assume a Q°_T equal to the total mechanical exhaust rate. Since the plant area would be under negative pressure relative to other areas, such an estimate would be completely appropriate when external wind speeds are low and/or there are not great temperature differences between the indoors and the outdoors.

Post-Recirculation Total Ventilation Rate (Q_T)--
The definition of Q_T is similar to that of Q°_T with the exception that post-recirculation conditions are to be evaluated. In consequence, Q_T will be equivalent to either:

1. The total rate of mechanically exhausted air volumes (including the volume rate to be recirculated); outward flows through open windows, doors, and vents; and outward flows due to exfiltration to the outdoors or to other plant areas.

2. The total rate of mechanically provided make-up air supplies (including the rate of incoming recirculated air); inward flows through open windows, doors, and vents; and infiltration into the plant area of interest from outdoors or other plant areas.

Estimation procedures for the quantity would be similar to those presented for $Q°_T$. The only exception would involve the need to address properly the flows associated with the recirculation system itself. If outward flows are to be used in the estimation procedure, the exhaust rate of air destined to be partially or fully recirculated must be included in the total. In the alternative case, the rate of the designated return air stream must be considered. Since some part of the recirculated air may be bypassed to the outdoors (either before or after an air cleaner), and since fresh make-up air can be mixed with recirculated air before the return air stream enters the work place, the outgoing and incoming rates of these streams may be different in some envisionable system designs.

Pre-Recirculation Mechanical Make-up Air Rate ($Q°_{MU}$)--
Most models contain an expression for determining the pre-recirculation mechanically provided make-up air rate ($Q°_{MU}$). This equation assumes the rate is equivalent to the total rate of mechanically exhausted air volumes in the plant area of interest.

The desired reformulation of the models requires that the current expressions for $Q°_{MU}$ not be used in this context when a perfect balance does not actually exist. Instead, $Q°_{MU}$ must be determined, when and if needed, from the equation:

$$Q°_{MU} = Q°_T - Q_T + Q_M$$

The parameters $Q°_T$ and Q_T in this expression are defined above. Q_M is a new parameter, however, and can be estimated from the expression:

$$Q_M = Q_R + (Q'_{MU} + Q_{MU2})$$

where:

Q_R is the volume rate of return air to enter the plant area; and

$(Q'_{MU} + Q_{MU2})$ is the post-recirculation total rate of fresh make-up air to be introduced to the plant area separately from the return air stream.

It is necessary to note that some part of the post-recirculation make-up air supply can be pre-mixed with recirculated air before this air enters the work place. The sum of Q'_{MU} and Q_{MU2} above does not include this other supply rate (called Q_{MU1} in Reference 1), but instead represents the total of all other such rates.

Recirculated and Return Air Rates (Q_D and Q_R)--
Equations presented in Reference 1 for the parameters Q_D and Q_R are correct
in all situations. No further discussions are therefore necessary.

Make-up Air Rates (Q_{MU1}, Q_{MU2}, and Q'_{MU})--
Pages 79 to 81 in Reference 1 define the parameters Q_{MU1}, Q_{MU2}, and Q'_{MU}.
Q_{MU1} is seen to be an amount of fresh make-up air which may be used to
dilute further recirculated air exiting an air cleaner before the combined
return air stream enters the working environment. Q_{MU2} is a rate of such
air which may enter the working environment separately from the recirculated
air volume. Finally, Q'_{MU} is essentially defined as some rate of make-up
air which is considered "fixed" in the analysis (i.e., a rate not considered
for change during the design process). With the assumption that a perfect
air balance will be desired in the plant area of interest after a recircu-
lation system is desired, it is evident that the sum of these three parameters
must equal the total exhaust rate to the external atmosphere.

Inspection of the derivation process for the various models leads to the
conclusion that these equations are also approximately correct for use if
a perfect air balance will not exist after a recirculation system is in-
stalled. In the case where there is actually to be an excess make-up air
capacity, they will ultimately provide slightly conservative results for
the overall analysis. In the alternative case, they are likely to provide
answers which can be considered correct within the limitations of the over-
all modeling concept. There is only a single cautionary note which must
be noted in the latter situation, and that involves the fact that Q_{MU1} should
not be assigned a positive value unless the model user actually intends
to pre-mix make-up air with recirculated air at the rate specified.

Return Air Concentration Prediction Equations

Each model in Reference 1 contains the elements of two equations which are
used sequentially or in combination to estimate the concentration(s) of con-
taminant(s) in the return air stream. The first of these (see page 110 of
Reference 1 for an example) provides concentrations at an in-duct point
immediately after the air cleaning equipment train. This point is designated
by the letter "D," and the concentrations there are designated by the symbol
C_D.

The second equation estimates concentrations (C_R) in the return air stream
which actually enters the work place. If make-up air from some source is
not pre-mixed with air exiting air cleaners, then C_R exactly equals C_D. In
the alternative case, C_R will usually be less than C_D for any particular
contaminant.

Application of these equations for the uncomplicated system design con-
figurations studied in this program did not reveal any deficiencies that
need or could be given detailed consideration. Indeed, the only obser-
vations were that there is a critical need for accurate air cleaner
efficiency data and that there is little need to estimate accurately a
value for the parameter k_R when the air cleaning equipment train is of high
efficiency.

Breathing Zone Concentraton Prediction Equation

The top of page 99 in Reference 1 and virtually all of the models presented in that document contain an expression called the breathing zone concentration prediction equation. The purpose of the equation is to predict post-recirculation concentrations and/or exposures at any specific work station or for any particular worker. The prediction is based upon a pre-recirculation evaluation of working conditions and a quantitative assessment of how return air streams will interact with the prevailing air flow pattern in the plant. In consequence, this equation is the most important, and also has the greatest associated uncertainty. To facilitate reference, it is presented in full as follows:

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

where:

C_{BZ} is the predicted concentration or exposure for post-recirculation conditions;

f is defined by Reference 1 to be the fraction of the work day that a worker spends "in a booth and/or in the flow field of a large volume local exhaust hood;"

Q_T° is the pre-recirculation total ventilation rate;

Q_T is the post-recirculation total ventilation rate;

C°_{BZG} is a pre-recirculation concentration or exposure in an "open" plant area;

C_{MU} is the contaminant concentration in pre-recirculation make-up air;

C°_{BZL} is a pre-recirculation concentration or exposure "in a booth and/or in the flow field of a large volume local exhaust hood;"

k_{BZ} is the volume fraction of air in the location or breathing zone of interest that originates in the return air stream; and

C_R is the concentration of contaminant in the return air stream at the point it enters the work place.

Local Exhaust System Influence Factor (f)--
Reference 1 explains that the exposure of a worker situated in a walk-in ventilated booth containing a contaminant-producing operation will not be significantly affected by changes in the total ventilation rate through the general area of the booth. Additionally, it extends this concept to all flow fields generated by large volume local exhaust systems when a worker is present in the field. Pages 90 to 95 of the document discuss the matter in great detail, and designates the fraction of the day that a worker may spend in the field by the parameter f.

During the course of this study, it was realized that the concept promoted by Reference 1 does not only apply to strong flow fields associated with exhaust systems. Indeed, it was surmised that the presence of a worker within the strong flow field of a make-up air supply system would experience the same phenomena as a worker in a booth. The situtation would be completely analogous in terms of the "shielding" of the worker from changes in total ventilation rates. It therefore follows that a system designer must account for the advantages or disadvantages associated with such flow fields, if particular work stations will not be directly affected by changes in total ventilation rates.

The Ratio of $Q°_T$ to Q_T--
The first term of the breathing zone equation contains the ratio of the pre-recirculation total ventilation rate ($Q°_T$) through the plant area of interest to the expected post-recirculation rate. Its presence suggests that exposures at any specific location in an "open" plant area (i.e., locations not within strong flow fields) will, with some qualifications, be directly proportional to the magnitude of the ratio.

A re-evaluation of Reference 1's supporting evidence for this concept, as presented on pages 104 to 106 of that document, as well as observations made during the assessment of Hard Chrome Plating Plant #2, suggested that some care must be taken in interpreting model results when the total ventilation rate will be significantly modified. The problem stems from an assumption that the air velocity passing every point in a plant area will vary linearly with changes in the total ventilation rate.

Further thought on the subject led to the finding that this assumption would be completely valid when the plant has an excellent air distribution system, and plans to modify the total ventilation rate by proportionately increasing or decreasing the intensity of all air inlet and/or outlet streams. In virtually every other case, the variation of the ventilation rate would not necessarily have an equivalent effect at every point.

The finding is significant because it better defines the limits of the equation's usefulness. Its basic ramification is that the results provided by the equation must be interpreted with due regard for the expected extent of deviation from the pre-recirculation air flow pattern in the plant area. The pertinent basis for the equation can be considered correct when:
1) all flows in a good distribution system are proportionately modified to affect the ventilation rate change; 2) a specific worker's exposure is of interest and that worker frequently travels throughout the affected plant area (and thereby experiences the averaged change in the working environment); or 3) a designer actually wishes to investigate the average effect of a ventilation rate change upon average worker exposures. Alternatively, when the effect of recirculation upon a specific work location is being investigated, the designer must note that the accuracy of predicted results will reflect the extent to which the ventilation rate (i.e., the dilutory effect of the rate) actually changes at that location. Such an assessment will require professional judgment and an added degree of conservatism during model application.

Contaminant Concentration in Make-up Air (C_{MU})--
The parameter C_{MU} in Reference 1's equations symbolizes the concentration(s) of contaminant(s) in make-up air supplied to the plant area of interest. Pages 103 and 104 note the assumption that such make-up air originates outdoors. Additionally, they indicate the assumption that such concentrations are constant and do not increase or decrease due to the installation of a recirculation system.

When a previously uncleaned exhaust stream is passed through an air cleaning equipment train and returned to the work place, a potential exists for an improvement in external ambient air quality. Reference 1 acknowledges this potential, but finds that it is inordinately difficult to quantify. Thus, to simplify matters, it chooses to assume that the contaminant level(s) in fresh air will not decrease. For most plants, the assumption adds a minor element of conservatism to the analysis and must be considered quite reasonable.

The situation in one of the dry cleaning establishments, however, indicated that it is not always prudent to assume that make-up air enters a work area with recirculation directly from outdoors, or that it be assumed that contaminant levels will always decrease or remain constant in such supplies. In consequence, the case study report concluded that the single parameter C_{MU} in the breathing zone equation be separated into two similar parameters: one which represents concentrations under pre-recirculation conditions and one which represents expected post-recirculation conditions. The revised equation would then be:

$$C_{BZ} = (1 - f) \frac{Q^{\circ}_T}{Q_T} (C^{\circ}_{BZG} - C_{MU1}) + f(C^{\circ}_{BZL} - C_{MU1})$$

$$+ k_{BZ}C_R + (1 - k_{BZ})C_{MU2}$$

where:

C_{MU1} is the concentration under pre-recirculation conditions; and

C_{MU2} is for post-recirculation conditions.

Return Air Contribution Factor (k_{BZ})--
Pages 85 to 90 of Reference 1 discuss the meaning of the parameter k_{BZ}, the usefulness of the concept it represents, and the methods by which a value can be measured or estimated. The measurement method entails the performance of a tracer gas study and requires further discussion. The more qualitative estimation techniques are based upon a deductive reasoning process and are seen to be logically correct.

In the case study for the spring grinding plant, it was observed that tracer gas study results were sometimes inconsistent with survey findings. The reason presented for this was the hypothesis that the metallic dust was settling out upon exposed room surface areas while the tracer gas was continuing its journey to distant sampling points. Thus, it was suggested that this aspect of such a study be considered when the dispersal of dense particulate matter is characterized a gaseous simulant. Although the results of the study would be appropriate for use in subsequent analyses, they could be substantially conservative.

Finally, it is appropriate to note that the results of tracer gas studies performed on operating recirculation systems tend to be conservative in nature. Since some amount of the tracer gas will be recirculated through the air cleaning equipment train, an accumulation of tracer gas may occur and concentrations may never attain steady-state levels. This potential problem is not pertinent when the tracer gas study is performed in a plant area under pre-recirculation conditions.

Errors in Model Equations--
There are two errors in Appendix B of Reference 1 which deserve comment. On page 139 in Figure B6, the equation for Q_T at the bottom of the page erroneously contains the parameter Q_{MU1}. This parameter should be deleted. Similarly, it should be deleted from the Q_T equation presented on page 140 in Figure B7.

Failure Analysis Equations

None of the case studies in this program provided the opportunity to test the validity of the failure analysis equations presented in Chapter 7 and Appendix F of Reference 1. Nevertheless, the program provided an opportunity to reconsider the derivation of these equations and to check whether they have been correctly presented. This latter effort led to the finding that many of the expressions in Appendix F were somehow published with gross typographical errors. In the following, therefore, corrected equations and other statements are presented on a page-by-page basis.

Page 180:   The user should note that the pre-failure breathing zone concentration throughout this appendix is represented by the symbol C_{BZ}. In Chapter 7, this concentration is designated C°_{BZ}.

Page 181:   The T_{C1} equation at the top of the page should be:

$$T_{C1} = t_o \ln\left(\frac{C^{FS}_{BZ} - C_{BZ}}{C^{FS}_{BZ} - C_{ceiling}}\right)$$

Page 181:   The TWA (t) equation should be:

$$TWA(t) = \frac{t}{8} C^{FS}_{BZ} + \frac{t_o}{8} (C^{FS}_{BZ} - C_{BZ})\left[1 - e^{-(t/t_o)}\right]$$

$$+ \begin{cases} \dfrac{8-t}{8} C_{BZ} & \text{for } t \le 8 \text{ hours} \\ 0 & \text{for } t > 8 \text{ hours} \end{cases}$$

Page 181:   The expression for T* should not include the term "- 1."

Page 181:   The table at the very bottom of the page should read:

T*	-1	0	0.5	1	1.5	2	3	4
(T_{C2}/t_o)	0	0.57	0.91	1.28	1.69	2.12	3.02	4

Other values for the table can be generated by trial and error from the expression:

$$T^* = \frac{T_{C2}}{t_o} - e^{-(T_{C2}/t_o)}$$

Page 182:   Note that the symbol C_D is used here and on following pages to denote the tracer gas concentration in the return air stream entering the plant. Throughout the rest of Reference 1, a concentration at such a point would be designated by C_R.

Page 184:   The list of assumed parameter values should read as follows:

$$TLV = 1000 \text{ ppm}$$

$$C_{ceiling} = 1500 \text{ ppm}$$

$$C_{BZ} = 300 \text{ ppm}$$

$$C_R^F = 5000 \text{ ppm}$$

Page 184:   The T_{C1} equation is confusing and contains a typographical error. For clarification, note that:

$$C_{BZ}^{FS} \cong C_{BZ} + k_{BZ}C_R^F$$

When this expression is inserted into the T_{C1} equation given above, then:

$$T_{C1} = t_o \ln \left[\frac{C_{BZ} + k_{BZ}C_R^F - C_{BZ}}{C_{BZ} + k_{BZ}C_R^F - C_{ceiling}} \right]$$

$$= 0.45 \ln \left[\frac{0.67 \times 5000}{300 + (0.67 \times 5000) - 1500)} \right] = 0.2 \text{ hours}$$

Finally, it is necessary to note that the failure analysis methodology inherently assumes that tracer gas concentrations in the work place will exhibit an exponential rise until some sort of steady-state condition is achieved. During the first few seconds or minutes of a tracer gas study, however, concentrations may increase almost linearly with time, and the equation for t_o on page 183 can give an answer of infinity or some other ridiculously high value.

31

Although such an answer might be correct in some cases (which should be readily identifiable), the answer will more often than not indicate that the measurement technique is not sufficiently accurate or that the concentration measurements used in the equation were both associated with times too close to the initiation of tracer gas release. The problem can be avoided by the development of a tracer gas concentration versus time curve for various sampling locations, and the selection of data sets (for use in equations) which obviously lie in curving sections of the resulting plots.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

It is not feasible to summarize all the conclusions which evolved from the findings of the individual case studies since most cannot be properly interpreted out of context. It is appropriate, however, to list generalized conclusions which pertain to the overall subject area. These conclusions are:

1. The overall approach of Reference 1 provides the _framework_ for a recirculation system design process which considers most, if not all, issues of importance. An experienced design team working within this framework should be capable of fully evaluating the feasibility of recirculation in any plant and of formulating and implementing appropriate system design concepts.

2. The overall Reference 1 approach is aimed specifically towards the health and safety issues pertaining to recirculation. Additionally, it presumes the availability of certain data and information necessary to the design process. Industry may experience difficulties in the implementation of recirculation systems where appropriate data or equipment are lacking, and/or where there are practical engineering-type problems to be addressed.

3. This study has demonstrated the usefulness and the validity of the basic concepts inherent in Reference 1's analytical design procedures. Additionally, it has led to a better understanding of the limitations of those procedures, and has attempted to resolve many of them.

4. A recirculating exhaust system absolutely and unequivocally requires frequent maintenance and inspection. Recirculation should be considered as an energy saving measure only by plants willing to provide the resources and manpower for such efforts.

5. There is a need for better information dealing with the actual efficiency of air cleaning devices installed and operating under field use conditions. Additionally, there is a need for a better understanding of currently available system surveillance methodologies and of their specific limitations and reliabilities.

RECOMMENDATIONS

Basic recommendations which evolved from this study include:

1. NIOSH should consider the development of recirculation system design criteria specifically directed towards common industrial operations. Such criteria should be extracted from Reference 1, but should provide more detail and useful information than was possible within the context of the generalized approach presented by that document.

2. The criteria developed above, along with information generated during current and future NIOSH-sponsored studies of air cleaning equipment and system surveillance methods, should form the basis for a series of individual design guides for common industrial operations. These guides should emphasize the need for maintenance and inspection, should minimally list and discuss the possible failure modes of systems, and should specify recommended system design and surveillance strategies.

3. Future NIOSH-sponsored engineering control technology assessments should be expanded in scope to provide additional useful data for recirculation system designers. Topics of interest include process emission profiles, long-term variability of exposures in the working environment, air cleaner efficiencies, and monitoring system evaluations among others.

4. The margin of safety associated with a recirculation system is a direct function of the effectiveness of pre-existing engineering controls. In consequence, NIOSH should consider research studies which expand (rather than record) the state-of-the-art of engineering control technology for common industrial operations.

APPENDICES

The individual case study reports follow in a series of attached appendices. Each is essentially a mini-report with its own table of contents.

As noted previously, these evaluations are intended to supplement, expand upon, and discuss the recommendations of Reference 1. Hence, it is necessary for a reader to be familiar with the contents of Reference 1 to gain a full appreciation of the findings of these case studies.

APPENDIX A. SPRING GRINDING

CONTENTS

FIGURES

TABLES

SPRING GRINDING

INTRODUCTION

The larger varieties of coil springs, once formed, generally require
grinding to flatten and square their ends. The process is a dry one,
and can be conducted on a batch or continuous basis, depending upon the
amount of grinding necessary and the nature of the specific machinery
utilized.

The plant of interest to this case study currently manufactures and grinds
springs in a large plant area housing numerous types of machinery and pro-
cesses. Each grinding machine in the plant is outfitted with one or more
local exhaust hoods which are ducted to one of eight unit dust collectors
using cotton bags. These units are located within the plant, near the
group of grinding machines they are attached to, and discharge cleaned ex-
haust air directly into the working environment.

The purpose of this case study is to describe the attributes of one of these
recirculation systems in the context of the overall objective of this study.
This is accomplished by an ordered description of the plant and processes
of interest followed by a review and evaluation of the recommendations of
Reference 1.

PLANT AND PROCESS DESCRIPTION

Plant Description

The plant is essentially one large open area with dimensions of 146 m by 137 m
by 5.6 m (480 ft/450 ft/18.5 ft). Construction is concrete block, externally
faced with red brick. Only a half dozen or so areas have windows, and these
consist of glass emergency exit doors with peripherally located panes of
glass.

The shipping and receiving area has both internal and external sets of garage
doors in an airlock configuration. The plant engineer indicated that employees
appreciate the need to keep the inner set closed to maintain negative pres-
sure in a nearby process area.

Process Description

The plant manufactures four different types of spring washers and four types
of springs (compression, extension, torsion, and constant force). Most of
the equipment utilized to manufacture these items do not generate airborne
contaminants and need not be described. Processes which do generate contamin-
ants involve grinding, abrasive blasting, and some operations to be found in
a somewhat isolated heat-treat or hardening area.

Grinding of metals is accomplished in approximately eight locations. Four of these contain long tables with rows of small, locally exhausted bench grinders used for occasional finishing operations. The remainder contain one or more larger machines for the simultaneous squaring and flattening of both ends of coil (compression) springs. These latter units, one of which was closely studied in this investigation, contain a horizontal and circular metal table in which arrays of springs are supported in openings. The table rotates the springs into a chamber containing horizontal grinding wheels; one which rotates above the plane of the table, and another which rotates below it. The heights of the grinding wheels are then adjusted until sufficient metal has been removed from the springs.

During the first several rotations of the table, coarse adjustments in the grinding wheel positions result in the rapid removal of metal. As the ultimately desired spring length is approached, however, the operator makes smaller and more careful adjustments alternated with length measurements of sample springs. When the desired length is achieved, the grinding machine is stopped, the finished springs are unloaded, and a new batch inserted. The entire cycle requires approximately 25 minutes, with grinding involving about 12 to 15 of these.

Located in the heat-treat area, the abrasive blasting operation is comprised of an enclosed and locally exhausted rotary blasting table. Other operations in this area were not cataloged, but can be considered typical of those commonly utilized for the hardening of metals.

Ventilation System

Local Exhaust Systems--
The heat-treat area and its immediate vicinity contain approximately 40 sites from which air is locally exhausted. Figures derived from the original plans for the area indicate that 27.1 m^3/s (57,500 cfm) of air are extracted and that about 25.5 m^3/s (54,000 cfm) are discharged outdoors. The plant engineer maintains that most of this air originates in other plant areas and that the heat-treat area was purposely designed to be under negative pressure relative to other plant areas.

The 1.6 m^3/s (3,500 cfm), which is the difference between the air extracted and that discharged outdoors, is attributable to the exhaust system on the rotary blasting table. The exhaust from this unit is directed to a nearby bag filter which cleans the air and returns it to the immediate work area. The system is rarely used and was never operated while researchers were present at the plant.

The exhaust from each bank of bench grinders is also directed to a nearby bag filter which cleans and returns the air to the immediate work area. It was observed these units were only occasionally utilized for very light grinding or buffing of small parts, primarily to remove burrs and smooth rough edges.

The larger grinders used to flatten the ends of coil springs had enclosed grinding areas fitted with four exhaust ducts. Figure A-1 presents a sketch of their arrangement on a representative unit. The exhaust air from each of these units was, as above, directed to bag filters and then returned to the immediate work area. It was one of these units, which was the largest in the plant and had its own separate bag filter, that was closely studied in this investigation.

Figure A-2 provides a side view of the particular grinding machine and bag filter unit of interest. Figure A-3 is a top view of the plant area in which they reside. To simplify the illustrations, the four exhaust ducts from the grinding machine to the air cleaner are not shown. Also not shown are the various air diffuser inlets, except for one, which were placed in a 9.1 m (30 ft) grid pattern throughout the area.

Make-up Air Systems--
The plant has 15 air-conditioning units which also incorporate 50 kW heaters. These are designed to provide approximately 118 m^3/s (250,000 cfm) of make-up air and are constantly in operation. Additionally, there are two "fresh-air make-up heaters" which provide a combined total of 12.5 m^3/s (26,500 cfm) to 24.1 m^3/s (51,000 cfm) of air to the periphery of the hardening area, presumably depending upon which of two or more settings are utilized. The total amount of make-up air entering the plant therefore ranges from 129.8 m^3/s (275,000 cfm) to 141.6 m^3/s (300,000 cfm).

The air distribution system in the plant was truly impressive. A rough count from plans indicated approximately 290 diffusers or registers. Most evident among these were 180 ceiling diffusers placed in a grid pattern and spaced about 9.1 m (30 ft) apart. In the plant area of interest to this study, these units were sized for 0.85 to 0.94 m^3/s (1,800 cfm to 2,000 cfm). Capacities in other areas ranged down to a few hundred cfm, with obvious consideration having been given to the nature of operations in each area.

Relief Vents--
These figures indicated that at least 106.1 m^3/s (225,000 cfm) more air was entering the plant than was leaving through local exhaust systems. Indeed, the plant was generally under positive pressure relative to the outdoors, and had a mechanically induced air change rate ranging from 4.1 to 4.5 changes per hour.

A closer look at plant plans revealed there were 32 relief vents situated at roof level, and that each of these was programmed to open when specified pressures occurred internally. Their combined capacity of approximately 127.4 m^3/s (270,000 cfm) additionally suggested that most must be open at any given time.

Air Cleaners--
As previously reported, the plant utilized bag filters (fabric arrestors) for air cleaning purposes. The particular unit of interest incorporated 27 bags with a total cloth area of 139.3 m^2 (1,500 ft^2). Complete specifications for the unit are listed in Table A-1; they indicate that the bags are automatically shaken whenever the grinding machine is completely deactivated.
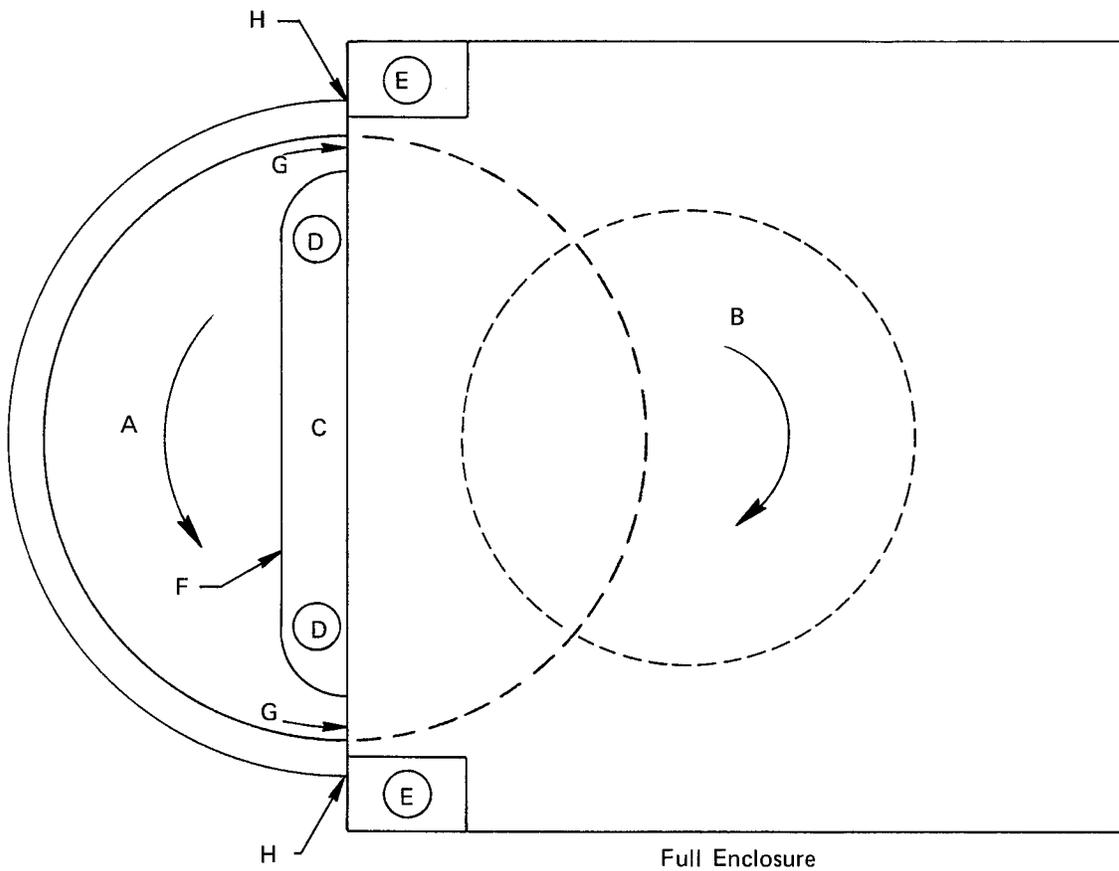
Full Enclosure

Legend:

A.   Rotating table with springs vertically supported in open slots.

B.   Grinding wheels above and below spring ends.

C.   Custom formed enclosure extension.

D.   Exhaust ports connected to 11.4 cm OD (4.5″) flexible ducts.

E.   Exhaust ports connected to 17.8 cm OD (7″) exhaust ducts.

F.   Slight opening under enclosure extension.

G.   Small openings partially covered with heavy fabric.

H.   Small openings under table.
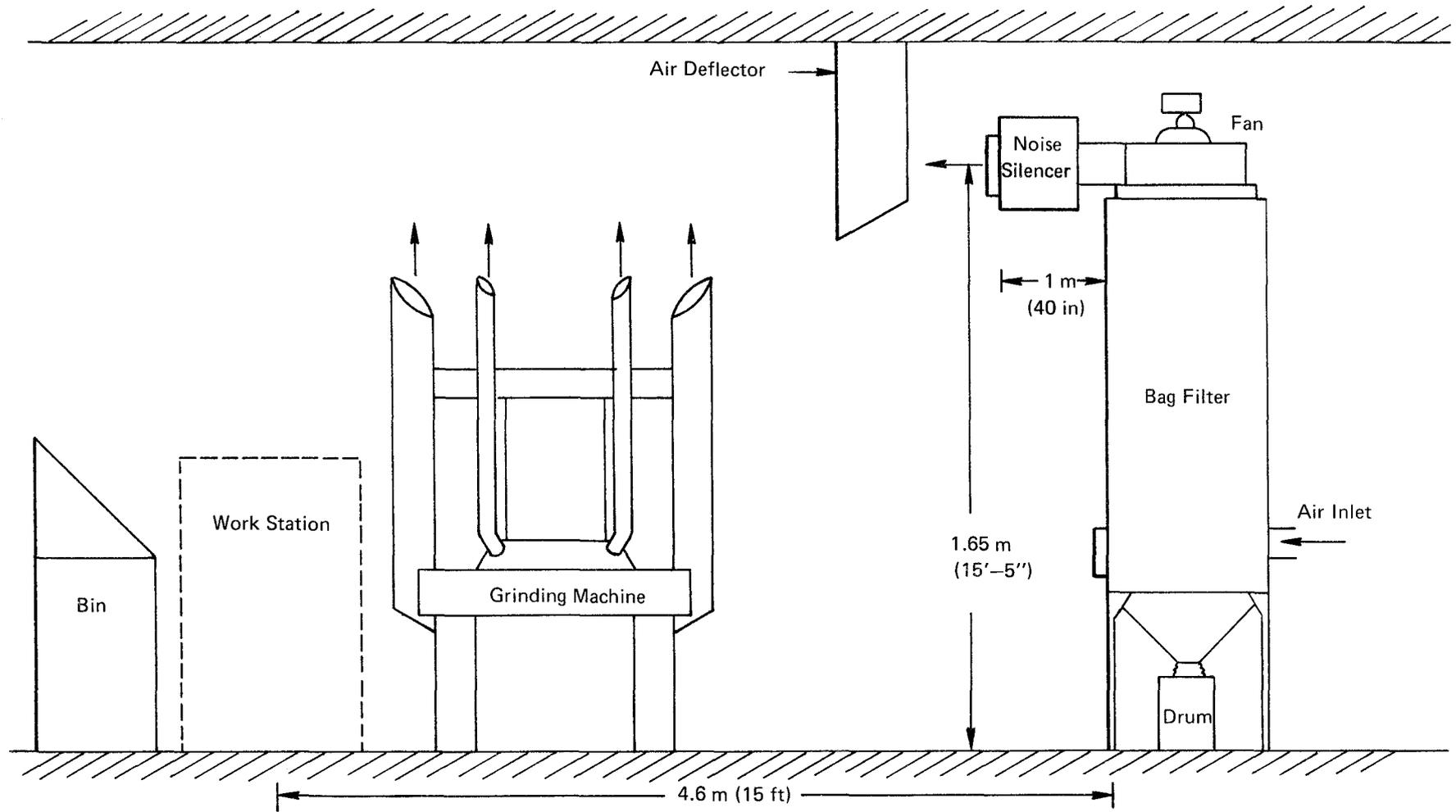
Figure A—1. Top view of spring grinding machine.

Air Deflector

Fan

Noise Silencer

Bag Filter

Air Inlet

1 m (40 in)

1.65 m (15'–5")

Work Station

Bin

Grinding Machine

Drum

4.6 m (15 ft)

Figure A–2.   Side view of recirculation system.

Figure A–3. Top view of plant area with recirculation.

41

This frequent cleaning of the bags raises an issue for which there is no clearcut answer. By cleaning the bags at least four times a day, the plant is ensuring that blinding does not occur, and that there is absolutely no possibility of overloading. Additionally, it is ensuring that each bag never accumulates more than roughly 200 gms (0.44 lbs) of dust which can be released in the event of a bag break.

These advantages, however, are being countered by the fact that the efficiency of a bag filter unit is usually lower immediately after bags are cleaned, and increases as dust accumulates. Thus, time-weighted average efficiency of the unit might be enhanced by fewer cleaning cycles.

For system surveillance, the plant relies upon the visual effects of bag breakage to inform employees that the air cleaner requires attention. In consequence, employees simply deactivate the equipment when a "puff" of dust is seen to exit a bag filter, or if dust suddenly begins to settle out un-usually on exposed room surface areas. Given the circumstances surrounding the operations of interest, one must conclude that the plant's decision is not completely without merit when non-toxic materials are processed. For any other type of contaminant, however, one must question the wisdom of such a procedure. Although bag breaks are rare, they have occurred in this plant.

EVALUATION METHODS

Sampling Strategy

Several types of measurements were attempted to evaluate the performance specifications of the recirculation system of interest. Included among these were:

- Velocity and flow volume measurements within inlet and outlet ducts of the bag filter;
- Total particulate measurements in inlet and outlet ducts of the bag filter to determine overall filter efficiency;
- Particulate size distributions within the inlet and outlet ducts to evaluate the fractional size efficiency of the bag filter;
- Tracer gas injection into the recirculation system's inlet accompanied by work area and breathing zone mapping of gas concentrations to characterize air flow patterns; and
- Measurement of respirable and total particulate concentrations in and around work stations.

Sampling and Analytical Procedures

Flow Measures--
The linear velocity through the inlet duct of the bag filter was character-ized through the use of a standard pitot tube coupled to an inclined mano-meter. The location for measurements complied with EPA Method 1 as des-cribed in Reference 2. Similarly, the 8-point velocity traverse conducted was in accordance with the requirements of EPA Method 2 as described in Reference 3.

Because of the configuration of the bag filter discharge, and the presence
of a noise silencer with baffles extended inside the duct, no location
allowed use of the pitot tube/manometer combination for determining the
velocity through the bag filter outlet. In consequence, an Alnor velometer
was utilized to crudely confirm an estimate based upon the inlet flow volume
rate and a proportioning of effective cross-sectional duct diameters.

Total Particulate Measurements--
The total particulate loadings within the inlet and outlet ducts of the dust
collector were determined by an extractive sampling technique derived from
EPA Method 5. Figure A-4 illustrates the collection train which was sequen-
tially comprised of a button-hook nozzle, a 30.5 cm (12 in) probe extender,
a stainless steel filter holder, a Drierite cannister, a leak-free pump, a
dry gas meter, and an orifice meter.

The only exceptions from established procedures involved the selection of
sites at which samples were extracted. Because of the short cycle time
between batches of springs, and an obviously extreme variation in inlet
loadings with time, it was not possible to conduct a full 8-point traverse
under uniform dust loading conditions. It was therefore decided that a
single point located at the midpoint of the duct would be reviewed for all
total particulate measurements within the inlet duct.

Particulate sampling on the outlet duct was conducted similarly at a point
located midway through one quadrant of the annulus. As previously noted,
it was not possible to even consider a traverse at this location because
of internal baffles for noise suppression. While it is realized that these
deviations from established procedures produce a degree of uncertainty
around recorded results, it is believed that the data do reflect actual pro-
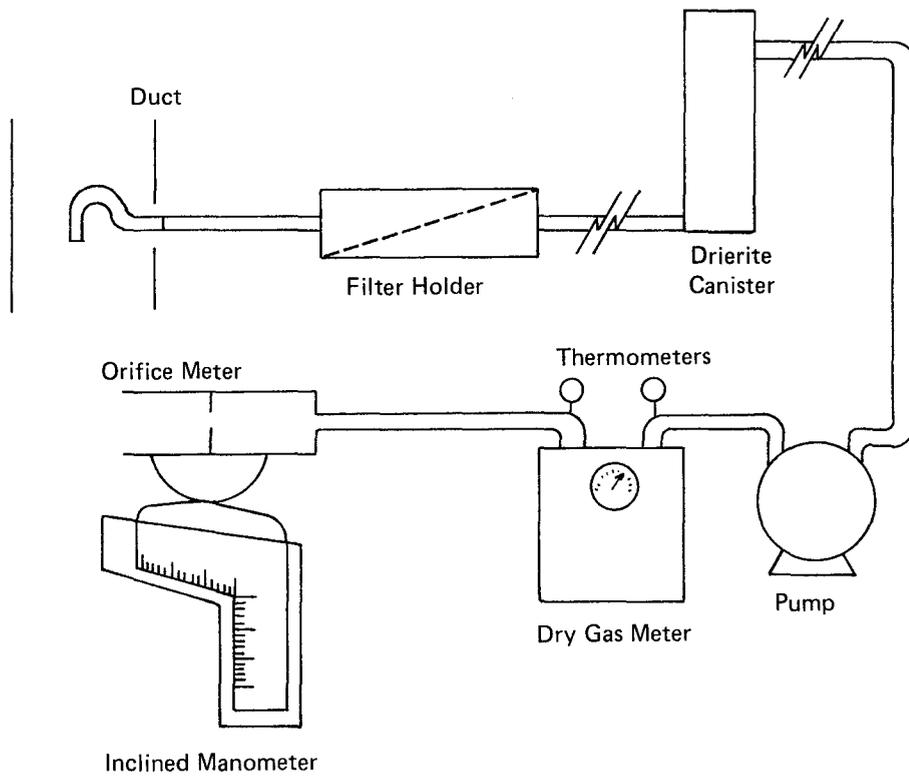cess conditions, and are of adequate accuracy for the purposes of this in-
vestigation.

Particle Size Distribution Measurements--
Size distribution samples were obtained from both the inlet and outlet ducts
of the air recirculation system using an Andersen 2000 cascade impactor and
established sampling and analysis procedures. With the exception that the
cascade impactor was substituted into the collection system in place of the
filter holder, the sampling equipment used for these determinations was iden-
tical to the system previously described and shown in Figure A-4.

Tracer Gas Studies--
To characterize the distribution of recirculated air throughout the work
place, a tracer gas was added to the inlet duct of the dust collector.
After passing through the entire length of this assembly, the gas discharged
back into the work area along with the recirculated air supply. A direct
reading h-Nu photoionization detector then allowed measurements of the re-
sulting tracer gas concentrations at various selected points.

Although several species were considered as appropriate for use as a tracer
gas, trichloroethylene was the compound selected. This decision was based
upon the following criteria:

Duct

Filter Holder

Drierite Canister

Orifice Meter

Thermometers

Dry Gas Meter

Pump

Inclined Manometer

FIGURE A–4   TOTAL PARTICULATE COLLECTION SYSTEM

- Trichloroethylene is not normally encountered around processes of this nature;
- The selected species has a comparatively high permissible exposure limit (100 ppm);
- Trichloroethylene could be readily and accurately detected on an available photoionization detector;
- The compound can be easily volatilized and added as a vapor to the recirculation system;
- The specie is non-flammable.

The actual method of adding the tracer gas to the recirculation system involved pumping a known volume rate of solvent from a reservoir into a heating coil. This coil consisted of approximately 6 meters (20 feet) of 6 mm (0.25 inch) copper tubing which was wrapped in heating tapes and later encased in fiberglass and aluminum insulation. To insure that the trichloroethylene was vaporized within the coil, the skin temperature of the copper tubing was preheated and maintained at 125°C (250°F). A diagram of the entire injection system is shown in Figure A-5.

In operation, the heating coil was preheated for approximately 10 to 15 minutes before 16 mls per minute of trichloroethylene were pumped into the coil and vaporized. After about 10 to 15 more minutes, the injection system reached equilibrium and the exiting concentration of tracer gas was recorded with the photoionization detector immediately downstream of the noise silencer. The detector was then carried around to seven stations within the work area and further readings were recorded. After one full swing about the processing zone, the detector was returned to the exit of the noise silencer and the entire cycle was repeated.

General Work Area and Personnel Samples--
Two methods were utilized to determine total and respirable dust concentrations in worker breathing zones and throughout the general work area. The first involved personnel samplers consisting of a 37-mm filter cassette, a 10-mm cyclone, and a calibrated battery powered sampling pump. It is the technique commonly used for such dust measurements, involves gravimetric evaluations in the laboratory, and is recommended by NIOSH in Reference 4 (method #29).

The second technique involved use of a GCA Model RDM-101 direct reading dust monitor. This instrument uses a low-energy beta-radiation source and a Geiger detector to not only measure the mass of contaminant collected during a known period of time, but to compute and numerically display results. It is minimally accurate to plus or minus 25 percent for the minimum concentration of given measurement ranges, and more accurate at higher concentrations.

RESULTS AND DISCUSSION

Data Summary

A series of tables at the end of this Appendix provides the detailed results of sampling activities. Table A-2 presents data for the inlet duct velocity
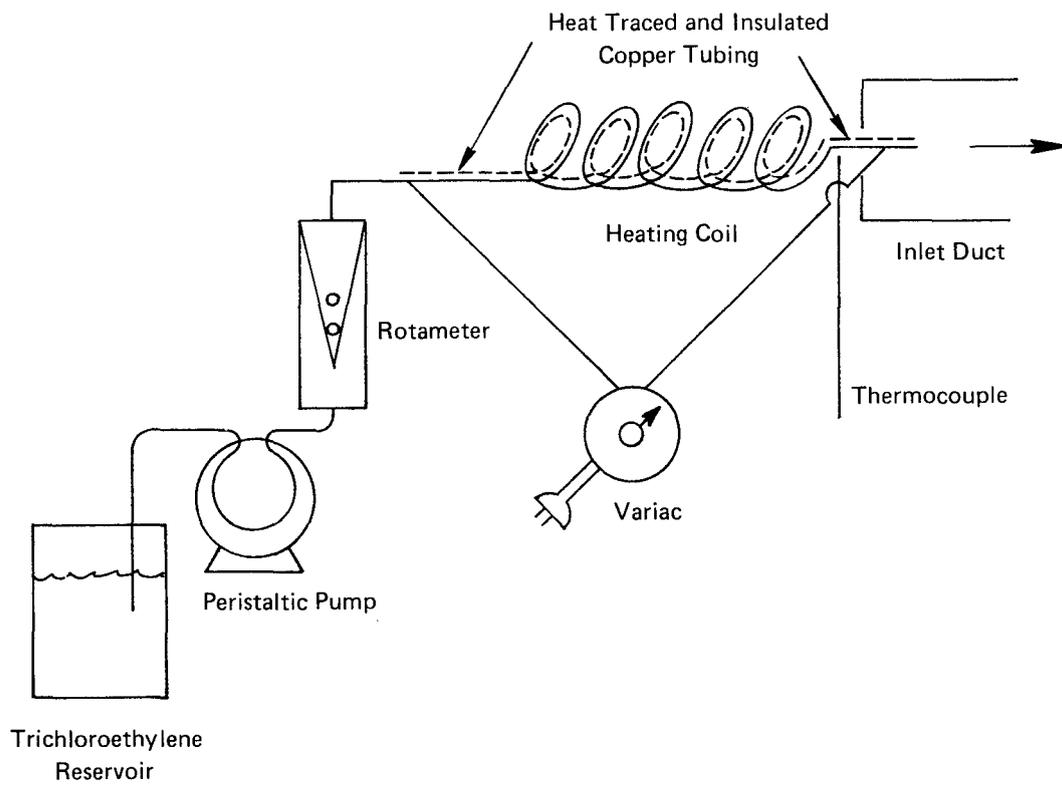
Figure A—5. Tracer gas injection system.

determination; Table A-3 for the total particulate measurements; Tables A-4 to A-7 inclusive for the particle size distribution analyses; and Table A-8 for general area concentrations determined with the GCA dust monitoring device.

Flow Estimates

From the velocity traverse data, a volumetric flow of 1.54 m^3/s (3,261 cfm) through the dust collector assembly can be computed. The average velocity in the inlet duct was 13.5 m/s (2,657 fpm), and as such, is well below the design velocity range of 17.8 to 20.3 m/s (3,500 to 4,000 fpm) recommended in Reference 5 for grinding dust. It is not surprising, therefore, that a layer of settled dust was observed in the ductwork preceding the inlet sampling location.

Inlet Duct Concentrations

Obtaining a particle size distribution is always a complex and difficult task. Not only must one literally hope that a measurable sample weight has been collected in each size range, but must simultaneously beware of collecting too much in any given range.

The results of inlet duct sample #1 with the Andersen impactor device indicate a degree of overloading on the first few plates, i.e., it is suspected that plates numbered 1 and 2 have some material which should have stayed on plate 0. Nevertheless, the sample suggests an average inlet dust concentration of 739.3 mg/m^3 while two entire batches of springs were processed.

The results for inlet duct sample #2 similarly indicate a slight degree of overloading, as evidenced by comparison of plate 0 and plate 1 results. During the first half of the time period that a batch of springs was being ground, however, it is quite clear that the average concentration was 1109.0 mg/m^3.

Total particulate samples taken during one entire cycle of grinding indicated a loading of 666.0 mg/m^3, a result which compares favorably with results from the first Andersen sample. A total particulate sample for the last third of the time period during which one batch was processed indicated a loading of 430 mg/m^3.

Overall, it can be deduced that the total dust concentration near the beginning of a batch is in excess of 1100 mg/m^3, near the end drops to 400 mg/m^3 or so, and averages on the order of 740 mg/m^3 while grinding commences. This latter result is roughly the average of the four concentrations reported above, and nearly equals the result of inlet duct sample #1.

Since 15-minute grinding cycles were spaced apart by roughly ten-minute periods when the rotating table was reloaded with springs, the 740 mg/m^3 inlet loading is not a true time-weighted-average. Instead, it reflects a worst case concentration for the particular set of process conditions studied. An assumption of no contaminant generation during 10 of every 25 minute period suggests that the time-weighted-average is on the order of 444 mg/m^3 (60% of 740 mg/m^3).

Outlet Duct Concentrations

Outlet duct sample #1 from an Andersen unit indicated a total dust loading of 12.4 mg/m^3. It was taken simultaneously with inlet duct sample #1 and also involves the grinding of two batches of springs.

The results for this sample are somewhat questionable for a variety of reasons. Chief among these is the suspicion that the 4.8 milligrams collected on plate 0 of the Andersen device resulted from a chunk of caked dust from the noise silencer annulus. It is rather inconceivable that such a result would otherwise occur when no contaminant was found on plates 1 and 2. Similarly, it is expected that the negative weight on plate 1 represents a piece of filter material transferred to plate 3 and others during handling, and that negative weights on plates 4 and 5 exist in results for plate 6 and below. If the data is adjusted to account for these anomalies, it is found that the normalized average concentration in the outlet duct was about 2.6 mg/m^3, a value which agrees with the 2.4 mg/m^3 measured in total particulate outlet sample #1.

Assuming the 2.4 mg/m^3 concentration is correct, one can simply compute that the time-weighted-average level is on the order of 1.44 mg/m^3 (60% of 2.4 mg/m^3).

Overall Air Cleaner Efficiency

The inlet and outlet dust loadings suggest a probable overall air cleaner efficiency of 99.68%. This result is completely in line with what is reported for such units in the literature.

Fractional Air Cleaner Efficiency

Anomalies in particle size distribution data obtained for the outlet duct prevent conclusions from being drawn regarding the fractional size efficiency of the unit dust collector.

General Area and Breathing Zone Conditions

Results of the gravimetric evaluation for the samples obtained with personnel samplers were considered to be of dubious value quantitatively and are not presented. All but one sample analyzed provided zero or slightly negative weight gains, although sampling times ranged up to 3 hours and 21 minutes. The reason for this complete failure of the sampling technique appears to have been unexpectedly low ambient dust levels in the area studied.

Results obtained with the GCA unit indicate respirable dust concentrations were consistently less than 0.1 mg/m^3 at all locations somewhat distant from the grinding machine. Additionally, they demonstrate that the total dust concentrations in the breathing zone of interest (area D on Figure A-3) were on the order of a milligram or two per cubic meter, and 0.2 mg/m^3 or less at all other sample locations. The former observation is collaborated by the single measurable sample obtained by the other method which indicated a total dust concentration of 3 mg/m^3 in the general area of the grinding machine operator. The sampling pump for this sample was only turned on while grinding was taking place, and was activated for a total time period of 185 minutes.

These data explain the problems experienced with the more common sampling method. At an air intake rate of 1.7 1/min, it would be necessary to sample 9.8 hours to collect a tenth of a milligram of respirable dust at a concentration of 0.1 mg/m^3.

Tracer Gas Study Results

The tracer gas study was an attempt at demonstrating a feasible methodology for evaluating the physical volume fraction of air in a breathing zone which originates in a return air stream. Results in Figure A-6 indicate that the configuration studied provided roughly 30 to 40% of the air breathed by the grinding machine operator, and 20% to 50% of the air volume in other nearby locations.

These results are not as expected from review of the dust concentrations found in areas other than the breathing zone of interest. If indeed 20 to 50 percent of the air volume at the various sampling points originated in the return air stream, then it would be expected that total dust levels measured would minimally be in the range 0.5 to 1.2 mg/m^3, and not the 0.2 mg/m^3 and less which was found. Hence, it appears that caution is necessary when attempting to describe the airborne path of particulate matter by observing the behavior of a tracer gas. Gravitational effects may cause significant settling out of dust if the distances involved are significant.

For the breathing zone of interest, which is close to and in line with the return air source, the data are somewhat more consistent. Here, one would expect total dust breathing zone concentrations due to the return air stream on the order of 0.72 to 0.96 mg/m^3, and would further expect higher actual concentrations due to contaminant contributions from the generation source. Thus, the previous time-weighted-average concentration estimate of 1 to 2 mg/m^3 is justifiable.

Summary of Results

Based upon the preceding analysis, the following characteristics of the recirculation system are judged to be appropriate for the observed operating conditions.

Inlet duct concentration: ∿740 mg/m^3 during grinding.
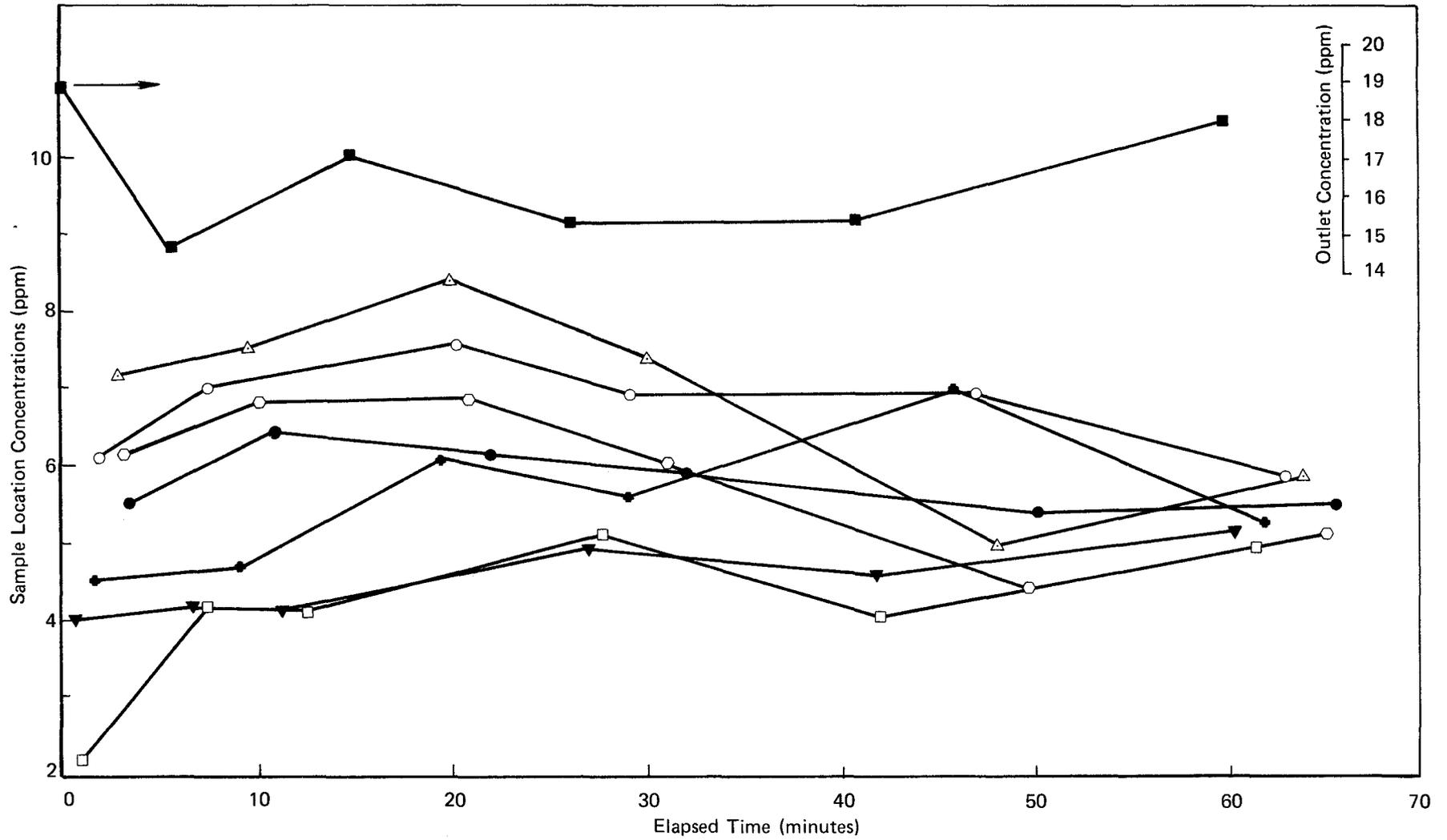
Inlet duct concentration TWA: ∿444 mg/m^3.

Outlet duct concentration: ∿2.4 mg/m^3 during grinding.

Outlet duct concentration TWA: ∿1.44 mg/m^3

Overall air cleaner efficiency: ∿99.68%

Respirable dust in breathing zone: ≤0.1 mg/m^3

Note: Time zero is actually 15 minutes after initiation of tracer gas injection.

Figure A—6. Tracer gas study results.

Area Designations*

● D	○ H
○ E	▼ J
△ F	◆ K
□ G	■ Return Air

*See Figure 3.

50

Total dust in breathing zone while grinding: ~ 3 mg/m^3

Total dust in breathing zone TWA: 1.0 - 2.0 mg/m^3

Respirable dust in general areas: ≤ 0.1 mg/m^3

Total dust in general areas: ≤ 0.2 mg/m^3

VALIDATION OF RECIRCULATION APPROACH

Introduction

Preceding sections of this chapter have described most characteristics of
the recirculation system investigated. The information provided does not
address all issues which the designer of a similar system for dry grinding
operations must be concerned with, however. Nor does it address how appro-
priate or inappropriate are various recommendations of Reference 1. Thus,
it is desirable to briefly review and apply in retrospect the design steps
outlined in Reference 1 with the purpose of evaluating their usefulness
and validity. The steps in question are listed in Chapter 2 of that docu-
ment and are discussed in various chapters and appendices.

Initial Feasibility Assessment

Reference 1 suggests the performance of an initial feasibility assessment
to provide an indication of whether recirculation is worthwhile or possible
before detailed and sometimes expensive design efforts are initiated. Its
outlined procedure entails consideration of legal issues, energy consumption,
contaminants present, air quality regulations, air cleaner availability,
monitor availability, the process emission profile, and the design of the
current or proposed ventilation system for a plant.

Legal Issues--
Both the state in which this plant resides and the Federal government do not
generally prohibit the recirculation of industrial exhaust air containing
metallic grinding dust. The qualification to this statement is simply that
employee exposures must be maintained at or below permissible limits.

Energy Consumption--
The total exhaust volume originally selected for design purposes for the
grinding operation of interest is currently unknown. What is known, however,
is that the system currently exhausts 1.54 m^3/s (3,261 cfm), but has the
capacity to handle 2.5 m^3/s (5,250 cfm). One can estimate that the cost of
tempering this exhaust volume (both heating and air conditioning) 5 days per
week, and 16 hours per day, would range from $600 to $1,500 per year depending
upon the fuel used and specific energy costs.

Of interest is that the initiating event which led to the decision to recir-
culate in this plant appears to have been the need to clean grinding exhaust
air so that cars in the parking lot would not be soiled. The unit collectors

solved the problem most inexpensively since they used little floor space, required a minimal amount of additional ductwork, and were relatively inexpensive when purchased (approximately $3,800 for a 2.5 m^3/s (5,250 cfm) rated unit in 1968).

Contaminant Classification--
Table A-9 lists the composition of four of the many metals from which the plant manufactures springs. These were carefully selected as representing alloys which could be the most troublesome in terms of contaminant concentrations if the grinding operations were not well controlled. The chrome-vanadium alloy which heads the list is the one utilized during the time period this particular investigation took place.

Also of concern as potential sources of contaminants were the grinding wheels used. Contact with the manufacturer, however, indicated that the abrasive is aluminum oxide, that the cement is a magnesium oxide - chloride mixture, and that the surface treatment is granular crushed glass. No free silica is present.

Reference 1 suggests that all contaminants present be identified, that substances designated as carcinogens by OSHA not be recirculated, and that the toxicity of contaminants be considered on a case-by-case basis. It further suggests that processes involving application or generation of heat, pressure, or reactivity will require careful study to insure that the contaminants present do not undergo changes to other, possibly more toxic forms, and that one must have some knowledge of particle size distributions when particulate matter is involved.

The list of substances in Table A-9, together with the composition of the grinding wheels, provides a total list of all possible contaminants which might be found in the air. This list is presented in Table A-10 along with OSHA mandated and ACGIH recommended exposure limits.

The list is rather ambitious in that it lists some contaminants which may evolve during the grinding process, but which are unlikely to be present. Specifically, these are carbon monoxide and sulfur dioxide. Additionally, it includes beryllium, which the plant does not (and should not) handle; and considers substances never present in more than trace quantities. Practically, it can be concluded that contaminant levels will be acceptable if breathing zone concentrations are below permissible exposure limits for the various metals which comprise the bulk of the alloys handled.

The recommendation that substances designated as human carcinogens by OSHA not be recirculated does not currently cause problems with this list of contaminants. However, recent developments concerning inorganic nickel, as evidenced in the NIOSH criteria document for the substance (Reference 6), suggest that elemental nickel and inorganic nickel compounds may have the potential to cause lung and nasal cancers. NIOSH has therefore recommended to OSHA that the permissible exposure limit for nickel be revised to 15 µg Ni/m^3, determined as a time-weighted average (TWA) concentration for up to a 10-hour work shift, 40-hour workweek. If OSHA promulgates this recommendation into a mandatory standard, then recirculation of grinding dust containing nickel must be discouraged.

52

Odors--
Chapter 4 of Reference 1, in discussing contaminant characteristics, suggests
that one must give some consideration as to whether recirculation will un-
acceptably increase odor levels preceived by employees. This is a topic
which must be addressed for grinding operations. The characteristic odor
associated with dry metal grinding can be objectionable to some employees,
especially if the odor is intense. It is an odor, however, to which the
vast majority appear to become accustomed.

In the plant investigated the odor was generally not noticeable except in a
few, isolated and small regions. Even in these, however, it was not con-
sidered objectionable. It is surmised that the generally low intensity of
odor was due to the relatively small fraction of air recirculated, the large
amount of fresh air entering the building, and the excellent air distribu-
tion system.

The authors are aware of another plant of a similar type which is attempting
recirculation of exhaust air from grinding operations. Details are not
available, but it is known that odors are considerably more intense and ob-
jectionable in this situation. This suggests that recirculation of exhaust
air may not be advisable if a plant has or is expected to have a strong
grinding odor in its internal atmosphere without recirculation.

Air Quality Regulations--
According to plant management, there are no state or Federal regulations
which prohibit their discharge of grinding dust to the outdoor atmosphere.
The decision to clean the exhaust air was based solely on the desire to
reduce soiling of cars in the parking lot.

Air Cleaner Availability--
The removal of particulate matter from exhaust volumes can be accomplished
by use of cyclones, wet collectors, fabric arresters, and a variety of other
devices commercially available and widely used in industry. Hence, the
availability of air cleaners for grinding exhaust volumes does not impose a
restriction on the decision to recirculate.

Monitor Availability--
Devices are commercially available for detecting broken bags and/or for moni-
toring dust levels in work areas or air streams. It thus suffices for this
analysis to simply conclude that a variety of mechanisms are available for
detecting reduced system performance.

Process Emission Profile--
Grinding operations are generally intermittent in nature. When more than
one grinder is to be handled by a single air cleaning equipment train, one
must insure that the equipment selected is of sufficient capacity and effec-
tiveness for the case when all machinery is operative and generating con-
taminants. In the present case, this fact does not impose restrictions on
decisions stemming from an initial feasibility assessment for recirculation.
It simply suggests that one must have knowledge of and must take into account
the worst case conditions that air cleaning equipment trains may be exposed to.

Ventilation System Design--
It is patently obvious that the design of the various ventilation systems
existing in the plant before recirculation was implemented did not adversely
influence the decision to recirculate. Indeed, there is reason to believe
that recirculation was considered attractive because the systems would be
less complex (and thereby less expensive) than conventional systems which
discharge outdoors.

Conclusions--
If such a feasibility assessment had been conducted by the plant of interest
before recirculation was implemented, it would have been found that:

1. There are no legal reasons against the practice if permissible
    exposure limits are not exceeded.
2. There is a definite potential to save energy by recirculation.
3. Existing airborne contaminant concentrations are low relative to
    most current and permissible exposure limits.
4. Odors are not an envisionable problem.
5. High efficiency air cleaners are available at reasonable cost
    relative to potential energy savings.
6. A full range of devices and techniques are available for
    detecting reduced system performance.
7. The loading to the air cleaner is known and is in a range
    suggesting reasonable contaminant concentrations in return
    air supplies.
8. There are no problems envisionable with the installation aspects
    of envisionable systems.

In consequence, the feasibility assessment would have been likely to indi-
cate that further design efforts are warranted.

Contaminant Characteristics

Overlapping somewhat with a similar step in the initial feasibility assess-
ment, this step requires identification of contaminants in the work place
air, quantification of their concentrations, and the selection of acceptable
exposure concentrations for each.

Identification of contaminants can generally be determined from detailed
knowledge of the materials handled and from consideration of the factors
which might influence the formation of new contaminants due to various
reactions. In the present case, this was accomplished by review of chemical
analyses of the various metals processed, and from qualitative judgments
concerning the formation of gases.

Section 3 of Appendix A in Reference 1 defines the various concentrations
which should be quantified for each contaminant of interest. These are:

- C°_{BZG} - The contaminant concentration in breathing zones which would
  be significantly affected by changes in the total ventilation
  rate through the plant and are destined to be affected by the
  return air stream.

- C_{BZL}^o — As above, but for breathing zones which would not be significantly affected by changes in the total ventilation rate through the plant (see pages 90-95 of Reference 1 for an explanation; these are unnecessary for the plant operation studied in this investigation but must be known where walk-in grinding booths are used);
- C_G^o — In the general exhaust air stream, if the plant area of concern has a general mechanical ventilation system intended for recirculation (not applicable for the system configuration of interest);
- C_E^o — In the main duct(s) from local exhaust systems intended for recirculation (including particle size distributions if appropriate); and
- C_{MU}^o — In make-up air volumes.

All of these concentrations are to be obtained before recirculation is implemented. They are designated by the symbols shown above, and are used in various sets of equations utilized to define an optimum system configuration for implementation.

A host of issues are discussed in Reference 1 which deal with how, when, and where these concentrations should be obtained. Of these, the most significance must be attached to variations due to intermittent operations, changing process conditions, and other factors.

Grinding operations in a job-shop environment may produce widely different contaminant concentrations in various locations as new products are handled, as more or less grinding machines are utilized, as machinery is altered in a fashion which affects the performance of local exhaust hoods, and possibly, as grinding speeds and metals are varied. Reference 1 clearly states that such variations must be accounted for by careful consideration of all influential factors and by utilizing concentration data representing both typical and worst case operating conditions.

In the present study, concentrations were defined for all of the listed locations except those involving make-up air volumes. This was an oversight of little consequence since dust concentrations in the outdoor air would be negligible. However, since the study only reviewed the performance of the system under one specific set of operating conditions, the data obtained are not necessarily representative of typical or worst case conditions. If this investigation had actually involved the design of a recirculation system, considerably more data would have been necessary.

The selection of acceptable or desirable breathing zone concentrations for use as "target" values in the design procedure can be facilitated by use of OSHA permissible exposure limits, with appropriate reductions to provide safety factors. Reference 1 explains that safety factors are necessary to account for uncertainties in the design procedure, and do not reflect upon the adequacy of exposure limits. It also explains that one should be reluctant to design a recirculation system which significantly degrades the working environment, even if the level of degradation is permissible in terms of OSHA mandated limits.

For example purposes in the following, even though this is not considered acceptable practice, it is assumed that desired breathing zone concentrations, designated by the symbol C_{BZ}^D in Reference 1, are equivalent to OSHA permissible exposure limits. Furthermore, it is assumed that the following concentrations existed before recirculation was implemented.

- C_{BZG}^o = 1.2 mg/m^3 total dust TWA for machine operator
    = 2.0 mg/m^3 total dust for machine operator while grinding
    = 0.1 mg/m^3 total dust TWA in other areas
- C_E^o = 739 mg/m^3 in main duct during grinding
    = 443 mg/m^3 TWA in main duct
- C_{MU}^o = 0.0 mg/m^3 in make-up air

Work Place, Process, and Ventilation System Characteristics

This step involves knowledge of all air volumes entering and leaving the plant area of concern and appreciation of how the various air flows in the area of concern interact. Specific data items which are required for an analysis of the system configuration of interest include:

- Q_L — The volume rate of local exhaust intended to be recirculated;

- Q_G' — The general exhaust volume rate not intended to be recirculated;

- Q_{MU}' — The make-up air supply rate not to be influenced by recirculation;

- Q_{MU}^o — The make-up air rate necessary before recirculation (assumes balanced system);

- Q_N — The natural ventilation rate;

- $Q_{L_{out}}$ — The total volume rate of all local exhaust systems not recirculated;

- k_{BZ} — The physical fraction of air in breathing zones which originates in the return air stream; and

- k_R — The physical fraction of air in the local exhaust system being recirculated which originates in the return air stream.

For the plant studied, data values assumed for the variables involving air volume rates are:

- Q_L ≃ 1.55 m^3/s = 3,260 cfm

- Q_G' ≃ 129.8 - 25.5 = 104.3 m^3/s

    ≃ 275,000 - 54,000 = 221,000 cfm

56

- Q'_{MU} = 129.8 m^3/s = 275,000 cfm

- Q^o_{MU} ≃ 129.8 + 1.55 = 131.35 m^3/s

  ≃ 275,000 + 3,260 = 278,260 cfm

- Q_N = 0.0 m^3/s

- $Q_{L_{out}}$ = 25.5 m^3/s = 54,000 cfm

Q_L is the rate of air drawn through the local exhaust system attached to the grinding machine. It is assumed to be a constant before and after recirculation is implemented. Q'_G is the amount of general exhaust air which will remain constant during the implementation of recirculation. Since the plant has a balanced system, it is the total current rate of make-up air supply minus the rate of local exhaust systems not being recirculated. Thus, it is assumed here that one is attempting to replace fresh make-up air on a one-to-one basis with recirculated air from the local exhaust system of interest.

Q'_{MU} is set equal to the current make-up air rate, since this is the rate which is (or was) desired after recirculation is implemented. Q^o_{MU}, the total amount of make-up air before recirculation, is then given by the sum of Q'_{MU} and the volume rate of the local exhaust system intended for recirculation.

The natural ventilation rate for subsequent examples is set to zero. This is fairly reasonable for this particular plant because the excessive make-up air supply rate and the presence of numerous relief vents suggests significant positive pressures. The amount of exhaust air for local exhaust systems not to be recirculated, $Q_{L_{out}}$, is simply the amount currently not recirculated.

The performance of a tracer gas study using existing equipment or a mock-up of the proposed recirculation system is suggested by Reference 1 to determine how return air streams will affect the working environment. Results for the study performed in this investigation allow the conservative estimates of 0.4 for k_{BZ} in the machine operator's breathing zone, 0.5 for k_{BZ} elsewhere, and 0.5 for k_R.

Selection of Air Cleaning Equipment for Further Consideration

This step involves identification and costing of the various alternatives to cleaning exhaust air. Options for consideration include not only the specific types of units to be utilized, but the configuration of devices. For example, one may wish to utilize two or more cleaners in parallel, or one or more units in series. According to Chapter 5 of Reference 1, the issues involved are the subject of continuing debate and warrant consideration on a case-by-case basis. For the purposes of this analysis, it suffices to assume that the only air cleaning equipment train of interest consists of the previously described bag filter unit.

Selection of Surveillance Equipment for Further Consideration

As previously noted, plant management concluded that the contaminants in-
volved did not warrant provision of equipment for detecting reduced sys-
tem performance. This decision is not without merit for grinding oper-
ations involving relatively non-toxic substances, and is supported by dis-
cussion in Chapter 6 of Reference 1.

This issue must be given careful consideration on a case-by-case basis
for other installations, however. The authors are not completely con-
vinced that some sort of monitoring system is not called for where some
contaminants present are not considered inert or nuisance materials by
OSHA and the ACGIH.

Determination of Feasible System Configurations

For the sake of simplifying subsequent discussions, it will be assumed
that the configuration utilized in the plant studied is the only one of
interest. Nevertheless, designers should be aware that options are many,
and are discussed in Chapter 7 of Reference 1.

Design Optimization for Feasible Configurations

At this point, a designer would wish to apply appropriate models, i.e.,
sets of equations in Reference 1, to define an optimum system design.
In some cases, this would involve an iterative procedure which attempts
to define the proper air volume rates of various streams necessary to
produce desired breathing zone concentrations. Various examples of this
procedure are presented in Appendices A and others in Reference 1, and
do not merit duplication here. Rather, a subsequent section will apply
the model appropriate to the problem at hand to determine if its results
are consistent with study findings.

Failure Analyses for Feasible Configurations

If it is assumed the current system in the plant still represents a feasi-
ble approach for this type of operation, Reference 1 suggests a failure
analysis be conducted. Details are in Chapter 7 and Appendix F of that
source. For this most simple recirculation system configuration, the
application of the methodology does not appear warranted. It is obvious
what the failure modes of the air cleaner are and that any failure of the
system to clean air will within seconds adversely influence breathing zone
conditions.

Final Equipment Selection

Given a choice of system configurations and associated results from detailed
or simple failure analyses, a designer would next select the configuration
which provides the best balance of health safety and cost savings. Reference
1 must be considered justified in suggesting this process requires an aware-
ness of all issues involved and the application of some degree of professional
judgment.

Detailed System Design and Installation

This stage of the overall procedure is self-explanatory. It involves only detailed design and installation of equipment by personnel skilled in the field.

System Performance Validation

The elements of this task include a check on air cleaner performance and breathing zone concentrations after the recirculation system is installed, testing the surveillance system and the alarm (if one is installed), testing to ensure surveillance equipment works quickly enough, and recording of performance data. Pertinent sub-tasks involve essentially the activities performed in this investigation when a surveillance system is not utilized.

Planned Maintenance and Inspection

Chapter 9 of Reference 1 strongly suggests periodic inspection, periodic maintenance, and failure response planning to ensure that the recirculation system continues to operate as intended. Also noted is the need for air sampling studies and record keeping. These tasks are of obvious importance and also do not warrant further discussion.

Recirculation Model

The model which is of specific interest to this investigation, and to most installations involving unit collectors, is described in Figure B-3 of Appendix B of Reference 1. This figure is reproduced as Figure A-7 in this report.

The top part of this figure illustrates a plant area before recirculation is implemented. The middle part of the figure shows the same plant area after recirculation is implemented, and the bottom gives the various equations for use. These contain symbols as yet undefined.

- Q_{MU2} – An amount of additional make-up air, if any, needed to provide a balanced system in the plant;

- η – The overall air cleaner efficiency;

- f – A local exhaust system influence factor defined on pages 90 to 95 of Reference 1;

- C_R – The concentration of contaminant in the return air stream; and

- C_{BZ} – Predicted breathing zone concentrations after recirculation is implemented.

Use of the first equation on Figure A-7 indicates that Q_{MU2} has a value of zero. This is as expected because the previously chosen make-up air rate for Q'_{MU} already provides a balanced system.

Before
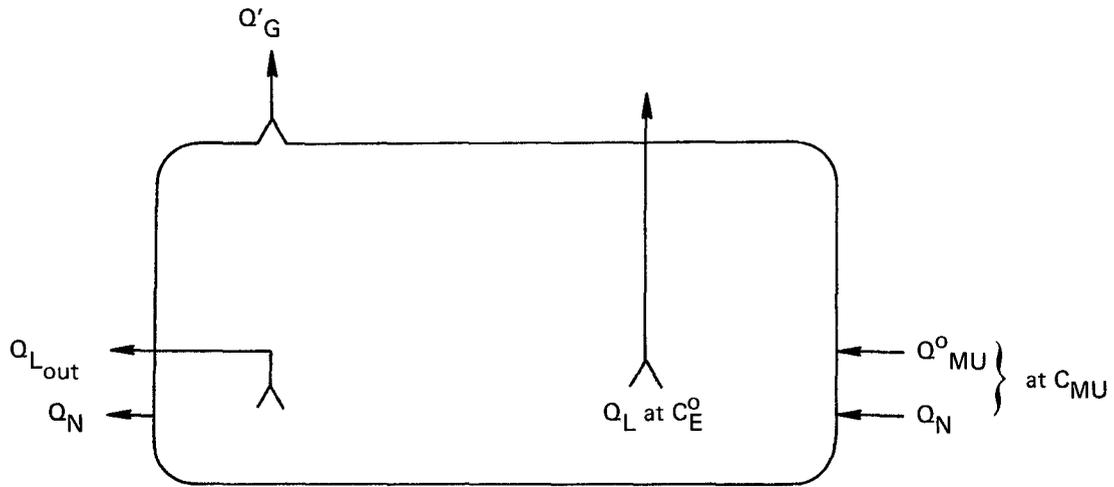
After
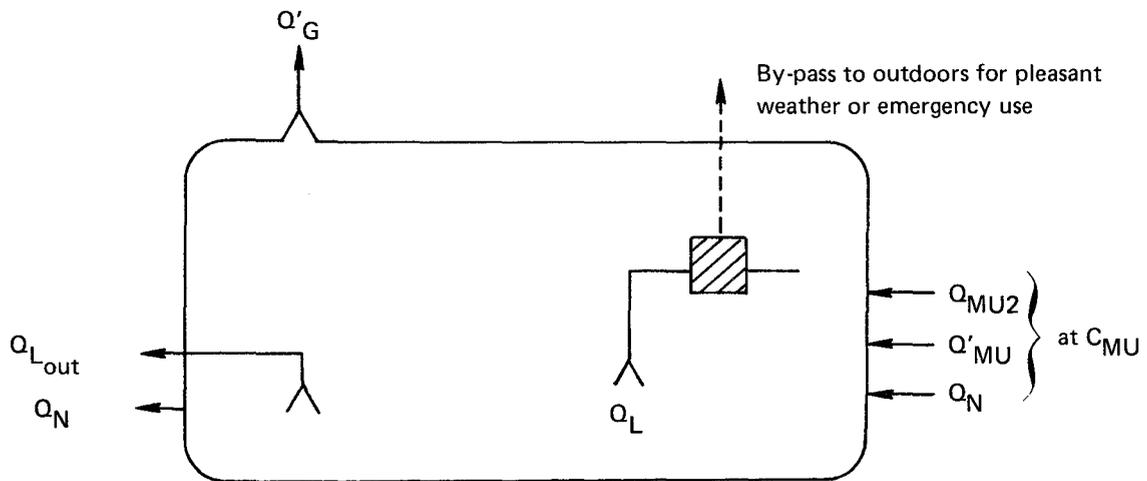
By-pass to outdoors for pleasant weather or emergency use

Determine Suitability of Unit Collector(s) from:

$$Q_{MU2} = Q_{L_{out}} + Q'_G - Q'_{MU} = Q^O_{MU} - Q_L - Q'_{MU}$$

$$C_R = \left[\frac{(1-\eta)\ (C^O_E - k_R\ C_{MU})}{1.0 - (1-\eta)\ k_R} \right]$$

$$C_{BZ} = (1-f)\ (C^O_{BZG} - C_{MU}) + f(C^O_{BZL} - C_{MU}) + k_{BZ}C_R + (1-k_{BZ})\ C_{MU}$$

Note: Q_L should be the total volume through all unit collectors, if more than one is to be installed.

Figure A–7. System design model.

60

The value for η becomes 0.9968 based upon the 99.68 percent overall weight efficiency estimated for the existing dust collector. For the operations of interest, Reference 1 explains that f has a value of zero.

Substitution of the various parameter values into the remaining equations allows estimation of C_R and C_{BZ} for post-recirculation conditions. These calculations are demonstrated in Table A-11.

Since this is an attempt to review the adequacy of the model without firm knowledge of pre-recirculation conditions, it is not possible to conclusively determine whether or not the model is valid. Nevertheless, this demonstration serves a purpose. The pre-recirculation concentrations assumed for the machine operator and other designated locations were not unreasonable. Through their use, it can be shown that the model provides predictions for the machine operator which are consistent with survey results. Also, it can be seen that results for areas distant from the source of recirculated air are not as consistent.

This latter situation is explainable with a logical hypothesis previously expressed, however. Since a tracer gas was used to study the airborne path of particulate matter, and since such matter has a strong tendency to settle upon exposed room surface areas, it appears that the estimated value for k_{BZ} for locations distant from the source of the recirculated air supply was significantly conservative. The dust simply settled out, while the gas continued its journey to the sampling locations.

Comparison of results with permissible exposure limits indicates that the recirculation system's performance is fully adequate for all substances designated as nuisance or inert contaminants. For the nickel-copper alloy listed in Table A-1, however, it is of borderline acceptability. If 60 to 70 percent of the alloy were nickel, the breathing zone TWA concentration for the machine operator could approximate or exceed the current permissible exposure limit for nickel. If more than 7 percent of the alloy was comprised of cobalt, the cobalt limit could be violated. Similarly, the beryllium-copper alloy could cause difficulties with both the copper and the beryllium permissible exposure limits, and during grinding, there is potential for the ACGIH short-term exposure limit for copper to be occasionally exceeded.

Given results such as these, a designer would review various alternatives discussed in Reference 1 to reduce the probability of the above events. Among these are the options:

- Experimentation with higher local exhaust volumes to achieve improved control of contaminants in the machine operator's breathing zone.
- Continuous by-pass of some part of the exhaust to the outdoors. This would reduce the total amount of dust entering the working environment.
- Use of a secondary air cleaner after the bag filter.
- Direction of fresh air from the make-up air system to the breathing zone of the machine operator to enhance dilution effects.

- Better distribution of the return air stream with the purpose of reducing effective k_{BZ} values.
- By-pass of all air to the outdoors when alloys are being processed which might cause violations of permissible exposure limits.

The first three options are entirely feasible, but are difficult to properly implement and have envisionable economic disadvantages. The fourth and fifth do not have the economic problems and must be given strong consideration. The last option, however, is most reasonable and can be successfully implemented with few attendant uncertainties. Additionally, it is seen to utilize a bypass duct and damper system which Reference 1 strongly recommends for inclusion in any recirculation system.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions can be derived from the results of this case study.

1. It is not believed that recirculation was implemented in this plant solely as an energy saving measure. Rather, it is surmised that the decision to recirculate stemmed from a desire to avoid the additional ductwork necessary to discharge air outdoors.

2. Application of the basic philosophy and guidelines of Reference 1 indicates that the route to substantial energy savings in this plant involves: a) reductions in the amount of fresh make-up air supplied; b) possible recirculation of general exhaust air extracted from "clean" plant areas; and c) exhaust of cleaned grinding exhaust volumes (from the larger machines only) to the outdoors. The plant is currently recirculating some of its most heavily contaminated exhaust volumes while discharging to the outdoors most of its cleanest exhaust streams.

3. An initial feasibility assessment for recirculation must fully consider the presence of objectionable odors. Reference 1 discusses this issue, but not in the context of such an assessment.

4. A characterization of air flow patterns by a tracer gas study has the potential to provide conservative results for the parameters k_{BZ} and k_R when the contaminant is an aerosol and has a strong tendency to settle upon exposed room surfaces.

5. This investigation provided a "snapshot" characterization of one system for the recirculation of exhaust air from grinding operations under what may or may not have been typical operating conditions. Nevertheless, its findings suggest that further study may lead to a generally applicable methodology for the recirculation of exhaust air from dry grinding operations involving inert or nuisance materials.

6. Incidents occurring during the inplant survey suggest that the planned maintenance and inspection activities recommended in Reference 1 are completely appropriate. Indeed, they may be necessary on a more frequent schedule than usual when exhaust air is discharged outdoors.

7. With the exception of conclusion #3, no serious deficiencies in the recommendations of Reference 1 are found based upon the findings of this case study. They clearly addressed all issues of importance for the basic and straightforward system configuration investigated. Additionally, they provided the basis for the identification of possibly safer and more beneficial measures for energy savings.

Recommendations

Recommendations which evolve from these conclusions are:

1. No merit is found in a decision to recirculate which results from a desire to avoid the installation of an exhaust duct to the outdoors. This sort of logic should be discouraged.

2. Plants with large-volume general mechanical ventilation systems should consider recirculation of general exhaust air. Such exhaust streams are usually much less contaminated than local exhaust volumes, and can provide equivalent energy savings for the same volume rate of air handled.

3. Where a number of candidate processes are available, the processes which have the lowest contaminant loadings to air cleaners, and/or which can best be characterized should be most favorably considered for recirculation purposes.

4. Consideration should be given to the modification of Reference 1's models to account for the settling of particulate matter in ducts and upon exposed room surface areas.

5. Consideration should be given to the development of a generally applicable methodology for the recirculation of exhaust air from grinding operations involving nuisance or inert substances.

6. The need for system maintenance and inspection should be repeatedly and strongly stressed whenever recirculation is discussed.

7. The possibility of objectionable odors should be considered during the initial feasibility assessment.

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2. Federal Register. Volume 42, No. 160, August 18, 1977. Pages 41755-41756.

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4. National Institute for Occupational Safety and Health, 1977. NIOSH Manual of Analytical Methods. DHEW (NIOSH) Publication No. 77-157 (3 volume set). U. S. Government Printing Office, Washington, DC 20402.

5. American Conference of Governmental Industrial Hygienists, Committee on Industrial Ventilation, 1978. Industrial Ventilation: A Manual of Recommended Practice, 15th Edition.

6. National Institute for Occupational Safety and Health, 1977. Criteria for a Recommended Standard. . . . Occupational Exposure to Inorganic Nickel. DHEW (NIOSH) Publication No. 77-164. U. S. Government Printing Office, Washington, DC 20402.

Table A-1. Bag filter characteristics.

Capacity: 2.5 m^3/s at 3.54 cm SP (5,250 cfm at 9" SP)

Type and number of bags: 27 cotton bags

Air/cloth ratio: 3.5 to 1 rating, 2.2 actual

Fan rpm: 2,692 (type unknown)

Fan motor: 15 hp at 1,800 rpm with multiple belt drive

Total height: 5.3 m (17 ft - 5 in)

Total length: 3.51 m (11 ft - 6 in)

Total width: 1.12 m (3 ft - 8 in)

Shaker mechanism motor: 1/2 hp at 1,800 rpm

Power: 440 volts, 3 phase, 60 cycles

Cost (1968): $3,821

Replacement bag cost (1972): $44.25 each

Cleaning cycle: Automatic - bags are shaken whenever the grinding
                 machine is turned off for a coffee or meal break.

Table A-2. Inlet duct traverse data.

Point No.	Location (cm)	(in)	ΔP (mm H$_2$O)	(in H$_2$O)	Temperature (°C)	(°F)
Horizontal						
1	4.1	1.6	10.9	0.43	18.9°	66°
2	12.4	4.9	11.4	0.45	18.9°	66°
3	25.6	10.1	11.4	0.45	18.9°	66°
4	34.0	13.4	10.9	0.43	18.9°	66°
Vertical						
5	4.1	1.6	10.7	0.42	18.9°	66°
6	12.4	4.9	10.9	0.43	18.9°	66°
7	25.6	10.1	10.9	0.43	18.9°	66°
8	34.0	13.4	11.2	0.44	18.9°	66°
Average			11.0*	0.435*	18.9°	66°

Duct Diameter: 38.1 cm (15 inches)

Static Pressure: -16.5 cm H$_2$O (-6.5 inches H$_2$O)

Barometric Pressure: 748 mm Hg (29.46 inches Hg)

Medium Transported: Air - mole wt. 28.83

$$V = 85.49 \times .99 \times \sqrt{\frac{526 \times (.435)}{28.83 \times 28.98}} = 44.29 \text{ ft/s} = 13.5 \text{ m/s}$$

Average Volumetric Flow:

$$Q = 44.29 \text{ ft/s} \times \frac{\pi (15)^2}{4 \times 144} \times \frac{60 \text{ s}}{\text{min}} = 3261 \text{ ft}^3/\text{min} = 92.3 \text{ m}^3/\text{min}$$

* Determined by squaring the average of the square roots of the individual readings.

Table A-3. Total particulate samples.

Sampling Location	Inlet	Inlet	Outlet
Sample Number	#1	#2	#1
Time of Sample	1348-1353	1428-1443	1310-1443
Grinding Cycle	Last 1/3 of grinding	1 Entire cycle of grinding	4 Entire cycles of grinding
Average Duct Temperature C° (F°)	19 (66)	19 (66)	19 (66)
Average Duct Pressure mm H_2O (in H_2O)	-165.1 (-6.5)	-165.1 (-6.5)	38.1 (+1.5)
Barometric Pressure mm Hg (in Hg)	748 (29.46)	748 (29.46)	748 (29.46)
Moisture Content % by volume	0.5	0.5	0.5
Gas Composition	Air	Air	Air
Total Sampled Volume at STP* m^3 (ft^3)	0.124 (4.379)	0.381 (13.455)	1.428 (50.429)
Total Particulate Collected mg	53.5	253.8	3.4
Normalized Particulate Loading, mg/m^3	430	666	2.4
Percentage Isokinetic	98.8	100.9	109.3

*STP = 21°C and 760 mm Hg or 70°F and 29.92 in Hg.

Table A-4. Andersen cascade impactor samples.

Sampling Location	Inlet	Inlet	Outlet
Sample Number	#1	#2	#1
Time of Sample	1035 1115	1310 1317	1035 1115
Grinding Cycle	2 Entire batches of springs	First 1/2 of one batch of springs	2 Entire batches of springs
Average Duct Temperature °C (°F)	19 (66)	19 (66)	19 (66)
Average Duct Pressure mm H_2O (in H_2O)	-165.1 (-6.5)	-165.1 (-6.5)	38.1 (1.5)
Barometric Pressure mm Hg (in Hg)	748 (29.46)	748 (29.46)	748 (29.46)
Moisture Content % by Volume	0.5	0.5	0.5
Gas Composition	Air	Air	Air
Total Samples Volume of STP,* m^3(ft^3)	0.758 (26.768)	0.177 (6.250)	0.703 (24.826)
Total Particulate Collected, mg	560.4	196.3	8.7
Normalized Particulate Loading, mg/m^3	739.3	1110.0	12.5
Percentage Isokinetic	100.8	100.6	108.6

*STP = 21°C and 760 mm Hg or 70°F and 29.92 in Hg.

Table A-5. Particle size distribution - Inlet duct sample 1.
Two Entire Cycles of Springs
Total Volume Sampled at STP* 0.758 m^3

Correction Factor 0.99 at 19°C (66°F)

Plate Number	Tare and Particulate (gm)	Tare Weight (gm)	Net Weight Gain (mg)	Normalized Gain (mg/m^3)	Percentage Distribution	Cumulative Percentage Distribution	Aerodynamic Diameter (μm)
0	69.6990	69.6748	24.2	31.9	4.3	100.0	>9.9
1	15.2719	15.0328	239.1	315.4	42.7	95.7	9.9
2	15.5556	15.4107	144.3	190.4	25.7	53.0	6.3
3	15.4670	15.3952	71.8	94.7	12.8	27.3	4.2
4	15.0436	15.0042	39.4	52.0	7.0	14.5	2.8
5	15.0108	14.9888	22.0	29.0	3.9	7.5	1.8
6	15.0526	15.0438	8.8	11.6	1.6	3.6	0.9
7	14.9490	14.9451	3.9	5.2	0.7	2.0	0.6
8	14.9357	14.9337	2.0	2.6	0.4	1.3	0.4
Final	15.0788	15.0739	4.9	6.5	0.9	0.9	<0.4
Total			560.4	739.3			

*STP = 21°C and 760 mm Hg or 70°F and 29.92 in Hg

69

Table A-6. Particle size distribution - Inlet duct sample 2.
First Half of One Batch of Springs
Total Volume Sampled at STP* 0.177 m^3

Correction Factor 0.99 at 19°C (66°F)

Plate Number	Tare and Particulate (gm)	Tare Weight (gm)	Net Weight Gain (mg)	Normalized Gain (mg/m^3)	Percentage Distribution	Cumulative Percentage Distribution	Aerodynamic Diameter (μm)
0	49.2819	49.2657	16.2	91.5	8.3	100.0	>9.9
1	14.6578	49.5908	67.0	378.5	34.1	91.7	9.9
2	15.1592	15.1114	47.8	270.1	24.4	57.6	6.3
3	15.4811	15.4575	23.6	133.3	12.0	33.2	4.2
4	14.6262	14.6059	20.3	114.7	10.3	21.2	2.8
5	15.4175	15.4106	6.9	39.0	3.5	10.9	1.8
6	14.9802	14.9738	6.4	36.2	3.3	7.4	0.9
7	14.6228	14.6198	3.0	16.9	1.5	4.1	0.6
8	15.0806	15.0790	1.6	9.0	0.8	2.6	0.4
Final	14.6075	14.6040	3.5	19.8	1.8	1.8	<0.4
Total			196.3	1109.0			

*STP = 21°C and 760 mm Hg or 70°F and 29.92 in Hg.

70

Table A-7. Particle size distribution - Outlet duct sample 1.
Two Complete Loads of Springs
Total Volume Sampled at STP* 0.703 m³

Correction Factor 0.99 at 19°C (66°F)

Plate Number	Tare and Particulate (gm)	Tare Weight (gm)	Net Weight Gain (mg)	Normalized Gain (mg/m³)	Percentage Distribution	Cumulative Percentage Distribution	Aerodynamic Diameter (μm)
0	67.4130	67.4082	4.8	6.8	55.2	100.0	>10.5
1	14.6442	14.6457	-1.5	--	--	--	10.5
2	14.9435	14.9435	0.0	--	--	--	6.7
3	15.4600	15.4590	1.0	1.4	11.5	44.8	4.5
4	14.6094	14.6098	-0.4	--	--	--	3.1
5	15.1152	15.1154	-0.2	--	--	--	1.9
6	15.4087	15.4073	1.4	2.0	16.1	33.3	1.0
7	14.9661	14.9654	0.7	1.0	8.0	17.2	0.6
8	15.0830	15.0828	0.2	0.3	2.3	9.2	0.4
Final	14.9908	14.9902	0.6	0.9	6.9	6.9	<0.4
Total			8.7	12.4			

*STP = 21°C and 760 mm Hg or 70°F and 29.92 in Hg.

Table A-8. Results from GCA RDM-101.

Area Designation*	Time of Day	Respirable Dust Concentration** (mg/m^3)	Total Dust Concentration** (mg/m^3)
A	10:30	0.10 (7)	--
B	3:15	0.04 (6)	0.09 (4)
D	10:50	0.01 (7)	--
	11:00		1.4 (1) and 0.5 (1)
E	11:10	0.02 (7)	--
	2:00	0.05 (7)	--
	2:15	--	0.05 (7)
F	11:30	0.02 (7)	--
G	1:00	0.09 (7)	--
	1:15	0.07 (7)	--
	2:30	0.02 (7)	--
	2:40	--	0.19 (7)
H	1:45	0.04 (9)	--
	2:00	0.00 (7)	--
J	2:45	0.03 (7)	--
	3:00	--	0.16 (7)

* See Figure A-3 in main body of case study report for locations of designated areas.

** Numbers in parentheses are sample times in minutes. Although GCA device is not highly accurate for very low concentrations, its results most definitely indicate the correct order of magnitude.

Table A-9. Specifications for metal alloys.

Chrome - vanadium alloy

Carbon	0.48 - .53%
Manganese	0.70 - 0.90%
Chromium	0.80 - 1.10%
Vanadium	0.15 - 0.25%
Phosphorus	0.35 % max
Sulfur	0.04 % max
Silicon	0.20 - 0.35%
Spring steel	remainder

302 Stainless Steel

Chromium	17 - 19%
Nickel	8 - 10%
Manganese	2% max
Carbon	0.15% max
Silicon	1% max
Phosphorus	0.045% max
Sulfur	0.03% max
Iron	remainder

Nickel - copper alloy

Nickel & cobalt	63 - 70%
Iron	2.5% max
Manganese	1.25% max
Carbon	0.3% max
Silicon	0.5% max
Sulfur	0.024% max
Aluminum	0.5% max
Copper	remainder

Beryllium - copper (on books but not used)

Beryllium	1.8 - 2.0%
Nickel & cobalt	0.2% min
Nickel & cobalt & iron	0.6% max
Copper & additive elements	99.5% min

Table A-10. Possible contaminants in grinding exhaust.

Substance	OSHA Permissible Exposure Limit	OSHA Ceiling	ACGIH TLV	ACGIH STEL
Aluminum	(N)	–	–	–
Aluminum oxide	(N)	–	–	–
Beryllium	2 $\mu g/m^3$	5 $\mu g/m^3$	2 $\mu g/m^3$	25 $\mu g/m^3$
Carbon	(N)	–	–	–
Carbon monoxide	55	–	55	440
Chromium	(N)	–	–	–
Cobalt	0.1	–	0.1*	
Copper (dust)	1.0	–	1.0	2.0
Crushed glass	(N)	–	–	–
Iron or steel	(N)	–	–	–
Magnesium chloride	?	–	?	–
Magnesium oxide (fume)	10.0	–	10.0	–
Manganese	5.0	5.0	5.0	5.0
Nickel	1.0	–	1.0	–
Phosphorus (yellow)	0.1	–	0.1	–
Silicon	(N)	–	–	–
Sulfur (dioxide)	13.0	–	13.0	–
Vanadium (metal)	(N)	–	–	–

* Change to 0.05 mg/m^3 has been proposed.

Notes – 1. All units are mg/m^3 unless otherwise noted.
2. N means substance can be considered as inert or nuisance dust. OSHA limits are 5 mg/m^3 for respirable fraction; 15 mg/m^3 for total dust. The ACGIH recommends 5 mg/m^3 for respirable dust; 10 mg/m^3 for total dust.
3. Permissible exposure limits for nickel, copper, manganese and similar substances are based on total dust concentrations.

Table A-11. Examples of calculation procedure.

For return air concentrations:

$$C_R = \frac{(1 - .9968)(443 - 0)}{1 - (1 - .9968)(0.5)}$$

$$= 1.42 \text{ mg/m}^3 \text{ on a TWA basis}$$

$$C_R = \frac{(1 - .9968)(739 - 0)}{1 - (1 - .9968)(0.5)}$$

$$= 2.37 \text{ mg/m}^3 \text{ during grinding}$$

For breathing zone concentrations:

$$C_{BZ} = (1.2 - 0) + 0 + (0.4)(1.42) + 0$$

$$= 1.77 \text{ mg/m}^3 \text{ for machine operator on a TWA basis}$$

$$C_{BZ} = (2.0 - 0) + 0 + (0.4)(2.37) + 0$$

$$= 2.95 \text{ mg/m}^3 \text{ for machine operator during grinding.}$$

$$C_{BZ} = (0.1 - 0) + 0 + (0.5)(1.42) + 0$$

$$= 0.81 \text{ mg/m}^3 \text{ for all other general areas on a TWA basis.}$$

NOTE: 1. Since all predicted concentrations are well below the respirable nuisance dust permissible exposure limit, there is no need in this analysis to separately estimate post-recirculation respirable dust levels. Such an analysis would be necessary, however, when predicted C_{BZ} values for total dust exceed the respirable dust limits.

2. The predicted breathing zone concentrations are for total dust. The exposure to specific contaminants is determined from these by use of metal alloy specifications presented in Table A-9.

APPENDIX B. HARD CHROME PLATING PLANT #1

CONTENTS

FIGURES

TABLES

HARD CHROME PLATING PLANT #1

INTRODUCTION

Hard chrome plating is a process by which chrome is deposited by an electric
current upon metal surfaces placed in a bath. These baths consist of chromium
trioxide crystals which, when dissolved in water, form chromic acid (H_2CrO_4).
In addition, they contain a sulphate, usually in the form of sulphuric acid,
which acts as a catalyst and enables chrome deposition.

The plant of interest to this particular case study utilizes nine small self-
contained wet scrubbers which clean and recirculate the air drawn from exhaust
hoods applied to 12 hard chrome plating tanks. Each scrubber is placed in the
immediate vicinity of the tanks it is associated with, and returns air to the
work place directly through an open exhaust port on its side.

The purpose of this investigation was to evaluate the feasibility of applying
such systems to similar plating facilities. Additionally, it was desired to
define those factors which are of primary importance for consideration in the
application and to determine whether the guidance of Reference 1 is adequate
for such purposes.

The plant itself was considered ideal for these purposes because: a) it
has been recirculating exhaust air from plating operations for approximately
20 years; and b) it is representative of a "backyard" operation which has
grown in a somewhat haphazard manner. Thus, it was felt that a conclusion
that recirculation was being successfully applied in this situation
might lead to a generalized and safe technique for application by others.

PLANT AND PROCESS DESCRIPTION

Plant Description

Figure B-1 presents an approximate layout of the facility showing the
locations of all hard chrome plating tanks, wet scrubbers, and other venti-
lated tanks. Construction is essentially concrete or stone block, with
windows only along the wall at the far right of the figure. Unshown are
numerous tanks containing fluids and processes not needing local exhaust
ventilation.

Process Description

Like other job shops specializing in metal finishing operations, this company
provides a variety of plating, anodizing, chemical processing, and special
services. The scope of these activities at the plant visited, however,
appears to be considerably limited. Hard chrome plating operations inhabit
the majority of floor space, and completely dominated the attention of
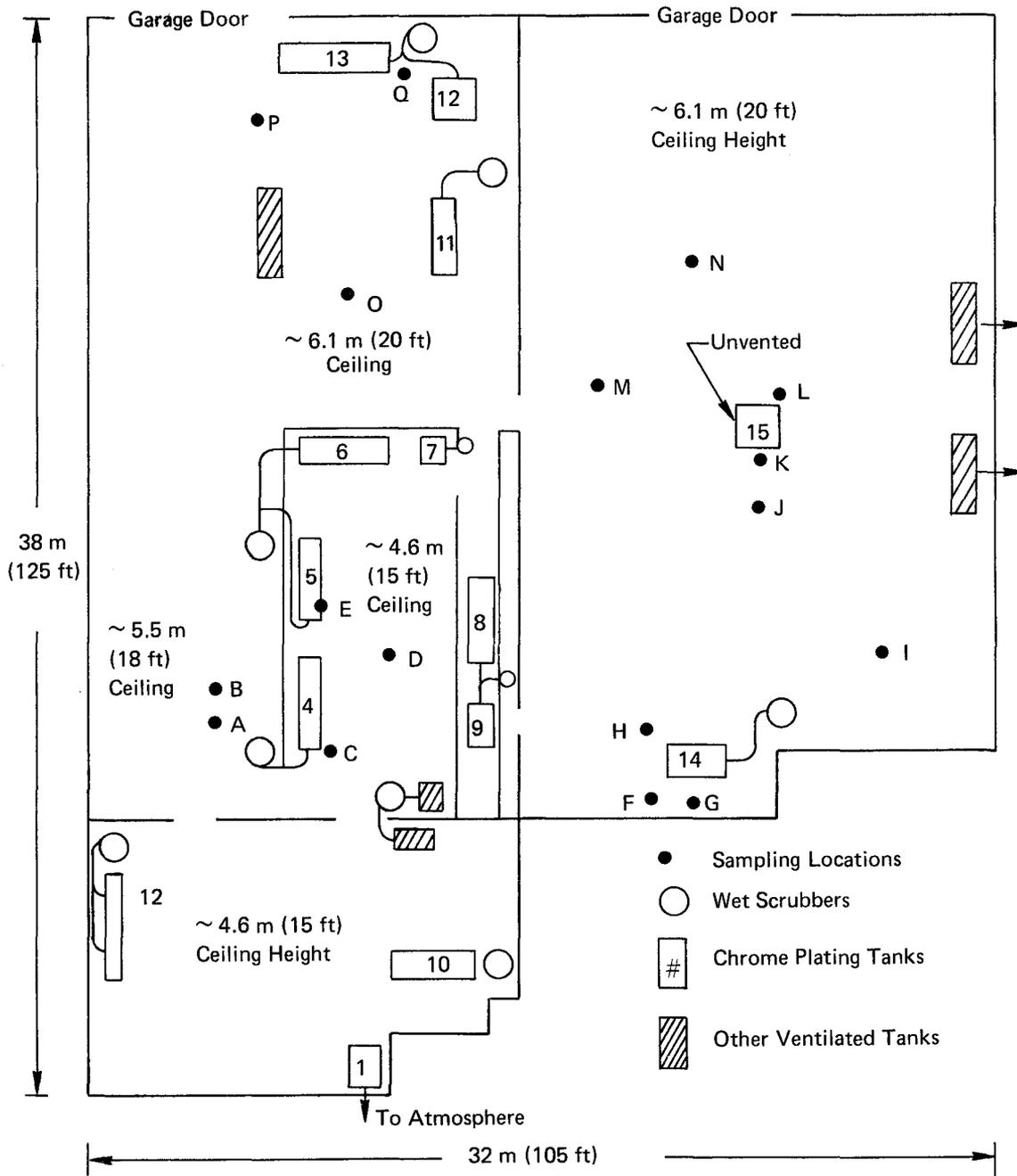employees during the survey. Presumably, other metals are plated in the

Figure B–1. Plant layout.

same tanks, if and when the need arises, or are handled at a second facility owned by the company.

The chrome plating tanks themselves were of diverse capacities and dimensions ranging from 0.58 m^2 (6.25 ft^2) to 4.27 m^2 (46 ft^2) in surface area. Bath compositions were uniform (checked at least weekly) at 247 grams per liter (33 ounces per gallon) of chromic acid, and 2.47 grams per liter (0.33 ounces per gallon) of sulphuric acid. Currents observed ranged from 400 amperes at 4.5 volts to 610 amperes and 5.4 volts.

To reduce acid mist generation from the baths, most tanks were covered with scrap sheets of corrugated fiberglass, heavy paper, or wood. Additionally, a common household detergent was sometimes used to form a foam blanket on liquid surfaces.

Ventilation Systems

Local Exhaust Systems--
All tanks requiring local exhaust were fitted with plenums and slots. Most resembled the design shown in Figure 4-12 of Reference 2 and reproduced as Figure B-2 in this report. Table B-1 lists measured characteristics of the tanks, while Table B-2 compares the flow volume (Q) per unit tank surface area (A) currently provided with the Q/A values computed from recommended procedures in Section 5 of Reference 2. It is apparent that the flow volumes resulting from the exhaust systems applied to these tanks are well below recommended minimum levels.

General Exhaust and Make-up Air Systems--
The general exhaust system consisted of 5 strategically located wall fans and 2 roof exhausters. Some of these were fitted with a humidistat that could activate the fan at a preset humidity level to eliminate a wall sweating problem in cold weather. Generally, however, most exhausters appeared to be intended for warm weather use and none were operating during the survey.

There were no mechanical make-up air systems in the plant. Whatever air entered did so through the garage doors. These were observed to be open at all times during three visits to the plant, two of which were during cold weather.

Five space heaters operating on fuel oil provided supplementary heating during extremely cold weather. Mostly, however, the recirculation of exhaust air along with the heat radiated by numerous hot liquid baths in non-insulated tanks provides sufficient heating.

Air Cleaners--
Wet scrubbers were from two well-known manufacturers and had rated capacities of 0.94 or 1.9 m^3/s (2000 or 4000 cfm). The basic design of the various re-circulation systems in which these were utilized is quite straightforward. Essentially, the exhaust from the hood plenum enters the bottom of a nearby cylindrical scrubber, passes through the unit, and reenters the work place through the normal exhaust port. There are no provisions for by-pass ducts, air quality monitoring, air flow monitoring, or water flow monitoring. Figure B-3 is a photograph of one system showing the plating tank in the foreground, the ductwork to an elevated wet scrubber, and an upward-turned exhaust port.
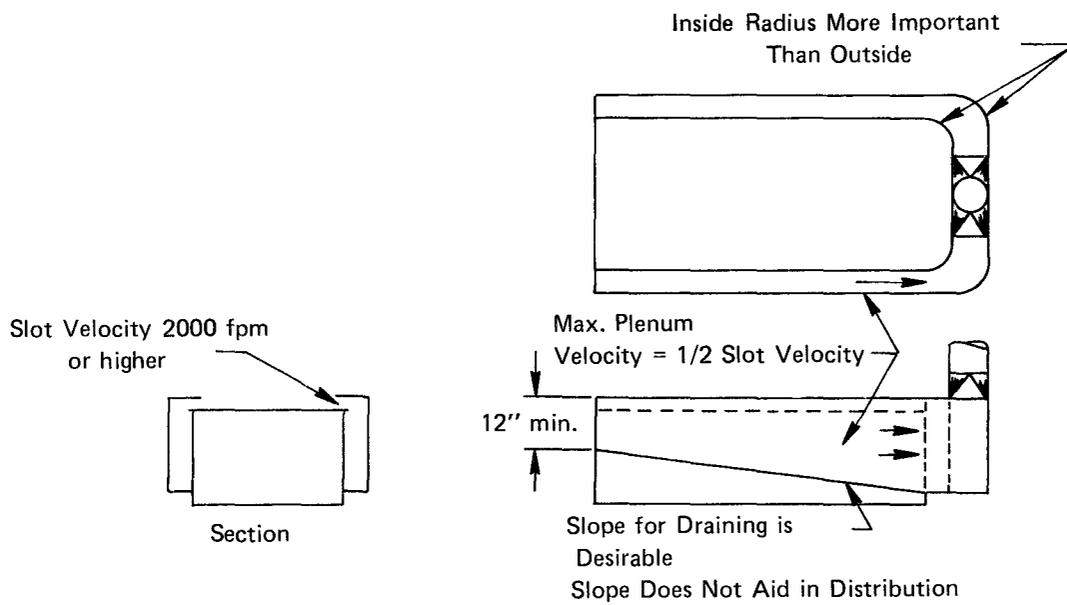
Inside Radius More Important
Than Outside

Slot Velocity 2000 fpm
or higher

Section

Max. Plenum
Velocity = 1/2 Slot Velocity

12″ min.

Slope for Draining is
Desirable
Slope Does Not Aid in Distribution

Figure B—2. Typical exhaust hood configuration.

Table B-1. Plating tank characteristics.

Tank #	Length m (ft)	Width m (ft)	Slot Size cm (in)	Slot Configuration*	Slot Velocities m/s (fpm)	Liquid Level Below Slots cm (in)
1	0.76 (2.5)	0.76 (2.5)	2.5 (1)	2	5.6-6.1(1100-1200)	10.2 (4)
2	3.66 (12)	0.76 (2.5)	3.8 (1.5)	2	Note 1	15.2 (6)
4	3.66 (12)	0.76 (2.5)	3.8 (1.5)	1	3.1-4.1 (600-800)	7.6 (3)
5	2.44 (8)	0.76 (2.5)	Note 3	2	Note 3	Note 3
6	3.05 (10)	0.76 (2.5)	Note 3	2	2.54-6.4 (500-1250)	Note 3
7	1.01 (3.33)	1.01 (3.33)	Note 3	2	Note 3	Note 3
8	3.05 (10)	0.61 (2)	Note 3	2	Note 3	.Note 3
9	1.22 (4)	1.22 (4)	Note 3	2	Note 3	Note 3
10	3.05 (10)	0.76 (2.5)	3.8 (1.5)	2	2.0-7.1 (400-1400)	7.6 (3)
11	2.44 (8)	1.22 (4)	3.8 (1.5)	2	6.1-11.4 (1200-2250)	7.6 (3)
12	1.01 (3.33)	0.76 (2.5)	3.8 (1.5)	2	Note 1	Note 3
13	3.66 (12)	1.17 (3.83)	3.8 (1.5)	2	Note 1	Note 3
14	1.83 (6)	1.37 (4.5)	3.8 (1.5)	2	5.6-8.1 (1100-1600)	20.3 (8)
15	1.22 (4)	1.01 (3.33)	Note 2	2	Note 2	Note 3

* Code: 1 = slot along one length
         2 = slots along two lengths

Note 1: Unit not in service
Note 2: Unit rarely used. Has no ventilation system.
Note 3: Characteristics not recorded.

81

Table B-2. Current and recommended Q/A values.

Tank #	Current Q/A ($m^3/s/m^2$)	Current Q/A (cfm/ft^2)	ACGIH Q/A ($m^3/s/m^2$)	ACGIH Q/A (cfm/ft^2)
1	0.37 - 0.41	73 - 80	1.27	250
4	0.23	44.7	0.97	190
10	0.2 - 0.71	40 - 140	1.27	250
11	0.38 - 0.72	75 - 141	1.27	250
14	0.44	87.4	1.27	250

NOTE: Current Q/A values for tanks 1, 10, and 11 based on slot velocity measurements using Alnor Velometer. Values for tanks 4 and 14 based upon duct velocity measurements.

Scrubber
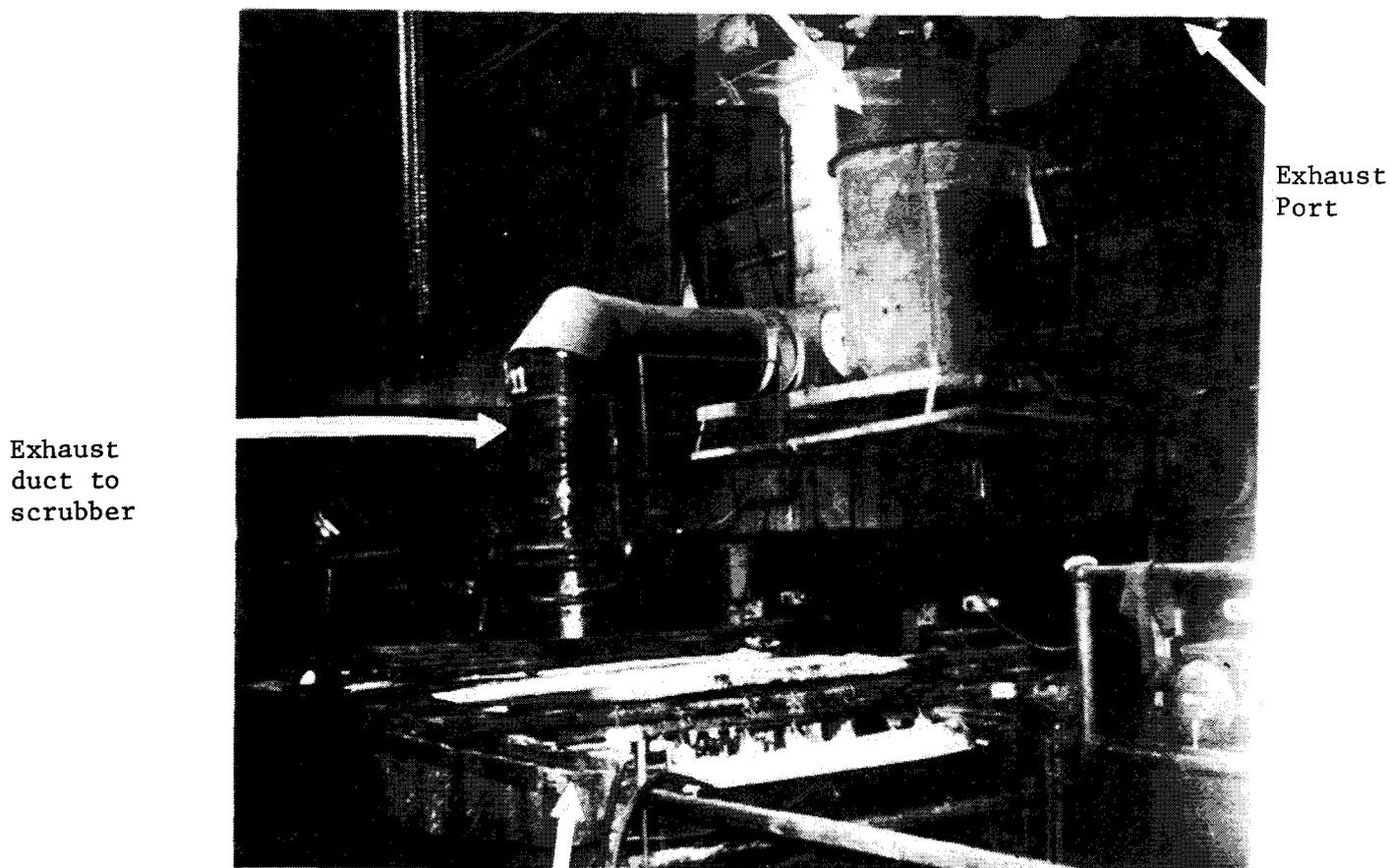
Figure B-3. A typical recirculation system in this plant.

The outlet ducts or ports on scrubbers were generally aimed away from the nearest work stations. For example, those on three scrubbers were upward-turned and discharged a few feet below ceiling level. Those on two other scrubbers were similar, but discharged just above head height in a room used for storage, while other streams were directed downward or horizontally as necessary to direct streams away from work stations.

EVALUATION METHODS

Sampling Strategy

The scope of this investigation did not call for a detailed industrial hygiene and duct sampling survey for every exhaust system and contaminant producing process in this job-shop environment. In consequence, sampling plans entailed measurement of chromic and sulfuric acids, with spot checks for concentrations of hydrogen (generated by the electrolysis of water in plating tanks).

Acid measurement efforts were planned to be comprised of series of general area and personal samples taken at strategically located sites throughout the plant. The main concern was simply the determination of whether or not the large-scale recirculation of plating exhaust air allows maintenance of acceptable breathing zone concentrations for contaminants of interest.

Three of the nine wet scrubbers in the plant were not operating at the time of the survey. Two were being overhauled, while one was out of service because of problems with a plating tank. Of the remaining six, two were randomly selected for detailed efficiency evaluations. One of these (on tank #4) was old and rusty in appearance, while the other (on tank #14) appeared to be fairly new and in excellent condition. It was hoped that this choice of an "old" and "new" unit would allow statements concerning maintenance and/or efficiency deterioration with time.

For efficiency evaluations, it was planned to take a number of isokinetically obtained samples from inlet ducts and outlet ports. Additionally, it was planned if at all possible, to measure water flows through the scrubbers, and to record other pertinent characteristics of the plating process. Overall, these data were considered sufficient to allow a definitive statement regarding the feasibility of recirculating plating exhausts under what can possibly be described as almost worst case conditions.

Sequence of Events

Just after a set of samples had been taken from the inlet and outlet ducts of the newer scrubber, it was discovered that the water line leading to this unit had a closed valve. When this distant valve was found and opened by a plant maintenance person, a large amount of strong acid literally poured and sprayed from the scrubber outlet port, severely contaminating the survey team's sampling equipment, their working platforms, and the air quality throughout the local plant area. It became obvious that the scrubber had somehow accumulated acid mist for some time, and that considerable effort would be necessary to decontaminate all equipment

after the area was safe to reenter. (Note: The drain pipe for this scrubber was hidden from view and difficult to access. Not suspecting that anything was wrong, researchers delayed checking the drain pipe until a maintenance person could locate and identify a point at which the water flow rate could be measured.)

After taking a single set of samples at the older scrubber, the survey team member in charge of this location concluded that the unit had passed its useful service life. Velocity traverses in ductwork had indicated dead spots and no clear pattern of flow. Additionally, before taking the samples, he had found it necessary to patch a rust hole on top of the unit.

Since two of six operating scrubbers were found to be in poor condition, and since the air quality in the plant could no longer be considered representative of typical conditions, the survey was prematurely terminated. In consequence, the data base presented in the following is not as complete as was originally desired. It is, however, sufficient to complete the desired analysis.

Sampling and Analytical Procedures

Several types of measurement and sample collection procedures were used to evaluate the performance of wet scrubbers in recirculating exhaust systems. Methods employed allowed collection of samples from ductwork leading to and away from the scrubber, and from the general work area. Each collection method chosen was either a standardized sampling technique (EPA or NIOSH) or was derived from best state-of-the-art methodology and specially adapted to fulfill specific data needs.

General area and/or personal samples were collected and analyzed in strict accordance with published NIOSH procedures, with a single exception involving the manner in which the chromates and chromic acid samples were chemically analyzed. With respect to the duct samples, however, more numerous liberties were taken. These were principally necessitated by the physical configuration of the processing equipment and/or because explicit collection procedures could not be identified.

Velocity Measurements in Ducts--
Two methods were available to measure the linear velocity of gases entering and leaving the wet scrubbers. The first approach utilized an Alnor velo- meter, while the second involved a standard pitot tube and inclined manometer combination. Of these alternatives, the pitot tube/manometer combination represents the preferred measurement method.

Unfortunately, all feasible sampling locations at the plant were poorly situated, often being immediately before or after a bend or discharge point. When the pitot tube was utilized at these locations, considerable variability was seen in the moment-by-moment pitot tube readings, making the estimation of an average value very difficult. Thus, any average

84

obtained would have represented an estimate of the true value, and it was decided that use of the Alnor velometer would provide data of equal validity, while facilitating the measurement process.

Chromic Acid and Sulfuric Acid Duct Samples--
Chromic acid and sulfuric acid samples were collected simultaneously with a commercial version of an EPA Method 5 sampling system.[3] The basic components of the system included a heated probe and quartz fiber filter backed up by a series of two wet and two dry impingers. Each of the wet impingers contained 100 ml of 0.1 N sodium hydroxide solution; one of the dry impingers was filled with 200 grams of silica gel, and the other dry unit was empty. A schematic of the sampling system is shown in Figure B-4.

After preliminary velocity determinations had been completed at the only accessible duct locations, it was decided to economize on the sampling effort by reviewing single points corresponding to the average velocity in the ducts. Since no accessible sampling location complied with Method 5 requirements, and since Reference 2 indicates that acid mists from open surface tanks have a mean particle size in the range of 0.5 to 3.0 micrometers, it was judged that duct traverses would not significantly improve the accuracy of results for the purposes of this investigation.

After the sampling system was assembled and leak checked under vacuum, the nozzle was placed at the chosen point, but oriented 180 degrees out of the direction of flow while the probe and filter were allowed to heat to 120 to 150°C (250-300°F). When ready, the probe was rotated so that the nozzle was in the direction of flow, and a sample was collected for approximately one hour. Subsequently, the system was allowed to cool before disassembly and cleaning. Three distinct sample fractions were retained for chemical analysis: 1) the probe distilled water rinse, 2) the quartz fiber filter, and 3) the impinger solutions and rinsings.

Upon return to the laboratory, all three of the collected fractions were analyzed for chromic acid content. Since the probe rinsings and impinger solutions were already in a dilute aqueous media, they were directly analyzed by direct current coupled plasma optical emission spectroscopy (DCPOES) without further sample preparation. The filters, however, were extracted with a 0.25 M solution of sulfuric acid before chemical analysis.

Sulfuric acid concentrations were measured in two sample fractions: the probe wash and impinger solutions. The analytical technique used for these determinations was the barium perchlorate thorin titrametric technique as described in detail within NIOSH reference method S-174 in Reference 4.

Moisture Determinations in Ducts--
The moisture content of the gas entering and leaving the scrubber was determined using gravimetric procedures normally associated with EPA Method 5 protocol. In operation, the water vapor either condenses within ice-cooled impingers or is removed by reaction with silica gel and measured during sample recovery.
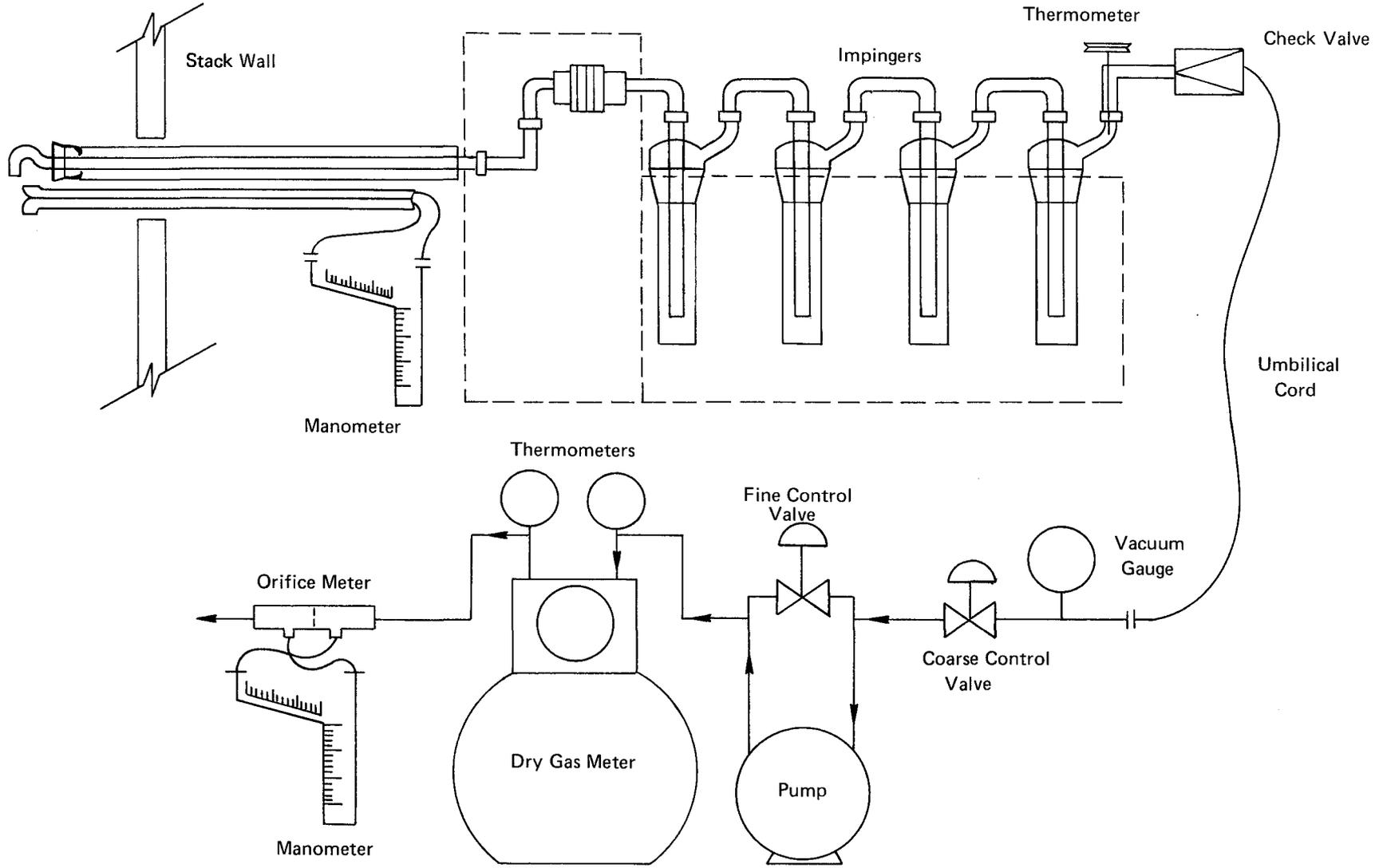
FIGURE B–4   SAMPLING TRAIN

Chromic Acid and Chromate Area Samples--
The sampling method used for these measurements is described in detail
within NIOSH reference method S-317 in Reference 4. It involved the
pulling of 1.5 liters of air per minute through a 37-mm polyvinyl chloride
(PVC) filter. Subsequent to collection, samples were returned to the
laboratory and chromic acid was extracted from filters with 0.25 M
sulfuric acid. The liquid extracts were then analyzed by direct current
plasma optical emission spectroscopy (DCPOES). This analytical technique
was chosen in lieu of described colorimetric procedures because of
the large number of samples collected during this investigation, and
because the lower detection limit of the DCPOES approach is stated to be 5
ug/l for chromium in solution.

Sulfuric Acid Area Samples--
Sulfuric acid samples were collected and analyzed in accordance with pro-
cedures detailed within NIOSH method S-174.[4] These entail drawing air
through a 37-mm cellulose membrane filter to collect sulfuric acid species.
Upon return to the laboratory, the filters are water leached, and sulfate
containing liquid is analyzed using a barium perchlorate-thorin titrametric
method.

Other Measurements--
In addition to the previously mentioned chemical measurements, hood face
velocity and room relative humidity (R.H.) determinations were conducted.
The relative humidity was measured with a sling psychrometer (wet bulb-
dry bulb thermometer), while all face velocity measurements utilized
the Alnor velometer. Results for the face velocity measurements are
listed in Table B-1. All room (and duct) humidity measurements indicated
95-100 percent R.H.

RESULTS AND DISCUSSION

General Area Samples

Chromic Acid--
Solid and lettered dots on Figure B-1 designate locations at which general
area samples were obtained. Table B-3 provides the results of this effort
for chromic acid and other contaminants of interest.

The results for chromic acid are encouraging. All concentrations measured
under normal operating conditions were substantially below OSHA's acceptable
ceiling concentration of 0.1 mg/m^3 and the 8-hour time-weighted average
(TWA) concentration of 0.05 mg/m^3 recommended by NIOSH and the ACGIH.
Indeed, not one exceeds 33 percent of the lower limit, and most are
considerably less.

The situation in the vicinity of location I after the scrubber released
accumulated acid was quite different. Initially after the release,
concentrations of chromic acid were more than 16 times the ceiling limit.
When all wall fans and ventilation systems were activated, concentrations
dropped significantly but remained well above limits for quite some time.

87

Table B-3. Area sampling results.

Position	Start Time	Contaminant	Concentration (mg/m^3)	Comments
A	8:42 am	Chromic acid	0.00199	At 1.22 m (4 ft) height
B	9:59	Chromic acid	0.00322	As above
C	8:52	Chromic acid	0.00374	At 1.37 m (4.5 ft) height
D	9:44	Chromic acid	0.01389	At 1.07 m (3.5 ft) height
E	9:17	Chromic acid	0.00941	0.2 m (0.67 ft) over tank rim
E	11:03	Sulfuric acid	0.59	As above but 155 minute sample
F	10:14	Chromic acid	0.03733	At 1.22 m (4 ft) height
G	11:45	Chromic acid	0.00243	At 1.68 m (5.5 ft) height
G	12:18 pm	Sulfuric acid	0.40	As above but 173 minute sample
H	10:40 am	Sulfuric acid	1.26	88 minute sample at 1.83 m (6 ft) height
I	10:45	Chromic acid	0.01644	At 1.68 m (5.5 ft) height
J	10:56	Chromic acid	0.00322	At 1.52 m (5 ft) height
K	10:25	Chromic acid	0.00356	On tank edge at 1.37 m (4.5 ft) height
L	11:12	Chromic acid	0.00051	As above
M	11:54	Chromic acid	0.00241	At 1.37 m (4.5 ft) height
N	11:37	Chromic acid	0.00217	As above
O	12:03 pm	Chromic acid	0.00192	At 1.22 m (4 ft) height
P	12:15	Chromic acid	0.00160	As above
Q	12:29	Chromic acid	0.00358	At 1.52 m (5 ft) height
I	2:46	Chromic acid	1.60259	Taken after acid release from scrubber
I	2:49	Chromic acid	0.47970	
I	3:12	Chromic acid	0.98551	
I	3:27	Chromic acid	0.45342	

Sulfuric Acid--
Since sulfuric acid is simply used as a catalyst in plating tanks at a
typical ratio of 100:1 chromic to sulfuric acids, researchers were
originally under the impression that only traces of sulfuric acid, if
any, would be found in the air. This contention was supported by
observations in a number of literature sources which reported that only
chromic acid mist was a significant contaminant generated from chrome
plating operations. In consequence, only a few sulfuric acid samples
were planned, simply to demonstrate the validity of what was thought to
be a well-known fact.

The concentrations measured, however, were significant, ranging from 0.40
mg/m^3 on one side of tank #14 to 1.26 mg/m^3 on the other side. Thus, an
area near this tank might expose an employee to sulfuric acid concentrations
in excess of OSHA's 8-hour TWA limit of 1.0 mg/m^3, if the employee were
to remain in this area for significant time periods. Since the area is
only occasionally visited by employees, however, this is not a significant
finding.

A concentration measurement of 0.59 mg/m^3 over the rim of tank #5 tends
to confirm the potential for sulfuric acid emissions. Nevertheless,
the researchers who performed the survey had some misgivings about the
cause of these results. It was entirely possible that the household
detergent used for mist suppression contained a sulphate-based surfactant,
and that emissions from this source had contributed to measured concen-
trations.

The only personal sample obtained before the survey was prematurely ter-
minated involved an employee who was "flash" plating a small batch of
parts. This required reloading of plating tank #6 every seven minutes,
and brought the employee closer to a tank much more often than any other
operation. Analysis of this sample gave a concentration for chromic
acid of 0.00847 mg/m^3. This was approximately the average for the three
area samples taken in the same room at locations C, D, and E, and is only
8.5 percent of the ceiling limit.

Duct Samples--
Table B-4 presents the results of the duct samples taken from inlets
and outlets to the scrubbers respectively installed on tanks #4 and #14.
These suggest that the efficiency of the newer unit on tank #14 was 98.23%
for chromic acid even though it was being improperly operated. It can
only be theorized that the mist was impinging upon exposed surfaces and
was being captured in this fashion. For sulfuric acid, the scrubber
efficiency is indeterminable because both measurements are at the lower
limit of the analytic method used.

The results for the old scrubber on unit #4 suggest efficiencies of 86.6%
for chromic acid and 79.3% for sulfuric acid. These are consistent
and reasonable, given that water was flowing through the unit, and that
the unit was obviously in poor condition.

Table B-4. Duct sampling results.

Scrubber on Tank #4 (old)

Inlet

Volume of sample: 1.411 m^3 (49.84 ft^3) at STP

Chromic acid concentration: 0.8599 mg/m^3

Sulfuric acid concentration[*]: 0.01 mg/m^3

Outlet

Volume of sample: 1.436 m^3 (50.72 ft^3) at STP

Chromic acid concentration: 0.0152 mg/m^3

Sulfuric acid concentration[*]: 0.02 mg/m^3

Scrubber on Tank #14 (new)

Inlet

Volume of sample: 0.865 m^3 (30.55 ft^3) at STP

Chromic acid concentration: 0.1970 mg/m^3

Sulfuric acid concentration: 0.29 mg/m^3

Outlet

Volume of sample: 0.865 m^3 (30.55 ft^3) at STP

Chromic acid concentration: 0.0264 mg/m^3

Sulfuric acid concentration: 0.06 mg/m^3

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[*] These concentrations are at the lower detection limit of the
analytic method used.

VALIDATION OF RECIRCULATION APPROACH

Introduction

To aid others who may consider the recirculation of chrome plating exhaust
volumes by use of small wet scrubbers, and to facilitate evaluation of
the recommendations of Reference 1, it is desirable to briefly review
and apply in retrospect the design steps outlined there. These steps
are listed in Chapter 2 of that document and are discussed in various
chapters and appendices.

Initial Feasibility Assessment

Legal Issues--
Both the state in which this plant resides and the Federal government do
not generally prohibit the recirculation of exhaust volumes containing
toxic contaminants if employee exposures are maintained at or below
permissible limits. State industrial hygiene personnel, however, do not
generally approve of the practice, and will discourage recirculation unless
numerous precautionary measures are taken.

Energy Consumption--
Estimates of the total exhaust volume recirculated in this plant range
up to 16.5 m^3/s (35,000 cfm) when all systems are operative. Estimation
procedures in Chapter 7 of Reference 2 provide a heating cost estimate for
an equivalent volume of make-up air which ranges up to $27,500 per year,
but is more likely on the order of $22,000 for oil heat at early 1978
prices. Since the local exhaust systems and air cleaners are necessities
at this site, savings related to these potential make-up air costs are
mostly attributable to recirculation.

Contaminant Classification--
The major airborne contaminants in the plant were chromic and sulfuric
acids generated for the numerous hard chrome plating tanks. Any others
could be assumed to be in trace quantities, since other tanks requiring
ventilation were few (4 to be exact) and control systems for these appeared
to be fully adequate. For a plant similar to the one studied, knowledge
of concentrations for these contaminants (before recirculation is
implemented) would be required throughout all work areas, exiting currently
installed air cleaners, or in ducts leading to the locations at which
new air cleaners are intended for installation. Such data would be
necessary for typical as well as worst case operating conditions.

In the plant studied, the potential cost of such an effort would likely
be reasonable relative to the magnitude of potential energy savings. Indeed,
if the plant had periodically conducted surveys of inplant air quality
in the past, costs would be rather minimal. Alternatively, if the number
of airborne contaminants had been substantially greater, and/or if many
radically different processes had been conducted in the same plant area,
these sampling costs could potentially be substantial.

Air Quality Regulations--
According to plant management, control of acid emissions into the external environment is a necessity. Specific air pollution regulations could not be cited, but are presumably in effect.

Air Cleaner Availability--
Wet scrubbers are obviously available and utilized for emission control purposes. Hence, the availability of air cleaners does not impose a restriction on the decision to further investigate the feasibility of recirculation. What does give some cause for concern is the fact that air leaving a scrubber may be saturated with water vapor. In a normally dry environment, recirculation of such air may be beneficial. In the somewhat warm and humid environment typical of a metal finishing shop, the additional humidity may accelerate equipment deterioration and/or cause internal condensation problems on walls or roofs.

Although air dehumidification devices are commercially available, these require capital expenditures and operating expenses which can easily negate the potential savings attributable to recirculation. Thus, each plant using wet scrubbers in recirculation systems must decide for itself whether additional humidity is undesirable.

The manufacturer of one of the unit types utilized in the plant of interest claims the following efficiencies for two types of packed tower fume scrubbers it markets:

	Removal Efficiency (%)	
Contaminant	Type 1	Type 2*
Alkaline cleaners	98-99	95-99
Anodizing solutions	99	98-99
Chromic acid	99	99
Cyanides	99	98-99
Hydrochloric acid	97-99	85-95
Sodium hydroxide	99	99
Sulfuric acid pickle	99	98-99
Misc. plating	99	97-99

Additionally, it notes that a highly efficient mist eliminator removes more than 99 percent of entrained moisture from the exhaust. Hence, it is clear that fairly high efficiency units are available for plating shop operations.

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*Type 2 is of lower cost than Type 1, has shallower packing bed depth and lower pressure drop

For the newer version of the type of unit utilized in the plant of
interest, which is of even lower cost and not packed, efficiencies
claimed are:

Contaminant/Operation	Removal Efficiency (%)
Alkaline cleaning	97-99
Anodizing	97-99
Caustic soda	97-99
Chromic acid plating	98-99
Cyanide	95-99
Detergent	97-99
Phosphate	95-98
Phosphoric acid	97-99
Sulfuric acid pickle	97-99

It will be remembered that the efficiency measured for the scrubber which
had accumulated acid was 98.23 percent for chromic acid. This result
suggests that the impingement action of certain scrubbers is quite
effective, and is supported by the fact that the survey team's probe
in the inlet duct was completely coated with greenish-black fluid, while
the probe on the outlet side remained clean. The claim of a 99 percent
efficiency for the unit's mist eliminator may therefore be quite valid.

Monitor Availability--
Devices for monitoring water and air flows and power usage are readily
available. A limited search, however, did not indicate the commercial
availablility of a continuous or intermittent monitoring system for
airborne concentrations of chromic acid or sulfuric acid. Thus, it is
possible to ensure that a scrubber is operating, but it may be difficult
to ensure it is performing at peak efficiency.

The lack of monitoring devices for concentrations is cause for concern
with these contaminants, and must be given further consideration before
any final decision to recirculate in similar plants. Obviously, there
is some risk in recirculating when equipment for automatic monitoring
is unavailable and the plant does not have the personnel or laboratory
facilities for manual sampling and analysis techniques.

Process Emission Profile--
The generation rate of contaminants from plating baths is apparently
a complex function of solution strengths, applied current density, tank
loading, exposed tank surface area, temperature, the effectiveness of
surfactants (if used), and also, if used, the effectiveness of floating
plastic balls. One would expect, therefore, that the concentrations of
contaminants in ducts to scrubbers can vary widely with specific
operating conditions.

In a job shop environment, this suggests the need for a conservative
approach to the implementation of recirculation. It also suggests a need
to define and/or establish the conditions under which the system may

potentially operate, and to ensure that all digressions from these conditions consider the effects on recirculated air quality.

Ventilation System Design--
Application of small wet scrubbers to plating tanks requires ducting from the tank to the scrubber, an open location to situate the scrubber (about 3-6 m^2 or 10-20 ft^2 of floor space for a 1.9 m^3/s, 4,000 cfm unit), and ideally, a bypass duct allowing discharge outdoors for emergency situations or warm weather use. Hence, any system would be relatively compact, and would not normally require significant modifications to existing or proposed conventional ventilation systems.

Alternatively, one may consider the use of one or more larger capacity units, each serving the needs of a number of plating tanks. This approach would have a cost advantage, would require fewer bypass ducts to the outdoors, and would facilitate inspection and maintenance activities. However, it would require larger open areas for unit placement, more complex ducting systems, and a greater dependence upon the reliability of the units. Also, it would complicate the task of return air distribution, since many small units inherently provide better distribution than one large unit when elaborate distribution systems are not desired.

Conclusion--
The purpose of an initial feasibility assessment is to provide an indication of whether recirculation is worthwhile or possible before proceeding with detailed and expensive design efforts. In this evaluation, it has been seen that there is substantial potential for energy savings, since only the capital costs for performance monitoring systems and bypass dampers are additional to those for normal air cleaning systems, and it appears feasible to maintain contaminant concentrations below permissible exposure limits. On the negative side, it was seen that additional humidity may be problematic, that one must consider the risks associated with the non-availability of monitoring methods for contaminant concentrations, that a conservative design approach is necessary to account for process emission variations, and that the cost for contaminant characterization and concentration measurements may be substantial in some plants.

Contaminant Characteristics

This step involves the identification of all airborne contaminants, and the quantification of their concentrations and characteristics at various locations in the work place. Additionally, it requires the selection of acceptable and/or desirable breathing zone concentrations for use as "target" values in the design process.

Discussions with plant management indicated that no attempt was made prior to implementation of recirculation 20 years ago to quantify existing contaminant levels. Rather, it was assumed (and to some extent still is) that wet scrubbers are 100 percent efficient. Obviously, in a present-day setting, a disregard for existing concentrations and the actual efficiency of air cleaning units could lead to exposures in excess of permissible limits.

The characteristics of the contaminants partially define the materials of construction necessary for air cleaners and ductwork. The observations of rusted-through ductwork and scrubbers suggests that there has been little concern for such matters. Many systems were operating below optimum conditions because of such deterioration.

Work Place, Process, and Ventilation System Characteristics

This step essentially involves a characterization of the work place in terms of air volumes handled, locations of air inlet and outlet locations, work station locations, air flow patterns, and other factors. The resulting data are used in the design approach recommended to assist in the estimation of work place conditions after recirculation is implemented. Without such a characterization, it is envisionable that return air streams could be poorly distributed, and could ultimately cause excessive exposures.

Selection of Air Cleaning Equipment for Further Consideration

To assist in the final selection of air cleaning equipment, Reference 1 suggests identification and information gathering for all equipments pertinent to the task of cleaning contaminated air streams. Since the availability, efficiency, economics, maintainability, and general reliability of air cleaners can vary among units of a particular type, this step helps ensure that the best overall unit is ultimately selected for use.

Given the erroneous assumption on the part of plant management that all wet scrubbers are essentially 100 percent efficient, it can be deduced that the selection procedure only considered price and rated capacity in the plant of interest. This is a dangerous practice, because the percentage point or two greater efficiency that may be provided by a slightly more expensive unit may mean the difference between final acceptability of the recirculation system and non-compliance with health standards.

Selection of Surveillance Equipment for Further Consideration

Reference 1 clearly denotes the need for some sort of reliable methodology to detect reduced system performance. The plant in question clearly did not consider utilization of surveillance equipment of any type. If it had, one would expect that the problems with the two wet scrubbers investigated would have surfaced long ago.

Determination of Feasible System Configurations

This step involves definition of all system configurations feasible for implementation, and sets the stage for selection of the one configuration which provides the best balance between overall health safety and cost savings. Additionally, it leads to consideration of bypass ducts for emergency and warm weather use.

The plant in question did not provide bypass ducts to the outdoors, presumably because of the expense involved and a non-appreciation for their usefulness. In direct consequence, the shop is considerably warmer and more humid than it needs to be during warm weather. If such ducts had been installed, one would also expect that the emergency situation encountered during the survey could have been provided a more appropriate response. As it was, plant personnel were rather helpless to promptly rectify the situation.

Design Optimization for Feasible Configurations

The optimization procedure in Reference 1 is intended to allow predictions as to the effect of recirculation upon the working environment. Thus, it will provide an indication of whether or not any proposed system will maintain an acceptable environment.

It is clear that the "success" of recirculation in the plant studied resulted from an accidental combination of circumstances and luck. If the loadings to the air cleaners were higher, and/or if the efficiency of the air cleaners in aggregate were lower, recirculation may have caused noncompliance with health standards. The value of an analytical approach to the design process is that it removes from consideration all obviously nonworkable concepts, and suggests a system design which should theoretically function safely.

Failure Analysis for Feasible Configurations

It is easy to assume that a recirculation system will never fail, or to assume that a failure would have inconsequential results. The assumption allows the design and installation of a system with no consideration of severities associated with failures. To guard against the real possibility that systems may fail, however, Reference 1 suggests the performance of a failure analysis for each system configuration of interest.

In the plant of interest, a failure analysis would have identified a failure mode as being the accumulation of strongly contaminated liquids when the water flow is off and/or when the drain connection becomes plugged. With the possibility that these liquids may be sprayed into the air, the analysis might have led to consideration of means to prevent this occurrence.

A deficiency in Reference 1 in this area, however, is the nonmention of the possibility that certain air cleaners can accumulate contaminants and discharge them at once with possibly catastrophic results. In that document, it was assumed in analytical procedures that air cleaner failure usually involves a zero air cleaner efficiency. In a previous case study dealing with bag filters, and in this case study, it has been seen that certain failures have the potential to expose employees to concentrations in excess of those associated with a zero cleaning efficiency.

Selection of the Best Configuration

Assuming several options for recirculation system designs are being evaluated, a selection process allows choice of the configuration providing the best balance of health safety and cost savings. With input from previous design steps, it forces attention to all issues involved. For the plant of interest,

it must be concluded that application of the recommended approach would minimally have suggested the provision of bypass ducts, and provision of surveillance equipment for scrubber air flow, power usage, and/or water flow.

Final Equipment Selection, System Design, and Installation

Final selection of equipment requires professional judgment for choosing specific types of equipment which will meet or exceed desired performance criteria. Detailed system design and installation entails translation of general system specifications into hardware requirements. These steps are listed by Reference 1, but do not involve or necessitate detailed discussion.

System Performance Validation

Once a system has been installed, Reference 1 suggests that it be inspected and tested to ensure it will operate as intended. This is a most reasonable recommendation and also does not warrant discussion.

Planned Maintenance and Inspection

In no uncertain terms, Reference 1 states "It is imperative that components of recirculating exhaust systems be maintained and inspected as necessary to insure continued, satisfactory performance." A chapter on the subject discusses equipment inspection and maintenance, periodic air sampling studies, record-keeping, and failure response planning.

It is in this subject area that the plant studied can be faulted. Although there was considerable activity underway to rebuild two scrubbers, two other units arbitrarily and randomly selected for inspection had serious deficiencies. If periodic and comprehensive inspections had been provided, the holes in one unit and the shut-off water valve in the other would have been promptly identified and corrected.

Except for an occasional and cursory inspection by an insurance company representative, and a single OSHA inspection some years ago, air sampling studies have not been performed in this plant. Although the plant was found to be in compliance with permissible exposure limits, it would not have had knowledge of this fact if it had not cooperated in this study program. It just as well could have been out of compliance.

Any sort of failure response plan communicated to employees could have facilitated actions necessitated by the scrubber malfunction. As it was, nothing was done until survey team members requested the activation of all exhaust systems in the affected plant area and a brief retreat by employees until the air began to clear.

Recirculation Model

A full evaluation of Reference 1's recommended approach to recirculation requires consideration of the analytical design procedures, i.e., "models," contained therein. The model of specific interest to this case study involves

application of unit collectors to local exhaust systems, and is designated
as System Configuration #3 in Appendix B of that document. Figure B-5 is a
reproduction of the page of interest. Table B-5 defines the symbols shown
on the figure, while a section in a previous case study for grinding operations
(see Spring Grinding) provides an example of how the model was intended for
use.

The model consists of three equations. The first of these assumes a perfect
air balance in the plant before recirculation is implemented, and allows
computation of the fresh make-up air rate necessary with recirculation. This
latter rate has two components; one which essentially describes a minimum
rate of fresh air selected by the system designer (Q'_{MU}), and one which des-
cribes an additional rate necessary for a balanced system with recirculation
(Q_{MU2}). The difference between the make-up air supply rate before recircu-
lation (Q°_{MU}) and the total rate with recirculation, i.e., the sum of Q_{MU2} and
Q'_{MU}, is the savings in make-up air to be realized. This difference is equiv-
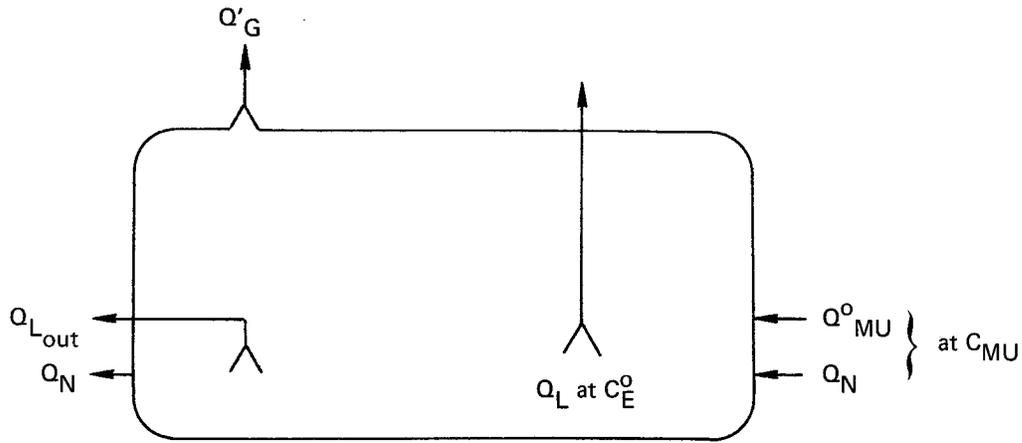alent to the total volume rate of air being recirculated through the unit
collectors.

The next equation (for C_R) on the figure utilizes various parameter values to
predict the concentration(s) of contaminant(s) in air leaving unit collectors.
It is followed by an equation which estimates the concentration(s) of contam-
inant(s) in selected breathing zones after recirculation is implemented.

A basic concept upon which the model is formulated is that a mechanical make-up
air supply system existed before recirculation, and that recirculation is de-
sired to reduce the volume of this air supply rate. Thus, the air balance
equation is not fully applicable to a plant which relies upon natural ventil-
ation for make-up air, and which utilizes internal heating devices for temper-
ature control. In such a plant, recirculation would simply reduce the natural
ventilation rate roughly by the rate of air being recirculated and reduce the
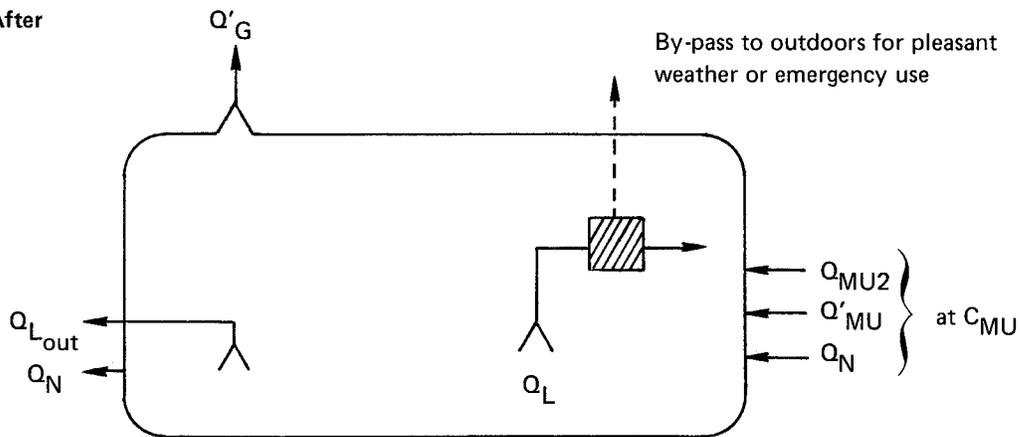need to operate space heaters.

The equation for estimating the concentration(s) of contaminant(s) in the re-
turn air streams from collectors utilizes an air cleaner efficiency, initial
contaminant loading(s), concentration(s) in fresh make-up air, and a factor
(k_R) which describes the fraction of air entering air streams to be recir-
culated which originated in such streams. The equation can be utilized in a
very straightforward manner when 1) only a single unit collector is to be in-
stalled; 2) a number of unit collectors are to be widely separated in the plant;
and/or 3) when all operations conducted and collectors to be utilized are
identical in important aspects.

When many collectors are to be located in a relatively small area, and each of
the systems has its own peculiar characteristics, rigorous application of the
equation requires a complex judgmental assessment of post-recirculation con-
ditions on a case-by-case basis. The basic problem stems from the fact that
each operation to be controlled may present a different process emission pro-
file, that each operation may not involve the same airborne contaminants in
the same proportions, and that more than one return air stream may provide air
to be recycled by a particular air cleaning device.

98

Before

After

By-pass to outdoors for pleasant weather or emergency use

Determine Suitability of Unit Collector(s) from:

$$Q_{MU2} = Q_{L_{out}} + Q'_G - Q'_{MU} = Q^o_{MU} - Q_L - Q'_{MU}$$

$$C_R = \left[\frac{(1-\eta)\,(C^o_E - k_R\,C_{MU})}{1.0 - (1-\eta)\,k_R} \right]$$

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

Note: Q_L should be the total volume through all unit collectors, if more than one is to be installed.

Figure B–5. System design model.

Table B-5. Definition of symbols.

Q_T^o — The pre-recirculation total ventilation rate through the plant area to be affected by recirculation.

Q_T — As above, but pertains to the post-recirculation rate.

Q_{MU}^o — The total volume rate of mechanically provided make-up air before recirculation.

Q_N — The natural ventilation (infiltration) rate.

Q_L — The total exhaust volume rate for local exhaust streams to be recirculated.

$Q_{L_{out}}$ — The total exhaust volume rate for local exhaust streams not to be recirculated.

Q'_G — The general mechanical ventilation (exhaust) rate.

Q'_{MU} — A minimum rate of fresh make-up air to be introduced during recirculation.

Q_{MU2} — An incremental rate of fresh make-up air to be introduced during recirculation.

C_{MU} — The concentration(s) of pertinent contaminants in fresh make-up air.

C_E^o — The concentration(s) of pertinent contaminants in local exhaust streams to be recirculated before recirculation.

C_R — The concentration(s) of pertinent contaminants in return air streams (i.e. leaving air cleaners).

C_{BZG}^o — The concentration(s) of pertinent contaminants in selected breathing zones in "open" plant areas.

C_{BZL}^o — The concentration(s) of pertinent contaminants in selected breathing zones in strong local exhaust induced flow fields.

η — The air cleaner efficiency for each contaminant.

k_{BZ} — The physical fraction of air, in selected breathing zones, which originates in return air streams.

k_R — The physical fraction of air which enters local exhaust systems being recirculated and which itself originates in return air streams.

f — The fraction of time that selected employees spend in strong local exhaust-induced flow fields.

Problems associated with the breathing zone concentration prediction equation are similar. In this case, it is unclear which value(s) to utilize for C_R, and how to attempt estimation of a value for k_{BZ} (the fraction of breathing zone air which originates in a return air stream).

Possible Solutions--
The model in Figure B-5 is a simplified version of more complex models presented in Reference 1. A review of these models indicates that the simplified model inherently assumes the total ventilation rate through the plant will not be modified, and recirculated air volumes will replace make-up air volumes on a one-to-one basis. Since the air flow balance equation is intended to reflect these assumptions, it is correct for use in any plant which will actually replace mechanically provided make-up air with recirculated air. In concept, if not in definition, it is also correct when naturally provided make-up air is to be replaced with recirculated air. It is only necessary to acknowledge this fact before remaining model equations are applied.

In the case of the C_R equation, a system designer could apply the expression to estimate the concentrations of contaminants in each of the several return air streams. This computation could be facilitated by the assumption that the parameter k_R has a maximum value of 1.0. Since air cleaner efficiencies are usually high, and contaminant levels in fresh make-up air are usually low, the effect of this assumption would generally be negligible.

Utilization of the breathing zone concentration prediction equation requires selection of parameter values for C_R and k_{BZ}. For the former parameter, it is feasible to utilize the highest concentration predicted for any given contaminant, and to assume that all collectors discharge air at the same high level. Similarly, k_{BZ} could be assumed to be at its maximum value of 1.0. Both of these assumptions lead to conservative results which are not necessarily optimal, but which help ensure the eventual acceptability of recirculation systems.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions can be derived from the results of this case study:

1. The recirculation of exhaust air from hard chrome plating operations, by the use of wet scrubbers, is generally considered to be feasible and safe under many circumstances. Qualifications to this statement are many, however, and can be deduced from previous discussions.

2. Reference 1's recommended overall decision logic for recirculation would have suggested a different system design and a number of precautionary measures not implemented in the plant studied. In each and every case, these recommendations would have enhanced the general acceptability and reliability of the systems installed. Incidents occurring during the survey graphically confirm these findings.

3. Wet scrubbers used in recirculation systems are likely to discharge air of high relative humidity. Any plant considering their use must give detailed consideration to the possible adverse effects of an increased humidity level on a case-by-case basis.

4. Analytical procedures in Reference 1 pertaining to failure analyses do not fully consider the possibility of contaminant accumulation and catastrophic discharge.

5. The model for the use of unit collectors has limitations for some applications. These are resolvable, however, if one understands the concepts from which the model is derived and utilizes a conservative design approach.

6. Air and duct sampling studies involving multi-contaminants in a job shop environment can potentially involve substantial expense. Any decisions regarding the implementation of recirculation must consider the magnitude of these costs and their effect on the overall economic basis for recirculation.

7. Sampling results obtained from the old wet scrubber indicated that the efficiency of such units can deteriorate significantly when they are poorly maintained.

8. Comprehensive inspection and maintenance of recirculation system components on a frequent basis is an absolute necessity.

Recommendations

Recommendations which evolve from the conclusions cited above include:

1. Reference 1's section on the use of unit collectors should be used with caution. Users should be informed of the specific limitations of the model presented.

2. A failure analysis should consider the possibility of contaminant accumulation in air cleaning devices, and of subsequent major discharges to the work environment.

3. In many cases, the limitations of sophisticated air cleaning devices, the potential hazards associated with recirculation, and the rationale for necessary precautionary measures are not appreciated. NIOSH should consider an information dissemination effort through widely read industry journals and the like.

4. NIOSH should stress that the installation of a recirculating exhaust system requires an irrevocable commitment to frequent inspection and maintenance of recirculation system components.

102

REFERENCES

1. Partridge, L. J., Nayak, P. R., Stricoff, R. S., and Hagopian, J. H., 1978. A Recommended Approach to Recirculation of Exhaust Air. DHEW (NIOSH) Publication No. 78-124.

2. American Conference of Governmental Industrial Hygienists, Committee on Industrial Ventilation, 1978. Industrial Ventilation: A Manual of Recommended Practice, 15th Edition.

3. Environmental Protection Agency, 1971. Test Methods and Procedures. Federal Register, December 23, 1971, Volume 36, No. 247, p. 21882-21895.

4. Taylor, D. G., 1977. NIOSH Manual of Analytical Methods, 2nd Edition. DHEW (NIOSH) Publication No.'s 77-157-B and 77-157-C.

APPENDIX C. HARD CHROME PLATING PLANT #2

CONTENTS

FIGURES

TABLES

INTRODUCTION

Immediately after the survey described in the previous case study, a survey was initiated in yet another metal finishing plant. Whereas the first such investigation involved a plant currently recirculating its exhaust air, this survey was in a plant that currently exhausts air to the atmosphere after cleaning with large capacity wet scrubbers. The purpose of the survey, therefore, was an attempt at applying the guidelines of Reference 1 to the process of designing a recirculation system for a plant which currently does not recirculate its air.

Although plant management had serious reservations about the basic concept, it was willing to allow the survey and listen to any resulting proposals. Its basic guidelines were that: a) a two-year payback would be necessary for any capital expenditures, b) there must be no possibility of excessive contamination of the internal working environment, c) it must be shown that the increased humidity in the plant would not significantly enhance equipment deterioration, and d) that estimated energy savings are sufficient to warrant the risks associated with recirculation.
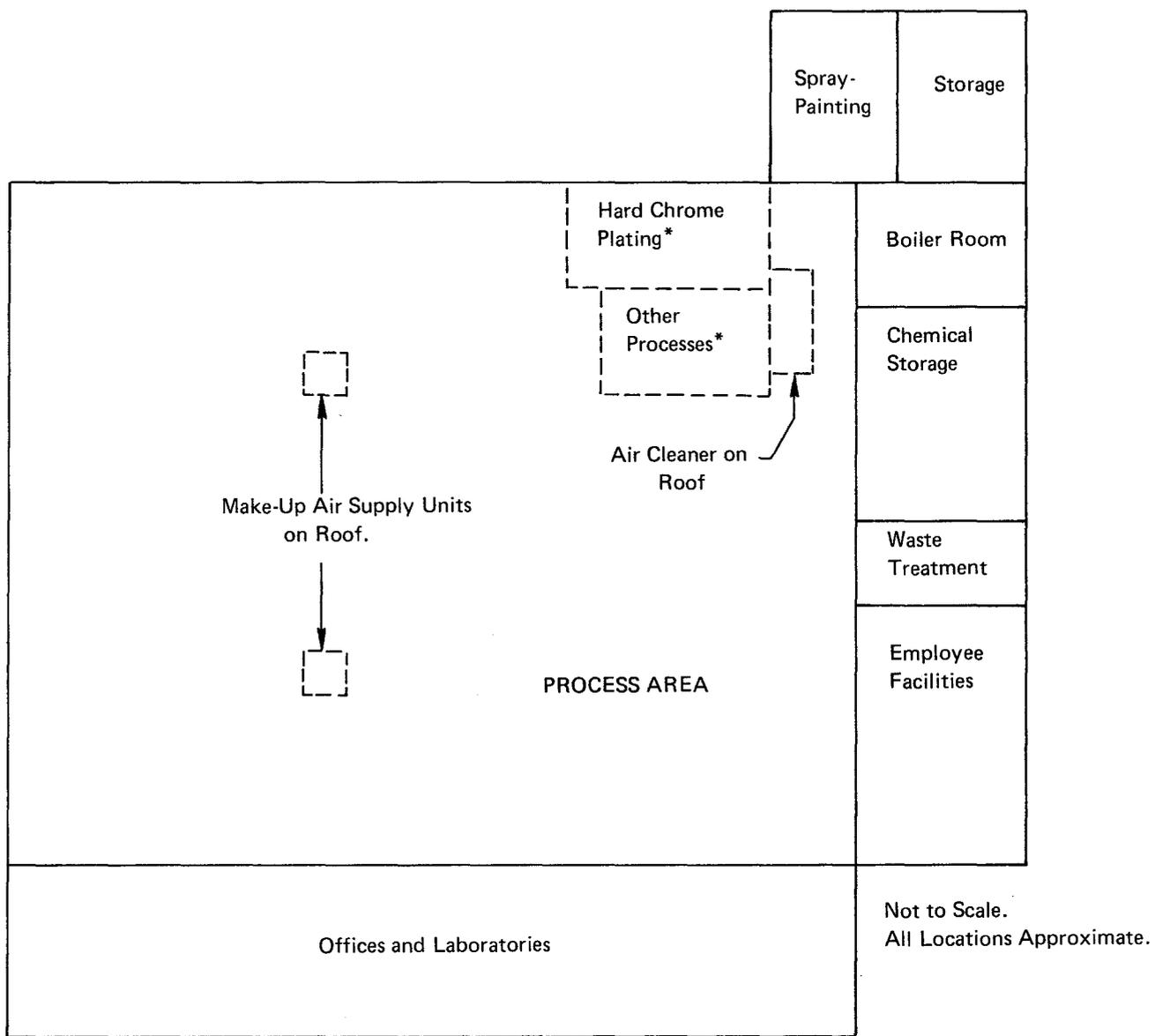
PLANT AND PROCESS DESCRIPTION

Plant Description

Covering over an acre of ground, this modern building houses metal finishing operations in a single open area with dimensions of 49 m (160 ft) by 61 m (200 ft) by 9.1 m (30 ft). Adjacent areas are rooms for spray-finishing, chemical storage, boilers, waste treatment, offices and laboratories, employee locker rooms and cafeterias, and shipping/receiving functions. Figure C-1 is a diagram showing the general outline of the plant and features of interest. Figure C-2 shows details of the specific area upon which this case study concentrated.

Process Description

Hard chrome plating is one of 22 metal plating processes conducted by the plant. All types of metal plating processes constitute 3 of the 19 metal finishing operations performed. Nevertheless, because of the high gassing rates of hard chrome plating tanks, the plating tank control systems account for 22 percent of the plant's total exhaust volume.

Adjacent to the hard chrome plating section of the plant, and controlled by the same exhaust system, were two sets of tanks utilized for a proprietary and confidential process. Based upon solution characteristics, contaminants from one set of tanks (noted as containing sodium cyanide solutions on Figure C-2) were concluded to be comprised of sodium cyanide, hydrogen cyanide, and traces of ammonia when the process is operational.

Spray-Painting

Storage

Hard Chrome Plating*

Boiler Room

Other Processes*

Chemical Storage

Air Cleaner on Roof

Make-Up Air Supply Units on Roof.

Waste Treatment

PROCESS AREA

Employee Facilities

Offices and Laboratories

Not to Scale.
All Locations Approximate.

*These share the exhaust system of interest.

Figure C–1. Overall plant layout.
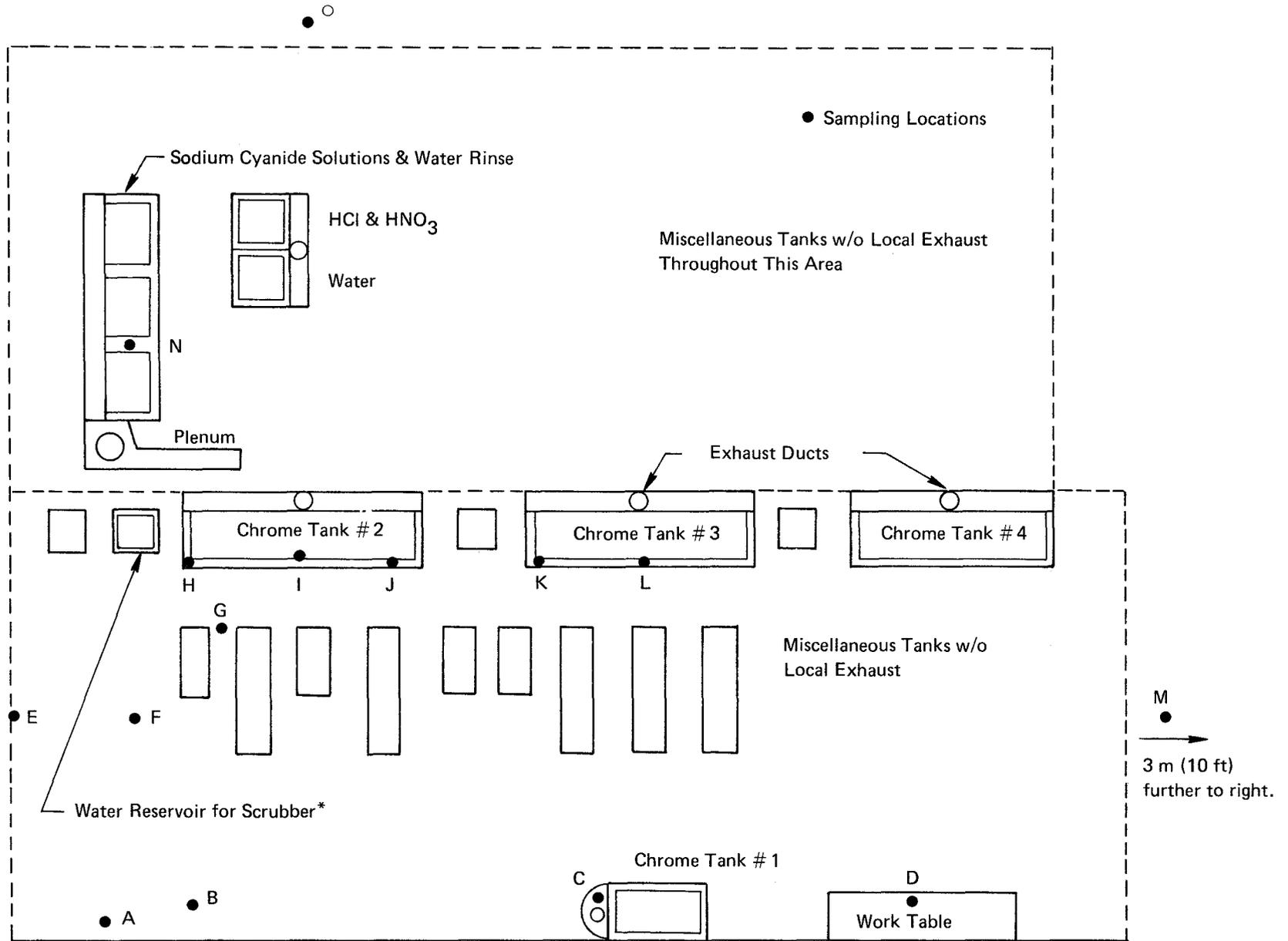
*The scrubber is on the roof immediately above.

Figure C—2. Plant area of interest.

The other tanks simply contained a solution of hydrochloric and nitric acids at ambient temperature.

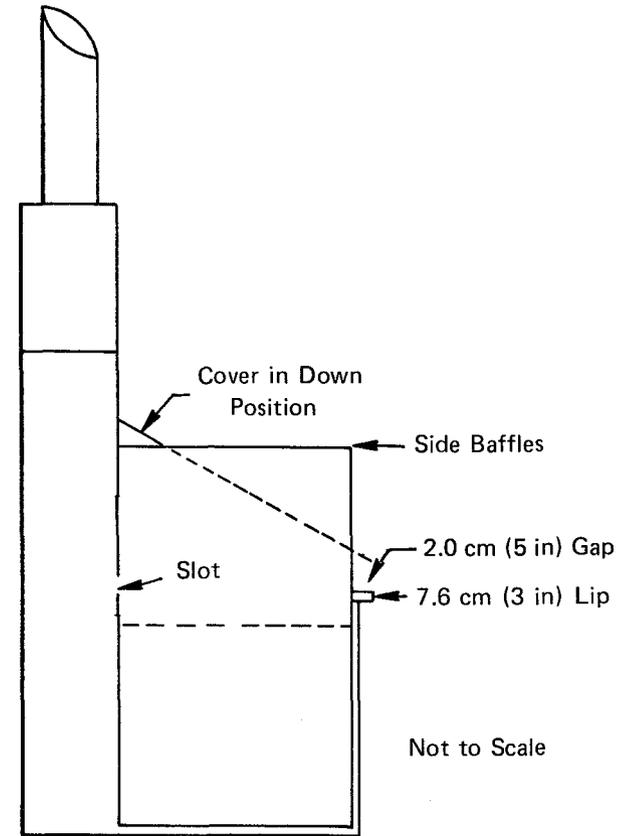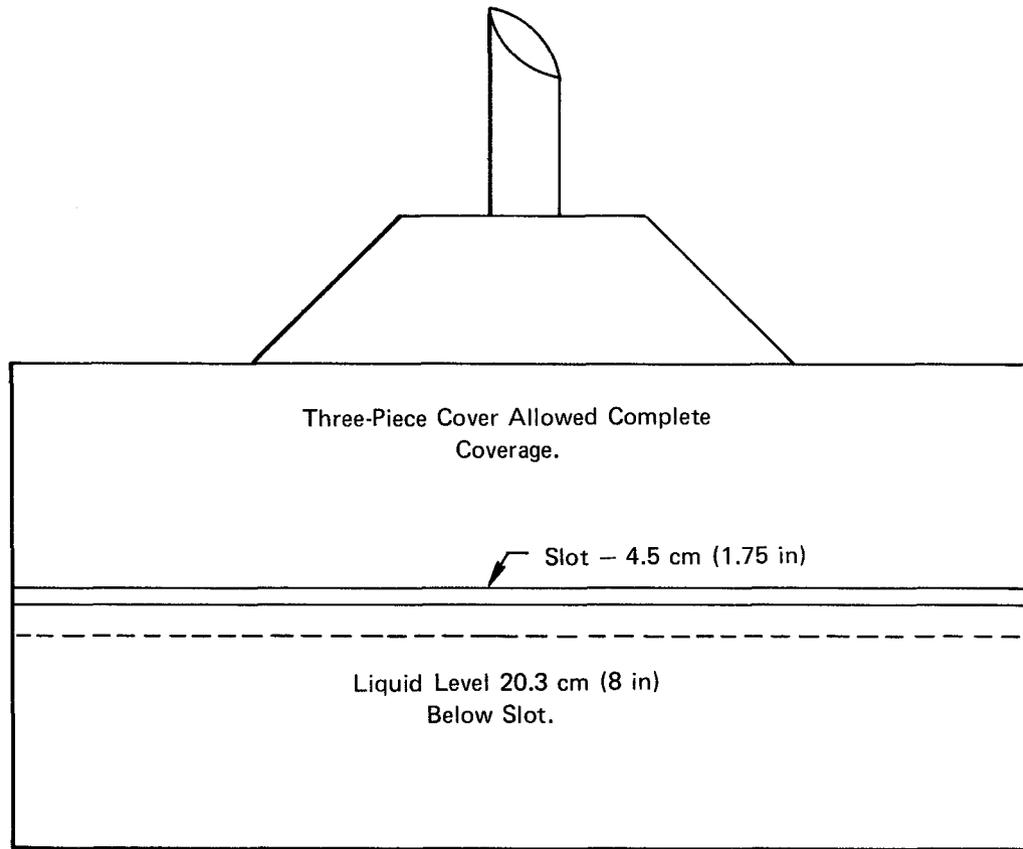Ventilation System

Local Exhaust Systems--
Within the main plant area are 4 similar local exhaust systems. One system exhausts 10 hoods over a large number of individual tanks. Solutions include chromic acid; nickel and hydrochloric acid; manganese phosphate; hot sodium hydroxide with nitrites; other hot alkalies; nitric acid; and others. Branch ducts from the hoods to the main duct are 40.6 cm (16 in) diameter. Main ducts, here and everywhere else in the plant, are 1.2 m (46 in) in internal diameter. Another exhaust system serves an anodizing area. Tanks here contain sulfuric acid, chromic acid, caustic, hydrochloric acid, and an aluminum bright dip solution which generates heavy nitrogen oxide fumes. A third system serves an area for electroless nickel plating and various processes for finishing magnesium, while the fourth system exhausts contaminants captured by the six hoods and associated tanks previously described and of interest to this study.

Each of the four systems could be operated at one of two exhaust volume rates selectable from a master control panel. A "low" setting rated at 4.7 m^3/s (10,000 cfm), or a "high" setting rated at 9.4 m^3/s (20,000 cfm). All were identical in terms of main and branch duct sizing and air cleaners utilized.

There were a number of interesting applications of lateral and enclosing hoods for controlling open surface tanks. Figure C-3 illustrates the specific hood design utilized on chrome plating tanks #2, 3, and 4, while Figures C-4 and C-5 describe hoods on the tanks with cyanide and acid solutions. Plating tank #1's design was similar to those described in the previous case study (slots along two sides) and does not warrant repetition.
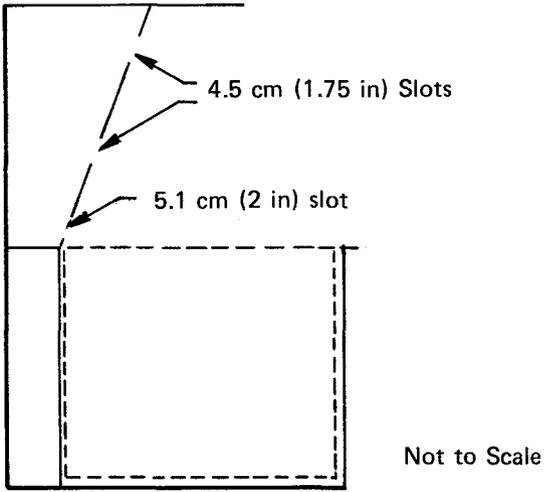
Further specifications of the various hoods and tanks are presented in Tables C-1 and C-2. The former table provides dimensions, capacities, slot velocities, solution characteristics, and other data pertaining to all tanks. The latter, for both high and low exhaust volume rate settings, compares the currently provided ratio of exhaust volume rate (Q) per unit tank surface area (A) with minimum recommendations presented in Reference 2 for chrome plating tanks. It is interesting to note that the exhaust system apparently does not satisfy the requirements of Reference 2 at either setting for any of the three operational plating tanks, although the hood on tank #2 is fairly close to Reference 2 requirements at the higher rate.

To further assess the effectiveness of the ventilation system, air velocities above the forward lip of tank #2 were measured at the high exhaust rate with the tank covers in both the upright and down position. In the former case, velocities were approximately one m/s (200 fpm). When the covers were lowered, there was a 12.7 cm (5 in) opening along the front edge of the tank, and velocities along it ranged from 2 to 2.5 m/s (400-500 fpm). These measurements indicate that higher than recommended control velocities can be achieved with lower than recommended total exhaust volumes with proper design of hooding.

Three-Piece Cover Allowed Complete
Coverage.

Slot — 4.5 cm (1.75 in)

Liquid Level 20.3 cm (8 in)
Below Slot.

Cover in Down
Position

Side Baffles

2.0 cm (5 in) Gap

Slot

7.6 cm (3 in) Lip

Not to Scale

Note: Non-functional or hidden features not shown.

Figure C—3.   Hood design for tanks # 2, 3, and 4.

4.5 cm (1.75 in) Slots

5.1 cm (2 in) slot

Liquid Level 38.1 cm (15 in) Below Lower Slot

Not to Scale
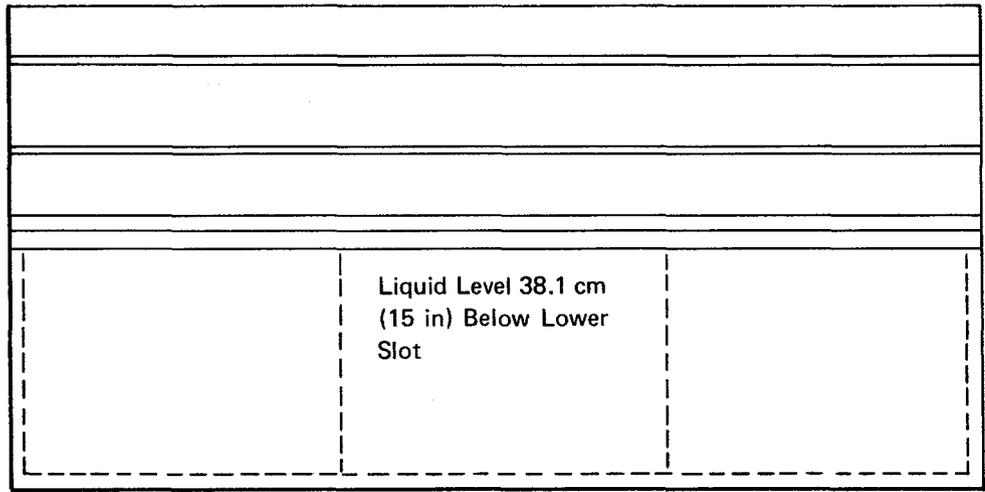
Note: Side baffles and non-functional or hidden features not shown.

Figure C—4. Hood design for cyanide solution tank.

81.3 cm
(32 in)

All Dimensions
Are 2.5 cm
(1 in)

Not to Scale

96.5 cm
(38 in)

96.5 cm
(38 in)
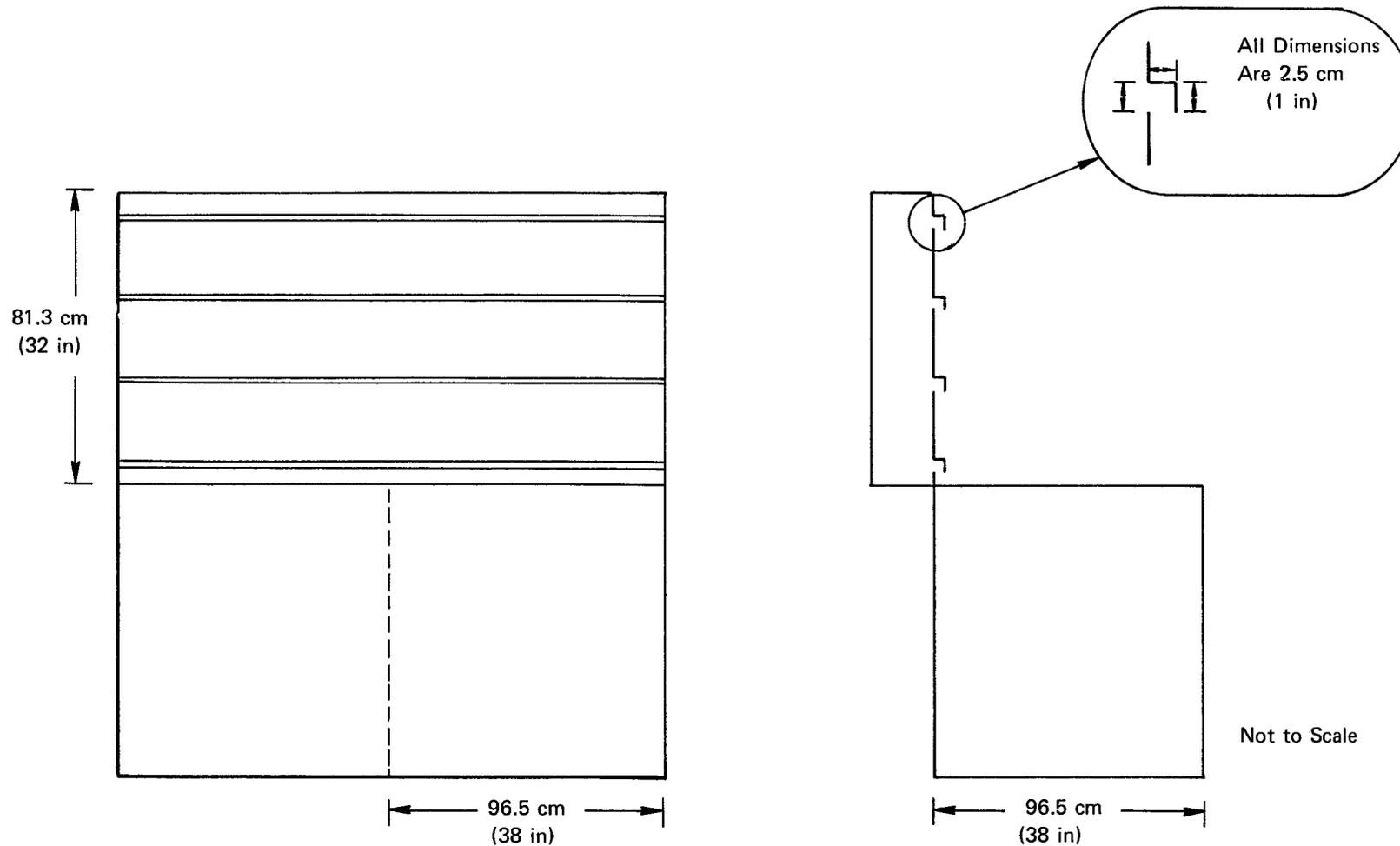
Note: This is not a normal design configuration for a slot hood.
Its use could result in an excessive hood pressure drop.

Figure C—5. Acid hood configuration.

Table C-1. Plating tank characteristics.

Tank	Surface Dimensions	Capacity	Slot Velocity on "High"	Slot Velocity On "Low"	Comments
Chrome #1	1.47 m x .76 m (4.83 ft x 2.5 ft)	0.95 m^3 250 gals	7.6-10.2 m/s (1500-2000 fpm)	3.0-4.3 m/s (580-850 fpm)	247 g/l (33 oz/gal) chromic acid and 2.47 g/l (.33 oz/gal) sulfuric acid; surface 60% covered with plastic balls and foam.
Chrome #2	3.66 m x .76 m (12 ft x 2.5 ft)	3.03 m^3 800 gals	13.2-17.3 m/s (2600-3400 fpm)	6.1-7.1 m/s (1200-1400 fpm)	397 g/l (53 oz/gal) chromic acid and 3.97 g/l (.53 oz/gal) sulfuric acid; surface 90% covered with plastic balls and foam.
Chrome #3	3.66 m x .76 m (12 ft x 2.5 ft)	3.03 m^3 800 gals	7.4-13.2 m/s (2200-2600 fpm) on left half; 2.5-3.8 m/s (500-750 fpm) on right.	6.6-7.1 m/s (1300-1400 fpm) on left half; 1.5-1.8 m/s (300-350 fpm) on right.	Solution characteristics like tank #2; right half of hood not operating properly; surface mostly covered with foam and plastic balls.
Chrome #4	3.05 m x .76 m (10 ft x 2.5 ft)	1.7 m^3 450 gals	Not measured	1.8-2.0 m/s (350-400 fpm)	This tank not used for years; mostly sealed with plastic sheeting; airflow is only through ∿ 0.6 cm (.25 in) crack running length of unit.
Cyanide	1.07 m x 1.07 m (3.5 ft x 3.5 ft) for each of three tanks.	2.3 m^3 600 gals	Unattainable	Unattainable	Solution characteristics not specified; not used often.
Acid	.97 m x .97 m (3.2 ft x 3.2 ft)	∿ 0.8 m^3 ∿ 200 gals	18.3 m/s (3600 fpm)	7.6 m/s (1500 fpm)	Contains cold solution of hydrochloric and nitric acids; not used often.

Table C-2. Comparison of current vs. recommended ventilation.

Tank	Current Q/A $(m^3/s/m^2)$	(cfm/ft^2)	Recommended Q/A $(m^3/s/m^2)$	(cfm/ft^2)
At high setting:				
Chrome #1	0.88	174	1.14	224
Chrome #2	0.89	175	0.97	190
Chrome #3	0.45	88	0.97	190
At low setting:				
Chrome #1	0.36	71	1.14	224
Chrome #2	0.39	76	0.97	190
Chrome #3	0.25	49	0.97	190

NOTE: All results pertaining to current conditions are
approximate because of difficulties in obtaining
measurements.

The ACGIH Q/A's are recommended by Reference 2.

General Exhaust and Make-Up Air Systems--
Make-up air is provided by two direct-fired supply units on the roof. Each
is designed to provide a fixed rate of 14.2 cubic meters per second (30,000
cfm). Neither has any sort of air distribution ductwork. Rather, air enters
the plant through the four sides of the bottom half of each unit near the
ceiling of the plant.

The overall air balance in the plant can vary widely. The make-up air rate
can be 14.2 or 28.4 m^3/s (30,000 or 60,000 cfm), depending on whether one or
two supply units are activated. The exhaust rate can range from 18.9 m^3/s
(40,000 cfm) to twice that in increments of 4.7 m^3/s (10,000 cfm), depending
on the number of local exhaust systems set at the high rate. The most usual
practice, however, is to mechanically supply 28.4 m^3/s (60,000 cfm) while
mechanically exhausting 18.9 m^3/s (40,000 cfm).

All air entering the plant leaves through local exhaust systems or otherwise
exfiltrates the building. There are no relief vents or other devices pro-
vided for exhaust of excess air supplies.

Air Cleaners--
The four exhaust systems include identical PVC air washers complete with woven
polypropylene mesh filter bed, water spray nozzles, liquid level sight glass,
and operation inspection port. Attached fans have 14.9 kilowatt (20 horse-
power) motors. To supply water to the spray nozzles, submersible polypropylene
pumps with 3.7 kilowatt (5 horsepower) motors and polypropylene strainer bas-
kets are supposed to provide 0.0025 m^3/s (40 gpm) water flow at 30.5 meters
(100 feet) total head. Pumps are located in small tanks on the floor of the
plant which allow recirculation of water.

Specifications for the units note the expectation that efficiency will be
"up to 90% of all water soluble contaminants." Thus, these units are the
lower cost types which provide high capacity air cleaning at efficiencies
usually sufficient for air pollution control purposes. Figure C-6 illustrates
how a typical unit appears on the roof.

In a preliminary inspection, it was noted that the drain system on the tank
holding water for the scrubber serving the chrome plating tanks was not
operational, and that the approximately 3.8 liters per hour (1 gallon per
hour) inflow of fresh water was only sufficient to offset losses out the
stack. Also, it was learned that an originally provided automatic system
for adjusting the pH or conductivity of the water supply had long ago mal-
functioned and disappeared. This led to a request for a fresh charge of water
to the tank, and confirmation that the air cleaner was operating properly
before a formal survey was initiated.

An immediate inspection of the tank upon entrance to the plant for the survey
revealed that the tank had been cleaned and filled with clear water, and that
the air cleaner on the roof had been checked two days previously. Nevertheless,
an inspection of the air cleaner indicated a water spray intensity much less
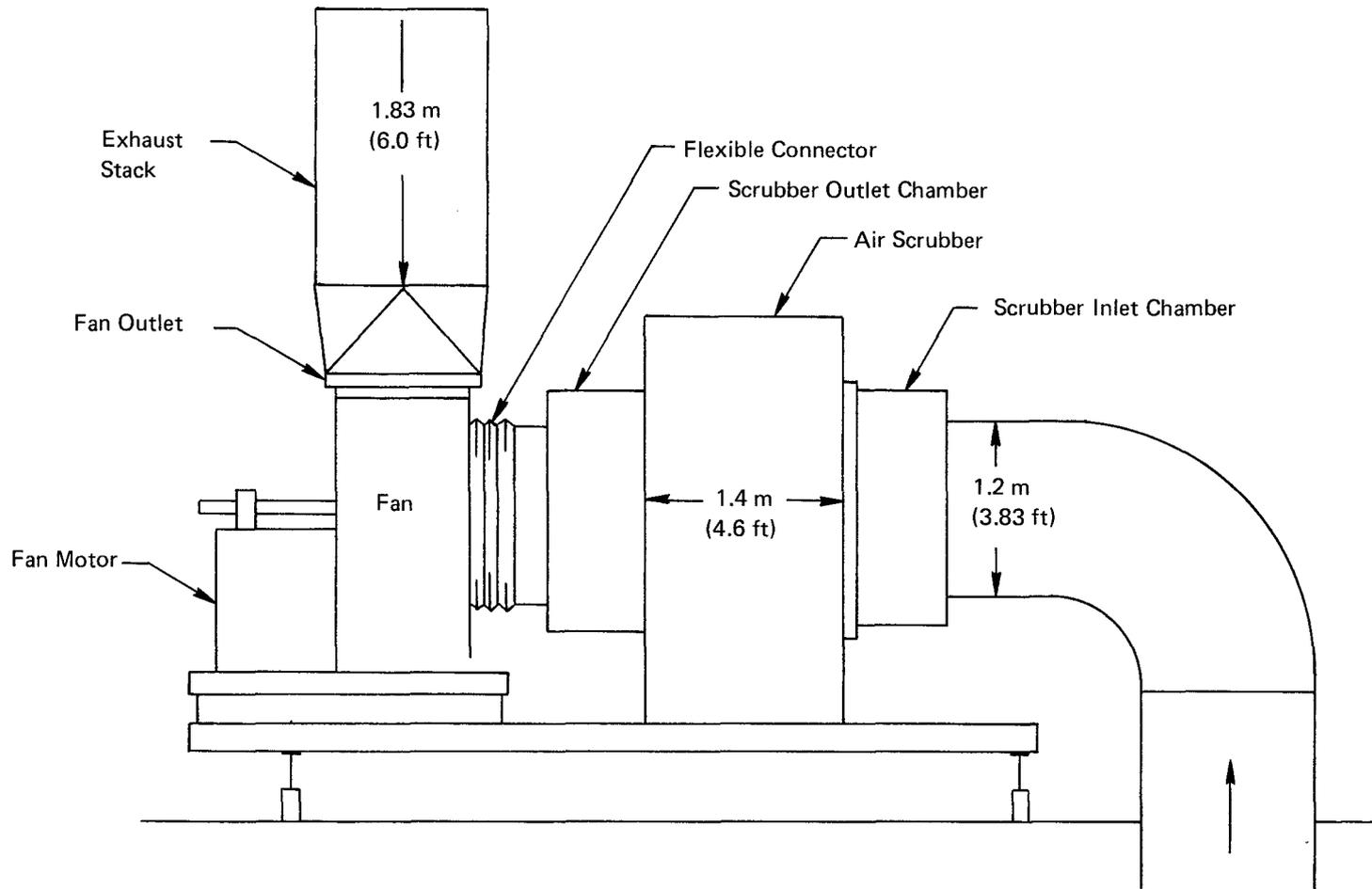than adequate for this type of unit.

Figure C–6. Air cleaner configuration.

A check of the water pump revealed a wad of masking tape partially blocking the outlet port. When this was removed, the pump was obviously operating correctly, but the water spray intensity was only negligibly improved. The conclusion was made, therefore, that the cleaning process had dislodged sludge which had plugged the almost inaccessible nozzles or some other part of the system.

Since the system was supposed to have an inline strainer at some point near the pump, the pump was given another inspection. Ultimately, it was learned that the original pump had malfunctioned some years ago and had been replaced by maintenance personnel with a spare 0.75 kilowatt (1.0 horsepower) unit without a strainer. Thus, a proper water flow could not be established even if the blockage, if any, could be found and removed.

EVALUATION METHODS

Sampling Strategy

Due to the unexpected state of the air cleaner at the time of the survey, changes in sampling strategy were indicated. Primary among these was the conclusion that the survey should proceed as planned, but that only inlet contaminant concentrations and airflows to the air cleaner should be measured.

Other desired data included general area and breathing zone contaminant concentrations for chromic acid, sulfuric acid, and cyanides; a characterization of the local exhaust system applied to the primary hard chrome plating area, and a characterization of the processes conducted during the survey within this area. For reasons cited below, other exhaust systems and plant areas were not addressed.

Sampling and Analytical Procedures

The measurement, sample collection, and sample analysis procedures utilized in this case study were essentially similar to those applied in the previously described case study involving hard chrome plating operations (see Hard Chrome Plating Plant #1). In consequence, only digressions from stated procedures are discussed below.

Velocity and Concentration Measurements in Ducts--
A standard pitot tube and inclined manometer set was utilized for duct velocity measurements. The sampling location, at the second of two rather close 90 degree bends in the duct, was far less than ideal but the only location practically accessible. The turbulence level in the duct was extreme, and results are best estimates based upon averages obtained while traversing the duct under rapidly fluctuating conditions.

For concentration measurements, a single point corresponding to the average velocity in the duct was chosen for review. Because of the turbulence level, and the numerous bends and nearby branch duct entrance locations, it was assumed that the exhaust air was well-mixed and that a traverse would not significantly improve the accuracy of the results. (According to Figure 11-14 of Reference 2, acid mists from open surface tanks have a mean particle size in the range 0.5 to 3.0 micrometers.)

Cyanide Samples--
Range-finding measurements with Kitagawa tubes indicated negligible concentrations of cyanide in work areas when cyanide generating processes were not activated. In consequence, samples were taken only at a point directly over the liquid surface in the cyanide tank to confirm that this source was of insignificant intensity.

Collection was accomplished by drawing room air through a cellulose membrane filter and a midget impinger containing 10 ml of 0.1 N sodium hydroxide solution. The total sampling time was 60 minutes and the flow rate was 1.5 liters per minute. After extracting the filter with 0.1 N sodium hydroxide, each sample was analyzed using an ion specific electrode. Specific details of the method are provided by NIOSH in Reference 3 (method S250).

RESULTS AND DISCUSSION

General Area Samples

Chromic Acid--
Solid and lettered dots on Figure C-2 designate airborne contaminant sampling locations. Table C-3 presents the results obtained on the first day of the survey when the exhaust system was on its "high" setting. Similarly, Table C-4 provides results for a second day when the system was on "low." These latter data were obtained simply to observe the effect of the lower exhaust volume rate on chromic acid concentrations.

All chromic acid concentrations measured at the higher rate were substantially below OSHA's acceptable ceiling concentration of 0.1 mg/m^3. Indeed, no measurement exceeded 1.92 percent of this value. Similarly, all were well below the 0.05 mg/m^3 concentration recommended as an 8-hour time-weighted-average (TWA) limit by the ACGIH and NIOSH. At the lower exhaust rate, all but two samples were well below cited limits.

One of these latter concentrations was obtained in the breathing zone of the operator of the chrome plating area at a table used for paperwork (i.e., location D). It exceeds the ACGIH and NIOSH recommended limit but is still below OSHA's at a 0.07143 mg/m^3 level. The cause of this unusual concentration cannot be definitively explained. Smoke tube studies suggested that chrome plating tank #4's exhaust system was operating perfectly about an hour and a half after the subject sample was taken. Thus, it can only be surmised that a disruptive influence on the performance of tank #4 was overlooked while the sample was being taken, or that this location near the wall was being affected by a system anomaly discovered. This latter irregularity may also explain the relatively high concentration of 0.17928 mg/m^3 measured at the front right corner of tank #2. Here, two boards across the top of the tank, acting in conjunction with a side barrier on the tank, were severely disrupting the smooth flow of air across the liquid surface. Any smoke released at just above tank height would swirl up and over the top of the hood in a very unusual fashion. On the previous day, with the boards removed and the higher exhaust rate, this problem was not evident.

Table C-3. Sampling results for "high" exhaust volume.

Position	Start Time	Contaminant	Concentration (mg/m^3)	Comments
A	3:30 p.m.	Chromic Acid	0.00033	On Table at 1 m (3 ft) height
B	2:45	" "	0.00074	At 1.22 m (4 ft) height on rack
C	3:01	" "	ND*	At 1.22 m (4 ft) height on tank sidewall
D	3:04	" "	0.00072	At 0.46 m (1.5 ft) over work table
E	3:08	" "	0.00078	On table at 1.22 m (4 ft) height
E	11:03 a.m.	Sulfuric Acid	0.38	110 minute sample on table 1.22 m (4 ft) height
F	2:04 p.m.	Chromic Acid	0.00043	On table at 1 m (3 ft) height
G	1:48	Sulfuric Acid	0.44	0.15 m (0.5 ft) over tank; 150 minute sample time
H	1:37	Chromic Acid	ND	At 1.52 m (5 ft) height
J	1:43	" "	ND	At 1.52 m (5 ft) height
J	1:52	Sulfuric Acid	0.14	148 minute sample time
K	1:58	Chromic Acid	ND	At 1.52 m (5 ft) height
L	2:42	" "	0.00192	Over tank; at 1.37 m (4.5 ft) height
L	4:25	" "	ND	
M	3:28	" "	ND	On table at 1 m (3 ft) height
N	3:48	Cyanide	0.60	On edge of tank; 65 minute samples
N	3:48	"	0.60	
O	3:29	Chromic Acid	ND	On barrel at 1 m (3 ft) height

*ND = not detectable below detection limit

118

Table C-4. Sampling results for "low" exhaust volume rate.

Position	Start Time	Contaminant	Concentration (mg/m^3)	Comments
B	10:23 a.m.	Chromic Acid	0.00642	See previous table
C	10:28	" "	0.00896	" " "
D	10:41	" "	0.07143	" " "
E	12:03	" "	0.01500	" " "
F	10:06	" "	ND*	Sample started when tank systems activated.
I	10:11	" "	0.00924	Over tank; at 1.37 m (4.5 ft) height
J	10:46	" "	0.17928	See previous table
L	11:06	" "	0.01101	" " "
L	11:39	" "	0.00844	" " "
M	11:02	" "	0.00217	" " "
O	11:37	" "	0.00142	" " "

*ND = not detectable; below detection limit

Sulfuric Acid--
At the higher exhaust rate, sulfuric acid concentrations ranged from 0.14 to
0.44 mg/m^3. The source of these must be questioned since the lowest level
recorded was above one of the large plating tanks (position J), and consid-
erably higher levels were found away from plating tanks at positions E and G.
It might have been an unventilated and unheated tank containing acid between
positions E and G (sometimes used for chrome stripping), or a process in an
entirely different section of the plant.

Cyanides--
Kitagawa tubes indicated negligible concentrations of cyanides throughout the
general work area of interest. The more elaborate NIOSH method indicated a
concentration of 0.60 mg/m^3 directly over the liquid surface in the large tank
containing cyanides. There were two potential sources of cyanide emissions,
one being the aforementioned tank used for a proprietary process, and one being
a non-ventilated bath for descaling and deoxidizing of metals. Both are only
used sporadically, and neither was used during the survey.

Since it was not practical to return to this plant on a day when both cyanide
producing operations were underway, the survey results are incomplete in re-
gard to this contaminant. It can only be concluded that cyanides are not
a problem when the tanks are not used.

Duct Samples--
Table C-5 summarizes the results of duct sampling efforts. These indicate
that the chromic acid concentration first measured at the high exhaust volume
rate setting was greater than the second measurement at that rate by a factor
of 2.3. This can be partially explained by a time period during the second
measurement in which finished parts were taken out of plating tank #1 and a
new batch was inserted. During this procedure, electric current was not
applied and misting from the liquid surface was negligible. Thus, the higher
concentration is expected to more typically represent normal operating con-
ditions.

At the lower exhaust volume rate, the chromic acid concentration was approxi-
mately 2.4 times the highest reading at the greater exhaust rate. This is
understandable since the higher rate provides a dilution factor of 1.9 and
better control of the operation.

Humidity and Temperature--
Despite the presence of numerous heated tanks, the primary chrome plating
area was quite comfortable. Temperatures near the tanks were on the order
of 25.6 °C (78°F), and relative humidities ranged from 50 to 60 percent.

VALIDATION OF RECIRCULATION APPROACH

Introduction

In contrast to previous case studies which involved plants which currently
recirculate exhaust air, this study involves a plant which might consider
future implementation of the practice. Thus, the design process requires
more detailed application of the design steps outlined in Reference 1. These
steps are listed in Chapter 2 of that document, and are discussed in various
chapters and appendices.

Table C-5. Duct sampling results.

HIGH EXHAUST VOLUME RATE $\simeq$ 9.9 m^3/s (21,000 cfm)

Inlet Sample #1 (morning)

      Volume of sample: 1.608 m^3 (56.79 ft^3) at STP

      Chromic acid concentration: 0.0729 mg/m^3

      Sulfuric acid concentration: 0.02 mg/m^3

Inlet Sample #2 (afternoon)

      Volume of sample: 1.877 m^3 (66.30 ft^3) at STP

      Chromic acid concentration: 0.0315 mg/m^3

      Sulfuric acid concentration: non-detectable

LOW EXHAUST VOLUME RATE $\simeq$ 5.2 m^3/s (11,000 cfm)

Inlet Sample #3 (morning)

      Volume of sample: 2.547 m^3 (89.96 ft^3) at STP

      Chromic acid concentration: 0.1719 mg/m^3

      Sulfuric acid concentration: 0.10 mg/m^3

The various steps are considered in the order suggested. The procedure assumes no special knowledge of recirculation, and approaches the subject with no pre-conceptions about the feasibility of recirculation in this specific plant. Additionally, in order to permit a review of as many of the design steps as possible, it does not allow certain roadblocks in the initial feasibility assessment to impede a decision to further consider recirculation.

Initial Feasibility Assessment

Legal Issues--
No prohibitions upon the practice of recirculation could be found in Federal regulations or in the regulations of the state in which the plant is sited. The primary standard is simply that employee exposures be maintained at or below permissible limits.

Energy Consumption--
Plant personnel made available a detailed evaluation of recent energy usage and costs. Data of interest are summarized in Table C-6, and are encouraging. Together with airflow data, and with the observation that the four large exhaust systems are usually operated at the low speed setting, a potential is seen for deactivation of one of the fixed capacity make-up air supply units by cutting back the fresh air requirement to roughly 14.2 m^3/s (30,000 cfm).

Contaminant Classification--
Reference 1 recommends that all contaminants in exhaust volumes to be recirculated be identified and their concentration levels quantified during an initial feasibility assessment or following design steps. Subsequent text implies that similar data are eventually necessary for all breathing zone locations which may be affected by recirculation, both before and after the system design and implementation procedure.

If Reference 1's comments were to be interpreted in an idealistic sense, it would be necessary to perform a comprehensive sampling survey for each of numerous air contaminants in each of numerous work locations in the plant of interest. Additionally, it would be necessary to evaluate how concentrations could vary as a function of process parameters. In this particular plant, the costs associated with such an effort would obviously be prohibitive.

To bypass this potential roadblock, it was decided to perform a preliminary sampling program of limited scope to provide sufficient data to allow further consideration of recirculation. Additionally, it was decided to account for resulting uncertainties in the design process by only considering system con-figurations which: 1) do not significantly degrade the working environment in the hard chrome plating area; and 2) which have insignificant effect on cur-rent conditions in the rest of the plant.

At the high exhaust volume setting, the greatest chromic acid concentration measured was 1.92 percent of the OSHA ceiling limit and 3.84 percent of ACGIH's and NIOSH's 8-hour TWA limit under what were said to be typical operating con-ditions. Obviously, any return air stream would have to be significantly con-taminated for these potential exposures to approach permissible or recommended limits, even if one were to apply large safety factors in the analysis.

Table C-6. Make-up air heating costs.

Fuel: Natural gas

Fuel cost (1976-77 average) = $0.113 per m^3

$= $3.20 per 1000 ft^3

Make-up air rate = 28.3 m^3/s

$= 60,000 cfm

Operational time = 80 hours per week

Fuel used FY 1977 = 219,690 m^3

$= 7,759,400 ft^3

Total fuel cost FY 1977 = $24,830

Yearly heating cost per unit make-up air rate = $877.39 per m^3/s

$= $0.4138 per cfm

Yearly fan motor electrical cost = $188.84 per m^3/s

$= $0.089 per cfm

Total make-up air cost rate = $1066.23 per m^3/s

$= $0.503 per cfm

Total make-up air cost = 60,000 x 0.503

$= 30,180 per year

The highest sulfuric acid concentration noted was 0.44 mg/m^3, or 44 percent of OSHA's 8-hour permissible exposure limit, and the cyanide concentration in breathing zones was negligible when the processes using cyanide were not activated. Therefore, there is substantial leeway within which to attempt to design an acceptable recirculation system. Pending the accumulation of further data, the only restriction would be a necessity to bypass exhaust air to the outdoors when cyanide generating processes are activated.

Air Quality Regulations--
Since air cleaners are installed and utilized at this plant, and since recirculation would not increase acid emissions to the external atmosphere, air pollution regulations are not a factor in the decision to recirculate.

Water Quality Regulations--
The plant in question has been avoiding potential problems associated with the discharge of acid contaminated scrubber effluent by recirculating wash water. As previously noted, there is no mechanism by which contaminated water can be automatically diluted, replaced, and/or neutralized in the holding tank. If a scrubber is to be utilized in an air recirculation system, it is mandatory that the wash water be of sufficient cleanliness to ensure optimum operating efficiency. Either a constant flow of clean water must be provided, or the water in a holding tank must only be allowed a limited number of passes through the system before being discharged.

The plant is in the process of installing a waste water treatment plant to neutralize and/or otherwise treat contaminated effluent streams. It will shortly have the facilities to handle scrubber wash water at little additional expense if such treatment becomes necessary. Thus, this issue does not restrict any decision to recirculate.

Air Cleaner Availability--
Wet scrubbers are available and utilized for air pollution control of plating operations. Data provided in this and a previous case study report demonstrate the availability of a wide variety of units with designs based upon the water wash principle. Although increased humidity levels are a distinct disadvantage of these, no other types of acceptable air cleaning devices could be identified.

Monitor Availability--
A limited search did not indicate the commercial availability of a monitoring system for airborne concentrations of chromic or sulfuric acid. It is, however, possible to monitor pertinent water flows, air flows, power usage, and wash water pH or conductivity to ensure these parameters comply with design specifications.

The lack of monitoring devices for airborne concentrations is cause for concern with these contaminants, and will require that this topic be given further consideration before any final decision pertaining to recirculation. Manual sampling and analysis techniques are available, but these are not seen to be practical for implementation on a frequent basis.

Process Emission Profile--
The generation rate of contaminants from plating baths is a complex and pre-
sently undefined function of numerous factors. In the job shop environment,
many of these factors are subject to change, and can significantly affect the
concentrations of pertinent contaminants in the working environment as well
as in ductwork.

Reference 1 indicates that conservative design approaches must be utilized
where widely fluctuating processes are operating. It also suggests a need
to define and/or establish the conditions under which the system may operate,
and to ensure that all digressions from these conditions be studied for their
potential effects on recirculated air quality. The conservative approach
recommended implies that safety factors must be incorporated in the analysis.
This is a requirement which can partially be met in the present case by spec-
ifying that:

- Contaminant levels in return air streams are very low relative
  to permissible limits;
- Exhaust air is bypassed to the outdoors when cyanide generating
  processes are activated (because of the lack of data on the
  subject); and
- Exhaust air is bypassed outdoors under any other unusual operating
  conditions.

Ventilation System Design--
The conversion from a conventional to a recirculating exhaust system may re-
quire extensive retrofitting and redesign of equipment. Reference 1 states
that consideration must be given to the possible extent of difficulties which
may be experienced, and their effect on the decision on whether or not to
further consider recirculation. To fully address the issue, it is necessary
to develop preliminary concepts of what forms the converted exhaust system
may take. For the plant of interest, a number of basic alternatives can be
envisioned.

One of these involves use of the existing wet scrubber located on the roof.
To utilize this unit:

- The discharge side must be reconstructed to provide an outlet port
  for air being returned to the work place;
- The discharge duct(s) must be fitted with motorized blast gates or
  dampers to allow direction of return air to the work place or to
  the outdoors;
- The duct conveying return air must be routed to the work place
  through a practical pathway; and
- Consideration must be given to whether the scrubber cabinet and/or
  the return air duct requires insulation.

The centrifugal fan has a casing of the scroll type design. Although it now
provides an upblast discharge, the casing can be remounted to discharge hori-
zontally. The configuration would involve a horizontal outlet duct attached
to a vertical stack for bypassing air and a separate branch returning air to
the work place, both fitted with appropriate dampers or blast gates. The

return air duct would either turn the air downward into the work place through a new hole in the roof, or would lead to the inlet port of one of the make-up air supply units.

Ducting to a make-up air unit involves a 30 meter ($\sim$ 100 feet) distance through an area covered with deep snow at times. Although it uses an existing entrance to internal areas:

- It complicates use of the make-up air unit when air is bypassed to the outdoors;
- It raises the possibility that residual contaminants may adversely affect internal components of the make-up air unit; and
- It requires consideration as to whether the return air would lose an excessive amount of heating value when external temperatures are low or snow is deep.

Heat loss problems are also possible with the alternative of a new hole in the roof, and there may be other difficulties associated with this option.

Moving the scrubber to a position just under the roof and inside the work area might also be considered. With proper modification of the unit, and the provision of a small platform, the existing outlet through the roof might be usable and the unit would be accessible. Heat loss and other potential problems would be solved, and there would be no need to significantly modify existing ductwork.

A major alternative to the existing scrubber involves one or more smaller units installed on elevated platforms within the work area itself and applied to only plating tank exhausts. These would: 1) allow bypass of air outdoors through a side wall of the plant; 2) would not present heat loss problems; 3) would more easily be accessed for inspection and/or maintenance; and 4) would allow the remaining portions of the existing exhaust system intact for use cyanide producing processes are being conducted.

Conclusions--
This initial feasibility assessment for recirculation of plating exhaust air has highlighted serious potential problems in regard to costs of detailed sampling efforts, and difficulties of implementing certain system configurations. Conversely, it has indicated a significant potential energy saving, and at least one system configuration without immediately evident, insurmountable problems. Given the successful use of high efficiency, internally placed scrubbers in the previous case study, it is possible to conclude that recirculation concepts are worthy of further consideration.

Contaminant Characteristics

Chapter 4 and other sections of Reference 1 discuss what must be known about the characteristics of contaminants. Data needs include existing concentration levels, as well as information concerning the toxicology and physical and chemical properties of the contaminants.

126

Physical and Chemical Description--
Chromic and sulfuric acids are well-known and understood commodities. As
such, they do not warrant detailed examination in this report. It is suf-
ficient to simply note that:

- Neither substance is flammable, but chromic acid is a powerful
  oxidizer.
- Both are corrosive to various metals.
- Chromic acid has no vapor pressure; it is present in the work
  place and in ductwork in airborne mist form.
- The mists will also contain sulfuric acid in solution, but this
  acid can also exist in the gaseous state.
- The pertinent mists and vapors can be washed from air streams with
  water sprays.

At the high speed exhaust volume setting, the highest TWA chromic acid con-
centration measured in the main exhaust duct was 0.0729 mg/m^3. The overall
generation rate associated with this concentration can be simply computed as
being 0.72 mg/s. At the lower setting, the concentration was 0.172 mg/m^3,
but the generation rate was a comparable 0.89 mg/s. Sulfuric acid concen-
trations, where detectable, were 0.02 and 0.10 mg/m^3 respectively at the high
and low settings. Loadings were on the order of 0.2 to 0.5 mg/s.

Health Effects--
Chromic trioxide and sulfuric acids, as utilized in plating operations, are
not classified as carcinogenic. Nor are there indications in the literature
that either substance in pure form is currently suspected of carcinogenesis.
A restriction on recirculation of carcinogens in Reference 1 is therefore
not pertinent.

The OSHA standard for chromic acid is a ceiling limit of 0.1 mg/m^3. NIOSH
has recommended that this limit be supplemented by a 0.05 mg/m^3 limit for TWA
exposures (8-hour workday, 40-hour work week), and this latter recommendation
is incorporated in recent recommendations provided by the ACGIH. Sulfuric
acid simply has a permissible limit of 1.0 mg/m^3 for TWA exposures.

A review of standard texts did not definitively indicate whether these con-
taminants display independent, additive, or synergistic effects. The know-
ledge that both are inorganic acids, however, coupled with the fact that both
are injurious to the mucous membranes of the upper respiratory tract, leads
to the reasonable conclusion that effects are best considered as additive.

Work Place, Process, and Ventilation System Characteristics

Most pertinent characteristics of the ventilation system and the working envir-
onment have previously been described. Nevertheless, there is merit in
taking a closer look at some aspects of the situation. Table C-7 provides
estimates of the exhaust volume rates attributable to the various tanks of
interest. Additionally, it lists recommended exhaust rates computed by the
procedures in the ACGIH Industrial Ventilation Manual.[2] It is interesting
to note that:

Table C-7. Exhaust volume rates.

Area Designation	Current Exhaust Volume (m^3/s)	Current Exhaust Volume (cfm)	ACGIH Exhaust Volume (m^3/s)	ACGIH Exhaust Volume (cfm)
Tank #1	1.0	2,100	1.3	2,700
Tank #2	2.5	5,250	2.7	5,700
Tank #3	1.25	2,650	2.7	5,700
Tank #4	0.1	200	Note 1	Note 1
Cyanide Tank	1.9	∿ 4,000	2.5	5,280
Acid Tank	2.0	4,200	1.2	2,560
Leakage	1.2	2,600[2]	–	–
	9.95	∿21,000[3]	10.4	21,940

NOTES:

1. Tank 4 not used; essentially sealed. Requirements would be similar to those for tanks #2 and #3 if used.

2. Openings were observed in plenum near cyanide tank.

3. All rates are for high exhaust system setting.

4. The right half of the hood on Tank #3 was not operating correctly.

5. All data are very approximate because of difficulties in obtaining measurements.

6. Although the system is rated at 9.4 m^3/s (20,000 cfm), it actually exhausts about 9.95 m^3/s (21,000 cfm) at the higher setting.

- Operational plating tanks are provided lower than recommended exhaust volumes, yet apparently provide excellent control.
- More than half the total exhaust volume is associated with tanks that are never or rarely used, or with leakage into the system.
- The simultaneous use of floating plastic balls and a surface-active agent appears to greatly enhance the effectiveness of chrome plating tank ventilation systems.

Selection of Air Cleaning Equipment for Further Consideration

There are two basic options regarding the selection of air cleaning devices. The first involves use of the existing air cleaner; the second involves new wet scrubbers for dedicated service to chrome plating tanks. The existing unit is claimed to have an efficiency "up to 90 percent." New scrubbers can be obtained with efficiencies on the order of 98 to 99 percent for contaminants of interest (see discussion in previous case study entitled Hard Chrome Plating Plant #1).

Selection of Surveillance Equipment for Further Consideration

As previously noted, it is not entirely satisfactory that a convenient method cannot be identified for the surveillance of contaminant concentrations. If subsequent analysis indicates that recirculation is feasible in this plant, it will be necessary to take a hard look at whether alternative measures can reliably indicate reduced system performance. Among the possible alternatives are devices which can monitor:

- water flow into the scrubber;
- water flow out of the scrubber;
- air flow into the scrubber;
- pH or conductivity of wash water; and
- return air humidity.

Determination of Feasible System Configurations

A number of feasible system configurations have been identified and discussed in previous text. These are reiterated below, with more attention given to details and associated problems. The basic objective of any option is a sufficient reduction in make-up air needs to allow deactivation of one of the two fixed capacity make-up air units.

Option #1--
The existing scrubber can be utilized with a major modification to its discharge side. Here, a horizontal outlet duct at roof level would be attached with a tee connection to a new vertical exhaust stack of 5 to 6 meters height (16 to 20 feet). This stack would be fitted with a motorized damper or blast gate. For recirculation of air, the outlet duct would be routed downward into the plant through a new hole in the roof. This branch would also require a motorized damper or blast gate with associated controls to allow bypass of air to the outdoors.

The option requires extensive modification of the existing scrubber, construction of a new exhaust stack, provision of motorized dampers or blast gates for two ducts of approximately 1.2 meter (3.8 feet) internal diameter, and a new hole in the roof. Additionally, it requires the ductwork necessary to return and distribute air to the vicinity of the chrome plating area, and involves the possibility of significant heat losses during cold weather. There is no doubt that the modifications called for by this option would be relatively expensive, and would present possibly insoluble new problems. In consequence, pending investigation of other options, this configuration is deleted from further consideration.

Option #2--
Also previously discussed was the possibility of using the existing scrubber in a configuration similar to that described above, but with the discharge duct leading across the roof to one of the nearby make-up air supply units. This option has virtually all of the disadvantages associated with option #1, and some significant new ones. It also is deleted from further consideration pending evaluation of alternatives.

Option #3--
A third option involves movement of the existing scrubber indoors to a position just under the roof. A clear potential exists with this alternative to resolve many of the problems associated with outdoor placement. There may be other installation problems, but these can be evaluated at a later stage of the analysis.

Option #4--
Having discussed all options dealing with the existing scrubber, it is appropriate to consider the use of one or more new wet scrubbers situated in the plant. In the best such configuration envisionable:

- Plating tanks #1, 2, and 3 would be disconnected from the present exhaust system and connected to one or more new scrubbers situated nearby within the plant.
- The new scrubbers would have an outlet duct to the inplant area, and a branch to the outdoors. Dampers or blast gates would allow a choice between recirculation or outdoor discharge.
- The duct to the outdoors would simply be directed through the nearby plant wall (which only consists of cinder blocks).
- The remainder of the existing system would be activated only when the operation using cyanide is underway.
- Tight-fitting covers would virtually eliminate emissions from the cyanide and acid tanks when their exhaust system is deactivated.
- The existing scrubber would be drained of water when not in use in cold weather to prevent freeze-ups.
- A damper or blast gate would be installed somewhere in the main duct for the existing scrubber to reduce infiltration of cold air through the system when it is deactivated in cold weather.

The option is desirable because it utilizes more efficient scrubbers, and therefore provides a greater safety factor. Nevertheless, it has the cost penalty associated with purchase of new air cleaning devices, and difficulties associated with keeping the current system operational during long periods of deactivation.

Option #5--
This option does not involve recirculation. Rather, it entails a simple reduction in the make-up air supply rate.

The current total make-up air rate is 28.4 m^3/s (60,000 cfm) provided by two supply units with 14.2 m^3/s (30,000 cfm) capacity. The exhaust rate is minimally 18.9 m^3/s (40,000 cfm), but can range up to 37.8 m^3/s (80,000 cfm) depending upon the number of exhaust systems set at the higher rate of exhaust. The original thinking, apparently, was that at least 2 of the 4 exhaust systems would be at their high setting at any time, and that the overall system would be balanced.

As best as can be determined, however, the plant usually utilizes all exhaust systems at their lower exhaust rate setting, and only allows shift supervisors the option of resetting the controls when and if there is reason to believe that a particular process is not sufficiently well controlled. Thus, there often is an excess make-up air supply rate of 9.4 m^3/s (20,000 cfm).

An obvious option for consideration, therefore, involves the installation of a new make-up air unit with a capacity of 4.7 m^3/s (10,000 cfm). Such a unit would utilize about one-third the energy of an existing unit, and would provide a perfectly balanced air handling system under the most common operating conditions. The unneeded larger supply unit could be kept for occasions when higher total exhaust rates are necessary and/or to increase ventilation during pleasant or hot weather conditions.

Summary--
There are three options worthy of further evaluations. These are:

- Option #3 - using the existing air cleaner at an elevated position under the roof;
- Option #4 - using new wet scrubbers only for hard chrome plating tanks; and
- Option #5 - using a new make-up air unit of lower capacity.

Design Optimization for Feasible Configurations

It is now appropriate to apply the analytical procedures of Reference 1 to assess the effect of each option upon pertinent breathing zone concentrations.

Options #3 and #4 involve use of air cleaning devices within the plant. Thus, the appropriate model for use initially appears to be that reproduced in Figure C-7. Inspection of the first equation for the air balance, however, indicates this model does not fully address all the changes intended for this plant. Rather, it is presented for use when one or more local exhaust systems are to be fully recirculated, and the make-up air supply rate is to be reduced on a one-to-one basis with recirculated air.
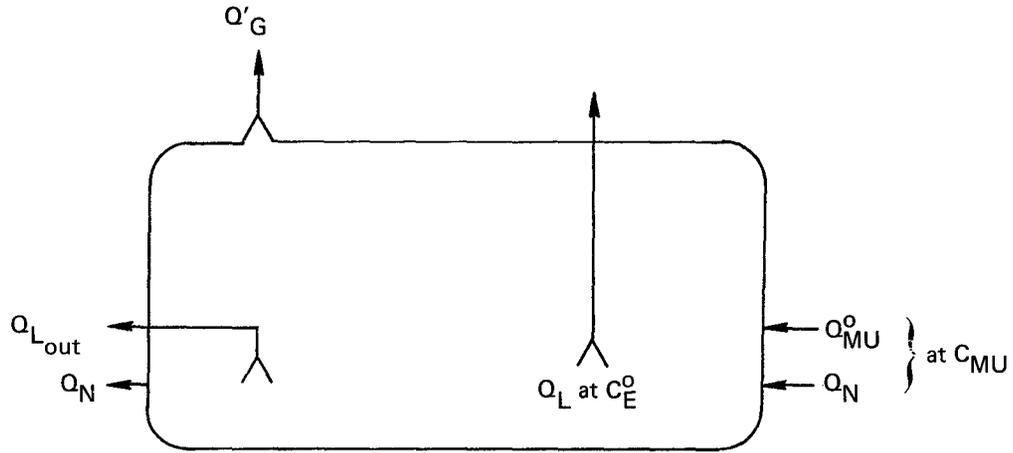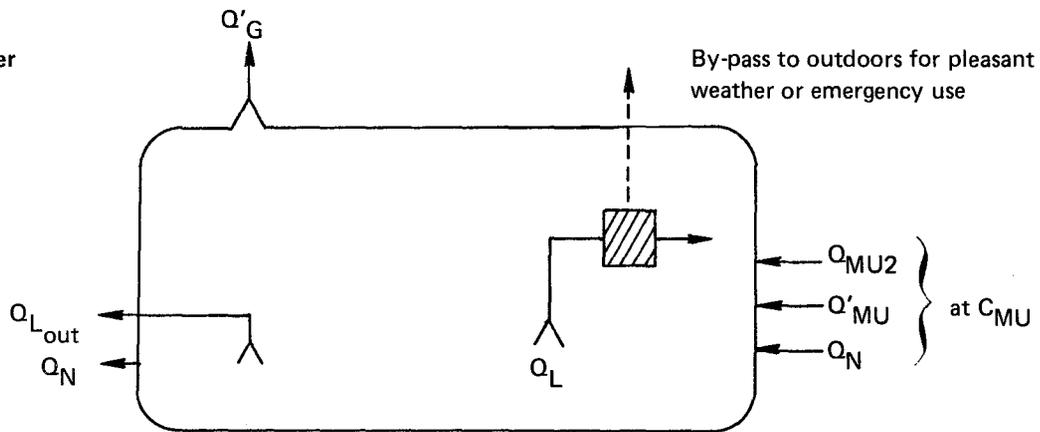
131

Before

After

By-pass to outdoors for pleasant weather or emergency use

Determine Suitability of Unit Collector(s) from:

$$Q_{MU2} = Q_{L_{out}} + Q'_G - Q'_{MU} = Q^o_{MU} - Q_L - Q'_{MU}$$

$$C_R = \left[\frac{(1-\eta)\,(C^o_E - k_R\,C_{MU})}{1.0 - (1-\eta)\,k_R} \right]$$

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

Note: Q_L should be the total volume through all unit collectors, if more than one is to be installed.

Figure C–7.   System design model.

132

A further search of Reference 1 for a model which specifically applies to the situation was not successful, although it was evident that a number of the models could be utilized if the air balance in the plant is properly defined for both pre- and post-recirculation conditions. In consequence, the following analysis is based on the concepts presented in Reference 1, but is tailored to meet the specific needs of the plant in question.

Airflow Balance--
Every model in Reference 1 contains one or more equations describing the airflow balance in the plant area of interest. For simple recirculation system configurations, their purpose is to ensure that the overall system is balanced after recirculation. All were derived with the assumption that the system was balanced before recirculation is implemented.

Table C-8 lists the various airflow rates estimated under current operating conditions. It assumes that the local exhaust system of interest for recirculation is on its high rate setting, and that all others are at the low setting. Symbols shown are mostly similar to those used by Reference 1, and are provided to facilitate comparisons. Table C-9 describes the balance expected if Option #3 is implemented. Similarly, Tables C-10 and C-11 describe the balances expected for Options #4 and #5.

The exercise satisfies the requirements of Reference 1 by ensuring that the overall air balance before and after implementation of any system configuration is understood and logical.

Return Air Concentration Equation--
Each of the recirculation models in Reference 1 contains an equation defining the concentration(s) (C_R) of contaminant(s) expected in return air streams. The equation provided in Figure C-7 is completely appropriate for use for options #3 and #4 when general exhaust air is not recirculated, there is no continuous bypass of exhaust air to the outdoors from the recirculation system, and fresh air is not mixed with the recirculated air stream within a duct. It is:

$$C_R = \frac{(1 - \eta)(C_E^o - k_R C_{MU})}{1.0 - (1 - \eta)\, k_R}$$

where:

η is the overall air cleaner efficiency for a particular contaminant.

C_E^o is the concentration of a contaminant in the local exhaust stream to be recirculated (before recirculation).

C_{MU} is the concentration of contaminant in make-up air from outdoors.

k_R is the fraction of the air volume entering the exhaust system being recirculated which originated in the return air stream (i.e., the fraction of air recycled more than once).

133

Table C-8. Estimated air balance before recirculation.

Symbol	Description	Rate** (m^3/s)	Rate** (cfm)
$Q_{L_{out}}$	Exhaust volumes not considered for recirculation (at low rate)	-14.2 to -15.6	-30,000 to -33,000
Q_L	Exhaust volume to be considered for recirculation (at high exhaust setting)	- 9.9	-21,000
Q_N'	Exfiltration* rate	- 2.8 to - 4.3	- 6,000 to - 9,000
Q_N	Infiltration rate	$\sim$ 0	$\sim$ 0
Q_{MU}°	Total make-up air rate	+26.9 to +28.3	+57,000 to +60,000
		$\sim$ 0	$\sim$ 0
Q_T°	Total ventilation rate = Q_{MU}°	26.9 to 28.3	57,000 to 60,000

* The excess air supply is assumed to cause an exfiltration rate on the order of 0.34 to 0.56 air changes per hour.

** The excess make-up air is suspected of boosting the capacity of each local exhaust system in the plant by roughly 0.46 m^3/s (1,000 cfm) over rated capacities. Additionally, high internal pressures are suspected to cause reductions in the performance of make-up air supply units. The ranges shown for certain flow volumes are intended to reflect the uncertainties caused by these effects.

Table C-9. Estimated air balance for option #3.

Symbol	Description	Rate** (m^3/s)	Rate** (cfm)
$Q_{L_{out}}$	Exhaust volumes discharged outdoors (at low setting)	− 14.2	−30,000
Q_L	Exhaust volume recirculated (current system at high setting)	− 9.4	−20,000
Q_N'	Exfiltration rate estimate*	− 1.9	− 4,000
Q_{MU}'	Make-up air rate not affected by recirculation	+ 14.2	+30,000
Q_{MU1} or Q_{MU2}	Any additional make-up air	+ 0	+ 0
Q_R	Return air rate	+ 9.4	+20,000
Q_N	Infiltration rate estimate*	+ 1.9	+ 4,000
		$\sim$ 0	$\sim$ 0
Q_T	Total ventilation rate = $Q_{MU}' + Q_{MU2} + Q_R + Q_N$	25.5	54,000

* For a tight plant, with a balanced air handling system, 0.25 air changes per hour due to infiltration and exfiltration is quite conservative.

** A perfect balance is expected in this option between mechanically provided make-up air and mechanically exhausted air volumes. In consequence, it is assumed that systems will no longer be influenced by an excess make-up air supply rate, and will operate at rated capacities. The previous Q_L rate of 9.9 m^3/s (21,000 cfm), therefore, becomes 9.4 m^3/s (20,000 cfm) and so forth.

Table C-10. Estimated air balance for option #4.

Symbol	Description	Rate* (m^3/s)	Rate* (cfm)
$Q_{L_{out}}$	Exhaust volumes discharged outdoors	$-$ 14.2	$-$30,000
Q_L	Exhaust volume being recirculated	$-$ 4.7	$-$10,000
Q_N'	Exfiltration rate estimate	$-$ 1.9	$-$ 4,000
Q_N	Infiltration rate estimate	$+$ 1.9	$+$ 4,000
Q_{MU}'	Make-up air rate not affected by recirculation	$+$ 14.2	$+$30,000
Q_{MU2}	Make-up air rate not mixed with return air	0	0
Q_{MU1}	Make-up air rate mixed with return air	0	0
Q_R	Return air rate	$\underline{+\ 4.7}$	$\underline{+10,000}$
		$\sim$ 0	$\sim$ 0
Q_T	Total ventilation rate = $Q_{MU}' + Q_R + Q_N$	20.8	44,000

* See pertinent note in Table C-9.

136

Table C-11. Estimated air balance for option #5.

Symbol	Description	Rate* (m^3/s)	Rate* (cfm)
$Q_{L_{out}}$	Exhaust volumes discharged outdoors	− 18.9	−40,000
Q_N'	Exfiltration rate estimate	− 1.9	− 4,000
Q_{MU}'	Make-up air rate after modification	+ 18.9	+40,000
Q_N	Infiltration rate estimate	+ 1.9	+ 4,000
		$\sim$ 0	$\sim$ 0
Q_T	Total ventilation rate = $Q_{MU}' + Q_N$	20.8	44,000

* See pertinent note in Table C-9.

137

The air cleaner efficiency for the existing unit is claimed to be "up to 90 percent" for all water soluble contaminants. Assuming the unit will be put into original working order, an efficiency of 0.90 is assumed for a first trial of equations for option #3. For new scrubbers in option #4, specific claims of 98 to 99 percent efficiency are noted for both chromic and sulfuric acids, and an efficiency of 0.98 is selected for both substances.

Duct measurements indicated chromic acid concentrations as high as 0.073 mg/m^3 and sulfuric acid levels as high as 0.02 mg/m^3 under what were said to be typical operating conditions. To account for time periods when the plant is exceptionally busy, and the plating tanks are fully loaded, it is apparent that these levels must be increased by a safety factor. Somewhat arbitrarily, therefore, these concentrations are tripled to provide C_E^o values for the existing scrubber in option #3.

It will be noted that Reference 1 only discusses safety margins in the context of the difference between breathing zone concentrations predicted by the analytical procedure and concentrations which constitute permissible exposure limits. It is clear in this analysis that it is also proper to sometimes apply safety factors to parameter values with uncertain upper or lower bounds. Of course, it is also clear that such uncertainties would not exist if actual worst-case data can be obtained from the work place.

Option #4 requires adjustment of C_E^o concentration levels to account for the fact that essentially clean air from the cyanide and acid tank hoods was diluting the exhaust stream, and that this dilutory effect will be absent. Simple computations provide values of 0.153 mg/m^3 for chromic acid, and 0.042 mg/m^3 for sulfuric acid under typical operating conditions. Tripling these, to provide a safety factor, respectively gives concentrations of 0.459 and 0.126 mg/m^3.

This action denotes a certain aspect of option #4 which was not heretofore realized. Since the dilutory effect to plating tank exhaust volumes will be absent in the configuration envisioned, this option bears inherently greater risk to workers in the event of air cleaner failure; especially in terms of chromic acid exposures.

The level of pertinent contaminants in outdoor air supplies (C_{MU}) is assumed to be negligible when all other air cleaners in the plant are operational and in good working order. It is, therefore, assumed that all contaminants of interest have a C_{MU} value of zero. For k_R, the most conservative value of 1.0 is selected with the knowledge that the return air stream is planned for distribution primarily within the hard chrome plating area.

An assembly of these data, and use of the equation for C_R, provides chromic acid return air concentrations of 0.024 and 0.0094 mg/m^3 for options #3 and #4 respectively. For sulfuric acid, the respective concentrations are 0.007 and 0.003 mg/m^3.

Breathing Zone Equation--
Reference 1 presents an equation which predicts breathing zone concentrations
after recirculation, based upon pre-existing conditions. The equation, some-
what simplified to delete portions not pertinent to this evaluation, is:

$$C_{BZ} = \frac{Q^\circ_T}{Q_T} (C^\circ_{BZG} - C_{MU}) + k_{BZ}C_R + (1 - k_{BZ}) C_{MU}$$

where:

C_{BZ} is the breathing zone concentration after recirculation is implemented.

C°_{BZG} is the breathing zone concentration before recirculation is implemented.

k_{BZ} is the fraction of air in the breathing zone which originates in a
return air stream.

From data presented in Table C-3, an average breathing zone chromic acid concen-
tration on the order of 0.00082 mg/m³ (not counting samples with non-detectable
concentrations) is computed. Tripling this value to provide an analogous safety
factor then provides a worse case average concentration of 0.00246 mg/m³.

For sulfuric acid, the situation is somewhat unclear because of the limited
data available, and the unexpected concentrations found in the plating area.
Since these concentrations are unlikely to have been generated from the chrome
plating tanks, an average concentration of 0.41 mg/m³ is computed using only
area samples in the region of interest and no safety factor.

Since there is an intention in all cases to distribute the recirculated air
primarily throughout the plating area (forced by an inability to completely
characterize contaminant-producing operations in other plant areas for economic
reasons), and since it is not feasible to perform any sort of tracer gas study
with the current ventilation system, k_{BZ} is assigned its most conservative
value of 1.0. All parameters necessary for model utilization are then defined
for all options.

Table C-12 presents results of computations along with a summary of input data
to the analysis. Additionally, it provides results obtained by applying the
breathing zone equation to the system configuration of option #5.

Interpretation of Results--
The predicted breathing zone concentration for chromic acid for option #3 is
approximately half the recommended 8-hour TWA exposure limit of 0.05 mg/m³,
and this value is almost directly proportional to the chromic acid concentra-
tion in the return air stream. The return air concentration is a strong func-
tion of the chromic acid concentration in the main exhaust duct, the air
cleaner efficiency, the magnitude of the safety factor selected for use, and
the value estimated for k_{BZ}. Breathing zone concentrations of chromic acid
would exceed the pertinent limit if:

Table C-12. Model input data summary and results.

Option	Acid Contaminant	$\overset{\circ}{Q}_T$ (m^3/s)	Q_T (m^3/s)	$\overset{\circ}{C}_E$ (mg/m^3)	η	k_R	k_{BZ}	$\overset{\circ}{C}_{BZG}$ (mg/m^3)	C_R (mg/m^3)	C_{BZ} (mg/m^3)
3	Chromic	28.3	25.5	0.219	0.90	1.0	1.0	0.00246	0.024	0.027
	Sulfuric	28.3	25.5	0.060	0.90	1.0	1.0	0.41	0.007	0.46
4	Chromic	28.3	20.8	0.459	0.98	1.0	1.0	0.00246	0.0094	0.013
	Sulfuric	28.3	20.8	0.126	0.98	1.0	1.0	0.41	0.003	0.56
5	Chromic	28.3	20.8	NA	NA	NA	NA	0.00246	NA	0.003
	Sulfuric	28.3	20.8	NA	NA	NA	NA	0.41	NA	0.56

NOTE: Option #3 involves placement of the existing air cleaner at a location beneath the roof and no change to exhaust system components preceding it.

Option #4 involves placement of one or more new air cleaners near the plating tanks. These would only treat and recirculate air from tanks #1, 2, and 3.

Option #5 involves provision of a new make-up air supply unit.

- All parameter values are correct, but the air cleaner efficiency is only 0.80.
- Or all parameter values are correct, but the exhaust duct concentration can vary by a factor of 6 over that measured when all plating tanks are fully loaded.

Alternatively, the concentrations may be less than predicted on the average if:

- The safety factor of 3 applied to observed exhaust duct concentrations is fully conservative;
- Or the air cleaner efficiency is better than assumed;
- Or the value assigned to k_{BZ} (1.00) is too conservative, and the true value is considerably lower.

For sulfuric acid, a roughly 12 percent increase is predicted for breathing zone concentrations. The root cause of this increase is the 10 percent decrease in the total ventilation rate caused by this option, since the sulfuric acid level in the return air is virtually negligible. Additionally, it is noted that:

- The predicted concentration is 46 percent of the permissible limit for sulfuric acid.
- The total additive exposure of the two acids would be exactly the permissible limit in the chrome plating area if all input data were correctly estimated.
- No safety factor was applied because it was assumed that sulfuric acid concentrations were not due to plating operations.
- The breathing zone equation suggests that all exposures in other plant areas will increase by an average of 12 percent if the total ventilation rate is reduced.

The results for option #4 are basically similar to those above with the exceptions that:

- The chromic acid breathing zone concentration predicted is roughly half that found for option #3.
- The sulfuric acid concentration is seen to increase by about 37 percent due to the decrease in the total ventilation rate.
- The breathing zone equation suggests that all exposures in other plant areas are likely to increase by an average of 37 percent.
- The predicted additive exposure is 82 percent of the permissible limit for the acids in the plating area.

Option #5 is seen to involve a similar large decrease in the total ventilation rate. As such, it also is seen to increase all exposures in the plant by an average of 37 percent.

Discussion of Model--
It is clear that the process of applying the model has highlighted certain issues which directly influence the feasibility of recirculation or other

energy-saving measures in this plant. Additionally, it is apparent that both
options #4 and #5 are feasible for implementation in regard to expected expo-
sures in the chrome plating area, but may not be acceptable due to their
effects on other plant areas.

The breathing zone equation in Reference 1 inherently assumes, with some qual-
ifications, that exposures at a given point in any plant area will vary pro-
portionately with the ratio of before and after total ventilation rates. The
assumption is well-supported on pages 104 and 105 of that document and may be
considered valid if: 1) the air velocity past any point in the room changes
linearly with changes in the total ventilation rate; 2) the basic air flow
pattern in the plant area is unchanged; and 3) if the change in total ventil-
ation rate will not affect the rate at which contaminants enter the air of
the working environment.

In the plant being considered, it is evident that the basic air flow pattern
in the plant will change when recirculated air replaces fresh make-up air.
Additionally, it can be surmised that some areas in the single large room
will be more affected by reduction of the total ventilation rate than others.
Hence, mean exposures throughout the plant are likely to increase by the
percentages computed above, but the actual case may see some specific exposures
affected more significantly than others.

This leads to a realization that the validity of the breathing zone equation
can be subject to question with regard to any specific worker's exposure
under certain circumstances. These circumstances are expected to occur
when:

    1. The total ventilation rate is significantly increased or decreased;
       and

    2. The change in ventilation rate is not evenly distributed throughout
       the plant area.

The circumstances are not seen to occur when:

    1. The total ventilation rate is not significantly increased or
       decreased; or

    2. A recirculated air supply rate replaces an equivalent make-up air
       supply rate using an unmodified air distribution system; or

    3. All make-up air supply rates to the plant area (whether fresh or
       recirculated) are proportionally increased or decreased.

Conclusions For These Options--
At this point of the analysis, the majority of Reference 1's important and
novel recommendations have been applied, and significant insights have
been gained into the theoretical and practical problems associated with the
implementation of recirculation in this plant. Additionally, pertinent con-
clusions concerning the design options considered and the effectiveness of
Reference 1's methodology in leading to these conclusions have been formulated.

For option #3, it is concluded that there is not sufficient data to attempt implementation, but that the methodology of Reference 1 has indicated what additional data are needed. More specifically, it is found necessary to:

- Exactly define the efficiency of the existing scrubber for contaminants of interest.
- Determine the maximum exhaust duct and area concentrations when all tanks are operated under peak-load conditions.
- Determine where sulfuric acid concentrations are originating and their possible range of fluctuation.
- Evaluate whether a 10-percent decrease in the total ventilation rate will cause excessive exposures elsewhere in the plant.

Application of the model to options #4 and #5 has indicated that exposures in the chrome plating area are very likely to be below any permissible exposure limit. As above, however, it is seen that the true feasibility of either option cannot be assessed until existing exposures throughout other plant areas have been characterized. It is entirely possible that current exposures are so low that the reduction in total ventilation rate would have negligible effect. Alternatively, it is possible that the change in rate would endanger compliance with health standards in some areas.

Conclusions For This Plant--
There is a definite potential for energy savings in this plant by implementation of one of the system design configurations considered in this case study. Nevertheless, unusual circumstances have defined a need for a comprehensive sampling program with the potential for considerable expense. Since there are significant uncertainties that such efforts would result in the identification of an acceptable energy saving methodology, it is concluded that further efforts in this area are not warranted at this time.

The unusual circumstances mentioned above involve:

- The presence of only two fixed-capacity make-up air supply units to serve the entire plant;
- The lack of a make-up air distribution system;
- The current use of only four relatively low-efficiency air cleaners to treat the exhaust air from literally dozens of different processes;
- A job shop environment with numerous process variables subject to change; and
- The inability to formulate a recirculation system design concept which would replace existing make-up air volumes with recirculated air on a one-to-one basis.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following general conclusions can be derived from the results of this case study. Most can be seen to have been derived from reported observations. Yet others, however, involve incidents not specifically reported upon, or conclusions which have slowly evolved as the overall study program has progressed.

143

1. Reference 1 generally provided a complete and adequate framework for the identification of all important factors in the analysis. Additionally, it provided the basic tools necessary to study the interactions between these factors.

2. Proper application of Reference 1's methodology requires an indepth understanding of its entire contents and the expertise to independently define the important implications and ramifications of its statements and model equations.

3. Reference 1 primarily addresses the health and safety issues pertaining to the recirculation of exhaust air. Widespread implementation of the practice in various industries will require the solution of practical engineering problems which do not involve these issues.

4. Recirculation is one of many possible alternatives to saving energy. A proper overall approach with this objective requires consideration of all energy saving measures and their comparative risks and benefits.

5. Significant uncertainties are introduced to the analysis when airflow patterns in the plant will be significantly modified by the implementation of recirculation. The best case appears to be when a fresh air stream will be replaced by a return air stream entering at the same location and at the same volume rate.

6. The presence of make-up air supply units of fixed capacity can complicate an analysis unless the amount of air to be recirculated is equal to the capacity of the make-up air unit(s) to be deactivated.

7. Recirculation appears better suited at present for plant areas with only a few types of airborne contaminants with readily identifiable sources. Additionally, the state-of-the-art is better suited to processes which have steady contaminant generation rates, or which have rates which fluctuate rapidly between known limits. Where numerous contaminants are involved, and/or a number of different processes can fluctuate in a cyclical long-term sense, it is difficult and expensive to evaluate the possible consequences of having all processes reach a peak at the same time.

8. Sampling data and computations confirm that it may be generally feasible to recirculate exhaust air from hard chrome plating tanks when high efficiency scrubbers are properly utilized, the total ventilation rate through the plant is unchanged, and full advantage is taken of the benefits of surface active agents and floating plastic balls or chips.

9. The recommendations of the ACGIH Industrial Ventilation Manual[2] in regard to minimum requirements for plating tank ventilation may be conservative when ventilation is supplemented with surface-active agents and floating balls or chips. The recommendations do not account for the beneficial effects of these measures.

10. This study confirms prior observations that there is a propensity for air cleaning devices and associated equipment to be poorly maintained.

11. The smooth flow of air across the surface of a tank controlled by a slot hood can be easily disrupted by the presence of boards, pneumatic dipping devices, etc.

12. The control provided by a slot hood can be vastly enhanced by the provision and use of properly designed tank covers.

13. It is difficult to identify duct or stack sampling techniques of proven accuracy when the contaminants involved differ from those of traditional concern to air pollution control agencies and the exhaust contains numerous interacting contaminants.

14. Although it is possible to estimate the increased humidity level in a plant due to the recirculation of water saturated air, it is not a simple matter to relate the increase to costs associated with accelerated equipment deterioration.

15. Part of the recirculation system implementation process must involve an educational program for employees exposed to the return air stream. This will foster an appreciation that good maintenance is mandatory, will facilitate the report of system anomalies, and should prove to the employees that the system will or does maintain acceptable working conditions.

16. Wet scrubbers applied to chrome plating operations may have a propensity for having clogged water drainage lines due to the nature of the contaminants involved.

Recommendations

The following recommendations evolve from the findings of this case study.

1. A user of Reference 1 should understand all aspects of the suggested methodology before initiating design efforts. The design steps in Chapter 2 of that document are not necessarily listed in the optimum order for every situation which might be encountered.

2. A user of the models should have knowledge of the concepts and assumptions upon which equations were formulated. Such knowledge should be sufficient to allow independent verification of model suitability, and to permit modifications to equations to account for unusual circumstances.

3. Recirculation should be considered as one of many possible approaches to energy saving.

4. Recirculation should be considered best suited to situations in which: 1) few contaminants are involved; 2) recirculated air replaces make-up air on a one-to-one basis; and 3) when the process does not have an emission profile which fluctuates in a cyclical long-term sense.

5. Hard chrome plating processes should be further studied. Such study has the potential to lead to a generalized and simple method for recirculation of exhaust air from such processes. Additionally, it might lead to more optimum ventilation requirements when auxiliary engineering controls are provided.

6. The development of a convenient method for chromic and sulfuric acid air sampling and analysis should be considered.

REFERENCES

1. Partridge, L. J., Nayak, P. R., Stricoff, R. S., and Hagopian, J. H., 1978. A Recommended Approach to Recirculation of Exhaust Air. DHEW (NIOSH) Publication No. 78-124. U. S. Government Printing Office, Washington, DC 20402.

2. American Conference of Governmental Industrial Hygienists, Committee on Industrial Ventilation, 1978. Industrial Ventilation: A Manual of Recommended Practice, 15th Edition.

3. National Institute for Occupational Safety and Health, 1977. NIOSH Manual of Analytical Methods. DHEW (NIOSH) Publication No. 77-157 (3 volume set). U. S. Government Printing Office, Washington, DC 20402.

APPENDIX D. DRY CLEANING PLANTS

CONTENTS

FIGURES

TABLES

DRY CLEANING PLANTS

INTRODUCTION

A majority of the dry cleaning establishments in this country utilize perchloroethylene as the primary solvent in washing machines. Additionally, many utilize air cleaning devices fitted with beds of activated carbon to recover solvent vapors from exhaust air streams, and to reduce emissions of this valuable substance to the external atmosphere. Yet a smaller subset of plants allow the cleaned exhaust air leaving air cleaners to directly reenter the work place, and in consequence, must be considered to have recirculating exhaust air systems.

Concurrently with this investigation, Arthur D. Little, Inc. (ADL), was under contract with NIOSH to perform a control technology assessment of the dry cleaning industry. When it was realized that such assessments would necessarily involve field surveys in plants which recirculate exhaust air, it was mutually agreed that ADL should extend the scope of these surveys to review the attributes of these systems. Special emphasis was to be placed upon an evaluation of the operating characteristics of air cleaners using activated carbon beds, as well as upon relevance of recommendations in Reference 1.

PLANT AND PROCESS DESCRIPTION

Plant Description

Two plants which currently recirculate, and one which vents exhaust air to the outdoors were surveyed. Two of these were large facilities handling literally tons of garments per week. The third, however, was more typical of a neighborhood dry cleaning store.

Process Description

Plant #1 processes about 6,800 kilograms (15,000 pounds) of garments per week using three cleaning machines. Each of these can wash, extract (i.e., spin dry), dry, and aerate the clothes in a single automated cycle referred to as a dry-to-dry process. The machine cabinets are well-sealed and only require exhaust during aeration and other time periods in which a loading door is open.

Plant #2 is the smaller storefront facility. Handling an average of 620 kilograms (1,370 pounds) per week of garments, it uses a single transfer process of cleaning. Here, clothes are washed and spun dry in one machine, and while damp with perchloroethylene, are manually transferred to a separate nearby drying unit.

The third facility, plant #3, also utilizes the single transfer process to handle an average of 17,700 kilograms (39,050 pounds) per week. It has one washer and two dryers in a system using perchloroethylene. Additionally, it has a set of equipment designed to use Stoddard solvent as the cleansing agent.

On the day prior to the survey at plant #3, a fire occurred in the room containing Stoddard solvent cleaning equipment. Because of resulting equipment malfunctions, production was accelerated in the perchloro-ethylene cleaning area by using the six somewhat distant dryers associated with the Stoddard solvent process along with the washing machine which uses perchloroethylene. Indeed, the Stoddard solvent washing machine and the perchloroethylene dryers were rarely used during the survey, and conditions in the plant must be considered abnormal.

Ventilation System

Local Exhaust Systems--
At plant #1, the three cleaning machines are connected with ducts to an air cleaning unit which has dual carbon beds and which discharges directly to the work place. A damper in the exhaust port of each cleaning machine is normally in the closed position when the machine is washing, extracting, or drying. During aeration, however, the loading door is opened slightly to allow influx of fresh air, and a microswitch in the door seal causes the appropriate damper to open and the exhaust fan to activate. Figure D-1 illustrates the system, and additionally shows a ventilated cabinet sometimes used to dry wet filters. To be noted is that the cleaning machine in the upper left of the figure was inoperative during the survey and essentially detached from the system.
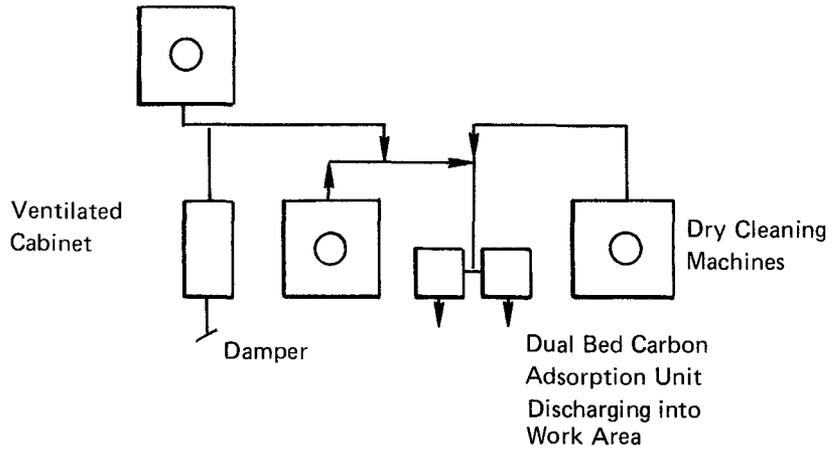
From duct traverses at various points, it was estimated that the total flow volume through the carbon bed can vary from approximately 0.19 m^3/s (400 cfm) to 0.27 m^3/s (570 cfm) when the exhaust fan is activated. The specific rate at any given time is apparently a function of which loading door is open. The overall system was in good condition and did not appear to have any obvious deficiencies.

The storefront facility's exhaust system, also shown in Figure D-1, is continuously operated and consists of ducts leading from a washing machine, a dryer, and a floor pick-up to a single-tank carbon bed discharging to the work place. As above, there is an automatic system which only allows exhaust of the dryer or washing machine when a door is opened. A flow characterization indicated that the volume rate through the air cleaner was a fairly constant 0.13 m^3/s (279 cfm).

Traverses in the various side branches provided results which were inconsistent with the air cleaner discharger rate, however, and this fact prompted a closer inspection. It was eventually found that up to 0.09 m^3/s (195 cfm) could leak into the system at a point near the carbon bed. A gasket here had literally disintegrated around the holder of a lint bag, and had left a gap through which air could enter the ductwork.

The system in plant #3 is similar to that in the storefront facility, but is attached to three floor pick-ups, two dryers, a washing machine, and an air cleaner with dual carbon beds which discharges to the outdoors. An unusual feature of the system is a specially designed slot hood over the washing machine door in lieu of a duct leading outward from the washing chamber.

Plant # 1

Ventilated
Cabinet

Damper

Dry Cleaning
Machines

Dual Bed Carbon
Adsorption Unit
Discharging into
Work Area

Plant # 2

Single Bed Carbon
Adsorption Unit
Discharging into
Work Area

Dryer

Floor
Pick-Up

Washer

Plant # 3

Dual Bed Carbon
Adsorption Unit

Vent to
Outdoors

Dryer

Floor Pick-Up

Slot Head
Over Door

Washer
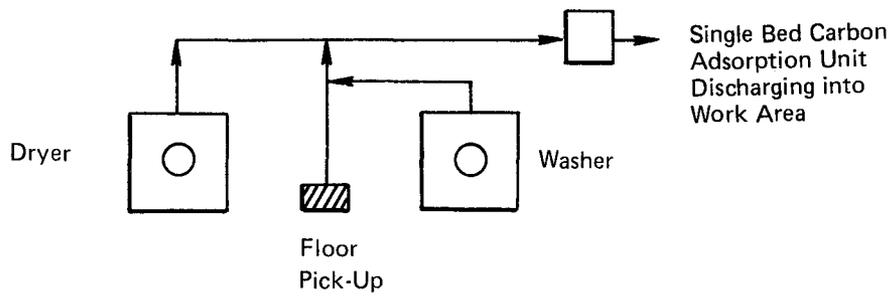
Dryer

Floor Pick-Ups

Figure D—1. Local exhaust system configurations.

150

Pitot tube traverses indicated that none of the floor pick-ups had a measureable flow of air, even when the dryer and washer doors were closed. At best, it was estimated that the air cleaner never discharged more than 0.14 m³/s (300 cfm), and would discharge less when all machine doors were closed.

General Exhaust and Make-Up Air Systems--
Plant #1 does not have any sort of mechanical make-up air system. In warm weather, it relies upon natural ventilation through numerous open external doors, and the action of exhaust fans in walls around the perimeter of the plan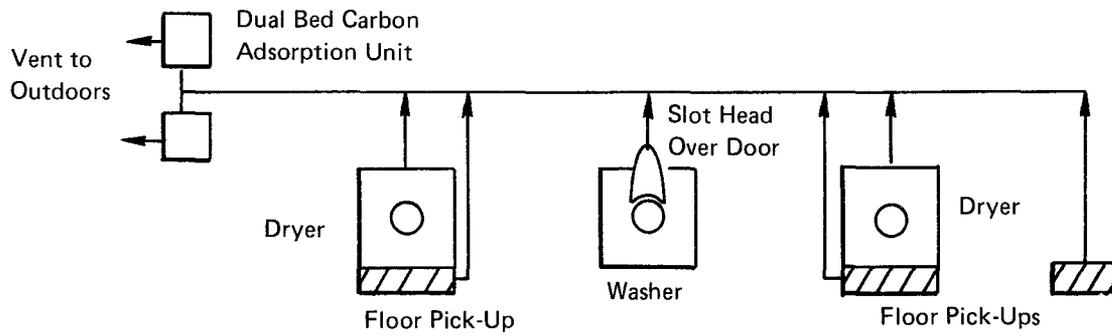t. In cold weather, many doors are closed, exhaust fans are deactivated, and infiltration provides the basic fresh air supply. In consequence, it is not possible to fully characterize ventilation rates for the plant as a whole, but it is possible to do so in the separate room containing most of the dry cleaning equipment. Here, based upon air velocity measurements in open doors, the air inflow rate estimated is on the order of 6.2 to 8.3 m³/s (13,150 to 17,500 cfm).

Plant #2 had an evaporative cooling system rated at 7.1 m³/s (15,000 cfm), and used only when the internal temperature was uncomfortably warm. Additionally, there were two roof fans which could each exhaust 5.7 m³/s (12,000 cfm), and various windows and doors which might be found open at any given time. On the first day of the survey, all fans were activated and all windows and doors were open, thus providing at least 18.4 m³/s (39,000 cfm) of fresh air inflow. On a cooler second day, only a single roof fan was activated, and the ventilation rate was on the order of 5.7 m³/s (12,000 cfm).

The third plant had several 2.64 meters (8.67 feet) diameter louvered wall fans and numerous open doors. During the survey, it was observed that air was flowing into the building through doors in a docking area, through the area with the dry cleaning machines of interest, and directly out through one of the large fans. Additionally, it was noted that make-up air was being mechanically provided to distant plant areas utilizing Stoddard solvent. Because of the many openings, and the nature of these flows, it was not possible to quantify the ventilation rate through the plant area of interest.

Air Cleaners--
When an exhaust air stream containing certain types of contaminant vapors is passed through a clean bed of activated carbon, a significant fraction of the contaminant molecules will become attached to the surface of the carbon. This action will continue until such time that the carbon becomes saturated with the contaminant. At subsequent times, the efficiency of the bed to remove vapors will drop significantly in a process termed as "breakthrough."

In general, air cleaners using activated carbon are more selective toward larger molecules and those having higher boiling points under a specific set of operating conditions. Their overall efficiency, however, is also a complex function of exhaust gas temperature, relative humidity, solubility of contaminants, carbon bed depth, and other factors.

Once saturated, the bed in a regenerative type of system is isolated
from the inlet air stream, and then subjected to superheated steam above
the boiling point of the contaminant to be removed from the carbon. The
steam causes the contaminant to vaporize, and is subsequently liquefied
in a cold water condensing system. If the contaminant is insoluble in water,
it can then be recovered by simple decantation. Finally, the bed is allowed
to cool to normal operating temperatures, and the total cycle is repeated.

The successful operation of the process has important prerequisites. More
specifically:

- The exhaust stream must be free of particulate matter so that
  the pores of the carbon particles are not clogged.
- The unit must be properly sized for the contaminant level and
  air inlet rate.
- The exhaust stream must be at a temperature below the boiling
  point of the contaminant to be recovered.
- The unit must be taken out of service before saturation occurs.
- The steam provided must be at a temperature near or above the
  boiling point of the contaminant.
- The duration of stripping by steam must be sufficient to allow
  the carbon bed and its container to attain a temperature in
  excess of the pertinent boiling point.
- The bed and its container must be allowed to cool before being
  put back in service.

If any of these prerequisites are not satisfied, the air cleaner will not
operate at its optimum efficiency, and may allow excessive passage of con-
taminant-laden air.

Plant #1 utilized an air cleaner with two separate beds, each with 160-180 kg
(350-400 lb) of carbon. Thus, it could use one unit to clean the exhaust
stream while the second was being stripped of solvent. Each bed was usually
stripped once a day with steam at a pressure of 692,250 N/m^3 (25.5 psia)
for a period of 45 to 55 minutes, and resulted in the recovery of 17 liters
(4.5 gallons) of perchloroethylene.

At plant #2, a single-bed unit was installed, so stripping was only feasible
when the exhaust system is not in use. This is done every 2 days with
534,800 N/m^2 (19.7 psia) steam for approximately 1.5 hours, and nets about
7 liters (1.85 gallons) of solvent.

Plant #3's unit was similar in size to the unit in plant #1. Stripped
daily with 589,100 N/m^2 (21.7 psia) steam for 3 to 4 hours, each bed nor-
mally recovers 11 to 15 liters (3 to 4 gallons) of solvent.

EVALUATION METHODS

Sampling Strategy

Characterization of the various recirculating exhaust systems entailed
measurements of perchloroethylene and Stoddard solvent concentrations in
general areas, worker breathing zones, and inlet and outlet ducts of the

pertinent air cleaning devices. Additionally, as best possible, it was desired to measure the volumetric rates of air flow at various points of the local exhaust systems, and wherever necessary to specify the total air balance through plant areas affected by recirculated air supplies.

Sampling and Analytical Procedures

Concentration Measurements--
Two measurement methods were utilized for contaminant concentration determinations. These include: 1) NIOSH standard methods involving collection of samples onto activated carbon; and 2) use of a direct reading and portable photoionization detector.

The technique using tubes of activated carbon is method S335 in NIOSH Reference 2 and pertains to perchloroethylene. Method S382 in the same document is similar and pertains to Stoddard solvent. Both entail collection of a sample on activated carbon, desorption in the laboratory with carbon disulfide, and subsequent analysis by gas chromatography. The only deviations from recommended procedures involved the length of sampling periods. From results of initial surveys, it was possible to adjust these such that a maximum amount of contaminant would be collected with a minimum risk of carbon saturation and breakthrough.

For instantaneous measurement of perchloroethylene area concentrations, a precalibrated photoionization detector was utilized. This device was manufactured by h-nu Systems, Inc. and is designated by their model number PI-101.

Air Velocities--
Velocities in ductwork were measured with a standard pitot tube and manometer combination. In virtually all cases, such measurements involved six-point traverses. Additional velocity data were obtained with an Alnor velometer. This device was most useful in spot checking velocities in open doors and at various hood openings.

RESULTS AND DISCUSSION

General Area and Personal Samples

In all three plants there were substantial fluctuations in perchloroethylene concentrations, not only as a function of location, but also as a function of time and specific operation being conducted. Since the numerous data obtained will be reported upon in detail in a future control technology assessment report concerning dry cleaning, it is sufficient here to simply report upon observed contaminant levels which are pertinent to the subject of recirculation.

Figure D-2 presents a top view of the area in which dry cleaning was performed in plant #1, while Table D-1 at the end of this appendix summarizes the concentrations found at various designated locations on the figure. Pertinent observations are that:

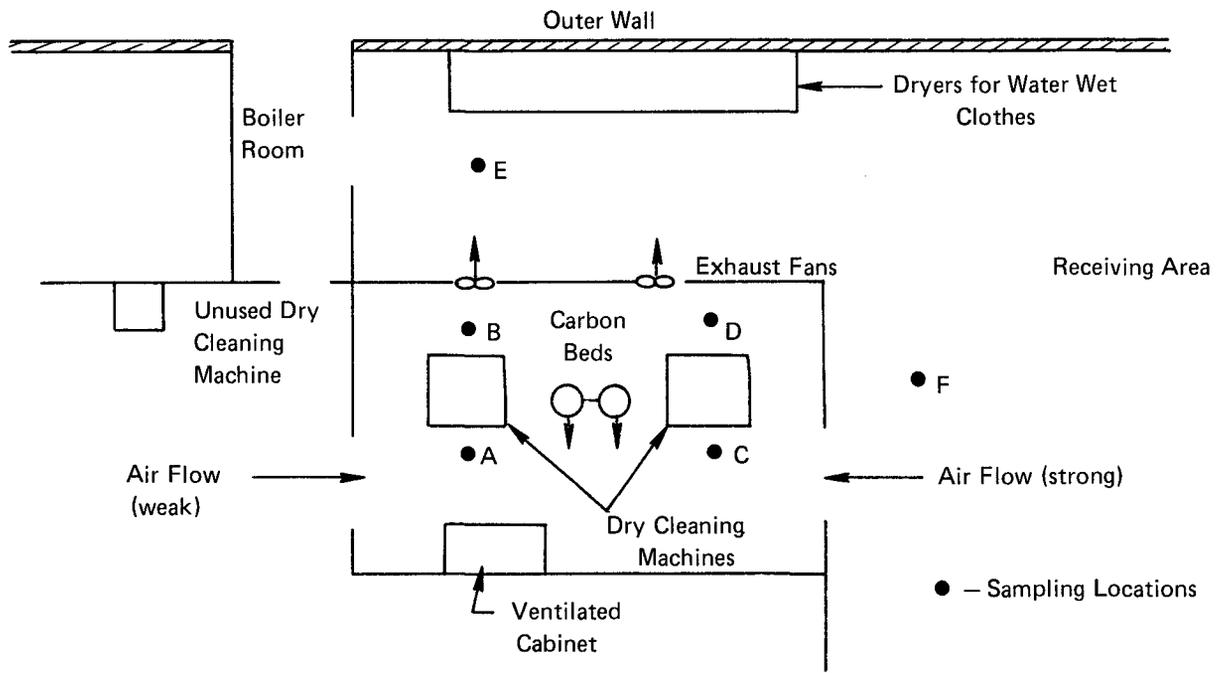- The TWA exposure of the dry cleaning machine operator ranged from 40 to 50 ppm.

153

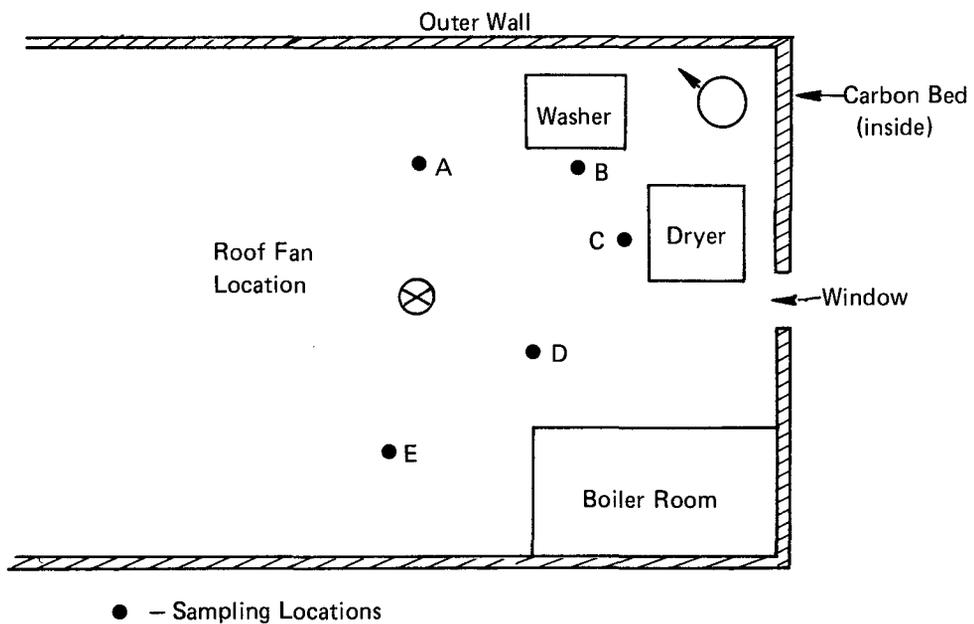FIGURE D–2   DRY CLEANING AREA IN PLANT #1

FIGURE D–3   DRY CLEANING AREA IN PLANT #2

154

- At locations A and E, concentrations in excess of the permissible exposure limit were measured, but concentrations were below this limit at all other sampling sites. Location A is strongly subjected to the outflow of the carbon adsorption units.
- The exhaust fans in the wall of the dry cleaning area are forcing contaminated air into the room containing the dryers for water wet laundry. The levels in that room are substantial when compared to the area in front of the dry cleaning machines.
- Some of the air at location E is flowing towards location F and subsequently back into the dry cleaning room.

It must be noted that only the results from one day of sampling activities are reported, although the plant was surveyed on two separate occasions. This was done because the characteristics of the carbon adsorption unit were only studied on the day for which data are presented, and it was desired to relate contaminant concentrations in the air cleaner outlet stream to observed conditions.

Overall for this plant, it was concluded that perchloroethylene exposures are well below permissible exposure limits under observed conditions. However, it is cautioned that the survey was necessarily conducted in warm weather when all doors and windows were open, and that a possibility exists that exposures would be somewhat higher in wintertime.

Figure D-3 similarly presents a view of the dry cleaning area of plant #2, while Table D-2 summarizes the sampling results for a two-day survey. Pertinent observations for the first day are that:

- All area samples showed concentrations less than 30 ppm.
- Ceiling concentrations of 13, 33, and 81 ppm were measured in the breathing zone of the dry cleaning machine operator during the course of the day.

On the second day:

- All area samples showed concentrations less than 22 ppm.
- Personal TWA concentrations for the dry cleaning machine operator were 15 ppm during the early morning and 69 ppm during the remainder of the morning.
- Ceiling concentrations of 7, 7, 8, 43, and 111 ppm were measured in the breathing zone of the dry cleaning machine operator at various times.

All measured exposures were well below permissible exposure limits under observed conditions, but it must again be cautioned that exposures may be somewhat higher under cold weather operating conditions.

Figure D-4 and Table D-3 describe results for the third plant. Results for the first day indicate:

- A 120-minute duration area sample at location B provided a TWA perchloroethylene concentration of 102 ppm. All other TWA area samples were at or below a level of 40 ppm for perchloroethylene.
- All area concentrations for Stoddard solvent were below 6 ppm.

155
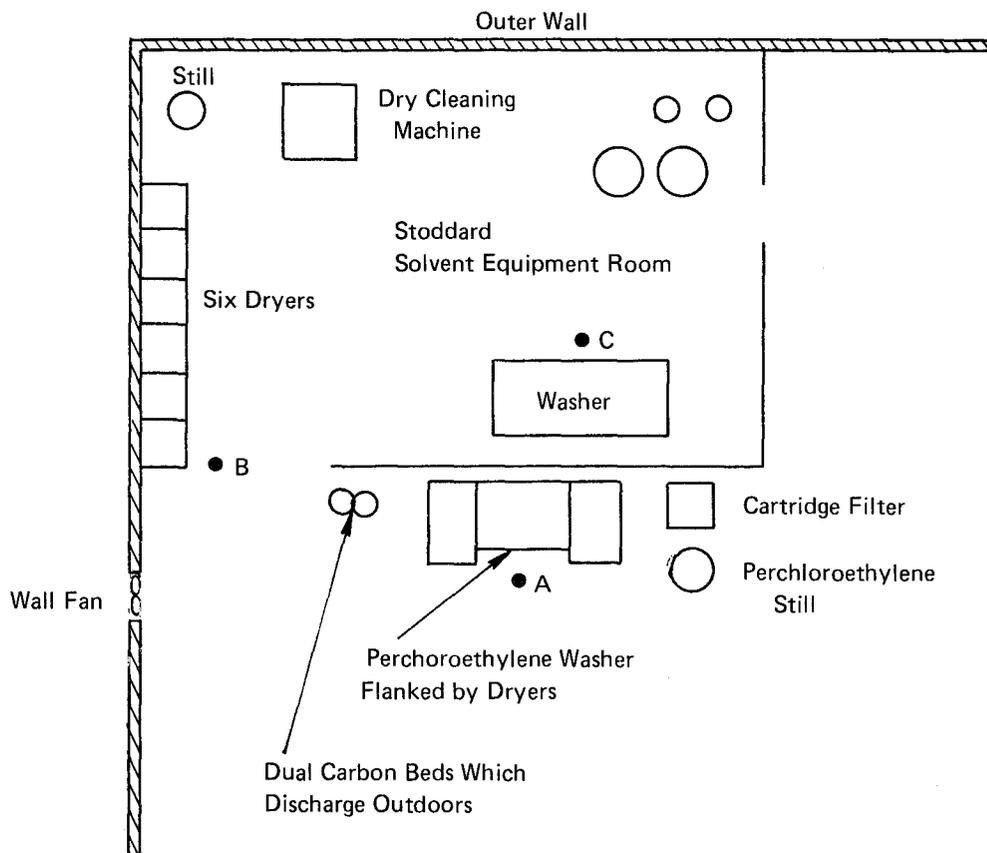
Figure D—4. Dry cleaning area in plant #3.

Outer Wall

Still

Dry Cleaning Machine

Stoddard Solvent Equipment Room

Six Dryers

● C

Washer

● B

Cartridge Filter

Wall Fan

● A

Perchloroethylene Still

Perchoroethylene Washer Flanked by Dryers

Dual Carbon Beds Which Discharge Outdoors

- The perchloroethylene dry cleaning machine operator had 26 ppm
  TWA exposure to perchloroethylene during the period 9:00 a.m. to
  2:35 p.m. His Stoddard solvent exposure during this same period
  was 5.3 ppm.
- The perchloroethylene machine operator was exposed to 161 ppm of
  perchloroethylene for a period of 15 minutes beginning at 10:02 a.m.

On the second day:

- Area concentrations for perchloroethylene ranged up to 41 ppm
  while Stoddard solvent levels were at or below 29 ppm.
- The perchloroethylene machine operator experienced TWA exposures
  of 25 ppm and 2.7 ppm respectively for perchloroethylene and
  Stoddard solvent between the hours of 7:07 a.m. and 1:24 p.m.
  Exposures for the Stoddard solvent machine operator were on
  the order of 2.6 ppm for perchloroethylene and 22 ppm for Stoddard
  solvent between 6:53 a.m. and 2:43 p.m.
- The highest level recorded was a 157 ppm exposure to Stoddard
  solvent by the Stoddard solvent machine operator at 7:55 a.m. for
  a period of 15 minutes.

TWA exposures for both contaminants of interest were obviously well below
pertinent permissible exposure limits under observed conditions. But again
it must be cautioned about changes due to a lower total ventilation rate in
the plant during cold weather.

Finally, it is appropriate to note that contaminant concentrations dropped
off rapidly with increasing distance from contaminant sources in all
three plants. Throughout most of plant #1, perchloroethylene concentrations
were on the order of a few ppm, with the exception of an area which was ad-
jacent to the dry cleaning room and had a door opening to the receiving area.
The average at this location during the survey period was roughly 14.4 ppm.

In plant #2, all areas not reported upon previously had perchloroethylene
levels which averaged at or below 3.2 ppm. Similarly, in plant #3, all
other areas had perchloroethylene or Stoddard solvent average levels on
the order of 1.0 ppm.

Duct Samples

Table D-4 at the end of this appendix summarizes the results of duct sampling
activities involving the inlet/outlets ducts of the air cleaning devices,
and it is here that the most interesting results are found.

In plant #1, where the exhaust system only activated during aeration, the
concentrations in the inlet duct to the carbon bed were generally quite
high. Indeed, it must be questioned whether the time period allowed for
drying in this plant was sufficient, since the time-weighted average air
cleaner inlet concentration computable from these data is approximately
4216 ppm. (Note: During drying, air extracted from the cabinet is passed
through cooling coils which act to condense perchloroethylene vapors to
the liquid state. If the drying period is too short, high concentrations of
perchloroethylene will leave the unit during the aeration step which immedi-
ately follows.)

During the overall period of sampling, wide variations in outlet concentrations are seen, with all values in excess of the 8-hour permissible exposure limit for perchloroethylene (100 ppm), and two values well above the 15-minute ceiling limit of 200 ppm. Indeed, on a time-weighted average basis, the outlet concentration of the air cleaner was roughly 314 ppm, and the average air cleaner efficiency was 92.54 percent while the system was operational. There would be an obvious potential for excessive exposures due to the high outlet concentrations if it were not for the fact that the system is only intermittently activated.

Previously, a number of prerequisites to the optimum use of carbon adsorption units were noted. Although variations in air cleaner efficiency cannot be definitively explained, it is suspected that the beds were not allowed to cool down sufficiently after stripping with steam. Additionally, it is noted that the temperature of saturated steam at the pressure provided by the plant is somewhat below the boiling point of perchloroethylene. It is entirely possible that beds were not being properly stripped of the contaminant and were partially saturated.

At plant #2, the pressure of steam provided suggests a saturated steam temperature on the order of 109°C (228°F). This also is below perchloroethylene's boiling point of 121°C (250°F), and raises the possibility of non-optimal air cleaner utilization if the steam was not superheated. Also, it is noted that one set of samples indicate an exhaust concentration higher than the inlet concentration to the air cleaner.

On an averaged basis, the inlet concentration was 642 ppm, the outlet concentration was 81.4 ppm, and the air cleaner efficiency was 87.32 percent when all data are utilized. If the odd set is deleted, these figures are respectively 799 ppm, 41.4 ppm, and 94.81 percent. Two sets of results are provided here because there is a slim chance that the odd set of samples were mixed up in handling. However, there is also a strong possibility that the outlet concentration was indeed higher than the inlet concentration for some not immediately evident reason.

The air cleaner at plant #3 was subjected to the lowest inlet concentrations and had the highest overall efficiency. Averaged values are 117.4 ppm at the inlet, 5.0 ppm at the outlet, and an efficiency of 95.74 percent. The steam pressure provided indicates a temperature of roughly 111°C (232°F), which is again below the boiling point of perchloroethylene, however. Additionally, it must be noted that Stoddard solvent is normally present in the air in low concentrations and has a significantly higher boiling point than perchloroethylene.

VALIDATION OF RECIRCULATION APPROACH

Introduction

One objective of this case study involved the investigation of carbon adsorption units under field conditions. Since such devices represent one of the few technologies currently available for removing gaseous contaminants from exhaust streams, it was considered advantageous to review their attributes for use in recirculating exhaust air systems.

Another purpose was to evaluate the recommendations of Reference 1 for
the recirculation system configurations commonly used in dry cleaning
establishments. In the following, therefore, the pertinent design steps
outlined in Reference 1 are briefly reviewed and applied in retrospect.
This process assumes that no plant currently recirculates its exhaust air,
that all are considering the practice, and that all currently utilize car-
bon adsorption units for solvent recovery purposes.

Initial Feasibility Assessment

Legal Issues--
The states in which the plants were located and the Federal government do
not generally prohibit the recirculation of exhaust volumes containing
toxic contaminants. The only stipulation is that employee exposures must
be maintained at or below permissible limits.

Energy Consumption--
It is not believed that plants #1 or #2 recirculate exhaust air for energy
saving purposes. Rather, it appears that they recirculate simply to avoid
the necessity of providing discharge ducts to the outside of their respec-
tive buildings. This opinion is based on the observations that:

- The hot recirculated air entered a normally warm plant area in
  both cases from directly beneath the carbon bed units.
- Distant plant areas which could benefit from a hot air stream
  in winter existed in both plants.
- The total flow volume of exhaust air in both plants was too low
  to warrant the provision of a tempered make-up air supply in cold
  weather.

Nevertheless, this opinion is ignored for the time being, and it is simply
assumed that the plants are considering recirculation as a heat saving
measure. As noted, they all have areas distant from heat sources which
might benefit from a sufficiently clean and hot air stream in winter. Since
it has been previously assumed that the exhaust air is being discharged out-
doors at all three plants, the potential energy savings are estimated by
using the calculation procedure in Chapter 7 of Reference 3, and results in
the finding that each plant would save on the order of $150 to $300 per year
by recirculating.

Contaminant Classification--
In plants #1 and #2 only perchloroethylene represented a significant contam-
inant. This substance currently has a permissible exposure limit of 100 ppm
for an 8-hour normal workday or 40-hour workweek, on a time-weighted-average
(TWA) basis. Additionally, it has a ceiling limit of 200 ppm for 15-minute
exposures and the stipulation that concentrations shall not exceed 300 ppm
for 5 minutes in any 3-hour period. Stoddard solvent simply has a permis-
sible exposure limit of 500 ppm on a TWA basis for an 8-hour normal workday
or 40-hour workweek.

The airborne contaminant concentrations reported upon earlier indicated that all plants are in compliance with these current permissible limits under the specific conditions observed. Indeed, if it is noted that exposures in plants #1 and #2 would have been somewhat lower if air was not recirculated, it is clear that there was and is substantial leeway within which to attempt the design and implementation of an acceptable recirculation system in each of the three plants. This assumes, of course, that levels would not increase substantially in winter months, a severe assumption which must be further evaluated.

A potential problem also exists with perchloroethylene. In a criteria document[4] for this substance published in 1976, NIOSH recommended that its permissible exposure limit be lowered to 50 ppm on a TWA basis for up to a 10-hour workday or 40-hour workweek. Additionally, it recommended a ceiling limit of 100 ppm. These are half the current limits. If they should be implemented, the practice of recirculation might lead to non-compliance in plants where the implementation of recirculation increases exposures from below the new limits to above them.

Another potential problem involves the possible carcinogenicity of perchloro-ethylene suspected by the National Cancer Institute. Although this possibility has not been confirmed, Reference 1 essentially cautions that such concerns must be considered in the decision to recirculate. If perchloro-ethylene is eventually designated as a carcinogen, the possibility of even lower permissible exposure limits will be greatly enhanced, and its recirculation must be discouraged.

Air Quality Regulations--
The issue of the effect of air pollution regulations upon the decision to recirculate is not highly relevant to the current study. Perchloroethylene is sufficiently expensive that a solvent recovery system is economically indicated for large users, regardless of whether or not exhaust air cleaning is mandated by Federal or local regulations.

Air Cleaner Availability--
From a chemical engineering viewpoint, most contaminants in gaseous form can be removed from air streams by gas to liquid or gas to solid absorption or adsorption techniques, chemical reaction, condensation, or incineration. Most of these require custom designed processing systems, however, and even fewer will leave the resulting air stream in a suitable form for recirculation.

For all practical purposes, there are two options for provision of a commercially available and simple packaged air cleaner for vapors and gases. The first is most pertinent to water soluble contaminants and involves the use of wet scrubbers and similar devices. These are also pertinent for use, with significant complications, when the air washing fluid is reactive with contaminants and does not itself generate toxic vapors or mists.

The second option involves the use of gas to solid adsorption units such as those which were discussed previously and which utilize granulated activated carbon filter beds. Such units are readily available. Although their initial cost, installation cost, and operating expenses can be quite high,

160

they have the distinct advantage of providing economic benefits due to contaminant recovery and reuse. Of course, the extent of this advantage is a direct function of the nature of the contaminant, its value, and the concentration in which it is present in exhaust air streams.

At plant #1 it was noted that approximately 34 liters (9 gallons) of perchloroethylene are recovered each day from the carbon beds. On an annual basis, a total recovery on the order of 8,840 liters (2,340 gallons) can be computed, with an attendant cost savings on the order of $6,350. This is obviously a significant savings considering the relatively small size of the air cleaner unit installed at this plant.

Monitor Availability--
At least one manufacturer of carbon adsorption units offers automatic monitoring and control systems on all of its solvent vapor recovery systems. Concentrations are measured in both inlet and outlet streams of the air cleaner, and the control system will automatically call for bed regeneration when the need arises. With both electrolytic and photoionization sensors available, a wide range of contaminants can be addressed.

Surveillance devices are also available for monitoring steam temperature, steam pressure, and all other necessary supplies to the air cleaner. Additionally, for perchloroethylene and many other gaseous contaminants, a host of other devices are available for monitoring inplant contaminant concentrations and the like.

Process Emission Profile--
The air cleaner outlet concentration at plant #1 varied significantly from a low of 128 ppm during aeration to a high of 707 ppm. Additionally, it must be noted that air was only recirculated when a machine door was open and/or when aeration was taking place. Indeed, it can be crudely estimated that the fan was activated no more than one-third of the time.

Significant variations were also seen at plants #2 and #3, but the ranges were lower. Disregarding the odd data set at the former plant, the range was 1 to 124 ppm. At the latter plant, the range was 1 to 12 ppm. In both cases there were specific reasons for the lower ranges. These include the air leak at plant #2 and the fact that the perchloroethylene dryers were rarely used during the survey of plant #3.

Variations such as these are difficult to consider properly when the contaminant has a ceiling limit and other restrictions, especially in the case of plant #1. The design procedure cannot simply work with time-averaged concentrations and efficiencies when the intended recirculated air stream is intermittent in nature and prone to discharge at concentrations near or above exposure limits. Rather, it must consider worst case as well as average operating conditions.

Ventilation System Design--
In all plants surveyed, the ventilation system were quite basic in configuration, and would not provide difficulties during the implementation of recirculation. Floor space was available for placement of the air cleaners, and

mostly bare overhead spaces could easily accommodate the necessary ductwork for an envisionable return air distribution system.

Conclusions--
Pending further analysis, this initial feasibility study has mostly identified the various pro's and con's to recirculation in these plants. On the positive side, there is a potential for saving an amount of heat energy during cold weather. Conversely, it is seen that savings are rather minor, that future changes in perchloroethylene permissible exposure limits are envisionable, and that the potential risks in plant #1 are considerable due to the short-duration, high-concentration nature of the air cleaner discharge stream. At plant #2, because of the lower all around concentrations, the risks are somewhat lower, as they are in plant #3.

Contaminant Characteristics

Previously, the significant airborne contaminants in the plant areas of interest and within the inlet and outlet streams to the various air cleaners were identified. Additionally, the toxicity of the contaminants and their physical and chemical properties were reviewed. These data are called for by Reference 1 and are in most respects adequate for use in the design process.

The term "most" is used in the previous sentence because Reference 1 suggests that concentrations be characterized under the conditions under which recirculation will take place. Due to the fact that all plants were studied in fairly warm weather, it must be realized that the data are influenced by natural ventilation effects which would generally be absent in cold weather.

Work Place, Process, and Ventilation System Characteristics

This step involves characterization of the work place in terms of air volumes handled, locations of air inlet and outlet locations, work station locations, air flow patterns, and other factors. Again, the surveys mostly satisfied the requirements of Reference 1, although there were complications due to the presence of open windows and doors.

Selection of Air Cleaning Equipment for Further Consideration

Where a new air cleaner is to be installed, Reference 1 suggests identification and information gathering for all equipments pertinent to the task of cleaning contaminated air streams. Since the availability, efficiency, economics, maintainability, and general reliability of air cleaners can vary among units of a particular type, this step helps ensure that the best overall unit is ultimately selected for use.

Selection of Surveillance Equipment for Further Consideration

Reference 1 strongly suggests consideration of some sort of reliable methodology for detecting reduced system performance. If its recommendations are to be followed, the air cleaners in all three plants would either require the retrofitting (if possible) of the automatic systems previously described, or a monitoring system for airborne concentrations of perchloroethylene would have to be considered.

162

Determination of Feasible System Configurations

A review of all feasible recirculation system configurations using the basic philosophy espoused by Reference 1 would have identified configurations in which:

- A bypass duct is provided to allow exhaust of air cleaner effluent to the outdoors in warm weather or under emergency conditions, and/or
- Return air is distributed to lowly contaminated plant areas which could benefit from the extra heat during cold weather.

Both of these suggestions have merit for self-evident reasons. Plants #1 and #2 are partially wasting the heating potential of the return air stream at present by distributing it within a usually hot work area. Additionally, both are aggravating the heat problem in the vicinity of dry cleaning machinery in hot summer conditions.

Design Optimization for Feasible Configurations

The optimization procedure in Reference 1 is intended to allow predictions as to the effect of recirculation upon the working environment. A subsequent section will review the suggested methodology.

Failure Analysis for Feasible Configurations

To guard against the real possibility that systems may fail, Reference 1 suggests the performance of a failure analysis for each system configuration of interest. In the present case, such an analysis would assume that the carbon bed has become saturated, and that its cleaning efficiency has dropped to zero. The result of such an analysis would indicate the time frame in which permissible exposure limits would be exceeded if a system failure were undetected.

Selection of the Best Configuration

This step involves selection of the system configuration providing the best balance of health safety and cost savings. With input from previous design steps, it forces attention to all issues involved.

Previous discussion has noted that Reference 1 strongly suggests provision of a system surveillance methodology, provision of an exhaust air bypass route to the outdoors, and distribution of return air to plant areas which could safely benefit from the heating value of the air. It is intuitively obvious that provision of one or all of these system features could negate the possible cost savings potentially available by recirculation in these plants. The potential yearly cost savings are simply too minor to justify large expenditures for monitoring devices, new ductwork, and the host of other sampling, analysis, and design procedures necessary for the initial and continued operation of an acceptable recirculation system.

In consequence, this evaluation is terminated at this point with the conclusion that recirculation of exhaust air is not warranted in any of the three plants being evaluated. Additionally, it is concluded that the recommendations of Reference 1 have suitably allowed us to evaluate the feasibility of recirculation in these plants. In support of these conclusions, the following findings of the overall analysis are reiterated.

1. The permissible exposure limits for perchloroethylene are likely to be lowered in the not too distant future.

2. The energy savings potential with recirculation in these plants is almost inconsequential.

3. Currently installed recirculation systems are not properly designed to make best use of the return air stream. Modifications with that purpose would negate any cost savings to be realized with recirculation.

4. Although one might debate the need for a surveillance methodology in these plants, it is clear that there is potential for excessive exposures in the event of system failure without such a methodology.

5. The plants which currently recirculate were found to be in compliance under the very favorable conditions of the surveys. Nevertheless, there is cause to suspect that the margin of safety would be considerably less under normal operating conditions in cold weather.

6. Pending a subsequent evaluation of the recirculation system design models, it can at this point be stated that Reference 1 has significantly helped in the identification of the above findings.

Recirculation Model

Because of the nature of the surveys conducted, it is not fully possible to apply the models of Reference 1 in retrospect to evaluate their validity. It is possible, however, to qualitatively evaluate whether they contain the elements necessary to properly predict post-recirculation conditions in dry cleaning plants.

The specific model used as the vehicle for this evaluation is that designated as Model #1 in Reference 1 and described on pages 107 to 113 inclusive of that document. Although this model describes a recirculation system configuration considerably more complicated than the basic configuration of interest, it allows more comprehensive consideration of expected conditions.

To avoid redundancy, only plant #1 is considered at this time. It is obviously the most complicated in terms of process variables and exhaust system configuration, and should be the most difficult to properly address.

Model Equations--
Table D-5 summarizes the model equations of interest after all non-pertinent terms have been assigned zero values and deleted from consideration. For

the reader who wishes to closely follow this analysis, it is noted that these terms are the parameters:

Q_G Q_{MU1}

Q_{GB} Q_{CB} f

Q_{LB} Q_G° C_{BZL}°

These and the other parameters in the equations are defined in Table D-6.

Model Application Methodology--
By closely inspecting the various equations, it is seen that there is potential for their use in two ways:

1. To predict the area and breathing zone in various plant areas in cold weather when most windows and doors are closed; and

2. Using the above results, to predict the effects of recirculation upon the various plant areas to which the return air stream might be distributed.

Reference 1 indicates that the equations are generally applicable to the evaluation of conventional ventilation systems, so an attempt for such a utilization for the first case may be enlightening. It would essentially be attempting to predict pre-recirculation conditions (cold weather) from data obtained at the wrong time of year (hot weather).

To perform the first part of the analysis, it is assumed that recirculation has not yet been implemented and the parameter Q_L is assigned a value of zero. This results in a Q_R value of zero, and logically, leaves only the breathing zone concentration prediction equation to contend with. This latter equation, with C_R and k_{BZ} values of zero, reduces to:

$$C_{BZ} = \frac{Q_T^\circ}{Q_T} \ (C_{BZG}^\circ - C_{MU}) + C_{MU}$$

where:

Q_T° is supposed to be the total ventilation rate through the plant in a "before" condition;

Q_T is as above but for an "after" condition;

C_{BZG}° is the concentration associated with the "before" condition;

C_{MU} is the contaminant concentration in make-up air; and

C_{BZ} is the predicted concentration in the "after" condition.

There are two areas of concern about the accuracy of the expression. First, it is noted that the generalized but appropriate definitions for the terms Q_T^o and Q_T are not properly represented by the equations presented for these terms. Next, it is noted that the use of a single term for contaminant concentrations in make-up air may not be appropriate under some circumstances for this type of analysis.

The first problem stems from the fact that the model formulation inherently assumes that the combined rate of natural ventilation and infiltration (Q_N) into any plant area will remain a constant in both the before and after conditions. More properly, Q_N should be divided into two terms, with one for a before condition, and one for the after condition. This would partially solve the difficulty associated with this sort of analysis, as well as others identified in a previous case study (see Hard Chrome Plating Plant #2). The full expressions for Q_T^o and Q_T would then become:

$$Q_T^o = Q_{MU}^o + Q_{N1}$$

$$Q_T = Q_{MU2} + Q_{MU}' + Q_R + Q_{N2} \text{ for evaluating recirculation systems}$$

$$= Q_{MU}^o + Q_{N2} \text{ for evaluating simple changes in } Q_N$$

where:

Q_{N1} is the combined rate of natural ventilation and infiltration in the before condition; and

Q_{N2} is as above for the after condition.

Retracing the model formulation procedure, the stated assumption is found that the concentration in make-up air is <u>conservatively</u> assumed to remain constant during any change of conditions. In the sense that C_{MU} represents the contaminant concentration in <u>fresh</u> make-up air entering a plant, this assumption is acceptable. However, if it is remembered that the dry cleaning area in plant #1 received its make-up air from other plant areas, and not from outdoors, it is found that the assumption is not conservative. Rather, for this particular plant area, it is non-conservative in the sense that such concentrations may actually increase when the total ventilation rate becomes lower under cold weather conditions, and/or when recirculated air streams increase contaminant levels in the vicinity of the dry cleaning room.

To resolve this difficulty, C_{MU} must be divided into two parts such that:

$$C_{BZ} = \frac{Q_T^o}{Q_T} (C_{BZG}^o - C_{MU1}) + C_{MU2}$$

where:

C_{MU1} is the contaminant concentration in make-up air in the before condition; and

C_{MU2} is as above for the after condition.

C_{MU2} can be crudely estimated with an expression of the form:

$$C_{MU2} = \frac{C_{MU1} Q_T^\circ}{Q_T}$$

The second objective calls for an evaluation of the effects of recirculation upon existing conditions in the plant. Clearly, it is for this type of analysis for which the model equations were formulated, and they should be capable of use in the form presented in Reference 1. The qualitative review did not indicate any theoretical obstacles to their proper application, but did discover some practical difficulties in the assignation of numerical values to certain parameters. These difficulties evolved because of the intermittent nature of the exhaust stream intended for recirculation, but were not seen to be insurmountable.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions can be derived from the results of this case study.

1. Recirculation has been shown to be safe and feasible in two dry cleaning plants under the conditions observed. As a general rule, however, it is concluded that there is insufficient economic justification for such plants to recirculate. The potential savings in many plants simply do not warrant the attendant risks of non-compliance with current or future permissible exposure limits.

2. From a health safety viewpoint, recirculation is not considered justified by cost savings due to the non-provision of an exhaust duct to the outdoors. This rationale has been witnessed in two dry cleaning plants which recirculate exhaust air, as well as in a plant which recirculates air from dry grinding operations. In all cases, it is found lacking in merit.

3. Activated carbon adsorption units have a highly variable efficiency when subjected to wide fluctuations in inlet contaminant concentrations, temperatures, and/or exhaust volume rates. Although they were quite efficient on the average under observed conditions, there is apparently some potential for periods of low efficiency to result in outlet concentrations far in excess of average values. This characteristic must be fully considered when contaminants have ceiling or other short-term limits.

4. There are many factors which can affect the efficiency of a carbon adsorption unit. Each of these factors must be fully considered if such a unit is to be utilized in a recirculating exhaust system.

5. The qualitative recommendations of Reference 1 appeared to be fully adequate for the identification and resolution of all issues pertinent to the consideration of recirculation in these plants.

6. Possible improvements were identified for incorporation into the recirculation system design models.

Recommendations

The conclusions expressed above lead to the following recommendations.

1. Situations where recirculated air replaces make-up air volumes provided by natural forces have been repeatedly encountered. It is therefore recommended that the models be revised to incorporate "before" and "after" air flow rates which are a combination of natural ventilation and infiltration rates.

2. The models assume that the contaminant concentration in make-up air volumes remains a constant. Although it is recognized that this is a necessary and conservative assumption in many situations, it may be desirable to incorporate "before" and "after" concentrations of this sort into the models. This action would allow the model user the option of using the above assumption instead of forcing it upon him.

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Table D-1. Sampling results at plant #1.

Area Designation	Sample Type*	Start Time	Duration (minutes)	Perchloroethylene (ppm)	Comments
A	HNu	7:00 am	–	20	At 1.4 m (4.5 ft) height in front of machine.
		8:30	–	40 – 70	Usually with door closed.
		9:30	–	95	
		10:30	–	10	
		1:00 pm	–	20	
		2:00	–	30	
	CT	6:40 am	140	131	Below door at front of machine.
		6:40	140	118	
B	HNu	–	–	50 – 70	Consistent throughout survey
C	HNu	7:00 am	–	11	At 1.4 m (4.5 ft) height in front of machine.
		8:30	–	40	Usually with door closed.
		9:30	–	30	
		10:30	–	6	
		1:00 pm	–	20	
		2:00	–	30	
D	HNu	–	–	30	Consistent throughout survey.
E	HNu	8:30 am	–	60	In room containing dryers for water wet laundry.
		9:30	–	40 – 70	
		10:30	–	22	
		1:00 pm	–	60	
		2:00	–	110	
	CT	8:58 am	60	90	
F	HNu	7:00 am	–	6	In receiving area adjacent to dry cleaning area.
		8:30	–	10	
		9:30	–	25	
		10:30	–	4	
		1:00 pm	–	20	
		2:00	–	7	
	CT	10:35 am	55	7	

169

Table D-1. Sampling results at plant #1 (concluded).

Area Designation	Sample Type*	Start Time	Duration (minutes)	Perchloroethylene (ppm)	Comments
Personal	CT	6:30 am	120	41	For dry cleaning machine
	CT	8:47	123	43	
	CT	10:02	15	16	
	CT	2:10 pm	15	38	

* HNu — photoionization unit
  CT   — charcoal tube

Table D-2. Sampling results for plant #2.

Area Designation	Sample Type*	Start Time and (Day)	Duration (minutes)	Perchloroethylene (ppm)	Comments
A	HNu	7:45 (1)	–	2	In front of cartridge filter and still.
		8:30 (1)	–	5	
		10:00 (1)	–	15	
		11:00 (1)	–	2	
		8:15 (2)	–	2	
		9:15 (2)	–	8	
		10:15 (2)	–	8	
		11:30 (2)	–	2	
		11:45 (2)	–	15 – 20	
	CT	9:45 (1)	120	3	
B	HNu	7:45 (1)	–	1.2	In front of washer.
		8:30 (1)	–	1.6	
		10:00 (1)	–	30	
		11:00 (1)	–	9	
		8:15 (2)	–	5	
		9:15 (2)	–	17	
		10:15 (2)	–	10	
		11:30 (2)	–	2	
		11:45 (2)	–	20	
	CT	7:55 (2)	99	17	Below washer door in front of machine.
		7:55 (2)	99	22	
		9:45 (2)	55	6	
		9:45 (2)	55	14	
C	HNu	7:45 (1)	–	1	In front of dryer
		8:30 (1)	–	1.4	
		10:00 (1)	–	15 – 20	
		11:00 (1)	–	6	
		8:15 (2)	–	5	
		9:15 (2)	–	18	
		10:15 (2)	–	9	
		11:30 (2)	–	2	
		11:45 (2)	–	15	

171

Table D-2. Sampling results for plant #2 (concluded).

Area Designation	Sample Type*	Start Time and (Day)	Duration (minutes)	Perchloroethylene (ppm)	Comments
D	HNu	7:45 (1)	-	1	
		8:30 (1)	-	1.2	
		10:00 (1)	-	10 - 13	
		11:00 (1)	-	4 - 5	
		8:15 (2)	-	6	
		9:15 (2)	-	15 - 20	
		10:15 (2)	-	8	
		11:30 (2)	-	2.5	
		11:45 (2)	-	20	
E	HNu	7:45 (1)	-	0.8	
		8:30 (1)	-	1.2	
		10:00 (1)	-	1.6	
		11:00 (1)	-	1.4	
		8:15 (2)	-	3	
		9:15 (2)	-	7	
		10:15 (2)	-	9	
		11:30 (2)	-	2	
		11:45 (2)	-	12	
Personal	CT	7:35 (1)	120	< 1	For dry cleaning machine operator.
		9:53 (1)	15	33	First sample taken mostly before dry
		10:25 (1)	15	81	cleaning started.
		10:55 (1)	15	13	
		7:40 (2)	145	15	
		9:04 (2)	15	111	
		9:34 (2)	15	7	
		9:56 (2)	130	69	
		10:06 (2)	15	8	
		11:30 (2)	15	7	
		12:15 (2)	15	43	

* HNu - photoionization unit
  CT - charcoal tube

172

Table D-3. Sampling results at plant #3.

Area Designation	Start Time and (Day)	Duration (mins)	Perchloroethylene (ppm)	Stoddard Solvent (ppm)
A	9:00 am (1)	60	11	1
	10:10 (1)	60	8	1
	11:08 (1)	120	19	1
B	9:23 am (1)	60	40	3
	10:27 (1)	120	102	4
	1:10 pm (1)	75	33	6
	6:50 am (2)	60	2	22
	8:35 (2)	60	41	2
	9:48 (2)	60	40	2
	11:24 (2)	60	35	20
C	6:50 am (2)	60	26	29
	8:00 (2)	60	2	4
Personal*	9:00 am (1)	124	43	2
	9:00 (1)	15	74	1
	9:27 (1)	15	130	1
	10:02 (1)	15	161	10
	10:30 (1)	15	137	0
	11:02 (1)	15	100	1
	11:04 (1)	133	18	8
	12:05 pm (1)	15	49	21
	1:17 (1)	78	13	6
	7:07 am (2)	134	27	6
	9:21 (2)	121	21	1
	11:22 (2)	122	27	4

173

Table D-3. Sampling results at plant #3 (concluded).

Area Designation	Start Time and (Day)	Duration (mins)	Perchloroethylene (ppm)	Stoddard Solvent (ppm)
Personal**	6:53 am (2)	143	3	43
	7:12 (2)	15	1	1
	7:28 (2)	15	7	57
	7:55 (2)	15	7	157
	9:16 (2)	15	2	2
	10:55 (2)	15	1	5
	11:19 (2)	69	3	18
	11:40 (2)	15	7	47
	1:20 pm (2)	83	2	9
	2:04 (2)	15	7	37

 * For perchloroethylene machine operator.
** For Stoddard solvent machine operator.
    NOTE: All samples taken with charcoal tubes.

Table D-4. Duct sampling results.

Plant	Date	Sample Start Time	Sample Duration (minutes)	Inlet Concentration (ppm)	Outlet Concentration (ppm)	Efficiency (%)	Comments
1	08-17-78	7:56 am	16	6923	707	89.79	All samples in Plant #1
	"	8:23	23	295	190	35.59	taken during aeration
	"	8:46	18	6923	183	97.36	of loads.
	"	11:05	14	3682	128	96.52	
	"	1:32 pm	16	4566	412	90.98	
2	09-12-78	10:27 am	53	514	11	97.86	During drying
	"	10:47	6	4109	1	99.98	During aeration
	"	11:00	20	83	50	39.8	During dry and cool
	09-13-78	9:02 am	22	1326	88	93.36	During dry and cool
	"	9:35	28	31	237	?	Whole cycle
	"	10:28	8	545	124	77.25	During aeration
3	08-24-78	10:00 am	15	162	6	96.30	
	"	12:54 pm	15	81	1	98.77	
	"	1:10	4	149	5	96.64	
	"	1:48	15	3	1	66.67	During wash cycle
	"	2:03	15	215	12	94.42	Washer door open

Table D-5.   Model equations.

Air Flow Equations:

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

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

$$Q_D = Q_L$$

$$Q_{MU2} = Q_G' - Q_{MU}'$$

$$Q_R = Q_D \doteq Q_L$$

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

Return Air Concentrations:

$$C_D = \frac{(1 - \eta)(C_E^{\circ} - k_R C_{MU})}{1.0 - (1 - \eta)k_R}$$

$$C_R = C_D$$

Breathing Zone Concentrations:

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

176

Table D-6. Definition of symbols.

Q_{T_o} — The pre-recirculation total ventilation rate through the plant area to be affected by recirculation.

Q_T — As above, but pertains to the post-recirculation rate.

Q_{MU}^o — The total volume rate of mechanically provided make-up air before recirculation.

Q_N — The combined natural ventilation and infiltration rate.

Q_L — The total exhaust volume rate for local exhaust streams to be recirculated.

$Q_{L_{out}}$ — The total exhaust volume rate for local exhaust streams not to be recirculated.

Q'_G — The general mechanical ventilation (exhaust) rate.

Q'_{MU} — A minimum rate of fresh make-up air to be introduced during recirculation.

Q_{MU2} — An incremental rate of fresh make-up air to be introduced during recirculation to provide a balanced system.

C_{MU} — The concentration(s) of pertinent contaminants in fresh make-up air.

C_E^o — The concentration(s) of pertinent contaminants in local exhaust streams to be recirculated before recirculation.

C_R — The concentration(s) of pertinent contaminants in return air streams (i.e. leaving air cleaners).

C_{BZG}^o — The concentration(s) of pertinent contaminants in selected breathing zones in "open" plant areas.

C_{BZL}^o — The concentration(s) of pertinent contaminants in selected breathing zones in strong local exhaust induced flow fields (not pertinent in these plants).

η — The air cleaner efficiency for each contaminant.

k_{BZ} — The physical fraction of air, in selected breathing zones, which originates in return air streams.

k_R — The physical fraction of air which enters local exhaust systems being recirculated and which itself originates in return air streams.

f — The fraction of time that selected employees spend in strong local exhaust-induced flow fields (has a zero value for these plants).

177

APPENDIX E. WELDING OPERATION

CONTENTS

FIGURES

TABLES

WELDING OPERATION

INTRODUCTION

A manufacturing company was in the process of designing and implementing a prototype recirculation system for welding exhaust fumes during the course of this study. Although the equipment could not be installed and tested in time for a detailed evaluation to be included in this report, there is considerable benefit in providing an overview of the plant's difficulties and successes in considering recirculation for the first time.

PLANT AND PROCESS DESCRIPTION

Plant Description

The plant building of interest is of such overwhelming size that no attempt was made to record all characteristics. Indeed, it suffices to note that construction was essentially cinder block, that there were numerous glassed-in areas to provide natural light, and that the total volume of the work area was on the order of 5.3 million cubic meters (187 million cubic feet).

Process Description

Welding operations of various types constitute the major contaminant-producing operations in the pertinent region of the plant. Additionally, there are a number of propane and gasoline fueled lift trucks which operate in the area.

The specific welding operation of interest consists of 4 manual arc-welding stations in an assembly line. The welders here continuously place arrays of stamped iron parts on work tables and arc-weld various edges together.

Ventilation System

Each work station had a free-standing, flanged taper hood suspended at an angle above one end of the work table. The four such hoods currently exhaust a total of 3.71 m^3/s (7,872 cfm), although the system was originally rated at 4.72 m^3/s (10,000 cfm).

Throughout the building are approximately 35 local exhaust systems of various types which provide a total exhaust volume of roughly 1,057 m^3/s (2,241,000 cfm). Similarly, numerous make-up air supply units provide a total fresh air inflow rate of 822 m^3/s (1,741,000 cfm). The difference is equivalent to an air volume change rate of 0.16 per hour and is easily provided by normal infiltration into the building.

VALIDATION OF RECIRCULATION APPROACH

Introduction

An independent consultant hired by the plant to assist in the design of the prototype system was familiar with the contents of Reference 1, and had considerable experience with the control of inplant emissions from welding operations. In the following, therefore, the scope and findings of his design efforts will be discussed in a format consistent with the design steps listed in Chapter 2 of Reference 1. Additionally, any digressions from Reference 1's methodology will be noted and discussed.

Initial Feasibility Assessment

Legal Issues--
The state in which the plant resides has specific regulations concerning the recirculation of industrial exhaust air. These are:

1. Recirculation of air containing a contaminant whose Maximum Acceptable Concentration*(MAC) is equal or exceeds 1000 ppm, 15 mg/m^3, shall be permitted if the exhaust ventilation system is equipped with an air cleaning device capable of reducing the contaminant concentration to 10 percent of their MAC in the returned air.

2. The Director may allow recirculation of air containing a contaminant whose MAC is less than 1000 ppm, 15 mg/m^3, if the toxicity of the contaminant and the degree of air cleaning to be achieved creates an environment which will not impair the health of the worker. . . the return air shall not exceed 10 percent of its MAC.

3. A . . . system shall include an alternate air duct connection to discharge the return air outside . . . if necessary to protect workers' health.

Because of the first two specifications, the consultant was restricted to only considering recirculation system configurations which reduce the return air concentration of each contaminant to 10 percent or less of its permissible exposure limit. Additionally, he was required to provide a bypass duct to the outdoors.

It is highly interesting to note that Reference 1 does not contain any recommendations which restrict contaminant concentrations in return air streams. Rather, it provides a methodology allowing prediction of the effect of recirculation upon workers' breathing zones, and then recommends comparison of predicted post-recirculation exposures with permissible limits. This is an entirely different approach from that suggested by the state regulation, and is obviously one which allows a more comprehensive assessment of the effect of recirculation upon the working environment. The 10 percent limit is not only somewhat arbitrary in nature, but also cannot ensure compliance with health standards in all cases if blindly applied.

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* A MAC is essentially the OSHA permissible exposure limit for a substance.

Energy Consumption--
The plant estimates a yearly average air heating cost of approximately $600
for each 0.47 m^3/s (1000 cfm) of make-up air. For the total make-up air
volume provided, it spends slightly more than one million dollars per year
on fuel bills. As energy costs rise, therefore, it is evaluating various
alternatives for energy conservation. The prototype recirculation system
represents one of the alternatives which has the potential to be copied for
installation on a number of welding exhaust systems.

Contaminant Classification--
Based upon experience and a review of the literature, the consultant iden-
tified iron oxide fume, fluorides, and manganese as the significant contam-
inants generated by the welding operation. Table E-1 lists the current per-
missible exposure limits for these substances.

Table E-1. Contaminants in welding exhaust.

Contaminant	Current OSHA Limit (mg/m^3)
Iron oxide fume	10
Fluorides	2.5
Manganese	5.

The main constituent of the exhaust was concluded to be iron oxide fume, a
substance which the literature reports is not associated with serious adverse
health effects. For fluorides, it was concluded that concentrations would be
much lower than exposure limits if iron oxide is below its limit, based on
the fact that fluorides in the flux are less than 5 percent of the welding
electrode. With knowledge that manganese is present in the deposited metal
in a maximum concentration of 0.65 percent, it was similarly concluded that
this material will not result in adverse exposures when the iron oxide is
under control.

Although the subject was not entirely pertinent to the manual welding oper-
ation being considered, the consultant also reviewed potential emissions from
carbon dioxide shielded arc welding operations of interest for future recir-
culation. From published contaminant production rates for this type of pro-
cess, he noted that carbon monoxide, nitrogen dioxide, and ozone are signifi-
cant additional contaminants, and estimated their expected concentrations in
exhaust streams. This resulted in the conclusion that carbon monoxide levels,
and possibly nitrogen dioxide levels throughout the plant, will require fur-
ther study before other welding exhaust volumes are recirculated.

Air Quality Regulations--
There were no air pollution control regulations which pertain to the decision
to recirculate. The plant currently discharges all exhaust air to the outdoors,
and would require the installation of air cleaning devices only if recircula-
tion systems are implemented. Thus, the cost of air cleaning must be fully
provided by savings resulting from recirculation.

Air Cleaner Availability--
In a preliminary assessment of air cleaning devices, the consultant reviewed
the characteristics of air filters of the extended area type, industrial
fabric collectors, and electrostatic precipitators. Noting that air filters
have successfully been applied for welding operations with light air cleaner
loadings, he decided against their use in this particular plant because: 1)
they usually have a limited holding capacity; 2) cannot be cleaned and reused;
and 3) because the operation being studied involves heavy and virtually con-
tinuous welding.

Fabric collectors for welding fume collection were rejected on the grounds
that they require a large space, need to be treated with filter aid material
to attain suitable filtering efficiencies, and have been noted in the past to
result in objectionable odors. This left electrostatic precipitators for
further consideration, a methodology which had no immediately evident dis-
advantages.

For others who may be interested in the recirculation of exhaust air from
welding operations, however, it is noted that this assessment did not neces-
sarily do full justice to the feasibility of using other cleaning methods.
A recent publication[2] and supporting evidence from its author suggest that
at least one brand of commercially available fabric collector does not re-
quire filter aid material and has not caused an odor problem in two large
recirculating exhaust systems for similar fumes. Additionally, it must be
noted that at least one manufacturer provides an air cleaner utilizing auto-
matically recleanable high efficiency air filters.

Monitor Availability--
The consultant knew of several monitoring devices which could potentially be
utilized to actuate bypass dampers in the event of air cleaner malfunction.
These all involved in-duct monitoring of contaminant concentrations.

Process Emission Profile--
In the production line environment of this plant, the process emission pro-
files of welding operations would not cause difficulties in the design and
implementation of a recirculation system. Although air cleaner loadings fluc-
tuate widely, they do so rapidly and in a fashion which does not change sig-
nificantly with time in the long-term sense.

Ventilation System Design--
There were severe space limitations in and around the welding stations. Never-
theless, overhead space was available for locating an air cleaner near a par-
tial wall separating the production line from a central storage space. This
location had the advantage of being close to the position that the existing
exhaust duct turns upward for exit through the roof.

Conclusion--
This initial feasibility assessment obviously indicates there is potential for
energy conservation by recirculation of welding exhaust fumes. It now remains
to retroactively review the more detailed system design efforts of the con-
sultant in the order suggested by Reference 1.

Contaminant Characteristics

Reference 1 indicates a need to accurately and comprehensively quantify con-
taminant concentrations in breathing zones and in exhaust streams before re-
circulation is implemented. Without such data, it is clearly difficult, if
not impossible, for a system designer to accurately assess the effects of
recirculation upon the working environment.

The plant's industrial hygiene staff attempted to satisfy this data need with
only three time-weighted average samples of total fume. Their findings indi-
cated concentrations of 3.5 mg/m^3 in the welding exhaust, 6.8 mg/m^3 in the
general area above the exhaust hood, and a level somewhat above iron oxide
exposure limits in the breathing zone of the single welder working in the
area while the survey was conducted. (Note: Although 4 welding stations
are involved in the system, no more than 2 are usually in use.) There are two
issues which require discussion here. The first involves the limited scope of
data acquisition activities, and the second involves the finding of an exces-
sive exposure.

Reference 1 does not specify exactly how many samples must be taken at each
desired location, but it does imply that there must be a sufficient number
to provide a firm data base for the design process. Although the data pro-
vided to the consultant may indeed be sufficient for design of this particular
prototype system, it is obvious that its paucity introduces a great deal of
uncertainty into the analysis.

The excessive exposure level necessitated, and indeed prompted, a close in-
spection of the welding station exhaust hood. This review indicated that the
hood configuration was designed to control the fumes from the welding of one
or two sets of parts placed directly in front of its opening. To facilitate
production, however, the welder was arraying a long row of parts upon the
work table and welding them at locations considerably distant from the hood
face. In consequence, the fumes were rising directly through his breathing
zone at times.

To ensure that workers do not inadvertently misuse control systems in the
future, the consultant and plant staff decided to provide redesigned exhaust
hoods at work stations as part of the recirculation system design process.
They did not, however, deem it necessary to perform this effort before the
final design of the recirculation system. Thus, from this point on, they were
working with concentration data which might or might not represent actual con-
ditions after the hoods are redesigned.

Work Place, Process, and Ventilation System Characteristics

With some limitations, the consultant had full knowledge of the work place,
process, and ventilation system characteristics necessary for system design.
The limitations evolve solely from the paucity of airborne concentration
data.

Selection of Air Cleaning Equipment for Further Consideration

Finding that electrostatic precipitators of the two-stage low-voltage type were appropriate and have been successfully used for cleaning welding fume, the consultant reviewed the equipment available from three manufacturers. His intention was to identify the specific model which had the desired capacity of 4.7 m^3/s (10,000 cfm), and which would be easiest to maintain.

The units of the first manufacturer were rejected because of the nature of available cleaning arrangements. These included manual removal and washing of cells, and an automatic water wash arrangement requiring detergent supplies, a water storage and transfer system, and a waste water handling and treatment methodology. Neither approach was considered desirable.

The second manufacturer's equipment could be provided with manual cleaning, wet wash cleaning, or dry rapping cleaning arrangements; the latter of which could be obtained with a belt conveyor hopper arrangement. Although the dry rapping arrangement was liked, these units were rejected because the company could at best supply a 3.8 m^3/s (8,000 cfm) capacity unit which can supposedly be overloaded to 4.3 m^3/s (9,000 cfm).

The third brand of equipment was available with a dry rapping cleaning system involving drawer type hoppers, and had a model with the exact desired capacity. This unit was selected as best suited for the recirculation system.

Finally, it was necessary to determine the overall efficiency of the device for welding fumes. This was accomplished through use of the estimated particle size distribution for the fume and a particle size versus efficiency curve provided by the equipment manufacturer. The result was an efficiency estimate of approximately 94 percent.

Selection of Surveillance Equipment for Further Consideration

Monitoring devices reviewed for possible use included: 1) an ambient mass monitor which performs sample mass measurements by means of beta-attenuation; 2) a filter tape sampling device which measures degree of filter soiling by light transmission attenuation; 3) direct light beam detection sensors; and 4) use of a secondary air filter after the precipitator.

The direct-reading beta-attenuation device was considered more suitable for determining general area concentrations than for air cleaning device monitoring. Additionally, it was deleted from further consideration because it apparently needs technical personnel for set-up, calibration, and servicing, and more importantly, because its relatively high cost could not be justified for a prototype recirculation system with low levels of fairly low toxicity contaminants.

The device which collects samples on a filter tape does not give readings in concentration units. Nevertheless, it was considered worthy of trial as a monitoring device because it has been shown to be rugged in use, can be set at a selected point of reading to give an electrical signal for activating a

bypass damper or alarm, requires a tape change once every 2.5 months, and is of comparatively moderate cost.

Also selected for trial use was a device which measures the degree to which airborne particulate matter attenuates a collimated beam of light. Actually designed as a broken bag detector for fabric collectors, there was cause to believe it might work well with fume. Like the unit above, it has the circuitry necessary to provide an alarm and/or electrical signal when excessive concentrations of particulate matter are exiting the air cleaner.

A high-efficiency air filter in series with a primary air cleaner can be used as a monitoring device. In this arrangement, the resistance to air flow of the secondary filter is constantly measured by a pressure drop gauge provided with an electrical pressure switch. When the filter attains a pre-set pressure drop, the switch triggers a bypass damper motor and/or alarm. A cost analysis for this approach indicated that the periodic cost of filter replacement and the additional resistance of the secondary filter would entail operating costs in excess of $1400 per year. Since this was considerably in excess of costs associated with other feasible surveillance methodologies, the concept was not further considered.

Determination of Feasible System Configurations

The system configuration of most interest to the plant and the consultant for this relatively low-capacity exhaust system is illustrated in Figure E-1. The system consists of ductwork from the exhaust hoods, a bypass duct to the outside discharge stack (with a motorized damper), a tapered enlarging connection to the precipitator to assure uniform air flow through its plates, a tapered converging section, a location for the monitor sensor, and an outlet with adjustable louvers. Additionally, there is an elevated platform around the air cleaner for cleaning, maintenance, and inspection activities.

The remaining system characteristic left to be defined involves the specific location in the plant for the air cleaner and its discharge. In this regard, it was decided to site the air cleaning system in an elevated position on the side of a wall which is between the welding area and a large storage area and which faces the latter area. Since the storage area has few contaminant sources (an occasional lift truck), and no constant work stations, the return air stream would have ample opportunity for mixing with other air supplies before entering any worker's breathing zone.

Design Optimization for Feasible Configurations

The concentration prediction equation in Reference 1 which pertain to the system configuration of interest are:

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

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

185

Outside Discharge Stack

Perforated Plate (inside)

Electrostatic Precipitator Cells

Damper Motor

Monitor Sensor

Damper

30°

Air Flow

Platform

45°

Louvered Outlet

Damper

Drawers

Monitor Control

Fan

Alarm

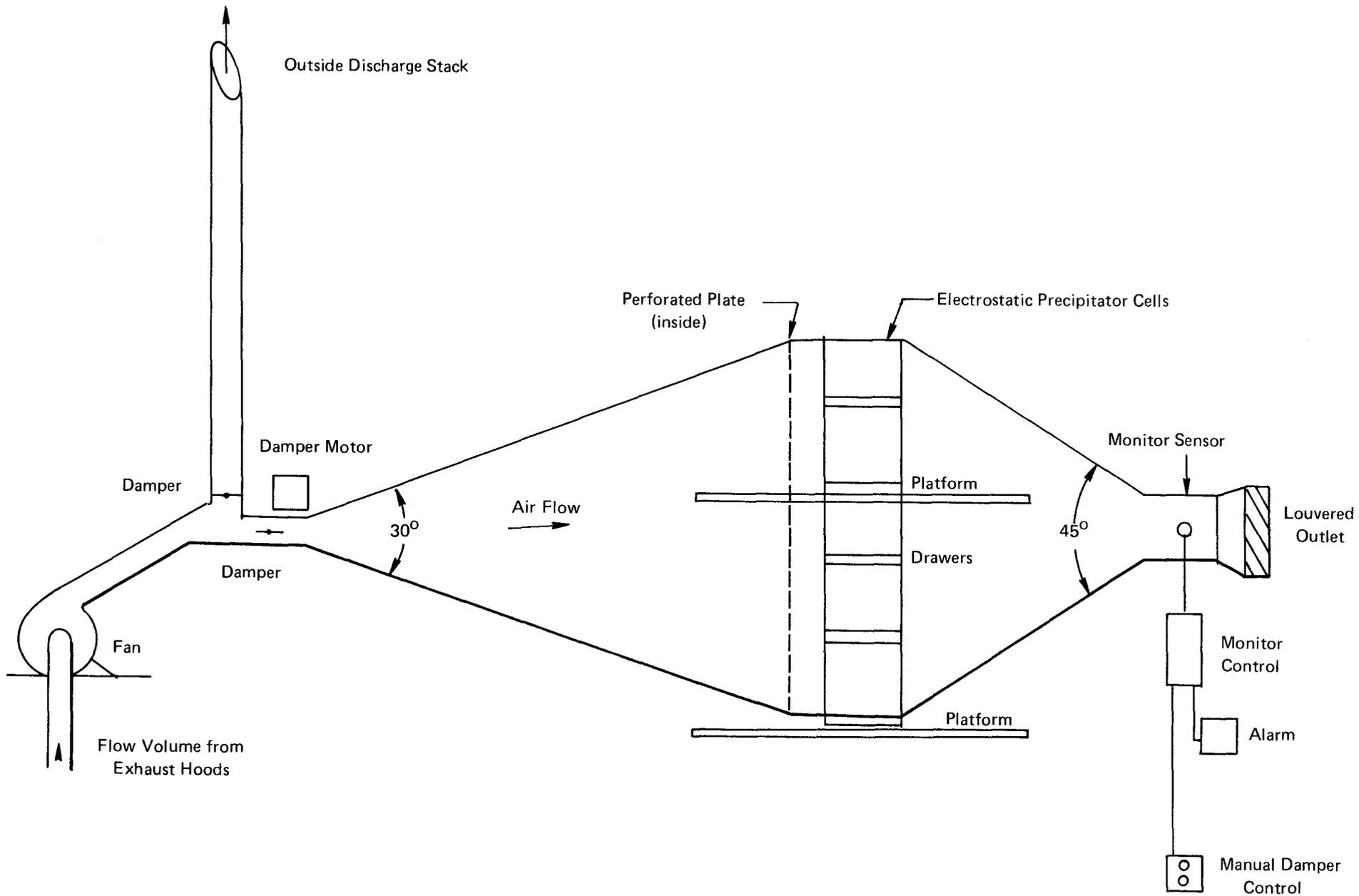Flow Volume from Exhaust Hoods

Platform

Manual Damper Control

186

Figure E–1. Recirculation system configuration.

The first equation can be used to estimate the contaminant concentration (C_R) in the return air stream. The second equation then predicts the post-recirculation concentrations (C_{BZ}) in selected breathing zones based upon pre-recirculation conditions. Terms in the equations are defined in Table E-2.

In applying the first equation, the consultant appropriately assumed that the contaminant concentration (C_{MU}) in fresh make-up air to the plant is essentially zero, and that the fraction (k_R) of air entering the welding exhaust hoods which originated in a return air stream would also be zero. These actions simplified the equation to the basic form:

$$C_R = (1 - \eta)(C_E^o)$$

where C_E^o is the contaminant concentration in the main duct from the exhaust hoods. Using what was considered to be a conservative air cleaner efficiency (η) of 0.90, he then computed a total fume C_R estimate of 0.35 mg/m^3.

This essentially is the extent to which any model in Reference 1 was utilized for design of this particular system configuration. Since the predicted return air contaminant concentration was substantially less than any permissible exposure limit, and since the return air stream would be distributed in a relatively large and clean plant area, it was concluded that recirculation would have negligible effects upon the exposures experienced by workers.

It is interesting to note that the air cleaning efficiency assumed is less than that suggested by literature obtained from the precipitator manufacturer. Clearly, the consultant was attempting to account for the fact that the unit may not maintain its 94 percent efficiency over a prolonged period of time.

In a recent study[3] of a very similar recirculation system with a similar air cleaner, researchers investigated the efficiency of a precipitator for fumes generated during shielded metal arc welding on mild steel. Measurements taken immediately after the unit had been serviced by its manufacturer, and while its performance was being monitored by a representative of that firm, indicated a cleaning efficiency of 96 percent. Two weeks later, however, a series of 8 efficiency measurements indicated that the mean efficiency had dropped to 76 percent. Hence, the study concluded "that specific maintenance and appropriate operation are (apparently) critical in maintaining high collection efficiencies."

The overall point to be made here is that the analytical procedures in Reference 1 are no more accurate than the accuracy of the input data provided to them. It is extremely important that recirculation system designers make every effort to obtain and utilize air cleaner efficiency data which are representative of field conditions. In the atypical present case, the difference between a 76 and 90 percent efficiency is unlikely to adversely affect final judgments pertaining to the acceptability of the recirculation system. In other plants, however, the difference could easily lead to non-compliance with health standards.

The logical next step was a cost analysis for the system to determine if there is sufficient potential for energy savings. Table E-3 presents the results of this effort for operating costs expected during the first year of recirculation

187

Table E-2. Definition of symbols.

Q_T^o – The pre-recirculation total ventilation rate through the plant area of interest.

Q_T – The post-recirculation total ventilation rate through the plant area of interest.

C_{MU} – The concentration(s) of pertinent contaminants in fresh make-up air.

C_E^o – The concentration(s) of pertinent contaminants in local exhaust streams to be recirculated before recirculation.

C_R – The concentration(s) of pertinent contaminants in return air streams (i.e., leaving air cleaners).

C_{BZG}^o – The concentration(s) of pertinent contaminants in selected breathing zones in "open" plant areas.

C_{BZL}^o – The concentration(s) of pertinent contaminants in selected breathing zones in strong local exhaust induced flow fields.

C_{BZ} – The predicted post-recirculation concentration(s) of pertinent contaminants in selected breathing zones.

η – The air cleaner efficiency for each contaminant.

k_{BZ} – The physical fraction of air, in selected breathing zones, which originates in return air streams.

k_R – The physical fraction of air which enters local exhaust systems being recirculated and which itself originates in return air streams.

Table E-3. First-year operating costs.

Present system cost	Annual cost
Heating cost (based on degree days)	$ 6,260
Fan power cost	2,075
TOTAL	$ 8,335

Anticipated cost with recirculation	
Fan power cost (new fan)	$ 2,024
Air cleaner power cost	219
Monitor system operating expenses*	206
Compressed air	9
Labor for hopper emptying	480
Labor for insulator brushing	60
TOTAL	$ 2,998

Anticipated first-year operating cost savings:	$ 5,337

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* For highest cost system selected for trial use.

Table E-4. Projected cost savings.

Item	Present	2nd year	3rd year	4th year
Present costs				
Heating	$6,259	$6,884	$ 7,573	$ 8,330
Power	2,075	2,386	2,744	3,155
TOTAL	$8,334	$9,270	$10,317	$11,485
Recirculation costs				
Power	$2,457	$2,825	$ 3,249	$ 3,736
Labor	540	540	540	540
TOTAL	$2,997	$3,365	$ 3,789	$ 4,276
Savings	$5,337	$5,905	$ 6,528	$ 7,209

NOTE: The analysis assumes a 10% per year increase in heating fuel costs, and a 15% per year increase in electrical power costs.

system operation. Table E-4 then provides a 4-year projection. Over this span, total savings are estimated to be approximately $25,000 when the various stated assumptions are applied.

The consultant was not able to fully consider the capital costs of the air cleaner and its installation in his initial analysis, and he noted this fact to plant management. Nevertheless, based upon the projected savings estimate, and the knowledge that the air cleaner would cost roughly $10,000, the plant committed itself to buying the air cleaner and its accessory equipment before a fuller analysis could be completed.

When the various cost estimates were eventually received for the custom sheetmetal work, the custom-made platform on which the air cleaner was to be mounted, and other cost items, it became clear that the recirculation system was going to cost on the order of $50-60,000. Thus, the payback period would not be 4 years or less, as was originally desired, but on the order of 8 to 10 years. Plant management was not entirely pleased with the outcome, but understood that the system would eventually pay for itself and would provide valuable data for developing a more cost-effective approach to recirculation in the plant.

Failure Analysis for Feasible Configurations

The major failure modes of the recirculation system were noted to involve the air cleaner. The specification of a monitoring system which can automatically activate a by-pass system to the outdoors ensured that worker exposures would not exceed permissible limits if this device failed to adequately clean the exhaust air. In consequence, a more formal failure analysis was not considered necessary for this particular prototype system.

Selection of the Best Configuration

Reference 1 somewhat assumes that a designer will investigate several recirculation system configurations for suitability. Since the plant of interest only considered a single configuration, it had no alternatives to compare and choose from.

Final Equipment Selection, System Design, and Installation

The detailed system design was performed by an engineering firm contracted by the plant. This firm worked in conjunction with the consultant, the air cleaner manufacturer, and the plant's engineering staff.

System Performance Validation

The plant experienced numerous and lengthy delays in obtaining and installing the various components of the recirculation system. In consequence, it was not possible for the performance of the system to be studied as part of this program. Nevertheless, it is clear that this prototype system would be unlikely to perform inadequately in regards to health safety issues.

190

DISCUSSION

There is a sense that the plant rushed the design stage of the prototype system. The prevailing philosophy appears to have been that the most complex issues could be better addressed after the operating performance of the prototype was fully evaluated. This resulted in the installation of a system which is barely cost-effective, and which will not be exactly copied regardless of its success in maintaining exposures below permissible limits.

During the concentration data acquisition phase of the effort, there was no attempt to comprehensively define pre-recirculation conditions either in and around the welding stations of interest, in the vicinity of other welding operations of future interest, or in areas which would be affected most significantly by a return air stream. In retrospect, one must consider whether it may have been more prudent to perform such an effort with the objective of analytically assessing whether recirculation can feasibly be implemented on a widespread basis in the plant. A negative outcome would have saved the plant the expense of the prototype system. Alternatively, a positive outcome would have been enhanced by a firm base of needed design data, and might have led to a more appropriate design concept based upon a broader perspective of envisioned problems.

CONCLUSIONS

The following conclusions can be seen to evolve from this evaluation:

1. Comprehensive and accurate knowledge of pre-recirculation conditions is usually a necessity to fully evaluate the effect of recirculation upon the working environment.

2. If local exhaust hoods or their exhaust volumes are to be modified, and the return air stream will substantially affect exposures near these hoods, it is best to assess pre-recirculation conditions after modifications have been performed.

3. The cost analyses for feasible system configurations should be carefully performed before expensive system design and installation activities are initiated. Indeed, a crude analysis of overall cost-benefits might be of value in the initial feasibility assessment.

4. It is less troublesome and expensive to design a system with the maximum number of readily available, off-the-shelf hardware. Custom fabricated components not only cost more, but can require excessive time periods for completion and debugging.

5. The air cleaner efficiency utilized in computations must realistically reflect field use conditions.

6. Rigorous application of Reference 1's analytical design procedures is not always necessary when the exhaust system is not highly contaminated, the amount of recirculated air is a small fraction of the total ventilation rate through the plant area, a relatively high efficiency air cleaning equipment train is utilized, and/or the return air will enter a relatively clean plant area.

7. Reference 1's design methodology was fully appropriate for the design of the system. All problems and uncertainties in the effort were caused by digressions from its stated approach.

CONSULTANT'S COMMENTS ON THIS APPENDIX

The consultant mentioned previously was given an opportunity to review and comment upon the contents and findings of this appendix. His comments are summarized below, and will be seen to contain some noteworthy points.

1. The methodology of Reference 1 is fairly complete in its presentation and is helpful in bringing many considerations to the designer's attention. The consultant would have to state, however, that in real life it is difficult to follow the complete methodology as this review presents. To obtain complete comprehensive air sampling and engineering data in the time frame of a contract is not always possible. Some of the difficulties are the cost of such studies, the press of work on Industrial Hygiene Departments, and the short time period in which a consultant's contract is to be completed. Possibly, in real life, the complete methodology can be best completed in detail by research contract investigation.

2. The consultant's report to management, which mostly provided the basis for this appendix, purposely did not contain a detailed application of the equations and models of Reference 1, since the models are somewhat complex and not easy to understand. However, most of the recommendations and mathematics would be helpful to the consultant in arriving at final design parameters more easily understood by management.

3. The recommended approach requires air cleaner efficiency data and data on k_{BZ} and k_R. At the moment, there are practically no manufacturers' guaranteed efficiencies for such common materials as various welding operation fumes and grinding, polishing, and buffing wheel dusts. Practical data on k_{BZ} and k_R obtained from tracer gas studies is needed but not easily available.

4. The rejection of fabric collectors was based on increased power costs as well as the other factors mentioned. A recirculation system using the fabric collector described in Reference 2 would require approximately $2,000 per year more in fan power costs in this plant because of the greater pressure drop across the filter. In addition, there would minimally be an annual filter cartridge replacement cost of $600. Thus, the electrostatic precipitator had a distinct advantage with regard to annual operating expenses in this particular application. It is appreciated, however, that the efficiencies cited for these fabric collectors are better than those achievable with an electrostatic precipitator.

5. Other factors in the decision to reject fabric collectors stem from noise and other considerations. Because of the higher pressure drop across the filter, it is likely that a fan silencer would have been required. In addition, it would not have been feasible (according to a local manufacturer's representative) to place the fan before the collector. With the fan after the collector, it is not possible to bypass exhaust air outdoors when the collector requires maintenance and the welding operation must be continuous on a 24-hour basis.

6. Electrostatic precipitator manufacturers presently sell the electrostatic section and recommend that the sheet metal approach and duct connection be fabricated by a local sheet metal shop. It would be desirable to use off-the-shelf hardware if it were available.

7. The configuration of the proposed design was selected because it was highly important that uniform velocity be obtained across the plates of the precipitator. The precipitator was placed on the pressure side of the fan for this round-the-clock operation so that air could be bypassed outdoors when the air cleaner requires repair or service. An alternative to the tapered diverging approach to the precipitator would be a shorter approach and the use of two air cleaners in series. This could double the cost of the electrostatic equipment, however.

8. The data obtained by the field evaluation of an electrostatic precipitator by Bialota and Verminski[3] is interesting, although the deterioration of efficiency after 2 weeks of use is difficult to assess. Electrostatic precipitators are sensitive to an increase in velocity or variations of velocity across the plates. In addition, any change in the dielectric properties of the insulators which will result in reduction of electrostatic charge will reduce the efficiency of cleaning. Although the manufacturer of the precipitator used in this plant stated that the only maintenance needed was vibrating the plates and emptying the drawers, the consultant added a maintenance cost of insulation cleaning to his analysis. Hopefully, this action will eliminate or reduce the deterioration cited in Reference 3.

9. The conclusion that a cost analysis should be performed before installation activities are initiated is appropriate and highly important in the present inflationary period. The management and the consultant were astounded by the high cost of sheet metal work for the prototype system.

REFERENCES

1. Partridge, L. J., Nayak, P. R., Stricoff, R. S., and Hagopian, J. H., 1978. A Recommended Approach to Recirculation of Exhaust Air. DHEW (NIOSH) Publication No. 78-124. U. S. Government Printing Office, Washington, DC 20402.

2. Pierce, L. A., Systems Design for Safe Control of Welding Fumes. Pollution Engineering. July 1978 issue, pages 51 to 53.

3. Bialota, A. S., and Verminski, E. R., 1978. Recirculation of Welding Local Exhaust Through Electrostatic Precipitators - A Field Evaluation. Paper presented at the American Industrial Hygiene Association Conference in Los Angeles, California, May 1978.

APPENDIX F. DEGREASING OPERATION

CONTENTS

FIGURES

DEGREASING OPERATION

INTRODUCTION

A manufacturer of electrical household appliances utilizes a rather novel recirculation system concept to simultaneously save energy, reduce solvent losses from degreasing operations involving trichloroethylene (TCE), and reduce worker exposures to solvent vapors. Additionally, implementation of a total systems approach to reducing costs has allowed a substantial reduction in the number of person-hours devoted to degreasing activities.

PLANT AND PROCESS DESCRIPTION

Plant Description

The plant area of interest is a single large room with approximate dimensions of 23 m by 23 m by 6 m (75 ft/75 ft/20 ft). There are few windows and doors, and these are normally closed. The room houses degreasing operations and a number of metal stamping machines.

Process Description

The installation of a recirculating exhaust system was the culmination of a series of events. It is therefore advantageous to provide a historical perspective to degreasing operations in this plant area.

Prior to 1977, degreasing of stamped metal parts was performed in 3 individual tanks of a type commonly utilized for the purpose. Because of the manual nature of the operation, degreasing was a continuous activity requiring three shifts and a total of 7 employees.

To reduce manpower needs and facilitate production, plant management decided to replace the individual tanks with a large-capacity, automated processing system. The capacity of the system would permit a single employee to complete all needed degreasing operations within the day shift, thus reducing manpower needs by 86 percent. Additionally, the configuration of the new system would allow future consideration of recirculation to further reduce costs.

Figure F-1 illustrates features of the current process and its integrated recirculation system as can be determined from an external inspection. Points of interest include:

- A complete sheet-metal enclosure around an automated vapor degreasing process.
- Entrance and exit openings covered by strips of rubber.
- Well-sealed access doors to the enclosure for maintenance.
- Exhaust of air from a central location behind the enclosure.
- An exhaust duct leading to a dual-bed carbon adsorption unit.
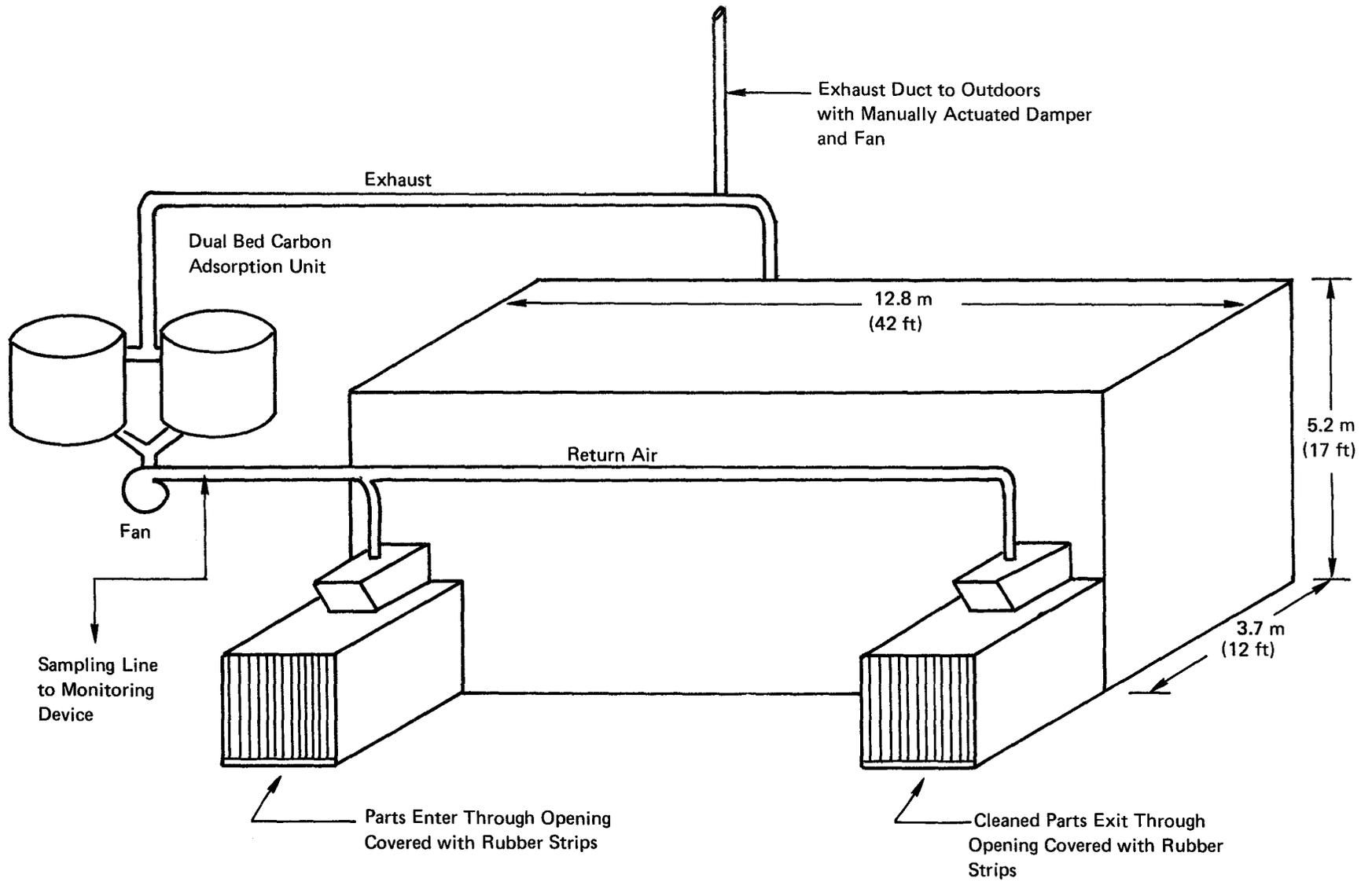- An exhaust air bypass duct to the outdoors.

Figure F—1.   External features of process.

- An in-duct concentration measurement sensor in the return air stream.
- Return air distribution to the entrance and exit openings of the enclosure. (Note specially designed chambers to direct air into main body of enclosure.)

In practice, a mechanized conveyor system places closed mesh cages containing 680 kg (1500 lb) of metal stampings into the entrance port. These are picked up by an internal conveying system which leads them through the degreasing process and deposits them at the exit port. Here, a delay mechanism forces each cage to remain in the hot return air flow for about 5 minutes, thus acting to vaporize any TCE remaining on parts.

The internal details of the degreasing process are difficult to properly display because it was not possible to actually enter the enclosure. Nevertheless, Figure F-2 illustrates the basic elements of the process as determined from verbal descriptions and a brief review of engineering drawings. Features of interest include:

- Two large degreasing tanks holding TCE at its boiling point. These have freeboard chillers.
- An "offset" small tank of boiling TCE which provides hot vapors to pre-warm the relatively cold machine stampings.
- Rectangular exhaust ducts in the bottom of a pit around the tanks. These have 46 cm by 10 cm (18 in by 4 in) slots every 46 cm (18 in) or so on their sides.

During the first and second shifts, the freeboard chilling system uses the city water supply in cooling coils. Since the temperature of this supply can vary, a flow regulator adjusts flow to maintain an outlet water temperature of 46 °C (115 °F). At night, when the degreaser is not needed, a refrigerator system provides liquid fluorocarbon to a set of coils at -18 °C (0 °F) to vastly reduce emissions from the tanks. Nevertheless, the recirculating exhaust system operates continuously.

Solvent from the offset tank in the process is continuously piped to a still at a rate of 1,136 l/hr (300 gal/hr). From there it flows to the second process tank, to the first tank, and eventually, back to the starting point.

RECIRCULATION SYSTEM CHARACTERISTICS

Exhaust System

In the interim period when the automated degreasing system was operational and recirculation was being considered, the exhaust system extracted air at a rate of 1.42 m^3/s (3,000 cfm) and discharged outdoors. TCE concentrations measured in the exhaust duct typically ranged from 500 to 800 ppm. In the move to a recirculating system, this rate was increased to 1.89 m^3/s (4,000 cfm) to achieve better control.

"Offset Tank" with 1514 ℓ (400 gal) Capacity

Conveyor Route

Exit Opening

Entrance Opening

9,464 ℓ (2,500 gal) Tank

9,842 ℓ (2,600 gal) Tank

Slot

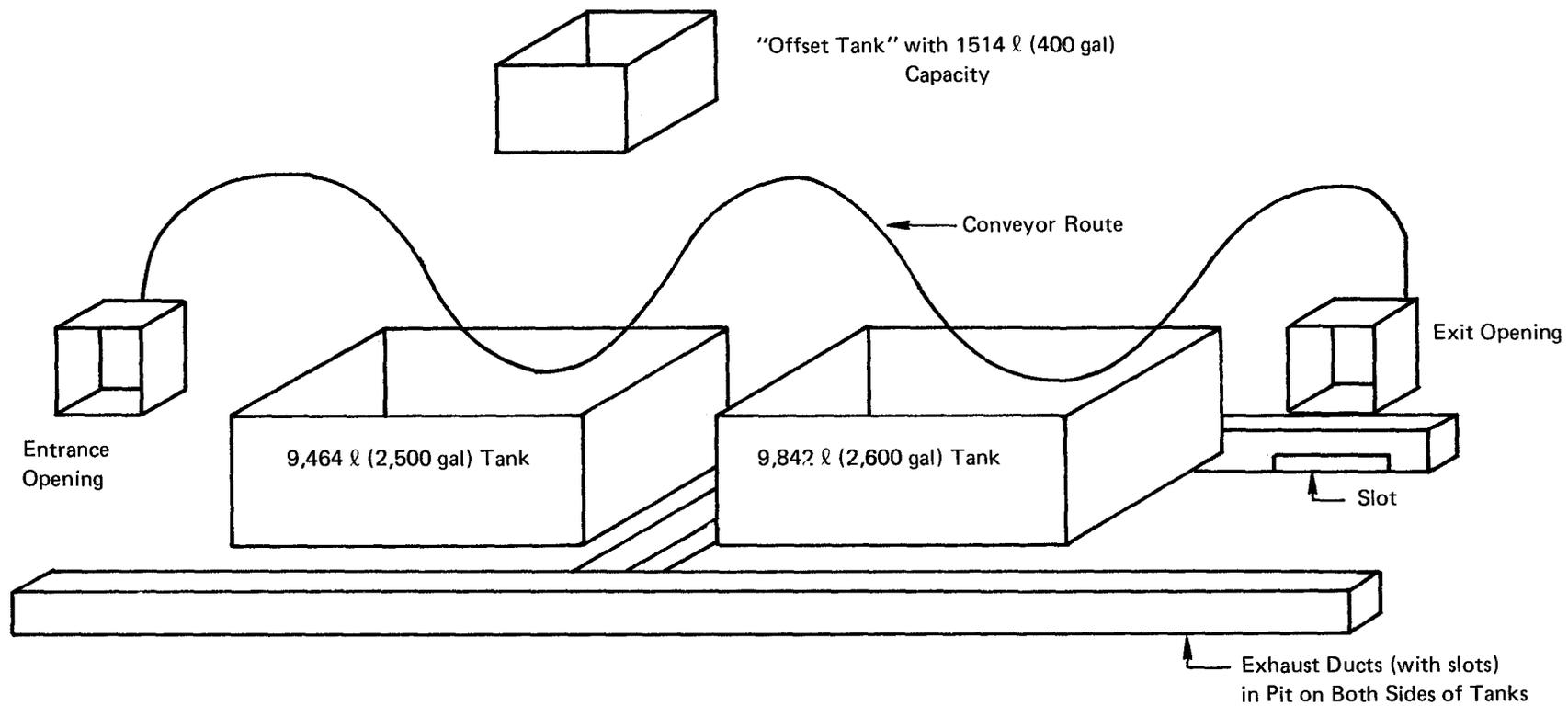Exhaust Ducts (with slots) in Pit on Both Sides of Tanks

Figure F—2.   Internal features of process.

Air Cleaning System

The carbon adsorption unit is a commercially available device incorporating two beds with 815 kg (1,800 lb) of carbon each. A bed freshly stripped with steam will operate for roughly 18 hours before discharging air with a TCE concentration in excess of 50 ppm.

During the first 12 hours of this period, the level is generally less than 20 ppm. Over the next 4 hours, the level rises to 20 ppm and begins to climb. Finally, about two hours later, it reaches the vicinity of 50 ppm.

Surveillance Systems

The complete system incorporates three monitoring systems. These address the concentration of TCE in the return air stream, the vapor level in degreasing tanks, and the temperature of liquid TCE in the tanks.

A small sampling line from the return air duct to a nearby laboratory area serves a General Electric Model TVM-1 toxic vapor monitor. Costing roughly $4,000 with accessory equipment, this unit can provide a direct readout of airborne concentrations for some 70 halogen compound gases. In its current use, it automatically performs an air analysis for TCE every 2 minutes and automatically recalibrates itself (using a pressurized cylinder of calibration gas) once every 8 readings. Because of a 3 minute delay involved in passage of return air through the sampling line, the readings it displays represent return air characteristics occurring 5 minutes previously in the return air stream.

The present function of this system is to effect changeover from one carbon bed to the other when return air concentrations exceed 50 ppm for 20 minutes. The time delay feature was provided so that occasional peaks in concentration will not trip the changeover. In the near future, it is intended to connect the unit's built-in audio alarm circuit to the plant's public address system. This will warn of situations in which a bed changeover has taken place and in-duct levels have not dropped.

A thermistor in the vapor space of each tank monitors the TCE vapor level. If that level rises beyond a preset point, an interlock system shuts off steam to tank jackets and deactivates the conveyor system. Finally, heat sensing devices monitor TCE liquid temperatures to prevent overheating and subsequent decomposition of the liquid to corrosive substances.

Inplant Concentrations

With the older type tanks, TCE concentrations in the general area of the degreasers ranged from 10 to 15 ppm. Currently, comprehensive semi-annual industrial hygiene surveys indicate maximum levels in the range 3 to 5 ppm.

Solvent Usage

The pre-1977 process with 3 tanks lost approximately 378.5 l (100 gal) of solvent to the atmosphere each day at a yearly cost of $34,000. At present, the

loss rate is about 19 1 (5 gal) per day, and total solvent make-up cost (mostly attributable to losses during solvent distillation) is about $6,000 per year. The carbon beds alone recover 83 1 (22 gal) of solvent each time one is stripped.

Cost/Benefit Factors

The 1977 cost of the new degreasing process, the enclosure, and the specially fabricated mesh cages was about $265,000 including installation. An additional sum of $35,000 was expended for the air cleaner and its associated equipment. Because of the tremendous savings in solvent use, manpower, and energy, however, the system payback period was on the order of only 2 years.

Maintenance and Inspection

As noted above, the company industrial hygiene staff surveys the plant twice a year. Additionally, the entire system (including degreasers and recirculation system components) is deactivated semi-annually for inspection and maintenance of all equipment. Of course, the operator of the process is also constantly monitoring the equipment for any abnormalities, and will smell any significant release of TCE to the work room atmosphere.

VALIDATION OF RECIRCULATION APPROACH

It is fairly obvious that the personnel in this plant not only complied with the most important recommendations of Reference 1, but somewhat ingeniously engineered a total systems concept worthy of commendation. In consequence, the following discussion simply highlights particular points of interest dealing with selected design steps listed in Chapter 2 of Reference 1.

System Surveillance Methodology

Reference 1 suggests that all failure modes of the system be identified and evaluated in terms of their potential effect upon worker exposures. The surveillance systems currently installed in this plant cover all important parameters but one; the rate of air passing through the air cleaner. Without delving into the matter very deeply, it appears there is potential for a malfunction in the recirculation system fan to cause accumulation of solvent vapors in the enclosure and eventual leakage of vapors to the work place. Since a bypass duct to the outdoors exists, and since this branch has its own fan, it appears to be a simple matter to monitor the recirculation system fan's performance. Although this is by no means a critical need, it would virtually ensure failsafe operation in the absence of a complete power failure to the plant, i.e., it would make an excellent system even better.

System Design Configuration

Buried in Reference 1 (see bottom of page 36 for example) are only a few statements alluding to the fact that recirculation might feasibly be accomplished with "well-designed push-pull systems." The existence of the system described in this study, and its many desirable attributes, suggests that this type of system concept should be considered wherever a contaminant-producing

operation can be fairly well isolated from employees. Through a combination of isolation and recirculation, it can lead to energy savings and reductions in exposures at lower risk levels than are otherwise achievable.

Future designers of similar systems should consider two important factors. First, it is essential to study whether a system failure mode can lead to accumulation of flammable or potentially explosive concentrations in the enclosure. Special precautions might be necessary in such cases.

Second, it is appropriate to realize that a mechanically provided return air stream at a rate equivalent to the exhaust volume rate may not provide the negative pressures necessary to ensure inflow of air through any cracks or other unintended openings in the enclosure. Thus, the enclosure should be well-sealed, and consideration should be given to maintaining a slight negative pressure in the enclosure by bypassing some part of the exhaust or return air streams to the outdoors or elsewhere.

Model Utilization

The models of Reference 1 are readily adaptable to the task of estimating post-recirculation conditions within the enclosure. This would simply require that the walls of the enclosure be assumed as the boundaries of the plant area being affected by recirculation.

The models, and particularly the breathing zone concentration prediction equation, are not applicable, however, for assessing post-recirculation conditions in the work room. Such conditions would be a function of the undefinable leakage rate of air from the enclosure to the work room and the degree to which recirculation lowers TCE concentrations in any air entering this area from other plant areas or outdoors. Nevertheless, it is clear that an installation similar to that observed would have little chance to increase worker exposures, and every opportunity to lower them through increased control of the operation.

CONCLUSIONS

Conclusions derived from this evaluation are:

1. The recirculation system in the plant of interest, and the details of the degreasing process, represent an exceptionally well-conceptualized and executed effort on the part of plant engineering personnel.

2. The concept of using "closed-loop" recirculating exhaust systems with completely enclosed operations has considerable merit. It should be explored by plants with similar operations.

3. Application of the concept requires that the enclosure be sealed properly. Since return air is mechanically provided, pre-existing negative pressures in the enclosure may no longer act to cause a net inflow of air through all cracks and other unintended openings in enclosure walls.

4. TCE is practically non-flammable. Similar system designs with flammable or potentially substances must fully consider the possibly catastrophic effects of air cleaner malfunction.

5. This system concept requires consideration of partial bypass of exhaust or return air to the outdoors. The shortage of make-up air in the enclosure should serve to ensure at least a marginal net inflow of air through entrance and exit ports of the enclosure.

6. The efficiency of a carbon adsorption unit is seen to vary with the degree of bed saturation. In more conventional recirculation systems, this variation must be considered in the design process.

7. Reference 1 does not fully address this type of system design concept. Nevertheless, its methodology is seen to provide the framework for its active consideration and evaluation.

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1. Partridge, L. J., Nayak, P. R., Stricoff, R. S., and Hagopian, J. H., 1978. A Recommended Approach to Recirculation of Exhaust Air. DHEW (NIOSH) Publication No. 78-124. U. S. Government Printing Office, Washington, DC 20402.