EVALUATION OF AIR CLEANING AND MONITORING EQUIPMENT USED IN RECIRCULATION SYSTEMS

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PREFACE

Recirculation of industrial exhaust air is an energy saving technique that is being applied in more situations every day. Unfortunately, recirculation is being implemented without an adequate base of technical information. The National Institute for Occupational Safety and Health (NIOSH), in coordination with the Environmental Protection Agency (EPA), has undertaken to provide guidelines for the safe and healthful application of recirculation.

A major accomplishment of the work completed to date has been the development and field validation of a modeling approach for design of recirculation systems. However, before the model can be effectively used, empirical information on the performance and reliability of both air cleaners and monitors must be available. It was the purpose of the present study to develop methods to obtain such information.

Most existing air cleaners were designed to meet codes regulating the air quality suitable for discharge to the ambient; recirculation, on the other hand, may require an effluent quality which is orders-of-magnitude lower in contaminant concentrations. Only the most efficient air cleaners have potential for this application. Because of the newness of some of these devices and the lack of information concerning their efficiency and reliability on various exhaust applications, much experimental work is required to produce the necessary information. Because of the potentially serious health effects which could result with this method, acquisition of this data by constructing and testing full scale systems is not advisable. Should the operating results indicate that recirculation is not feasible, significant funds will have been wasted. A pilot scale approach is an effective method of developing the needed information and it was the mandate of this study to develop and test such an approach.

Second only to the need for an efficient air cleaner is the need for a method to assure the continued, proper operation of the recirculation system. It is well-known in industry that the performance of ventilation systems deteriorates, in many cases, with time. Deterioration of performance is unacceptable in a recirculation system and justifies taking careful precautions to assure that:

1. The system is properly maintained.
2. If a malfunction should occur, a warning will be provided before a hazard develops.

Recirculation system monitoring goes a lot further than the installation of a single monitoring device to sense some parameters which may be affected in the case of a failure. The development of a suitable monitoring system requires not only knowledge of the ways in which the recirculation system could fail, but it also requires the selection of a sensitive monitor which can detect deviations from normal operating conditions in time to prevent overexposure of workers. Monitoring is an application-specific situation, i.e., a specific monitor must be selected for a specific air cleaner, operating on particular contaminants, in a system with certain risks to the workers. It has been the purpose of this study to develop ways in which monitors can be evaluated and selected.

This study was performed using a pilot scale test facility at a welding training center. The intention was to generate an approach and methodology which are universal in application to any particular exhaust system which is a candidate for recirculation. It must be carefully borne in mind that each application has its own requirements and peculiarities and each deserves a thorough, scientific approach such as was used here.

ABSTRACT

The purpose of this study was to evaluate several pilot scale air cleaners and monitors to determine their performance characteristics, maintenance requirements, and reliability for use in a recirculating exhaust system.

This was done by first developing a set of evaluation criteria for recirculation system components. Then, selected system components (including an electrostatically augmented fabric filter, electrostatic precipitator, aspirated cartridge filter, four different extractive type particulate air monitors, three different extractive ozone monitors and a safety monitoring filter) were installed and tested on a welding process exhaust located at an industrial test site. Each device was operated for a length of time sufficient for evaluation of its performance characteristics, potential failure modes, and maintenance requirements in terms of the predetermined criteria. It was found that this approach was an effective method of screening devices for use in recirculation systems.

The results indicate that many factors must be evaluated before a decision can be reached concerning the use of a particular device. For example, the acceptability of an air cleaner would have to be evaluated in terms of its performance characteristics, such as penetration and maintenance requirements, in addition to parameters associated with the specific application, such as the toxicity and concentration of contaminants in the workplace and return air distribution.

Additionally, components of a complete recirculation monitoring system were identified and the need for the development of commercial devices incorporating all of these components was evidenced by the fact that each of the commercially available devices tested lacked one or more of these components.

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ACKNOWLEDGMENT

This study could not have been conducted without the help and cooperation that the Harnischfeger Corporation provided by allowing their Corporate Manufacturing Training Center to be used as the study site. A special thanks is also due the several manufacturers of air cleaning and air monitoring equipment who participated in the study by supplying devices for testing. These included the following:

1. American Precision Industries, Inc.
2. Farr Company, Inc.
3. GCA Corporation.
4. Mast Development Company.
5. Research Appliance Company.
6. Texas Electrostatic Precipitator Company.
7. Thermo Systems Inc.

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INTRODUCTION

BACKGROUND AND PURPOSE

Need for Industrial Energy Conservation

To combat escalating energy costs and threatened shortages of certain types of fuels, viable alternatives to reduce energy consumption are needed. It has been estimated that the use of energy for ventilation represents up to 10 percent of all energy used in industry and could probably be reduced by 50 percent by using energy conservation measures (1).

Energy conservation in industry can be accomplished by a variety of methods, depending on the specific situation encountered. Some of these methods are listed below:

1. Substitution of low for high energy consuming processes.
2. Close capture of contaminants to reduce the need for general ventilation.
3. Indirect heat exchange from hot process exhausts.
4. Recirculation of cleaned exhaust air into the workplace.

Items 2 to 4 can reduce energy consumption in plant ventilation systems by reducing the amount of fuel needed to temper makeup air.

Each conservation measure has inherent advantages and limitations which must be considered prior to deciding to employ it. Two of the major concerns in recirculating exhaust air while maintaining a safe and healthful workplace are the ability to sufficiently clean the return air and to monitor the air cleaning system to insure that it is functioning properly. Because ventilation control and air cleaning systems are constructed of various components which can fail for a variety of reasons, including lack of proper maintenance, effective methods of monitoring vital system parameters must be employed. These failures can cause one or both of the following problems:

1. Contaminants penetrating the air cleaners and being recirculated back into the workplace through the return air plenum (breakthrough).

2. Reduction or cessation of air flow through the system resulting in lower hood efficiency and contaminant loss.

The potential health hazards and process disruptions associated with recirculation system failures demand that provisions be made in the design for early detection of failures or conditions that could lead to failure.

Government Sponsored Research--
Recently, the National Institute for Occupational Safety and Health (NIOSH) has undertaken several studies aimed at developing a sound engineering approach to recirculation that is supported by reliable data. In the first two research efforts, technical criteria and practical guidelines were developed for the design, installation, and operation of recirculation systems. Major areas of achievement included:

1. Identification of available air cleaning and air monitoring devices.
2. Development of an engineering design approach to recirculation.
3. Development of a mathematical model for recirculation.

These efforts resulted in NIOSH publications entitled, "Recirculation of Exhaust Air" (no. 76-186) and "A Recommended Approach to Recirculation of Exhaust Air" (no. 78-124).

More recently, two additional NIOSH funded studies entitled, "Validation of a Recommended Approach to Recirculation of Industrial Exhaust Air", (no. 79-143 A and B) were undertaken which gathered actual data from various manufacturing facilities where full scale recirculation systems were operating.

An in-depth evaluation of each system was performed, which included measurement of air cleaner efficiency and determination of contaminant concentrations in the workplace air, in the breathing zones of workers and in the return air. From this data, the usefulness and predictive ability of the model was assessed.

Before the modeling approach can be used in the design process, several pieces of empirical information must be made available. Specifically, the following must be known:

1. The efficiency of the air cleaner, both on a total and fractional mass basis.
2. The ability of the system to be properly monitored.
3. The reliability of both air cleaners and the air monitoring systems.
4. The maintenance requirements necessary to assure that the components of the system will function properly.

The scope of this study was aimed at filling this critical need by developing a data base in these four areas for several pieces of equipment which appeared to be viable for recirculation.

Until recently, most of the generic types of air cleaners and monitoring devices were designed for cleaning and monitoring air exhausted to the ambient (outdoors). It should be noted, however, that to meet the OSHA Permissible Exposure Limits (PEL) for air contaminants in the breathing zones of workers often requires a level of contaminants in the return air that is many times lower than the allowable limits for discharge to the outdoors.

Very little field data concerning the application of both air cleaners and monitors in recirculation systems is available because recirculation is a new area. Clearly, because the health of the worker is dependent upon the proper design and operation of these devices, a field evaluation of existing air cleaners and monitoring devices is needed, with emphasis on their potential for recirculation. This study is intended to help fill this gap by:

1. Developing a universal format for evaluation incorporating criteria and testing procedures.
2. Providing a field evaluation of several air cleaners and monitors used to clean and monitor the air quality of welding fume exhaust.

Purpose

The purpose of this study was to evaluate three pilot scale air cleaners and eight air monitoring devices to determine each device's suitability for recirculation. Suitability was evaluated in terms of the following areas:

1. Performance: For an air cleaner, this relates to total and fractional penetration and outlet contaminant concentrations (both particulate and gaseous). For an air monitor this includes measurement accuracy, measurement range, zero drift and response time.
2. Failure or Malfunction Modes: This involves the identification of the possible malfunctions which could occur and an assessment of methods and the relative ease with which these malfunctions can be detected and prevented.
3. Maintenance: This includes the manpower and resources necessary to insure the continued efficient and reliable performance of air cleaners and monitors.
4. Costs: This includes the costs of purchasing and maintaining air cleaners and monitors.

APPROACH

This study was conducted by obtaining commercially available air cleaners and air monitors, installing them at an industrial test site, and operating them for a sufficient length of time to determine, through a series of tests, their operating characteristics and possible failure modes. It should be noted that an attempt to identify ultimate failures was not included in the scope of this study because of the extremely long test times required for such determinations, as well as inherent uncertainty about their occurrence.

Test Site Selection

An actual process exhaust was chosen as the test aerosol rather than a laboratory generated aerosol because it is difficult to accurately simulate the composition, particle size distribution and unique properties of process exhausts using aerosol generation and gas injection methods. Data collected using an aerosol generated by an actual process adds more credence to the observations and conclusions of the research effort.

After a comprehensive review of several manufacturing processes, a welding process located in a corporate training center was chosen as the aerosol generator for the following reasons:

1. Welding is widely used throughout industry, involving a substantial number of workers, and representing a significant potential for energy savings via recirculation of exhaust air.

2. The specific process site chosen, a welding training center, offered "the best of both worlds" in that the contaminants were generated by an actual industrial process but a large degree of control could be exercised over the process. This allowed many tests to be repeated several times under identical conditions.

3. Welding produces both particulate and gaseous contaminants, which allowed information to be gathered for both of these types of contaminants.

4. Quite often, welding exhaust is low in toxicity, thus reducing the potential health risks.

Test Equipment Selection

Many air cleaners and monitors with potential for use in recirculation systems could have been chosen for evaluation. The choices made were especially aimed at gathering information concerning recent advancements in technology.

Air Cleaner Selection--

The air cleaners evaluated in this study were selected using the following criteria:

1. Potential ability to effectively remove welding fume from exhaust air.

2. Availability of a pilot scale device for testing purposes.

Fabric filters and electrostatic precipitators, as well as units employing these two cleaning methods together were considered. The following air cleaners were tested:

1. American Precision Industries, Inc. (APITRON) - electrostatically augmented fabric filter.

2. FARR Company, Inc., Model 6 - aspirated cartridge dust collector.

3. Texas Electrostatic Precipitator Company, Inc. (TEPCO) - Model 2001 ST - two pass, two stage (low voltage) electrostatic precipitator.

Inertial-type air cleaners were not considered because of their inability to remove fine particles, and wet collectors did not appear to be a promising method because they produce a saturated exhaust air stream which could cause humidity problems in the plant and require a high energy input to remove fine particles.

The primary goal in the study was to examine different generic types of air cleaning devices, however, because of differences among air cleaners of the same generic type offered by the various manufacturers, an attempt was not made to choose devices that would represent an entire generic class.

Air Monitor Selection--
Air monitor selection was based on the following criteria:

1. Commercially available.
2. Able to measure contaminant concentration on a continuous or real time basis.
3. Able to detect contaminants of interest in welding fume.
4. Output signal available for use in a failure response network.

An attempt was made to cover the spectrum of available devices by testing both the newest and the most technologically advanced as well as the more traditional devices. Because neither nitrogen dioxide nor fluorides were found in significant quantities, monitors for these substances were not evaluated.

The following particulate and gaseous monitors were tested:

1. Analytical Instrument Development Inc., Series 560 ozone monitor.
2. Farr Company Inc., Riga-flo 200 glass fiber safety monitoring filter.
3. GCA Corporation, Model RAM-1 real time aerosol monitor.
4. GCA Corporation, Model APM aerosol mass monitor.
5. Mast Development Company, Model 727-2 ultra-violet ozone monitor.
6. Mast Development Company, Model 724-5 oxidant monitor.

7. Research Appliance Company, Model G1SE AISI tape sampler.
8. Thermo-Systems, Inc., Model 5500 airborne particulate mass monitor.

Process Operation

The pilot facility was constructed inside of a corporate training center used to train welders for a period of several months prior to placing them in a manufacturing facility. The welding done by the students was performed on small pieces of mild steel which were welded inside work booths (Figure 1). Some welding on larger pieces was also performed on tables in an adjacent area of the training center. The school ran on a three shift schedule, five days per week.

Welding Methods--

The vast majority of the welding performed inside the booths was classified as shielded metal-arc welding, however, a limited amount of carbon dioxide shielded flux cored metal-arc welding was also performed. Schematic diagrams of each of these processes appear in Figure 2.

Flux coated stick welding was performed with a Lincoln Idealarc® Model TM 400/400 AC/DC arc welder. Although most of the welding was done in the 75 to 300 amp range, these machines had a 400 amp capability. A limited amount of carbon dioxide shielded flux cored wire welding was performed in one booth using a Hobart® Model RC-600 welding machine, which had a 600 amp capability.

Exhaust Contaminants

The fume composition and gases produced during welding originate from the following sources:

1. Base metal.
2. Electrode or filler metal.
3. Electrode coating or flux material.
4. Chemical reactions that occur in the surrounding atmosphere that result from the heat developed during welding or the ultraviolet radiation emanating from the arc.

When the base metal and filler metal compositions are known, it is possible to predict the potential fume constituents (but not their quantities) contributed by these materials. However, because electrode coatings and flux compositions are proprietary, and the reactions between the coating and fluxing ingredients are extremely complex, it is very difficult to predict their quantitative contributions to the total fume content (2).

Three types of welding electrodes were used during the course of this study. Electrode types, manufacturers, and diameters were as follows:

Electrode	Manufacturer	Diameters used, mm	Diameters used, inches
E7018	Lincoln, Chemetron	6.4, 4.8, 4.0, 3.2	1/4, 3/16, 5/32, 1/8
E7024	Chemetron	6.4, 4.8, 4.0, 3.2	1/4, 3/16, 5/32, 1/8
E70T-5	Chemetron	2.4 only	3/32 only

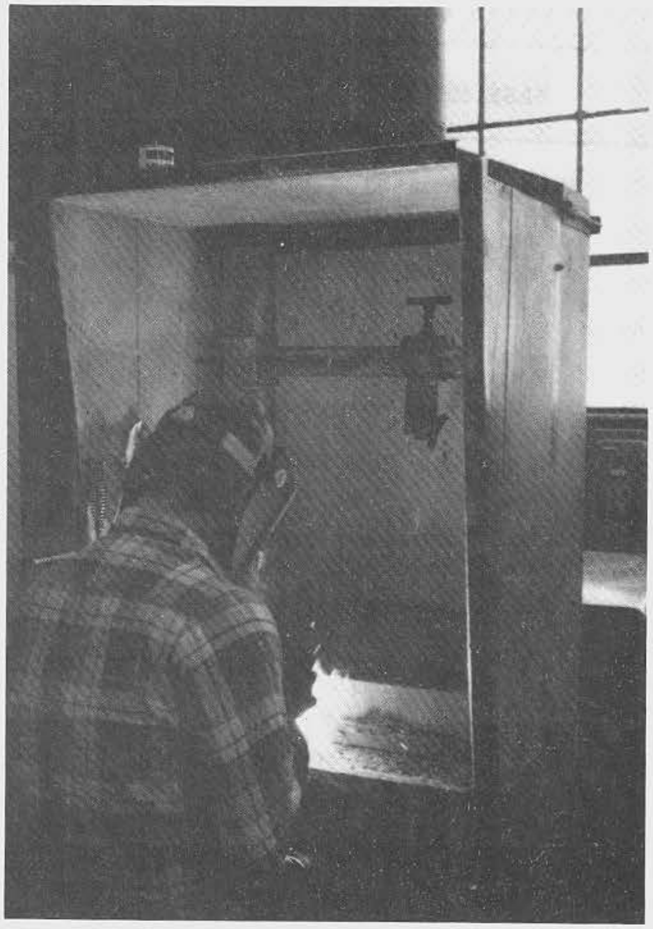
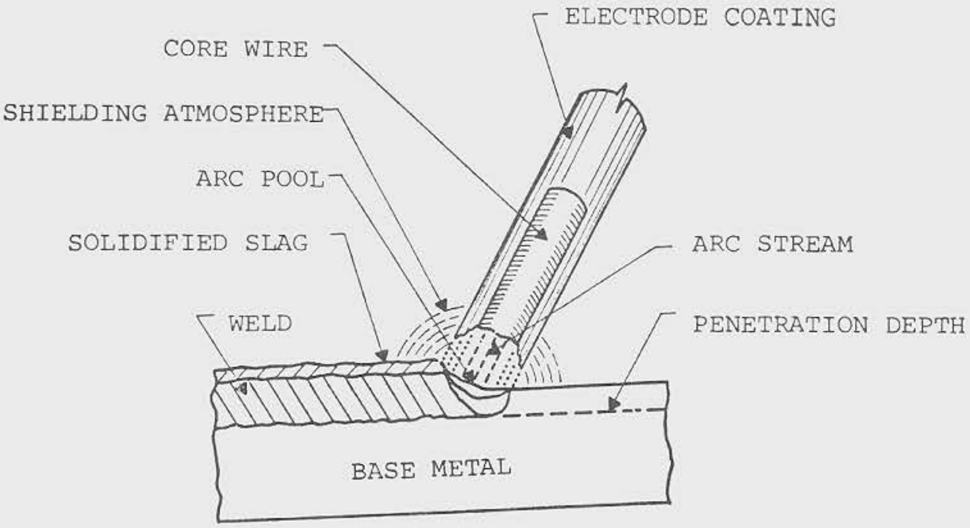


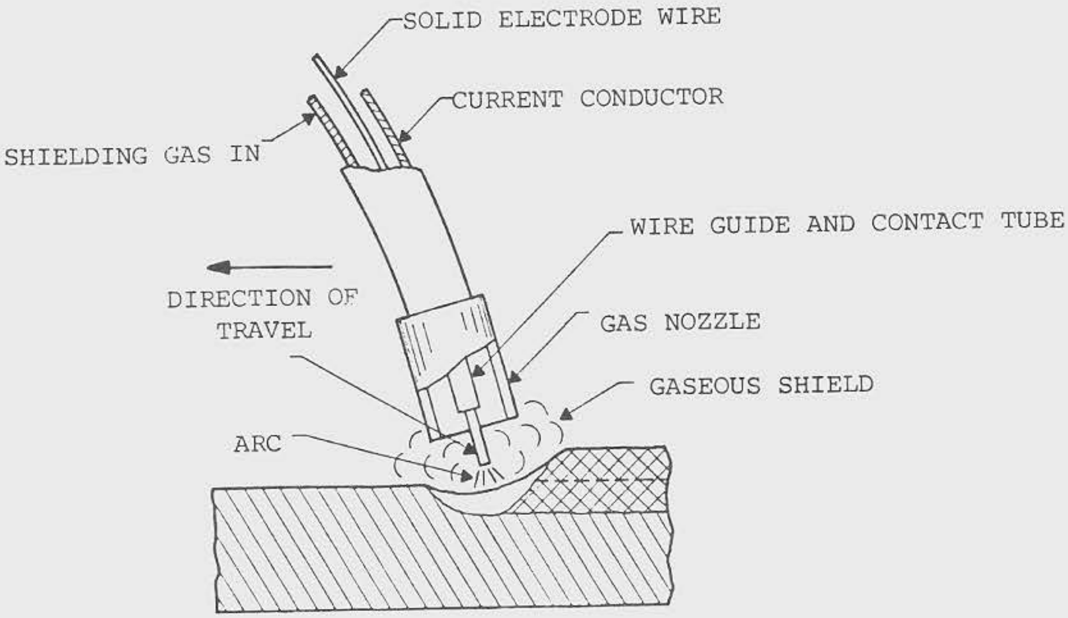
Figure 1. Typical welding operation within the ventilated booth.

Both the base metal and the filler metal in the welding rod used in the process were mild steel. The approximate compositions of each are listed in Table 1.

Experimental investigations of welding fume have been conducted as part of an experimental study performed by the American Welding Society (2). These investigations indicate that the following contaminants could be present in significant quantities when the aforementioned electrodes are used in the shielded metal arc welding process:



Shielded metal - arc welding (2)



Carbon dioxide shielded flux cored metal - arc welding (2)

Figure 2. Welding processes used in this study.

Particles
  - Iron
  - Iron oxides
  - Manganese oxide
  - Particulate fluorides

Gases
  - Ozone
  - Nitrogen dioxide
  - Gaseous fluorides
  - Carbon monoxide

Table 1. Base metal and electrode compositions.

	C, %	Mn, %	Si, %	P(max), %	S(max), %	Other, %
Base metal (mild steel)	0.25 - 0.30	0.60 - 1.20	0.80	0.05		Ni - 0.50, Cr - 0.40 Mg - 0.20, Cu - 0.30
Welding rod E 7018	0.06	1.10	0.50			
Welding rod E 7024	0.06	0.79	0.79	0.010	0.022	Cr - 0.06, Mo - 0.03 Ni - 0.04, V - 0.02
Welding rod E 70T-5	0.06	1.40	0.45	0.012	0.013	

Data from metal analyses performed on air samples collected from the welding booth exhaust in this study indicated that the fume was primarily composed of iron and some manganese. Chromium, nickel, lead, copper, zinc and cadmium concentrations were all less than 10 $\mu g/m^3$. Early in the evaluation of the first air cleaner it was discovered that carbon monoxide, gaseous fluorides and nitrogen dioxide were present in very small quantities, much less than current OSHA Permissible Exposure Limits (PEL). The average and peak concentrations measured in the air cleaner exhausts for each of these contaminants are listed in Table 2.

Table 2. Gaseous contaminants measured in welding exhaust in this study.

Contaminant	Average concentration	Peak concentration	OSHA PEL
Carbon monoxide	10 ppm	20 ppm	50 ppm
Gaseous fluorides	Not detected		2.5 mg/m^3 total fluoride
Nitrogen dioxide	0.19 ppm	0.27 ppm	5 ppm
Ozone	<0.001 ppm	0.005 ppm	0.1 ppm

As a result, further measurement of these contaminants was not performed except for ozone, which, in addition to being generated by the process, was also generated by the electrostatic air cleaners and, at times, was present in significant quantities in the ambient air. Particulate fluorides were measured during the evaluation of the first air cleaner, but, because it was found that low particulate penetrations resulted in exhaust air concentrations far below the current standards, measurements were discontinued.

PILOT TESTING FACILITY

The pilot testing facility included an air contaminant source (welding booth exhausts), fume transport ducting, testing station, and a blower. A schematic diagram of the test facility layout is shown in Figure 3. The following is a description of each component of the system.

Fume Capture Hoods

The localized exhaust booths were already in place and effectively controlling fume from escaping into the breathing zones of the welders before this study was undertaken. The exhausted booth was of the backdraft type, with air drawn through two slots located at the top and the bottom of the back of the booth (Figure 1). Approximately 18.7 m^3/min (670 ft^3/min) was exhausted from each booth. The air flow rate through each booth was regulated by dampers.

Ductwork

To gather sufficient exhaust air needed for each air cleaner test, the exhausts from three welding booths were utilized for the study (Figure 4). A duct takeoff and dampers were added to the existing ductwork to permit bypassing of exhaust air to the pilot test facility (Figure 5). Duct velocities ranged from 12.80 to 14.55 m/sec (2500 - 2865 ft/min). Periodic checks confirmed the lack of fume or dust buildup in the ducts.

Testing Station

The test devices and testing instruments were located at a station in the corner of the plant. A small enclosed lab was constructed on an elevated platform (Figure 6). Air cleaners were either installed within the enclosure or on the floor below depending on the size of the units.

Blower

A Twin City Fan and Blower Company size 913 RBO fan, driven by a 14.9 kw (20 hp) motor was used as the primary air mover. The unit was rated at 100 m^3/min (3500 ft^3/min) at 38.1 cm wg (15 in. wg) static pressure to insure that the needed air flow rate of 56.6 m^3/min (2000 ft^3/min) could easily be met for each air cleaner. Air flow rate through the system was regulated by a blast gate damper that was placed 1.2 m (4 ft) upstream of the blower intake. Because the blower assembly was located outdoors near a

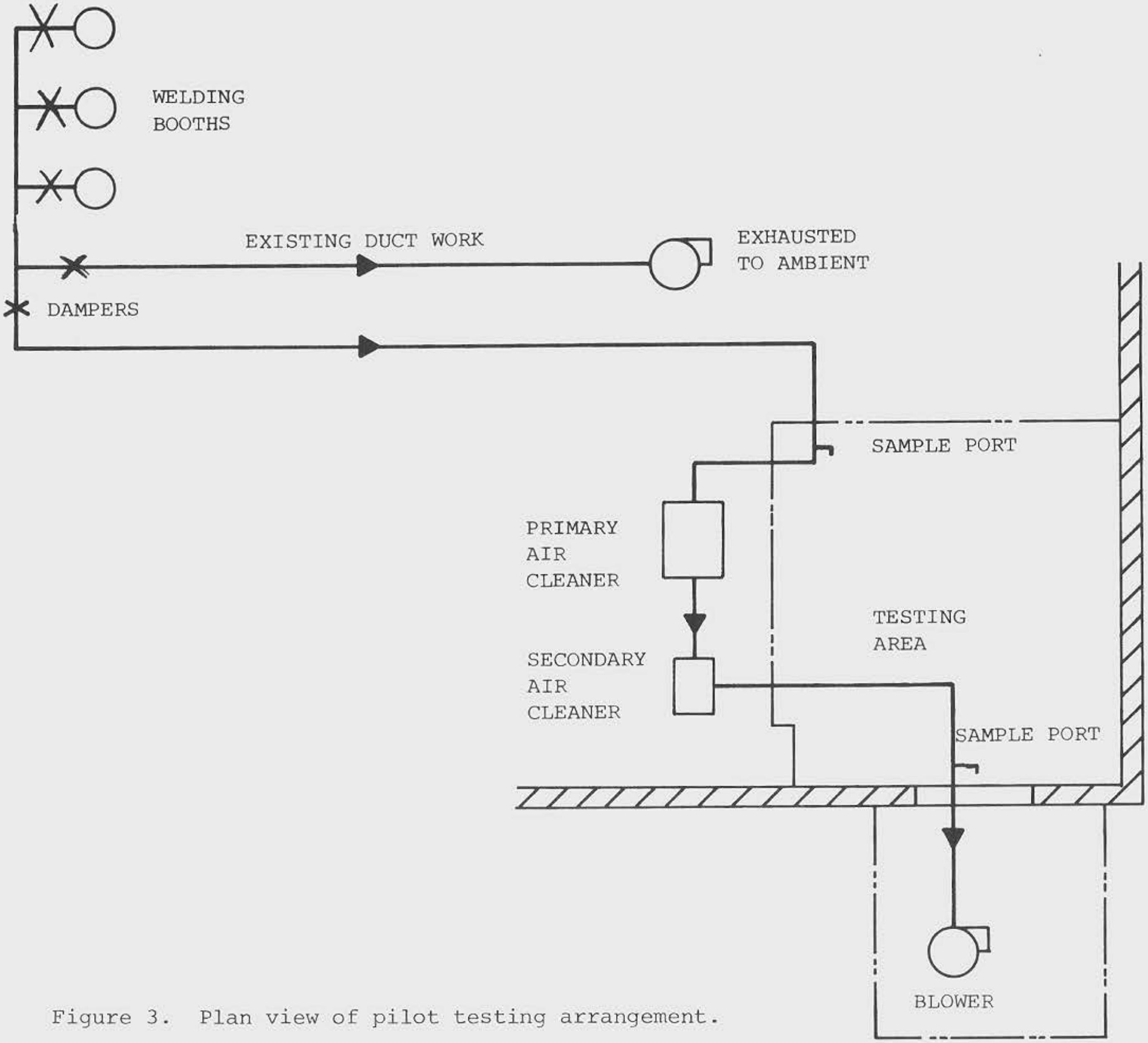
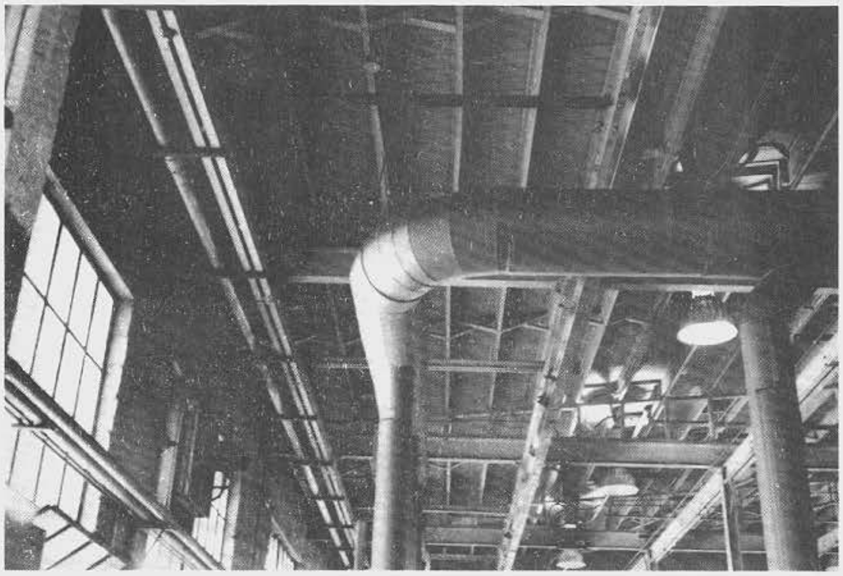


Figure 3. Plan view of pilot testing arrangement.

residential area, an Alronca, Inc.,Ⓡ Model FS-55 rectangular sound trap was mounted on the fan discharge to reduce noise levels. A photograph of this configuration appears in Figure 7.

Figure 4. Three booth localized exhaust system.



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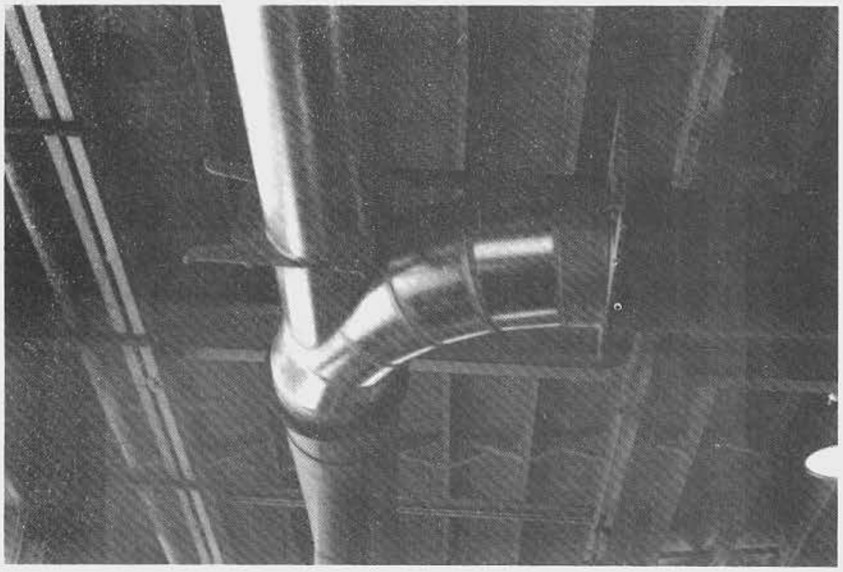


AFTER

Figure 5. Damper control system.

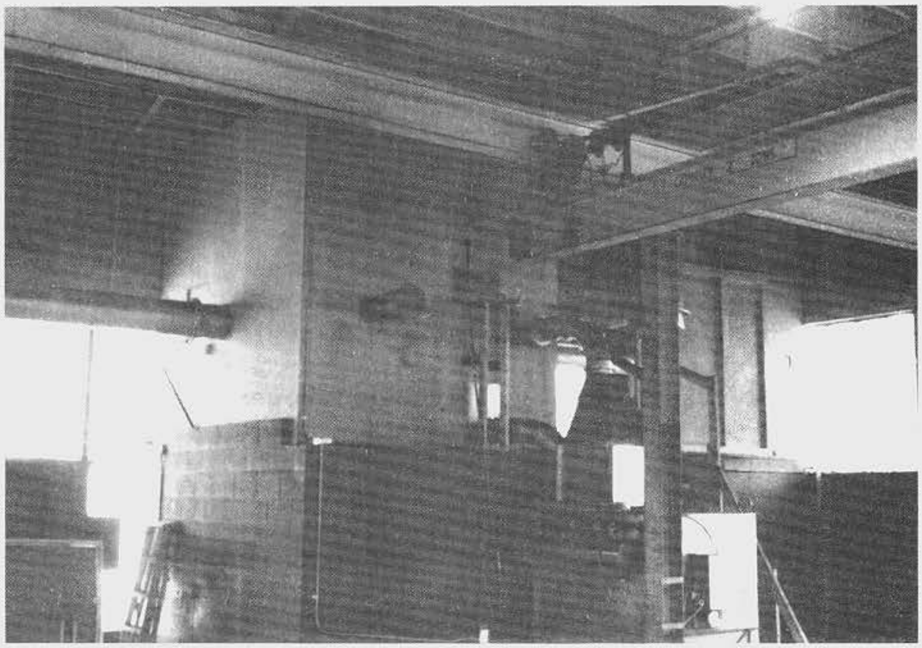


Figure 6. Enclosed testing laboratory.

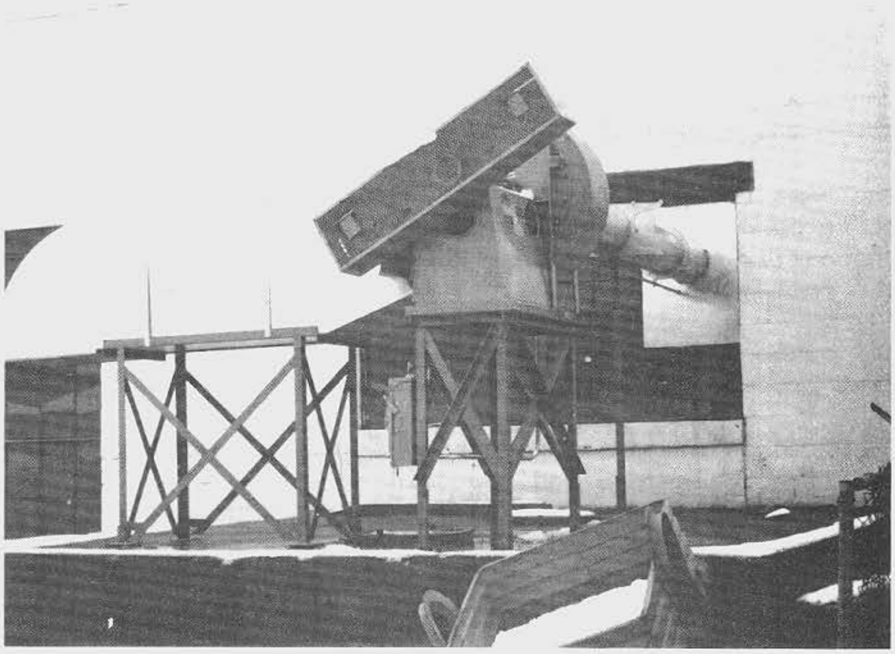


Figure 7. Blower and sound trap.

CONCLUSIONS

1. The pilot testing approach employed in this study, which involved evaluating air cleaners and monitors on an actual industrial process (welding), is an effective method of evaluating devices for use in a recirculating exhaust system. The method is particularly useful if data are not available for a particular process being considered, which is usually the case for recirculation design because of the numerous processes that may be considered and the relative newness of the technique. Not only does pilot testing help the design engineer quantify important operating characteristics of the components being considered, it can also provide valuable insights into potential failures and maintenance requirements associated with the devices.

2. The following criteria were developed and found to be useful in assessing the suitability of air cleaners and monitors for recirculation:

   Evaluation Criteria for Air Cleaners

   The contaminant penetration, i.e., the percentage of material that passes through the air cleaner without being retained, should be as low as possible, especially in the respirable size range (<10 micrometers), to prevent the buildup of contaminants in the workplace and exposure of workers above the allowable limits.

   The time required for the air cleaner to reach a steady-state condition (equilibrium point) should be short, and thereafter the air cleaner should operate continuously and reliably with a predictable amount of penetration.

   Air cleaner failures, defined as any disturbances in operation that produce deviations from equilibrium, should be infrequent.

   Required maintenance procedures should be simple, infrequent, not time consuming, and economical.

   The air cleaner should not introduce new potential hazards.

   Evaluation Criteria for Extractive Type Air Monitors

   The measurement accuracy should be high enough to provide a reliable measurement of a contaminant's concentration when a preselected action level has been reached.

The measurement range should include the desired action level. The minimum detectable change in contaminant concentration should be much less than the action level.

Zero drift should be minimal over extended periods of time to reduce the frequency of required re-adjustments and to insure measurement accuracy.

The response time should be as close to instantaneous as possible to provide a fast warning of a change from system equilibrium.

Evaluation Criteria for Safety Monitoring Filters

The action level for the safety monitoring filter must be set no higher than the limiting differential pressure which, if exceeded, will cause insufficient indraft into the exhaust hoods, resulting in the escape of contaminants into the workplace and exposure of workers above the allowable limits.

The contaminant penetration of the safety monitoring filter, i.e., the percentage of material that passes through the filter without being retained, should be low enough, especially in the respirable size range (<10 micrometers), to prevent the buildup of contaminants in the workplace and exposure of workers above the allowable limits with any increase in the penetration of the primary air cleaner over the equilibrium level, until the action level has been reached.

Evaluation Criteria for both Extractive Air Monitors and Safety Monitoring Filters

To insure reliable operation, potential malfunctions should be few in number, easily detectable, and preventable if recommended maintenance schedules and procedures are followed.

Required maintenance procedures should be simple, infrequent, and not time consuming.

3. The criteria developed in this study can be applied to almost any recirculation system application. The criteria are purposely general because quantification of many of the parameters such as allowable penetration are dependent upon many factors which are specific to the situation, e.g., the toxicity of the contaminants, workplace contaminant levels, the potential for overexposure of workers, and the nature of the process and ventilation system.

4. A summary of the conclusions for each air cleaner device tested follows:

   a. Electrostatic Precipitator (ESP)

      1. The average two pass penetration was 8.85 percent and the average one pass penetration was 19.71 percent under normal operation.

2. A fourfold increase in inlet particulate concentration (from 6 to 23 mg/m^3) did not cause a significant increase in particle penetration.

3. Penetration was higher and more variable during the first 1 to 2 hours of operation after the precipitator was vibratory cleaned.

4. The fractional penetration increased as the aerodynamic diameter of the particulate increased above 1 micrometer for both one and two pass operation. This was probably due to agglomeration of the fume within the ESP caused by electrostatic attraction between charged particles.

5. Equilibrium was reached soon after the ESP was turned on, so that an initial "break-in" period was not necessary.

6. Positive identification of a failure would probably require aerosol monitoring because small variations in system voltage and current produce large variations in penetration.

7. When cleaning air containing a high aerosol concentration (23 mg/m^3) manual cleaning of the ionizers and collection plates could be required as often as every few days.

8. The ESP does not introduce any new hazards that would prevent it from being employed in a recirculating ventilation system for the control of welding exhaust.

b. Electrostatically Augmented Fabric Filter (EAFF)

1. Total penetration ranged from 0.302 to 0.956 percent and averaged 0.444 percent with electrostatic augmentation, and 0.956 percent without.

2. Electrostatic augmentation decreased the penetration of particles less than 2 micrometers in diameter and increased the penetration above 2 micrometers, probably due to agglomeration of the fume particles in the electrostatic portion of the air cleaner.

3. Electrostatic augmentation eliminated the need for a break-in period by causing penetration at startup to approach equilibrium values.

4. Electrostatic augmentation reduced the differential pressure from 16.5 cm wg (6.5 in. wg) to 9.9 cm wg (3.9 in. wg) at a filter velocity of 2.1 m/min (6.5 ft/min) while also reducing total penetration.

5. The failure of primary concern from a recirculation standpoint was welding fume buildup on ionizer wires resulting in increased ozone generation.

6. Blinding failures could most easily be detected by monitoring air cleaner differential pressure, but breakthrough and excessive ozone generation would probably require air monitoring to insure positive identification.

7. Ionizer wire cleaning to prevent excessive ozone concentrations is the primary maintenance task which would have to be performed regularly, possibly as often as once per month. Not only would this task have to be performed often but the task would be difficult and time consuming due to the physical location of the wires within the unit.

c. <u>Aspirated Cartridge Filter (ACF)</u>

1. The lowest penetration (0.193 percent) was achieved with precoated filter elements operating at a low filter velocity.

2. The average penetration determined for each of the operating modes was as follows:

   Low filter velocity, not precoated - 0.545 percent.
   precoated - 0.193 percent.

   High filter velocity, not precoated - 0.432 percent.
   precoated - 0.399 percent
   Precoated with afterfilter - 0.240 percent

3. The combined penetration of the ACF and a fiberglass afterfilter was not significantly lower than for the ACF alone.

4. Total penetration increased significantly during filter cleaning. During the cleaning cycle the afterfilter helped to reduce the amount of penetration increase.

5. If inlet concentration were high enough to require very frequent cleanings, the increases in penetration during the cleaning period could have a substantial impact on the average penetration of the device and may require an afterfilter or a system change to permit the air cleaner to shut down during cleaning.

6. Fractional penetration was 0.7 percent or less for all aerodynamic particle diameters between 0.22 and 7.2 micrometers.

7. Equilibrium penetration and differential pressure can be achieved immediately by precoating new filter elements.

8. Maintenance requirements, necessary to assure proper operation are minimal.

9. No new hazards associated with the operation of the ACF were identified.

5. All of the air cleaners evaluated had similar capital and operating costs. However, the electrostatic precipitator (ESP) capital cost doubled for a two pass system and the operating costs tripled if the aerosol concentration was above 20 mg/m^3 due to the increased number of manual cleanings needed.

6. The following is a summary of the conclusions for the air monitoring devices tested.

   a. Airborne Particle Mass Monitor (Piezobalance)

      1. Comparisons made between gravimetric and piezobalance measurements indicate that the piezobalance accuracy was approximately ±10 percent or less in the range of 0.02 to 0.30 mg/m^3.

      2. The large range of selectable measuring time periods gives the piezobalance the capability of measuring a wide range of concentrations, from one to several hundred $\mu g/m^3$.

      3. Instantaneous indications of concentration changes can be obtained from the analog output signal.

      4. Base frequency rise was found to be significant, requiring frequent manual cleaning, especially when charged particles from the electrostatic air cleaners were sampled.

      5. Routine inspection and maintenance would be effective in reducing the likelihood of occurrence of all five malfunctions that could disrupt proper operation of the piezobalance.

      6. Although all of the maintenance requirements that are necessary to assure accurate and reliable operation of the piezobalance are simply performed, several must be performed frequently, i.e., every two weeks or less.

7. The cost of the piezobalance is high and the first production model will not incorporate any features which could reduce the per point cost of a multi-point monitoring system, although later models may.

b. Aerosol Mass Monitor (APM)

1. APM measurement accuracy with a 5-minute measurement cycle time (15-minute response time) was approximately ±40 percent as indicated by paired measurements made with gravimetric measurements in the 0.3 to 10 mg/m^3 concentration range.

2. The accuracy is reduced as the sample measurement time is shortened, but the upper concentration limit is increased.

3. Zero drift increases as the measurement cycle time is reduced.

4. The minimum response time for the APM is nine minutes.

5. Automatic monitoring of the malfunction modes by the microprocessor system increases the overall reliability of the APM and helps prevent malfunctions from going unnoticed.

6. Maintenance requirements necessary to insure accurate and reliable operation of the APM monitor are infrequent and easily performed.

7. The APM is not suitable for applications where high accuracy and short response times are required. Cost would also be a serious consideration for use of the instrument in a recirculating exhaust system.

c. Tape Sampler

1. The tape sampler is best suited for providing a qualitative rather than a quantitative indication of air quality because variations in such factors as aerosol composition and particle size distribution can cause large shifts in response.

2. The tape samplers available from RAC combine low and high flow rates with selectable sample times providing the potential for a large concentration measurement range, probably from a few μg to several mg.

3. Changes in operation such as switching the tape sampler on and off and replacing the filter tape altered the initial transmittance by as much as 10 percent. The optional, automatic standardization would be necessary to correct this.

4. The tape sampler has a rapid response time.

5. Routine maintenance and inspection would be effective in reducing the likelihood of a malfunction.

6. All of the maintenance procedures necessary to assure reliable operation of the tape sampler are easily performed and infrequent.

7. The low cost of the tape sampler makes it attractive.

d. Real Time Aerosol Monitor (RAM)

1. RAM measurement accuracy was approximately ±10 percent as indicated by paired measurements made with gravimetric and piezobalance measurements in the 1 to 5 mg/m^3 and 50 to 400 $\mu g/m^3$ concentration ranges.

2. Use of longer time constants reduces the noise level from ± 0.005 mg/m^3 at two seconds to ± 0.001 mg/m^3 at 32 seconds, thus improving sensitivity.

3. The manufacturer's calibration setting of 2.5, based on Arizona road dust, allowed accurate measurement of welding fume also.

4. The zero drift was minimal over the test period, indicating that the purge air system effectively protected the optical surfaces from contamination and the electronic circuitry used was effective in reducing drift and noise.

5. Response time is almost instantaneous, even with the time constant set at the longest setting of 32 seconds.

6. Reliability of the RAM system is enhanced by automatically monitoring vital sensor parameters which include air flow rates and calibration.

7. The maintenance requirements needed to assure accurate and reliable operation of the RAM monitor are relatively few and can be simply performed.

8. The RAM system lends itself to multi-point monitoring which reduces capital costs per sampling point. The RAM system provides information processing and malfunction monitoring which helps to increase the system's overall reliability.

e. Ozone Monitors

1. The ultraviolet attenuation method suffers from particulate interference and optical contamination which necessitates that an inlet air filter be used. Use of the filter adds another maintenance step and an element of uncertainty concerning possible ozone attenuation by the material collected on the filter media.

2. The coulometric detection method suffers from a positive interference from other oxidizing or reducing gases besides ozone, which could cause it to be an unreliable indicator of ozone if gases such as nitrogen dioxide or sulfur dioxide are present in significant quantities.

3. The chemiluminescent detection method is best suited for monitoring ozone in welding exhaust air because:

   a. The method is specific for ozone and free from interferences.

   b. An inlet air filter is not needed for the particulate concentration range encountered in this study (0.05 to 15 mg/m^3).

   c. Maintenance requirements are low.

4. Zero stability and measurement accuracy were excellent for all three devices tested.

f. Safety Monitoring Filter (SMF)

1. Because of high initial penetration, the glass fiber SMF would not prevent significant amounts of particulate material from being recirculated into the workplace in the event of a breakthrough failure of the primary air cleaner. However, a higher efficiency filter such as a HEPA type filter would provide this protection at the expense of a higher pressure drop, increased unit cost, and reduced service life.

2. The response time of the SMF could be on the order of minutes or days depending upon the differential pressure across the SMF at the time of breakthrough and the aerosol concentration.

3. If the penetration of the SMF were low, it would provide effective back-up filtration, eliminating the need for a short response time.

4. Both the initial and final differential pressures across the SMF tested were relatively low.

5. A change from the initial to the final differential pressure (action level) during breakthrough resulted in only 3.3 percent decrease in air flow rate through the system.

6. Malfunction modes are few, but could be difficult to detect.

7. Replacement of the filter elements is the only maintenance requirement and the frequency of replacement is dependent upon the aerosol concentration introduced to the SMF.

8. The capital cost of a HEPA filter is four times that of a glass fiber filter and the operating cost is twice as high.

6. The largest gap in the technology exists in the area of system monitoring. The four components needed for a complete monitoring system, i.e., signal transfer, detector/transducer, signal conditioner, and information processor, are rarely found in a commercially available monitoring package. Rather, the engineer must select various components and assemble a system for matching components. This is often difficult and expensive and can result in misapplication if a device is used to perform a task for which it was not designed. A great need exists to incorporate the monitors that are available (most of which represent a detector/transducer only) into complete systems that are easily engineered specifically for recirculating exhaust systems.

RECOMMENDATIONS

1. The technical and economic feasibility of recirculation should be assessed by pilot testing procedures if the following circumstances exist :
    - a. The unique properties of the aerosol stream pose questions concerning the effectiveness of available air cleaners.
    - b. The potential cost savings for installing the proposed system are of such a magnitude as to justify a preliminary study to check feasibility and establish system parameters.
    - c. The chief contaminants are particles but gases are present and their levels must be assessed before deciding on an air cleaning strategy.
    - d. A matched collector-monitor combination cannot be established theoretically or from experience.
    - e. Modes of potential system failure are unknown, as well as required maintenance intervals and costs.
2. Complete monitoring systems composed of all four of the necessary stages needed for monitoring the performance of a recirculation system (signal transfer, detector/transducer, signal conditioner and information processor) need to be developed and made available in the marketplace.
3. A mobile, recirculation van incorporating several pilot scale air cleaning and monitoring devices should be built to reduce the cost and time required to conduct pilot scale tests.

One drawback to pilot scale testing that may discourage industry from using this method is the high cost involved and the time necessary to carry out such a program. In many cases, justification for such a program would require that an industry had multiple places to utilize the method should it prove viable. If the candidate process were a single, isolated process, it is doubtful that the pilot approach would be considered.

This mobile unit could include a variety of air cleaners and monitors which could be tested singly or in combination, depending on the application. The unit would include the measuring devices for gathering the necessary data and calibrating the monitors. The mobile unit would be self-contained and only require a ducting hookup to an existing ventilation system. Such a system would need to be operated by trained personnel.

MEASUREMENT METHODS

SUMMARY

Air sampling was conducted to identify, quantify, and characterize both particulate and gaseous contaminants contained in the exhaust from a welding process both upstream and downstream of air cleaning devices. Table 3 summarizes the methods used in air sampling. Particulate sampling methods included a modified EPA Method 5 and a high volume method developed for sampling low particulate concentrations. Gaseous sampling was performed using NIOSH recommended methods or those recommended by the American Public Health Association (APHA) intersociety committee (3). The suitability of a particular sampling method was based on its lower detectable limit, concentration range, and accuracy. A brief description of the sampling program follows. After this discussion, measurement methods for air flow, pressure, and temperature are described as well as the method for determining total welding time.

PARTICULATE SAMPLING

Two particulate sampling trains were employed: one having a low air flow rate (low volume) designed for sampling air having a high aerosol concentration (>1.0 mg/m^3), and the other having a high air flow rate (high volume) for sampling low aerosol concentrations (<0.5 mg/m^3).

It can be generalized that particles less than 3 to 5 micrometers in diameter do not have sufficient inertia to cause them to deviate significantly from gas flow streamlines. Therefore, because the particles being sampled were all less than 4 micrometers in diameter with 90 percent by mass less than 2 micrometers, strict isokinetic sampling was not adherred to, but was approximated.

Low Volume Sampling Train

The sampling train described in EPA sampling method 5 was used as a basic guide with modifications made to the portions of the sampling train which provide adaptation to a high temperature and humidity environment. Because the air being sampled was at room temperature and humidity, these portions of the sampling train were eliminated. A schematic diagram showing all of the major components of the train appears in Figure 8. Major components of the train include:

1. Control case, either a Research Appliance Company® Model 2343 or a Glass Innovations® Model G11-200.
2. Flask containing silica gel to remove moisture from sampled air.

Table 3. Summary of air sampling methods.

Analyte	Method used	Literature reference	Measurement range
Aerosol concentration	Modified EPA Method 5 (low volume) sampling train (Parts of the train used for high temperature and moisture were removed).	4	1 mg/m^3 and more depending on sampling time.
	High volume sampling train employing a 20 x 25 cm (8 x 10 in.) filter, high volume/pressure blower and an integrating positive displacement gas meter.	Specially designed	500 $\mu g/m^3$ and less depending on sampling time.
Aerosol size distribution	For high concentrations, a Sierra Instruments Model 228 in-stack cascade impactor. For low concentrations, a Sierra Instruments Model 230 high volume cascade impactor adapted for use in the high volume sampling train (See Figure 10).	4	Model 228 - 0.30 to 18 μm aerodynamic diameter for the flow rate used. Model 230 - 0.49 to 7.2μm aerodynamic diameter.
Nitrogen dioxide (NO_2)	Fritted bubbler employing a colorimetric azo dye.	3	0.005 to 5 ppm
Fluorides-gaseous and particulate	Collection of particulate fluoride on a membrane filter and gaseous fluorides on an alkaline filter. Analysis was performed with an ion selective electrode.	3	0.05 to 5 mg F^-/m^3
Ozone (O_3)	Two methods were used, a wet chemical method and an instrument which employed a chemiluminescent detection system.		
	a. Wet method: Colorimetric method employing a neutral KI solution.	3	0.01 to 10 ppm
	b. Chemiluminescent method: Analytical Instrument Development (AID) Inc. Series 560 portable ozone analyzer.		0.001 to 10 ppm
Carbon monoxide (CO)	Electrochemical oxidation method: Ecolyzer Model 2000 portable monitor.		0-500 ppm

3. 47 mm Gelman type 1235 inline filter holder.
4. Stainless steel goose neck nozzle sized for near isokinetic sampling.

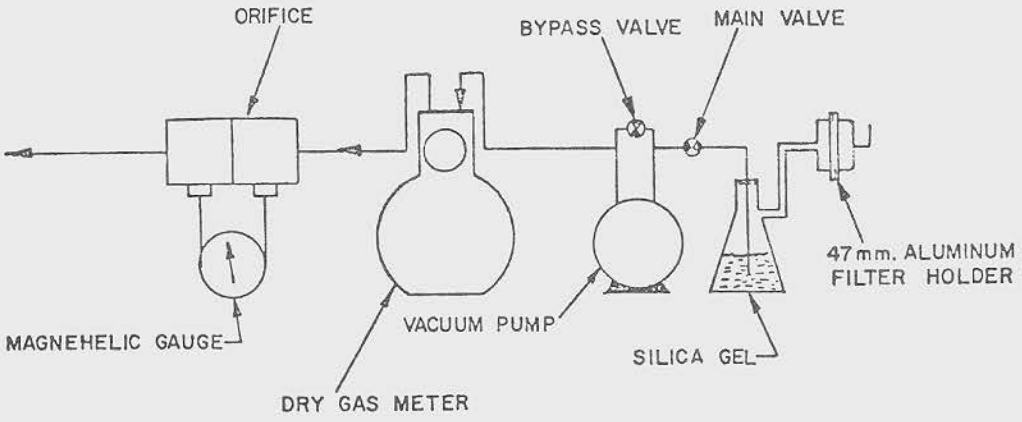


Figure 8. Low volume sampling train.

Both control cases were precalibrated with a wet test meter.

High Volume Sampling Train

Because of the extremely low aerosol concentrations in the exhaust stream of the high efficiency collectors, a high volume sampling train was designed to sample at a flow rate of 0.85 to 1.70 m^3/min (30 to 60 ft^3/min) to reduce sampling time.

The basic design was similar to the high volume samplers that are commercially available from Rader® Companies Inc., with the exception of the flow meter; a Roots® Model 5M125 positive displacement flow meter was substituted for the orifice meter. A schematic diagram showing all of the major components of the sampling train appears in Figure 9. These components include the following:

1. Anodized aluminum nozzle.
2. Filter holder, 20.3 x 25.4 cm (8 x 10 in.).
3. High volume, high pressure blower.
4. Rheostat to control blower motor speed.
5. Rootsmeter.

To compare the measurements made by the high and low volume sampling trains, three tests were performed employing both sampling trains simultaneously in the outlet duct with particulate concentrations in the range of 1 to 2 mg/m^3. The results, compared at standard conditions, agreed to within ±10 percent. Due to the long sampling time needed for the low volume sampling train at concentrations in the 25 to 75 $\mu g/m^3$ range, it was impractical to perform a comparison between the methods in this range.

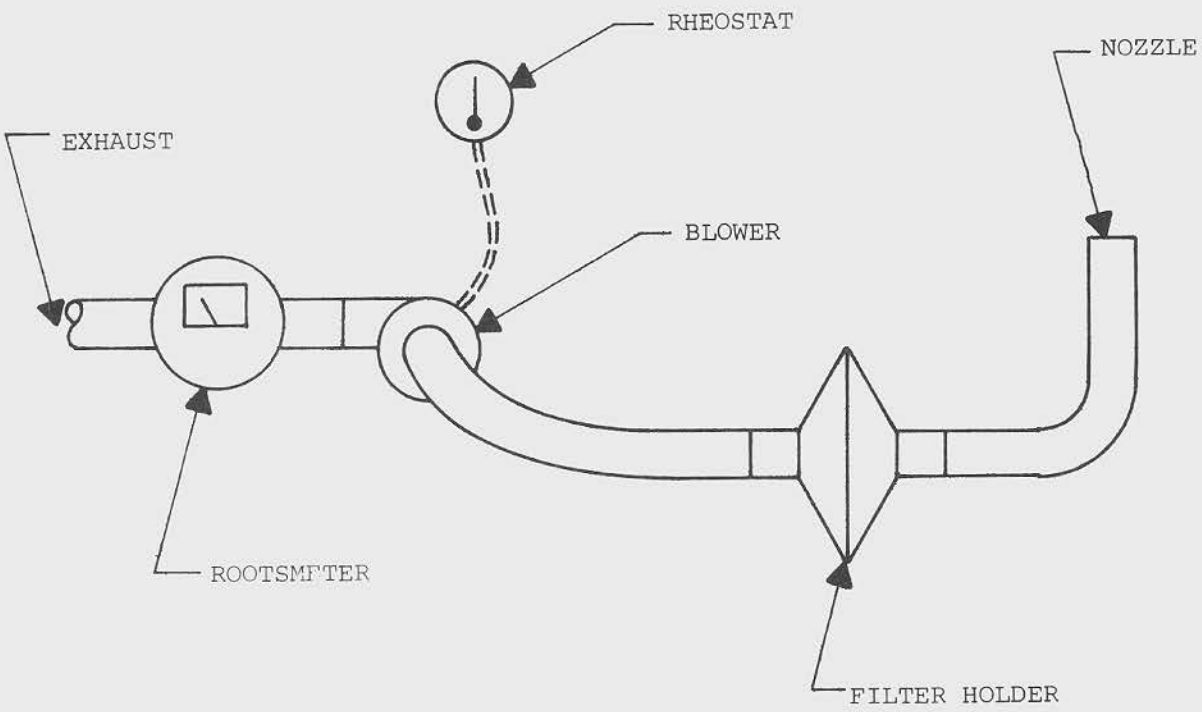


Figure 9. High volume sampling train.

Gravimetric Determinations

Gravimetric samples used for particulate concentration determinations were collected using Gelman Type A glass fiber filter substrates. This type of filter media was selected because of the following considerations:

1. High collection efficiency with a relatively low pressure drop.
2. Reduced hygroscopicity.
3. Good sample retention.

All of the filters used were pre-and post-desiccated for at least 24 hours prior to weighing. A Mettler type H-20 analytical balance was used for weighing, which is accurate to 0.01 mg. A guideline set by the American Society of Mechanical Engineers (ASME) for particulate sampling states that the scale should be accurate to ±0.5 percent of the weight of particulate matter caught on the filter. Based on this guideline, the minimum differential sample weight is 2 mg. Sampling times were adjusted to insure that this minimum weight was caught during each test. To determine the amount of particulate material deposited in the sampling train, sampling nozzles and casings were backwashed with acetone. Total weights were determined by adding the filter and backwash weights.

PARTICLE SIZING

Two impaction methods were used for determining aerodynamic particle size distribution: a low volume method for high aerosol concentrations (>1 mg/m^3) and a high volume method for low aerosol concentrations (<0.5 mg/m^3) found in the air cleaner exhausts.

The low volume method used all of the components of the low volume sampling train shown in Figure 8, except that the 47 mm filter holder was replaced with a Sierra Model 228 eight stage in-stack cascade impactor. The impactor was operated at 0.10 m^3/min (0.35 ft^3/min), which provided an aerodynamic size breakdown ranging from 0.30 to 18 micrometers. A stainless steel gooseneck nozzle, sized for near isokinetic sampling, was fitted to the impactor.

The high volume aerodynamic particle sizing method used a 20.3 x 25.4 cm (8 x 10 in.) filter holder and a Sierra model 230 high volume cascade impactor. The Model 230 impactor was custom fit to the filter holder by cutting the base plate to reduce its size. The components and arrangement of this method are detailed in Figure 10. This method had a particle size breakdown of 7.2 to 0.49 micrometers at an air flow rate of 1.13 m^3/min (40 ft^3/min).

To compare the results obtained using high and low volume methods, simultaneous samples were collected with both methods at the inlet to the air cleaners. The results of this test, which show good agreement between the methods, are presented in Figure 11.

GASEOUS AND PARTICULATE FLUORIDE SAMPLING

Gaseous and particulate fluoride measurements were made using method no. 810 described in Reference 3. Advantages of this method include simplicity, elimination of distillation or diffusion, speed and specificity.

Both particulate and gaseous fluorides were collected using a 47 mm diameter filter "sandwich" composed of a membrane filter (mixed cellulose ester, 0.8 micrometer pore size) used to collect the particulate phase and an alkali-impregnated cellulose pad used to collect the gaseous phase. The membrane filter and collected solids were made alkaline and ashed, the residue was fused with additional alkali, and the fluoride content was determined in a solution of the melt through the use of a fluoride ion selective electrode. Gaseous fluoride was determined in an aqueous extract of the cellulose pad, also by means of the fluoride ion selective electrode.

This filter sandwich was placed in a 47 mm filter holder and simultaneous isokinetic sampling of both the inlet and outlet gas streams was performed. The filter sandwich was then removed from the filter holder, placed in plastic containers and returned to the laboratory for analysis.

GASEOUS SAMPLING METHODS FOR NITROGEN DIOXIDE, OZONE AND CARBON MONOXIDE

Gaseous sampling for nitrogen dioxide, ozone, and carbon monoxide was accomplished using either wet methods or portable direct reading instruments.

Nitrogen Dioxide

Nitrogen dioxide was measured using method no. 817 described in Reference 3. The major advantage of the method is its simplicity with direct coloration of absorbing reagent, which can be put directly into cuvettes and read.

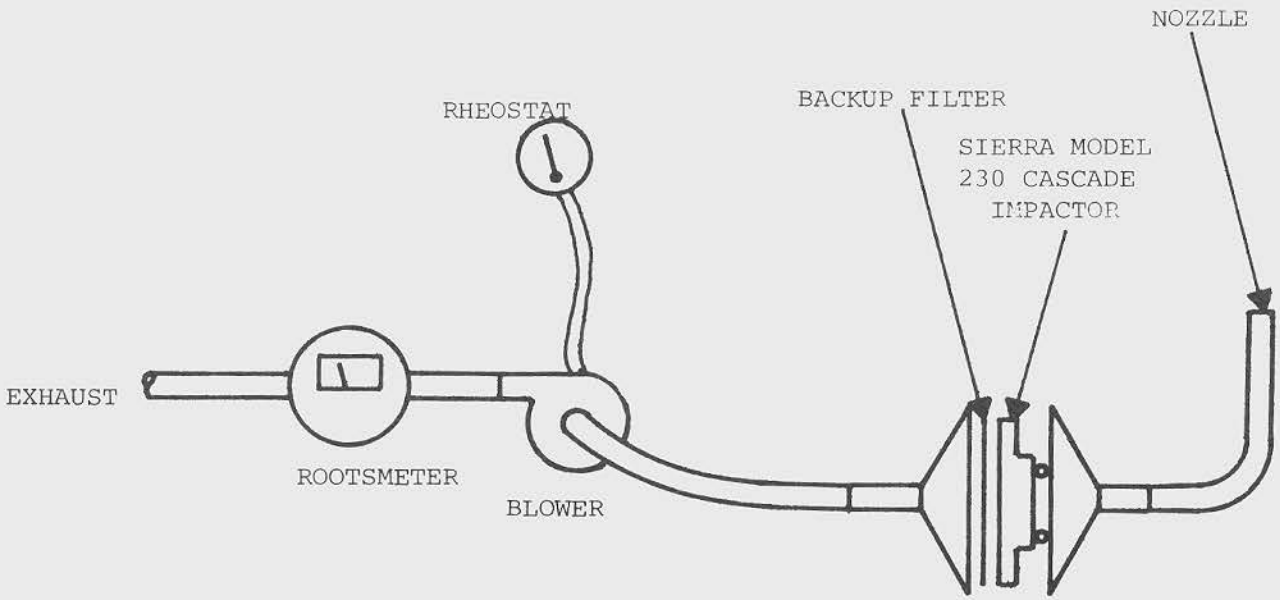


Figure 10. High volume cascade impactor sampling train.

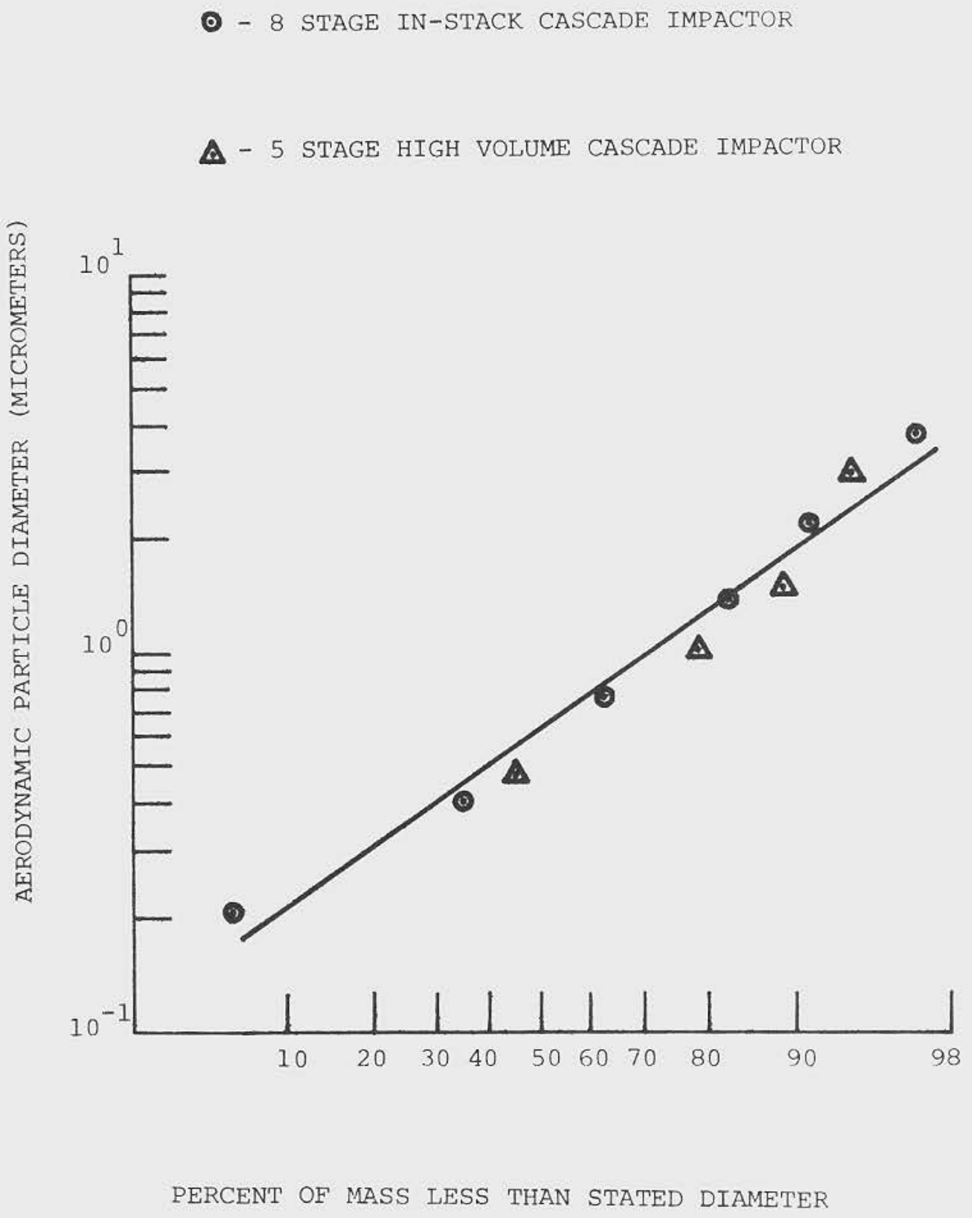


Figure 11. Comparison of high and low cascade impactor data (inlet particle size distribution, concentration = 8 mg/m^3).

Sample air, regulated by a critical flow orifice, was drawn through a fritted bubbler with a frit having a maximum pore diameter of 60 micrometers and containing an azo dye forming reagent. Any nitrogen dioxide contained in the air sample reacts with the reagent producing a stable pink color within 15 minutes which can be read on a spectrophotometer at 550 nm. This method has a measurement range of 0.005 to 5 ppm with no interferences expected from welding exhaust.

Ozone

Initially, wet methods using potassium iodide (KI) solutions were used to measure ozone concentrations but were determined to be unsuitable because of negative interferences caused by sulfur dioxide and positive interferences caused by other oxidants present in welding exhaust, such as nitrogen dioxide. Instead, a portable, direct reading device, the Aid® Series 560 ozone analyzer, employing the chemiluminescent detection method (which is ozone specific), was used. This unit is a fully portable, self-contained device which utilizes the vapor phase chemiluminescent reaction of O_3 and ethylene. An internal charcoal trap provided a source of ozone-free air for zeroing. The range of the device was 0.001 to 10 ppm. Sample air was drawn through the device at approximately one l/min and the output was recorded on a strip chart recorder.

Prior to being used, the ozone analyzer was calibrated against the neutral-buffered KI method using ozone-containing air generated by a Monitor Labs® Model 8500 ozone calibration unit.

Carbon Monoxide

An Ecolyzer Model 2000® series portable carbon monoxide monitor was used to measure carbon monoxide in the exhaust air stream. The instrument uses an electrochemical oxidation process for carbon monoxide detection. Before being used, the instrument was zeroed and calibrated with 50 ppm span gas. Sample gas was extracted from the duct via teflon tubing and passed through an interference filter prior to entering the instrument. The instrument output signal was recorded on a strip chart recorder to produce a permanent record.

OTHER MEASUREMENT INSTRUMENTS USED

Air Flow Rate and Air Pressure

Air flow rates through the electrostatic precipitator were determined using an Annubar® type 735 flow meter. Air flows through the two fabric filter air cleaners were measured with custom designed orifice meters, calibrated with a standard pitot tube using a traverse scheme as prescribed by standard EPA procedures.

Static pressure at both the inlet and the outlet of the air cleaners was measured using Dwyer® static pressure taps installed in the ductwork and connected to manometers.

Temperature and Humidity

The wet and dry bulb temperatures of the air stream were determined using mercury thermometers. The wet-bulb thermometer was fitted with a "sock" and saturated with distilled water prior to determining the wet bulb temperature.

High Voltage

Two of the air cleaners tested employed electrostatic charging to remove particulate material, so it became necessary to make high voltage measurements to determine if the unit was functioning properly and to study the relationships between voltage, current and air cleaner performance. High voltage was measured with a Simpson® Model 260-6 VOM fitted with a 10 KV DC high voltage probe. Measurements could be made to the nearest 100 volts. Current measurements were also made with the Simpson meter.

Welding Time

The welding time was determined during each air sampling test by connecting a timer circuit to each welding machine. The timer consisted of an ASCO® Model 151-35 relay and an electric timer that measured elapsed time to the nearest tenth of a minute. The cable carrying current to the welding rod passed through the relay and served as a "coil" to activate the relay during welding. When energized, the relay, in turn, operated a 115 V, 60 cycle clock. Both the AC and DC welding modes triggered the relays which were adjusted so that they energized when 75 amps or more passed through the cables.

AIR CLEANER EVALUATIONS

This section presents the results of evaluations performed on three air cleaning devices tested. Table 4 lists the air cleaners, assigning a reference abbreviation to each, used through the remainder of the report. The cleaning method employed by each air cleaner is also specified.

Table 4. Air cleaning devices evaluated.

Air cleaner	Reference abbreviation	Collection method
Texas Electrostatic Precipitator Co., Inc. (TEPCO) - Two stage (low voltage) two pass electrostatic precipitator.	ESP	Low voltage electrostatic precipitation.
American Precision Industries, Inc.- Electrostatically augmented fabric filter.	EAFF	High voltage tubular type electrostatic precipitation followed by bag-type filtration.
Farr, Inc. - Aspirated cartridge filter.	ACF	High fabric area cartridge type filtration.

Prior to initiating testing of each air cleaner, the installation and operation of the test device was inspected by each manufacturer to insure that the unit was installed and operating properly.

EVALUATION CRITERIA

Various tests were performed on each air cleaner to determine how well it met a series of preset criteria which relate to the suitability for use of the device in a welding recirculation system. Following are the statement and definition of criteria as well as a description of the methods used to assess each air cleaner's performance.

Contaminant Penetration

> The contaminant penetration, i.e., the percentage of material that passes through the air cleaner without being retained, should be as low as possible, especially in the respirable size range (<10 micrometers), to prevent the buildup of contaminants in the workplace and exposure of workers above the allowable limits.

The actual amount of penetration tolerable can only be determined when important factors specific to each application are considered, among them:

1. Toxicity of the contaminants in the air stream leading to the air cleaner.
2. Ratio of fresh to recirculated makeup air introduced into the workplace.
3. Concentrations of contaminants in the general workplace atmosphere prior to recirculation.
4. Location and method of distribution of return air to the workplace.

Since the scope of this study was limited to evaluating the performance of air cleaners on a test stand rather than in an actual recirculating exhaust system definite conclusions about the upper limits for allowable penetration could not be drawn. Therefore, the evaluation of each air cleaner according to this particular criterion was limited to reporting each device's total and fractional penetration.

Total penetration is the percentage of the total incoming airborne particles that is not retained by the air cleaner. Fractional penetration is the percentage of the incoming particles in a particular size range that is not retained by the air cleaner. Penetration, defined in terms of air cleaner efficiency, is (1-efficiency) x 100 percent.

Total penetration was determined by simultaneously measuring the total particulate concentrations at the inlet and outlet of the air cleaner, reducing the concentrations to standard conditions, subtracting them, and then calculating total penetration according to the following equation:

$$P_T = [1 - \frac{(C_I - C_o)}{C_I}] \times 100\%$$

Where: P_T = Total penetration.
C_I = Inlet concentration.
C_o = Outlet concentration.

Fractional penetration was determined by first measuring the aerodynamic size distribution of the inlet and outlet air streams of the air cleaner. The results obtained from these measurements abong with the total penetration, were used to determine algebraically the fractional penetration for each of the particle size diameters measured.

Equilibrium

The time required for the air cleaner to reach a steady state condition (equilibrium point) should be short, and thereafter the air cleaner should operate continuously and reliably with a predictable amount of penetration.

Prior to reaching equilibrium, penetration could be higher than normal, depending on the air cleaning device. High initial penetration is of particular concern if the air cleaner cannot be taken off line during the break-in period. After equilibrium is reached, periodic and unpredictable rises in penetration are to be avoided.

For the air cleaners tested, measurement of penetration over a period of days was used to monitor the rise to and maintenance of equilibrium. In the case of the fabric filters, differential pressure across the filter media was also used to monitor equilibrium.

Failure Modes

> Air cleaner failures, defined as any disturbances in operation that produce deviations from equilibrium, should be infrequent and detectable.

Air cleaner failures can occur for many reasons, including improper or neglected maintenance, breakage, and wear. They result in two characteristic types of failure: breakthrough and blinding. Breakthrough is defined as an increase in penetration over and above the equilibrium amount. Blinding is defined as excessive buildup of contaminants on a filter media which results in reduction in air flow through the ventilation system and possible damage to the filter.

Clues to possible failures that could occur for each air cleaner were gathered from three different sources: operational theory, information provided by the manufacturer, and insights gained from the experience of this study.

Maintenance

> Required maintenance procedures should be simple, infrequent, not time consuming, and economical.

Maintenance is not an automatic function; it depends on people to do it. For this reason, and also because it is important to the reliability of the air cleaner, the less needed, the better.

Required maintenance procedures were determined based on manufacturers' suggestions as well as insights gained from the field tests.

New Potential Hazards

> The air cleaner should not introduce new potential hazards.

New potential hazards could include the creation of hazardous levels of a contaminant such as ozone, exposure of workers to contaminants during maintenance, fire, explosion, and electrical shock hazards. The only major suspected new potential hazard encountered during the course of this study involved the generation of ozone by the electrostatic devices. The extent of the hazard was evaluated by determining the amount of ozone produced by the device and calculating an emission rate.

ELECTROSTATIC PRECIPITATOR (ESP)

PRINCIPLE OF OPERATION

The low voltage (10 kv), two stage electrostatic precipitator which was evaluated works on the same basic principle as a high voltage (25 - 40 kv) unit, and is preferred over it for ventilation systems because it produces less ozone. In the low voltage unit (Figure 12), a corona discharge ionizes gas molecules that, in turn, cause particles suspended in the air stream to become charged. As the charged particles enter the collecting section of the precipitator, they migrate because of electrical forces toward electrically grounded or oppositely charged surfaces, where they are deposited. Vibratory action is periodically used to remove the deposited particle layers from the collecting plate and ionizer surfaces.

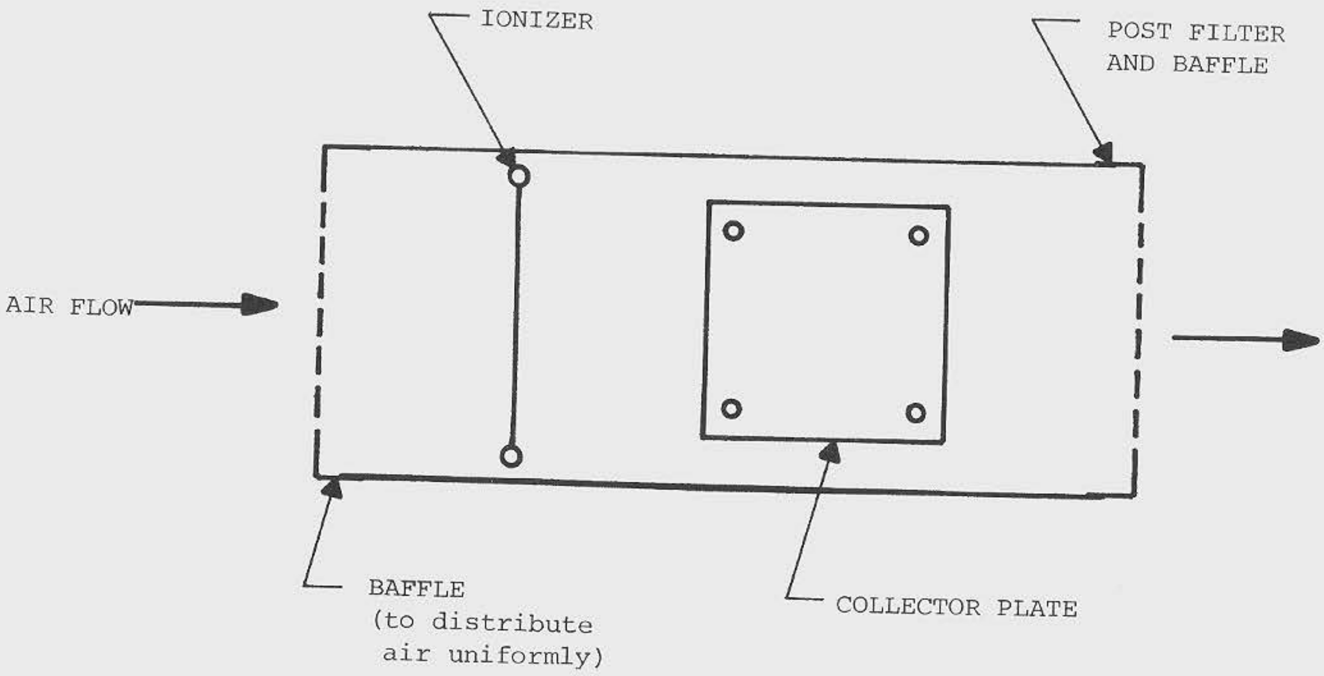
TEST DEVICE DESCRIPTION

The test device consisted of two identical low voltage electrostatic precipitators connected in series, constituting a two-pass system. Two-pass operation was used to decrease the particle penetration through the air cleaner system. Each ESP consisted of the following components:

1. Solid state high voltage power supply.
2. Ionizing section.
3. Collecting plate section.
4. Postfilter to remove large particles.
5. Pneumatic vibration cylinder attached to plates and ionizers.
6. Unit housing constructed of 16 gauge welded steel, finished with a chemical and oil resistant paint.

A photograph of the unit, installed for testing, appears in Figure 13. The units were equipped with a self-cleaning feature whereby the ionizers and collecting plates were vibrated. Vibratory cleaning was accomplished by supplying compressed air at 7.03 kg/cm^2 (100 psig) to pneumatic vibration cylinders. Cleaning cycle intervals were controlled either manually or by optional timers.

Manufacturer's specifications for the ESP are given in Table 5.



SIDE VIEW

Figure 12. Schematic diagram of typical two stage (low voltage) Electrostatic Precipitator.

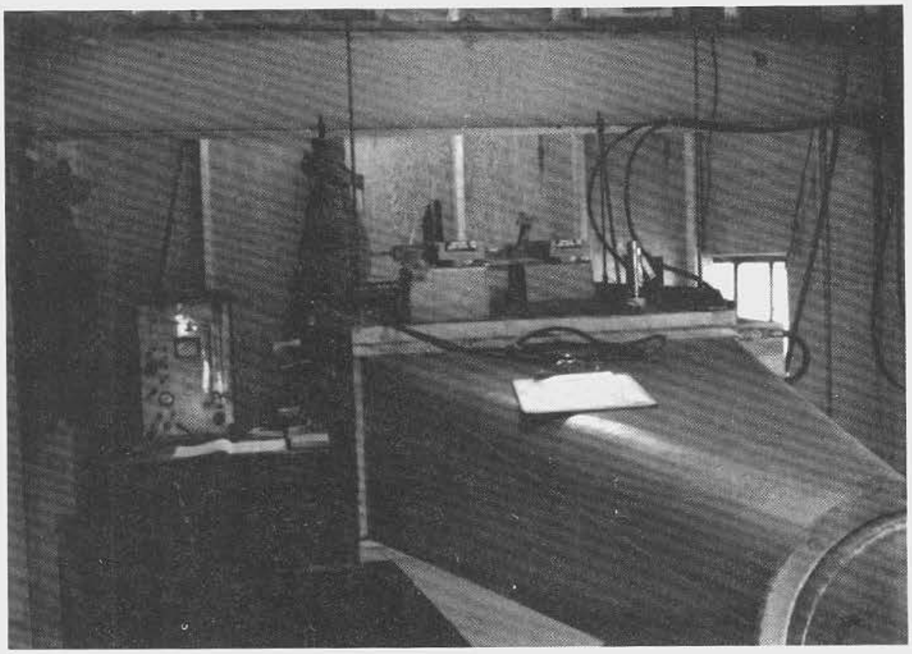


Figure 13. Electrostatic Precipitator installed for testing showing ductwork.

Table 5. Electrostatic Precipitator specifications.

Input voltage:	120 volts, 60 cycle, single phase
Input current:	1.0 amp nominal
Power consumption:	100 watts/0.94 m^3/sec (100 watts/2,000 ACFM)
Weight:	138 kg (320 lb)
Maximum recommended air capacity:	0.94 m^3/sec (2,000 ACFM)
Ionizer section:	
Voltage:	8,600 - 11,000 VDC, positive corona
Current:	2.0 ma nominal
Collector section:	
Plate material:	Aluminum
Plate voltage:	4,500 - 5,000 VDC

TESTING PROCEDURE

Installation

Special provisions were made on the inlet and discharge of the precipitator to insure an even air velocity distribution which was critical if the maximum efficiency was to be obtained. This was accomplished by:

1. Installation of a straight section of duct upstream of the ESP.
2. Construction of a diverging inlet plenum with angles less than 15°.
3. Installation of a perforated plate with 40 percent open area covering the cross-section of both the inlet and outlet plenums.

An air velocity traverse made directly in front of the ionizing section revealed an even velocity distribution across the inlet opening (variation less than 10 percent) with an average velocity of approximately 2.79 m/sec (550 ft/min).

Operating and Testing Routine

The unit was usually operated for one shift a day after which time it was shut off and self-cleaned. The control dampers were closed to prevent air from being drawn backward through the system because of the negative pressure in the building during the off hours. Startup each day was accomplished by opening the control dampers and turning the exhaust blower on. The blower was run with the precipitator off for five to ten minutes to remove any loose material that might have settled on internal surfaces of the precipitator during cleaning. The precipitator power supp;y was then turned on and the unit was operated for 30 to 45 minutes before particulate sampling was initiated. During this initial time period, system temperature, air flow rate, static pressure, and precipitator voltages were monitored to insure that all important parameters were at the desired levels and that the system was at equilibrium. Experimentally these parameters were found to be relatively stable after a few minutes of operation.

Constant Experimental Conditions--
The following variables were held constant:

1. The air flow rate was set at approximately 0.94 m^3/sec (2,000 ACFM) as specified by the manufacturer.

2. Collector plate and ionizer geometry and voltages were set at the factory according to the manufacturer's standard design specifications.

3. The unit was self-cleaned with pneumatic vibrators for 60 seconds at the end of each 8-hour shift as recommended by the manufacturer.

4. The collector plates and ionizers were steam cleaned when necessary using the procedure recommended by the manufacturer.

EVALUATION RESULTS

Penetration was determined for the following operating modes:

1. Two passes, high aerosol concentration (average = 24 mg/m^3).
2. Two passes, low aerosol concentration (average = 6 mg/m^3).
3. One pass, medium aerosol concentration (average = 14 mg/m^3).

Penetration tests were conducted during the beginning, middle and end of each 8-hour shift to determine if the penetration changed during the 8 hours of operation between vibratory cleanings. In addition, tests were performed during succeeding shifts to determine if the penetration changed from day to day.

Total Penetration

The results of the total penetration tests for operating modes 1 to 3 above are presented in Table 6. Statistical test results concerning the effect of high and low inlet concentrations, one and two passes, and time within the day between cleanings are presented in Table 7.

The results were as follows:

> Inlet concentration - Concentrations in the range of 6 - 24 mg/m^3 had no significant effect on penetration.
>
> Number of passes - Two-pass operation resulted in significantly less penetration than a one-pass operation. The average two-pass penetration was 8.57 percent, approximately 1/2 the average one-pass penetration of 19.71 percent. This decrease can be attributed to further ionization and collection of particles in the second pass.

Time Between Vibratory Cleanings--
During the period of operation just after cleaning (first period), penetration was higher and more variable than it was later in the cycle, as evidenced by a significant difference in variances and average penetrations. This could have been due to re-entrainment of small amounts of particulate material that had settled out on the internal surfaces of the precipitator during cleaning. A "puff" of particulate material was visually observed in the exhaust immediately following startup after vibratory cleaning.

Fractional Penetration

The results of the particle sizing tests performed on the inlet and air exhausted from the ESP are presented in Table 8. From this data, fractional penetrations were calculated and are plotted in Figure 14. These results indicate that fractional penetration increased as aerodynamic diameter increased above one micrometer for both one and two pass operation. The minimum penetration occurred between 0.4 and 0.8 micrometer diameter.

Table 6. Electrostatic Precipitator total penetration test results.

Operating mode	No. of tests performed	Average inlet concentration, mg/m^3	Average outlet concentration, mg/m^3	Average penetration*, %	Standard deviation, %	CV**, %
Two-pass, high inlet concentration	9	23.34	2.05	8.57	1.60	18.7
Two-pass, low inlet concentration	25	6.12	0.54	9.03	4.67	51.7
One-pass medium concentration	8	15.11	2.96	19.71	2.84	14.4
Two-pass combined averages of low and high concentration operation						
Beginning of the shift (1)	10	9.48	0.96	11.53	6.5	56.4
Middle of the shift (2)	14	10.24	0.83	8.08	1.48	18.3
End of the shift (3)	10	12.51	1.06	7.46	2.05	27.5

* Based on calculations made for individual tests.

**CV is defined as the mean divided by the standard deviation multiplied by 100 percent and is a measure of the relative magnitude of the variation among measurements.

Table 7. Electrostatic Precipitator statistical test results.

Variable effect tested	F test on variance	F test critical value*, $\alpha = 0.10$	Conclusion concerning variance	t test on mean penetration	t test critical value*, $\alpha = 0.10$	Conclusion concerning mean penetration
Effect of high and low inlet concentration on 2 pass operation.	8.50	$F_{24,8} = 3.12$	Variances are not equal.	0.43	$t_{30} = 1.70$	No significant difference in penetration with high and low inlet concentrations.
Effect of one vs. two pass operation.	3.14	$F_{7,8} = 3.50$	Variances are equal.	9.78	$t_{11} = 1.80$	Two pass operation significantly reduces penetration.
Between the beginning and middle of the shift (1 - 2).	19.16	$F_{9,13} = 2.71$	Variances are not equal.	1.65	$t_{10} = 1.81$	No significant difference in penetration between the first and middle period.
Between the beginning and end of the shift (1 - 3).	9.98	$F_{9,13} = 2.71$	Variances are not equal.	1.91	$t_{10} = 1.81$	Last period penetration is significantly lower than the first period.
Between the middle and end of the shift (2 - 3).	1.91	$F_{9,13} = 2.71$	Variances are equal.	0.81	$t_{16} = 1.75$	No significant difference in penetration between middle and last period.

*Upper tail values used ($\alpha/2$).

Table 8. Electrostatic Precipitator particle sizing results.

Test	Sample location	Operating mode 1 - single pass 2 - double pass	Mass median diameter, µm (D_{p50})	Geometric standard deviation, (D_{p84}/D_{p50})
1	Inlet		0.60	2.17
2	Inlet		0.64	2.34
3	Inlet		0.66	2.20
4	Outlet	2	1.0	2.60
5	Outlet	2	0.82	2.68
6	Outlet	2	0.74	2.30
7	Outlet	1	0.64	2.34

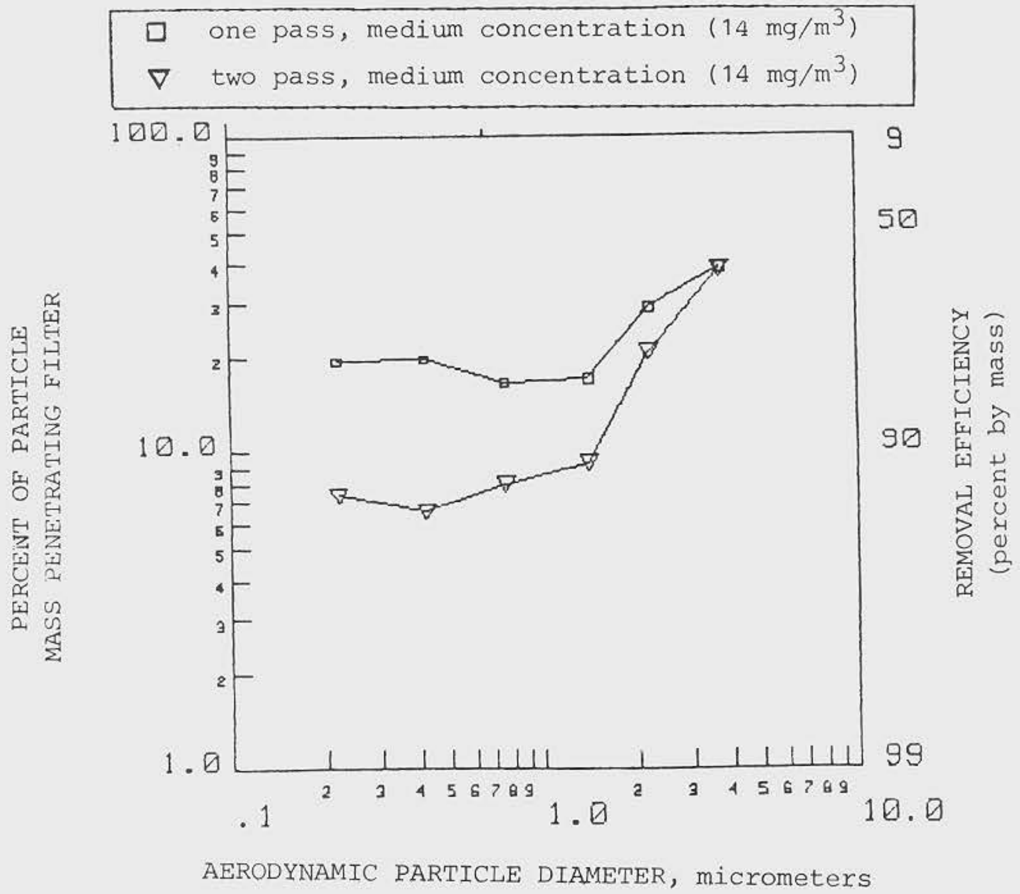


Figure 14. Electrostatic Precipitator fractional penetration.

The inlet particle size data was consistent (Table 8), indicating minimal variation in the mass median and geometric standard deviations. Exhaust air particle size distribution exhibited a slightly larger mass median diameter than the inlet with similar geometric standard deviations, indicating that the ESP is apparently less efficient at removing larger sized particles. This conclusion contradicts accepted theory which predicts decreased penetration with increased particle size. There are, however, other factors besides ESP performance in various particle size ranges which could have affected this result, such as:

1. Particle agglomeration within and downstream of the ESP resulting from particle attraction after charging (5).

2. Re-entrainment of large, agglomerated particles from the collection plates and other internal surfaces.

Equilibrium

The ESP does not depend on the presence of a filter cake for equilibrium penetration to be reached; therefore, steady state operation occurs immediately. However, during the test program it was found that, under high inlet particulate concentration, the average penetration increased and became erratic after four, 8-hour shifts. Repeated vibratory cleaning did not correct the problem, however, steam cleaning the ionizers and collection plates did restore normal operation. When operating with a low aerosol concentration, air was cleaned for 20 8-hour shifts without any deterioration in performance occurring.

Failure Modes

Five failure modes were identified, all of which could disrupt the proper operation of the ESP, resulting in a breakthrough. These are summarized in Table 9. Three failures were actually experienced during the evaluation which caused a partial breakthrough. These were fouling of the ionizer and collection plates, which could not be corrected by vibrational cleaning, and shorting of the collection plates, which were bent during cleaning.

Failure Description--

The failure caused by fouled ionizer and collection plates was characterized by:

1. An increase in the average penetration.
2. Erratic variations in penetration, as reflected in the larger standard deviations.

Figure 15, a plot of penetration versus operating time after steam cleaning, clearly shows the failure occurring after three 8-hour shifts of operation with a high inlet aerosol concentration (23 mg/m^3).

A similar set of tests was performed under identical conditions, except using a lower inlet aerosol concentration (6.12 mg/m^3). With this loading 20 shifts of operation were completed without any deterioration in performance.

Table 9. Electrostatic Precipitator failure analysis.

Failure mode	Effect upon ESP					Effect upon recirculation system		Possible causes	Expected frequency	Was this failure encountered during the evaluation?
	Ionizer voltage	Ionizer current	Plate voltage	Plate current	Sparking rate	Velocity pressure	Outlet concentration			
Breakthrough	↓	↓	NE	NE	NE	NE	$\underline{\uparrow}$	Fouled ionizer.	Dependent upon aerosol concentration, could range from a few days to one month.	Yes
	NE	NE	↓	↑	NE	NE	$\underline{\uparrow}$	Fouled collection plate.	Dependent upon aerosol concentration, could range from a few days to one month.	Yes
	↓	↑	NE	NE	↑	NE	$\underline{\uparrow}$	Shorted ionizer.	Could happen at any time, if a fragment caused an ionizer wire to break - unexpected.	No
	NE	NE	↓	↑	↑	NE	$\underline{\uparrow}$	Shorted plate.	Caused by precipitated material bridging or by a plate being bent during manual cleaning.	Yes
	0	0	0	0	0	NE	$\underline{\uparrow}$	High voltage power supply not operating due to component failure.	Unexpected component failure.	No

↓ ↑ - arrows indicate direction of relative deviation from steady state.
— - denotes failure effect of primary concern.
NE - no effect.
0 - becomes zero.

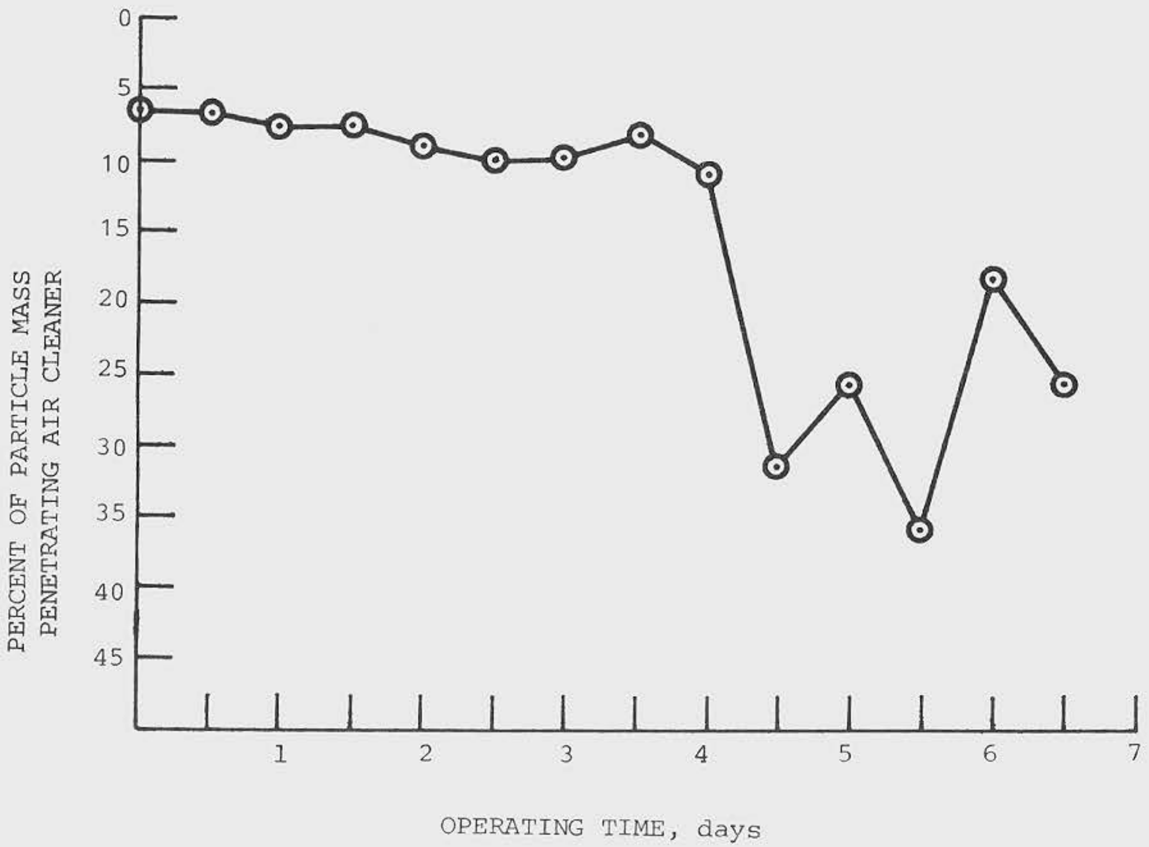


Figure 15. Electrostatic Precipitator operation preceding and during a breakthrough failure (high inlet concentration, 23 mg/m^3).

Failure Detection--Prior to and during this failure, plate and ionizer voltage and current measurements were made to determine if these measurements could be used to provide a warning of this failure. To make these measurements, the ionizer had to be isolated from the ESP housing with plastic insulating material. A schematic diagram of the measurement arrangement is shown in Figure 16. The results of these measurements (Table 10) indicate that increases in penetration are reflected by decreases in plate voltage and ionizer voltage and current. These measurements would be helpful in diagnosing a failure but, because slight changes in voltage and current can cause large variations in penetration, other monitoring methods such as extractive aerosol monitoring are required to insure positive warning of a failure condition.

Table 10. Electrostatic Precipitator ionizer and collection plate voltage and current measurements during normal and failure operation.*

Operating mode	Penetration, %	Plate voltage, volts	Ionizer voltage, volts	Ionizer current, ma
Normal	15.0	4,400	9,400	2.00
Normal	17.9	4,400	9,400	1.92
Normal	19.2	4,400	9,400	1.85
Normal	19.4	4,500	9,400	2.03
Normal	22.7	4,400	9,200	1.85
Failure	33.9	3,800	8,800	1.51

*Operating conditions: Single pass, inlet aerosol concentration = 15 mg/m^3.

Corrective Measures--
Steam cleaning the ionizers and collection plates corrected the failure and restored the penetration to normal limits. This was done by manually removing the components from the housing and cleaning them with high pressure steam. To determine the effect of cleaning each component, the single pass precipitator was operated until a failure condition was encountered and then just the ionizers were steam cleaned. Finally, both ionizers and plates were cleaned. Table 11 presents the results of this investigation.

From this data, it can be seen that steam cleaning both of the ionizers and collector plates provided the best reduction in penetration, although steam cleaning only the ionizers provided almost the same amount of reduction. It appears that vibratory cleaning is effective for cleaning the

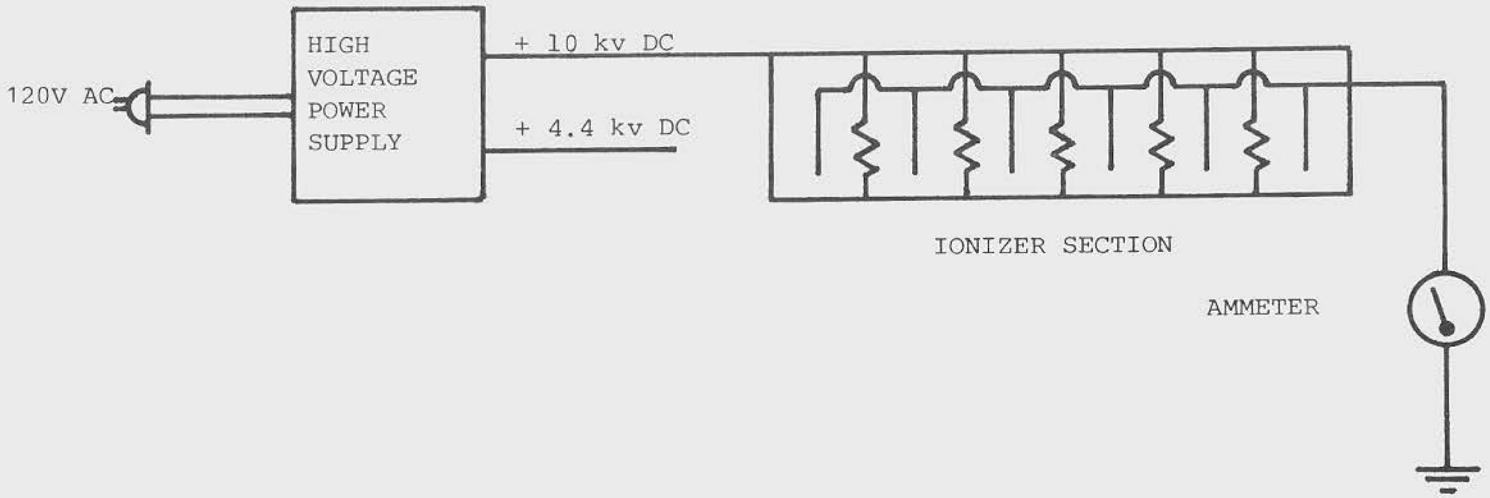


Figure 16. Schematic diagram of Electrostatic Precipitator ionizer current measurement arrangement.

plates but the ionizer section requires steam cleaning to remove the material buildup.

Table 11. Effect of steam cleaning on total penetration for the Electrostatic Precipitator.

Condition	Average total penetration*, %	Number of tests	Standard deviation, %	CV**, %
Normal operation	21.10	5	2.20	10.4
Failure condition	48.30	3	22.30	46.2
After failure, ionizers steam cleaned only	24.70	3	1.50	6.1
After failure, both ionizers and plates steam cleaned	19.20	3	0.72	3.8

* One pass operation, inlet aerosol concentration = 15 mg/m^3.

** See Table 6.

Maintenance

Prior to installing, the ESP's maintenance requirements should be evaluated thoroughly. The ESP performance, being dependent upon frequent routine manual maintenance (steam cleaning), introduces uncertainty into the reliability of the system and added operating costs. An assessment of the potential impact of this aspect should include consideration of the following:

1. Aerosol concentration of the air being cleaned - higher aerosol concentrations will require more frequent steam cleaning.

2. The toxicity of the contaminant - this could effect the needed reliability which would also effect the sophistication of the monitoring/warning system employed. The toxicity may also effect the cleaning and disposal method.

3. The location of the ESP - additional manpower may be required to manually clean the components if the ESP is not easily accessible.

New Potential Hazards

The ESP does not introduce any new potential hazards that would prevent it from being employed in a recirculating ventilation system. The ozone generation rate was determined for both single and double pass operation. The results are presented in Table 12. From this data, it does not appear that ozone generation would present a significant hazard. Other potential hazards that could be present depending on the properties of the contaminant being removed include:

1. Fire or explosion hazard from sparking.
2. Overexposure of maintenance personnel during cleaning and disposal of the precipitate.

Table 12. Electrostatic Precipitator ozone generation data.

Operating mode	Average inlet concentration, ppm	Average outlet concentration, ppm	Average emission rate, mg/min	
			Process	ESP
Two pass No welding	ND*	0.006	0	0.666
One pass No welding	ND	0.003	0	0.333
Two pass Three welders (E 7018 1/4" chemtron rod)	0.001	0.007	0.111	0.666

* - Not detected.

ELECTROSTATICALLY AUGMENTED FABRIC FILTER (EAFF)

PRINCIPLE OF OPERATION

The EAFF combines both electrostatic and conventional (bag type) fabric filtration into a single air cleaner. Electrostatic preconditioning of the incoming particulate laden gas stream is accomplished by directing the air flow through a tubular-type high voltage electrostatic precipitator.

Charging particles prior to filtering them has two effects:

1. Some particles are collected on the tubular walls of the precipitator.
2. The remaining particles are deposited on the fabric in a more loosely packed structure than would occur without the electrostatic preconditioning.

These effects allow high filter velocities to be used because the aerosol concentration seen by the fabric portion of the air cleaner is lower and the filter cake is more permeable. This reduces the physical size of the air cleaner and lowers the differential pressure across the fabric.

DESCRIPTION OF TEST DEVICE

The unit tested consisted of four tubular type electrostatic precipitator sections preceding eight felt-type filter bags. Manufacturer's specifications are presented in Table 13. A photograph of the unit installed for testing appears in Figure 17.

High voltage electrical power was supplied by an external power supply shown in Figure 18. Built-in meters provided a direct reading of ionizer voltage and current draw.

CLEANING CYCLE

A schematic diagram depicting the flow of air through a single filtering unit during normal operation and during the cleaning cycle is presented in Figure 19. During normal operation, air enters the precipitator tube from the bottom (Diagram A, Figure 19). As the air passes up through the precipitator tube, particles are charged by the ionizer wire located in the center of the tube. A portion of these particles are deposited on the precipitator walls. After it leaves the precipitator section of the tube, the air continues upward through the fabric bags where filtration occurs. Clean air exits the unit through an exhaust located at the top of the metal enclosure.

Table 13. Manufacturer specifications for the Electrostatically Augmented Fabric Filter.

Number of tube/ionizer wires:	4
Number of filter bags:	8
Filter bag specifications:	
Type:	Felt
Size:	20.32 cm dia. (8 in.) 2.44 m long (8 ft)
Area:	8.18 m^2 (88 ft^2)
Material:	Polyester
Construction:	
Baghouse:	12 ga
Precipitator section	
Walls:	12 ga
Tubes:	10 ga
Channel sections:	12 ga
Corona wires:	0.114 cm (0.045 in.)
Insulators:	Ceramic
Hopper:	12 ga
Weight:	682 kg (1500 lb)
Power supply:	Variable 20 - 35 kv, 50 ma

Collected particles are removed from the precipitator tubes and filter bags at pre-determined and set intervals. Upward (forward) flow is stopped and a short (fraction of a second) downward blast of air is introduced at the top of the precipitator section (Diagram B). The force of this blast cleans the unit in two ways:

1. Particles clinging to the wall in the precipitator tubes are removed by the pressurized air. Material clinging to the corona wire is also blown off.

2. The downward, primary blast of air induces a secondary air current through the filter bags. This reversal of air flow through the filter media causes the fabric to collapse in an inward direction, thus dislodging the filtered particles.

Particles dislodged by both of the above mechanisms fall freely into a collection hopper below (Diagram C). After the cleaning cycle the air cleaning process resumes (Diagram D).

TEST CONDITIONS AND EXPERIMENTAL VARIABLES

During the evaluation of the EAFF, two filter velocities were tested to determine the effect of velocity on penetration. Low velocity tests were conducted at 2.0 m/min (6.5 ft/min) and high velocity tests were conducted at 3.1 m/min (10 ft/min). These velocities represent the

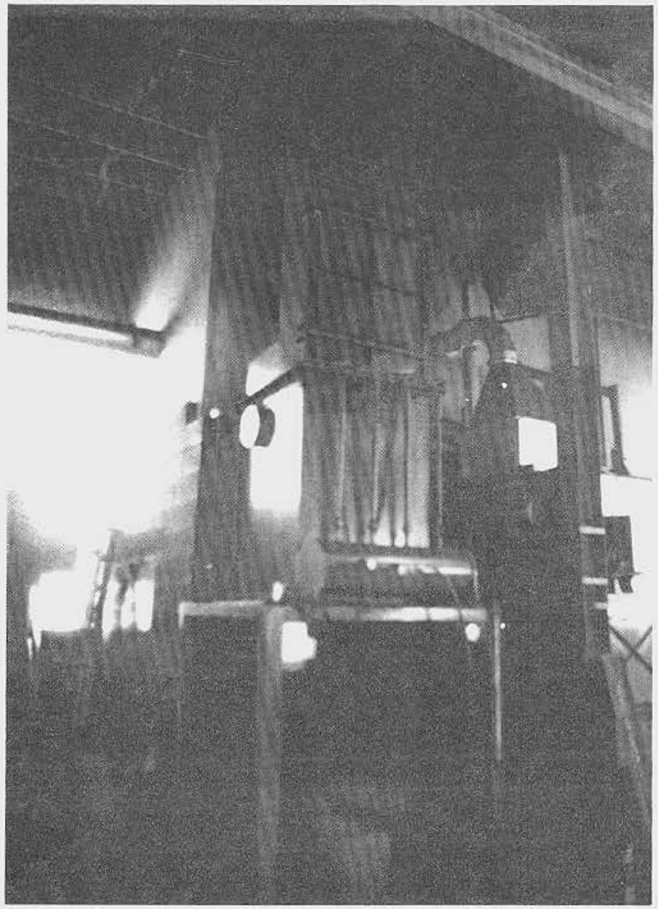


Figure 17. Photograph of the Electrostatically Augmented Fabric Filter installed for testing.

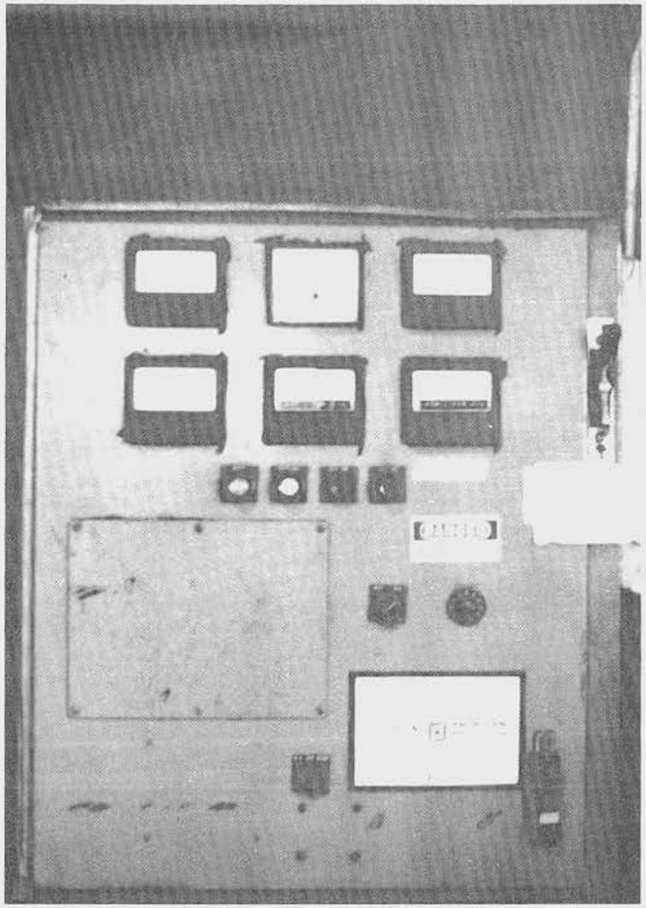


Figure 18. Photograph of high voltage power supply.

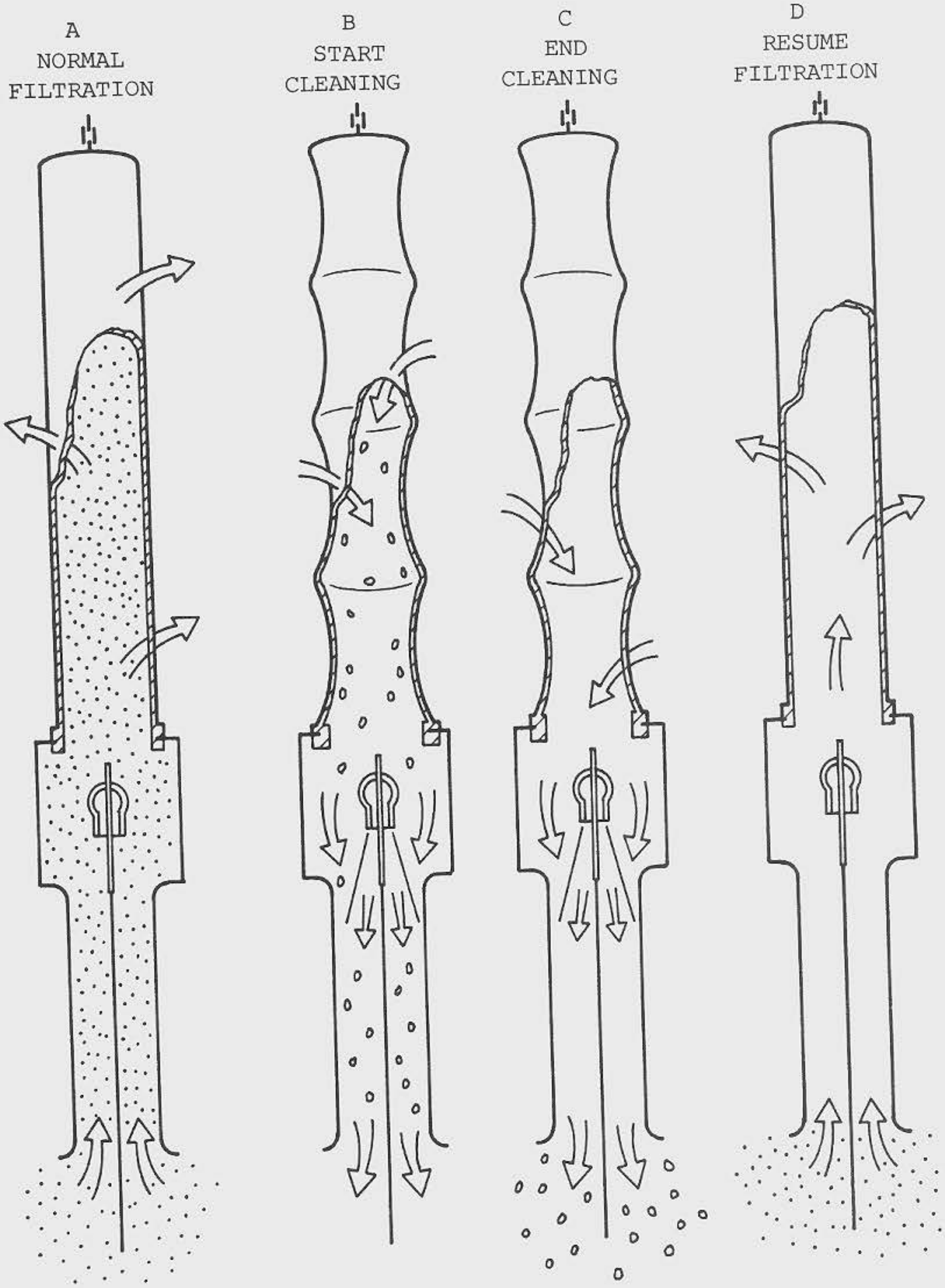


Figure 19. Electrostatically Augmented Fabric Filter operating and cleaning sequence.

normal and maximum values recommended by the manufacturer for welding fume filtration. In addition, the air cleaner was operated with and without high voltage (31 - 32 KVDC, 4.5 ma) applied to the precipitator section to determine its effect on filtration. Excessive pressure drop across the filter prevented testing at the high filter velocity without electrostatic augmentation. Testing of the above variables, therefore, resulted in three different operating modes:

1. High filter velocity with electrostatic augmentation.
2. Low filter velocity with electrostatic augmentation.
3. Low filter velocity without electrostatic augmentation.

Penetration tests were not initiated until the unit reached equilibrium differential pressure, which required 50 days of operation. In similar fashion, when operating modes were changed, tests were delayed until the system returned to equilibrium. Inlet air stream particulate concentrations ranged from 10 - 20 mg/m^3 throughout the testing period. The timer was set to clean the air cleaner every eight hours; penetration tests were conducted within these eight hours.

CONTAMINANT PENETRATION

Six tests were performed under each of the three operating modes to determine the average penetration as well as differential pressure drop across the air cleaner. The results of these tests, tabulated in terms of averages for each operating mode, are presented in Table 14. Total penetration ranged from 0.302 - 0.956 percent and averaged 0.444 percent with electrostatic augmentation and 0.956 percent without*. A summary of the statistical test results is presented in Table 15.

Effect of Electrostatic Augmentation--

As can be seen from Table 14, the use of electrostatic augmentation was effective in reducing both the total penetration and the differential pressure across the filter. A summary of the statistical test results is presented in Table 15.

Effect of Filtering Velocity--

Lower filtration velocity resulted in a slight but statistically significant reduction in total penetration from 0.585 to 0.302 percent with electrostatic augmentation. As expected, the lower velocity had an associated lower differential pressure across the air cleaner.

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*Tests made without electrostatic augmentation were characterized by a high standard deviation (0.742 percent).

Table 14. Electrostatically Augmented Fabric Filter total penetration test results.

Operating mode		No. of tests performed	Average inlet concentration, mg/m^3	Average outlet concentration, mg/m^3	Average differential pressure, cm, wg	Average penetration*, %	Std. dev. penetration, %	CV**, no.
Filter Velocity	Electrostatic augmentation							
Low	Yes	6	12.324	0.037	10.0	0.302	0.183	60.5
High	Yes	6	10.953	0.064	14.1	0.585	0.207	35.4
Low	No	6	12.573	0.113	16.5	0.956	0.742	77.6

* Based on calculations made for individual tests.

** Coefficient of variation, see Table 6.

Table 15. Electrostatically Augmented Fabric Filter statistical test results.

Variable effect tested	F test on variances	F test critical value**, $\alpha = 0.10$	Conclusion concerning variances	t test on mean penetrations	t test critical value**, $\alpha = 0.10$	Conclusion concerning total penetration
Filter velocity (with electrostatic augmentation).	1.29	$F_{5,5} = 5.05$	Variances are equal.	2.51	$t_{10} = 1.81$	Lower filter velocity results in lower penetration with electrostatic augmentation.
Electrostatic augmentation (low filter velocity).	16.68	$F_{5,5} = 5.05$	Variances are not equal.	2.09	$t_6 = 1.94$	Electrostatic augmentation results in lower penetration under similar filter velocities.

**Upper tail values used ($\alpha/2$).

Fractional Penetration

Fractional penetration, calculated for each of the operational modes tested, is plotted in Figure 20. It was found that electrostatic augmentation of the fabric filter moderated variations in penetration throughout the particle size ranges tested. In addition, it was also determined that changes in filter velocity had minimal effect upon fractional penetration. Throughout the aerodynamic particle size range of 0.22 to 7.2 micrometers the penetration was 1.5 percent or less for all tests conducted.

Generally, in all three operating modes, the penetration increased with decreasing aerodynamic particle diameter. However, electrostatic augmentation decreased the penetration of particles less than 2 micrometers in diameter and increased the penetration above 2 micrometers. This was probably due to agglomeration of the fume particles in the electrostatic portion of the air cleaner resulting in the fabric filter section being exposed to a higher number of particles greater than and a lower number of particles less than 2 micrometers in diameter than were contained in the inlet air stream. A similar effect was also observed on the electrostatic precipitator (see Figure 14).

Calculations of mass median diameter are presented in Table 16 for the air cleaner inlet particle size distribution and the air cleaner outlet particle size distribution for the various operating modes. As expected, the mass median diameter was always smaller at the outlet than at the inlet of the air cleaner, indicating that the air cleaner removes larger particles more efficiently than smaller ones.

Table 16. Electrostatically Augmented Fabric Filter aerodynamic particle size distribution results.

Sample location	Operating mode		Mass median diameter (D_{p50}), micrometers	Geometric standard deviation, (D_{p84}/D_{p50})
	Velocity	Electrostatic augmentation		
Inlet			0.35	4.29
Outlet	Low	Yes	0.20	3.75
Outlet	High	Yes	0.15	4.00
Outlet	Low	No	0.22	2.82

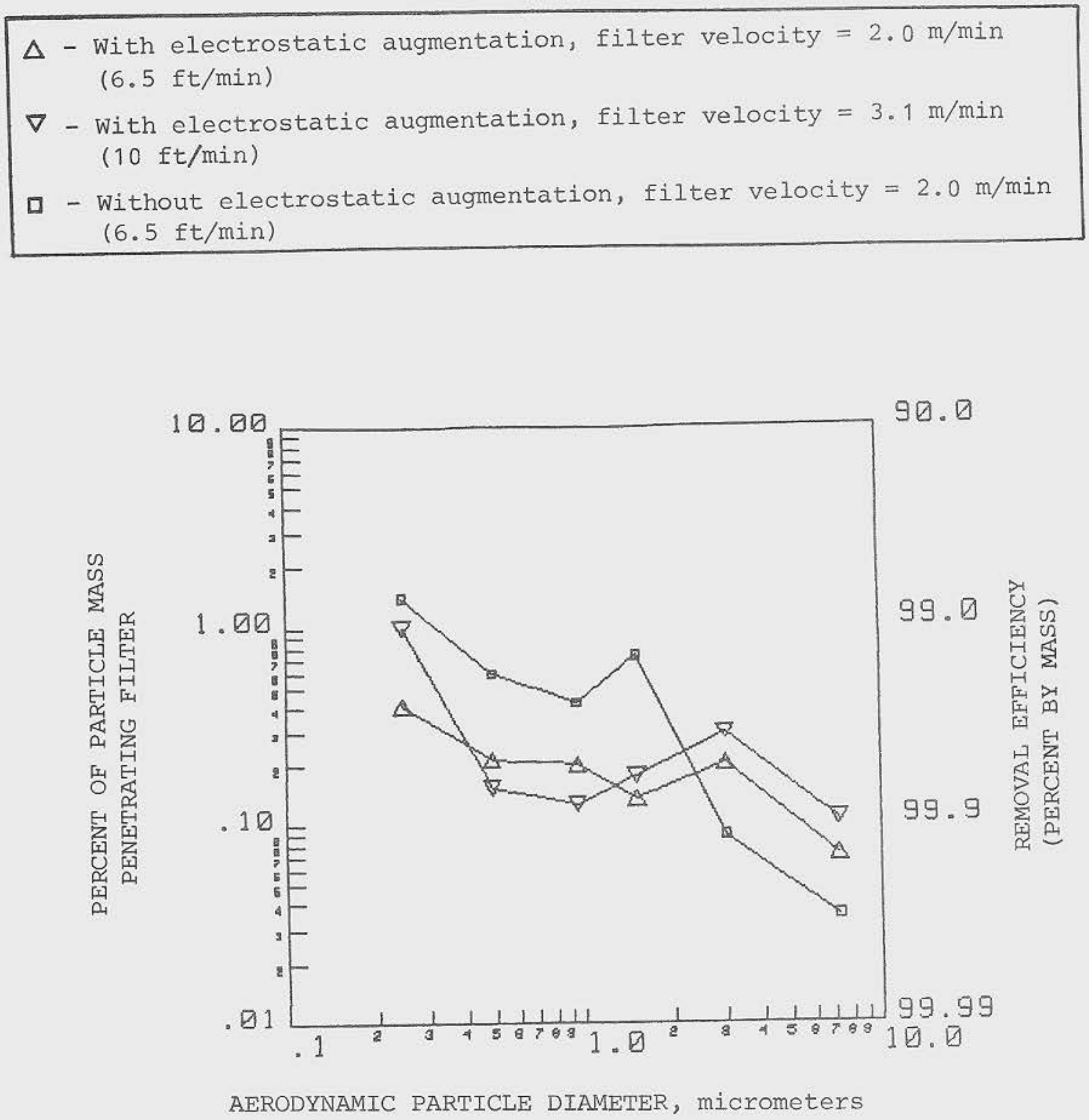


Figure 20. Electrostatically Augmented Fabric Filter fractional penetration.

Equilibrium

Starting with new polyester bags, penetration approached equilibrium values very shortly after startup, even though it took 50 days for the differential pressure to reach steady state. After operating for only a day the penetration was measured at 0.880 percent, a value which approached within one-half percent of the average penetration (0.302) after the differential pressure reached steady state.

The measured progression of differential pressure increase after startup with new filter media is shown in Figure 21 for the first 90 days of operation at the lower velocity and with electrostatic augmentation. It can be seen that the rate of differential pressure rise was greatest during the first 50 days during which it rose to 4.6 cm wg (1.8 in. wg). It then slowed to a very low rate of rise after 50 days, rising only another 0.5 cm wg (0.2 in. wg) in the next 40 days. Precoating of bags, which can result in lower equilibrium differential pressure and extended filter bag life, could have been used to quicken the rise in differential pressure.

Failure Modes

Three types of failures are possible with the EAFF air cleaner: blinding, breakthrough, and the creation of a new potential hazard, ozone. A summary of the possible failures identified, the expected frequency of occurrence, and the effects of these failures on the recirculation system is presented in Table 17.

Of most concern was the increased ozone generation rate which occurred after the EAFF was operated for several months. Ozone generation rates increased from 1.56 mg/min at startup to rates ranging from 18 to 26 mg/min after three months operation. The results of these measurements are presented in Table 18, and ozone concentration as a function of voltage is shown in Figure 22.

Also associated with the increased ozone production was an increase in ionizer current from 4.5 ma to approximately 5 ma. Visual inspection of the ionizer wires revealed a large buildup of welding fume particulate on the surface, producing a rough surface. It is well documented in the literature that ozone production by an ionizer increases as the surface becomes more irregular (7). Therefore, the increased ozone production rate was attributed to the fume fouling of the ionizer wires, and was confirmed by reduced ozone production rates after a partial cleaning of the wires. However, examination of a fouled wire after cleaning revealed large pits on the surface which would probably result in continued elevated ozone production rates. Therefore, periodic replacement of the ionizer wires may also be necessary to reduce the ozone production rate to acceptable levels.

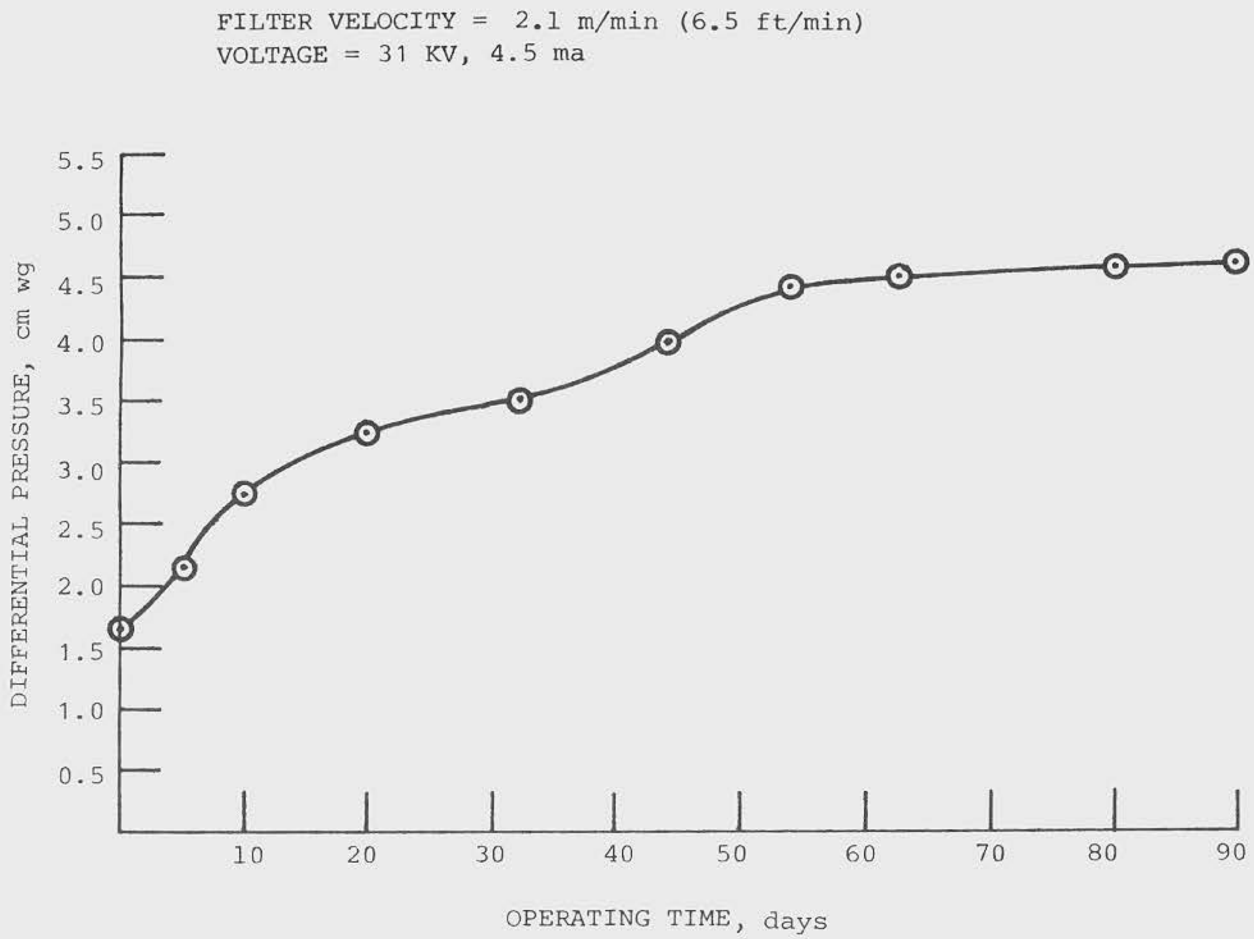


Figure 21. Electrostatically Augmented Fabric Filter differential pressure after cleaning cycle vs. operating time in days.

Table 17. Electrostatically Augmented Fabric Filter failure analysis.

Failure mode	Effect upon recirculation system						Possible causes	Expected frequency	Was the failure encountered during the evaluation?
	Collector Δ P	Velocity pressure	Workplace aerosol concentration	Exhaust aerosol concentration	Hood collection efficiency	Workplace ozone concentration			
Blinding	↑	↓	$\underline{\uparrow}$	↓	$\underline{\downarrow}$	NE	1. Penetration of small particles into cloth.	Gradual process expected to occur over a long period of time when small particles are filtered.	No
							2. Electrostatic malfunction.	Unexpected component failure that would probably occur instantaneously.	No
							3. Cleaning mechanism malfunction.	Unexpected component or compressed air failure.	No
Breakthrough	↓	↑	$\underline{\uparrow}$	$\underline{\uparrow}$	↑	NE	1. Bag tear or wearing hole into bag.	Primarily dependent upon the abrasiveness of the collected aerosol.	No
							2. Thimble seal failure.	Most likely to occur at startup, but could occur at any time due to an unexpected component failure.	No
							3. Gasket leak between clean and dirty air compartments.	Most likely to occur at startup but could occur at any time due to an unexpected component failure.	No
Excessive ozone generation	NE	NE	NE	NE	NE	$\underline{\uparrow}$	Fume fouling of wire electrode surfaces.	Could occur as often as every several weeks of operation.	Yes

↑ ↓ - Arrows indicate direction of relative deviation from steady state.

_ - Denotes failure effect(s) of primary concern.

NE - No effect.

Table 18. Electrostatically Augmented Fabric Filter ozone emission rates.

Temperature = 70°F
Pressure = 760 mm Hg

Operating condition	Inlet ozone concentration, ppm	Ozone concentration immediately downstream of EAFF, ppm	Air flow rate, m^3/min	Ozone emission rate, mg/min
Clean ionizers (at startup)	<0.001	0.050	15.58	1.56
Dirty ionizers (after 3 months operation)	<0.002	0.60-0.85	15.58	18.68-26.49

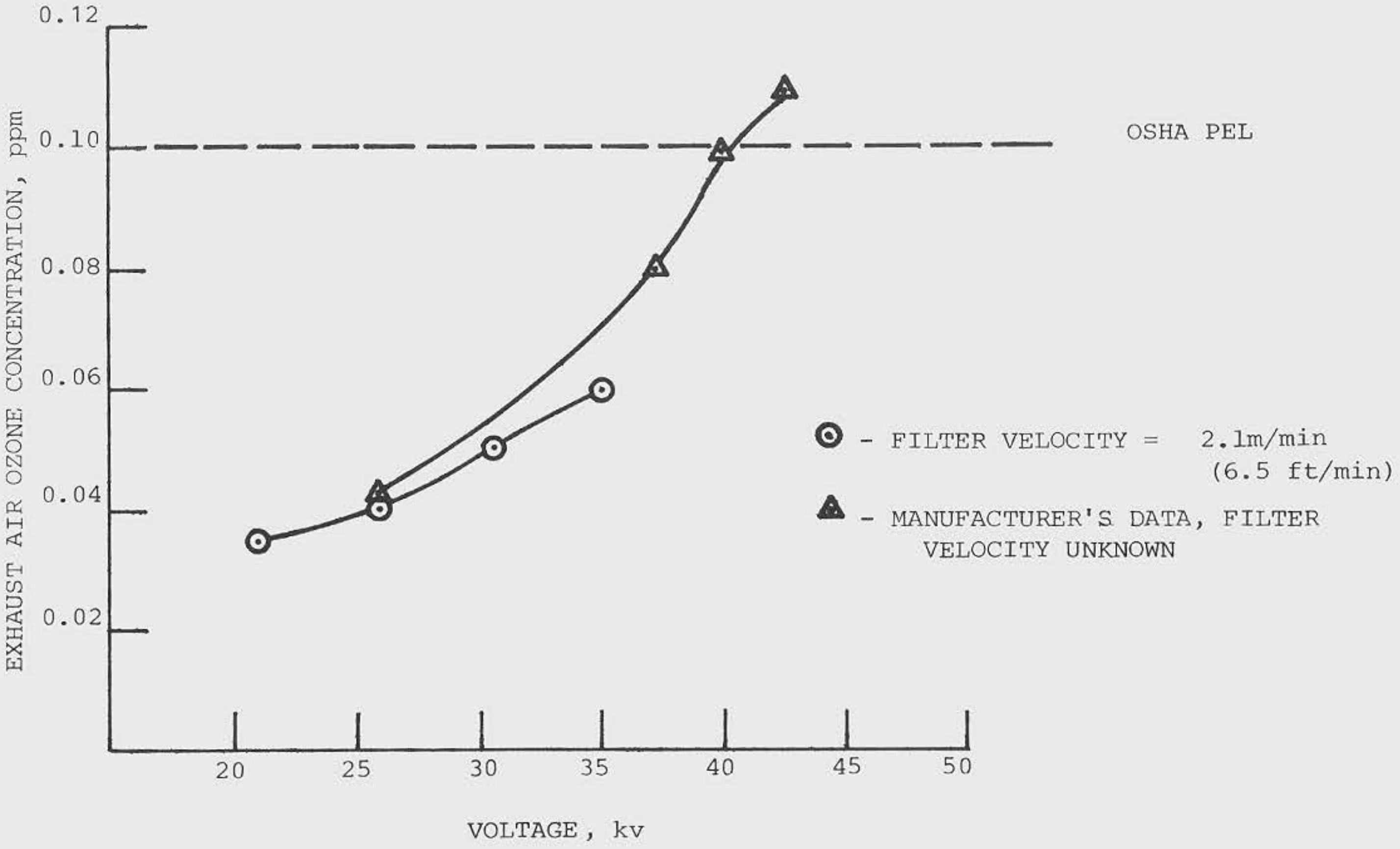


Figure 22. Electrostatically Augmented Fabric Filter outlet gas stream ozone concentration vs. voltage - positive corona (no welding) at startup, with new ionizers.

If the increased ozone generation rate was determined to create a hazard in the workplace, a more viable solution such as installation of an activated charcoal afterfilter or the addition of makeup air could be investigated.

Another factor effecting ozone concentration in the EAFF exhaust air was the presence of welding fume in the inlet air. As shown in Figure 23, welding fume reduced the ozone concentrations, probably by destroying the ozone generated by the electrostatic section on the EAFF.

Failure Detection--

Blinding failures produce a large increase in the collector differential pressure (ΔP) and could easily be detected with a differential pressure monitor. Breakthrough, on the other hand, may result in only a small decrease in differential pressure and would most easily be detected by increases in exhaust air aerosol concentration with an aerosol monitor. Excessive ozone generation was reflected by a small increase in the average ionizer current, but positive identification would probably require in-duct or workplace ozone measurements.

Maintenance

If the ozone generation rate caused a hazard in the workplace, some maintenance tasks may be required as part of the engineering solution, such as replacement of activated charcoal afterfilter elements and/or ionizer wire cleaning and replacement. The frequency and relative difficulty of these tasks would have to be evaluated for each specific system.

Other routine maintenance tasks would include filter bag replacement and emptying the collection hopper. Each of the tasks would require maintenance personnel to come into direct contact with the collected particulate air contaminant. Care would have to be taken to insure that overexposure did not result from execution of these tasks.

New Potential Hazards

Whether or not ozone, produced by the EAFF, will present a workplace hazard is dependent upon the ozone concentration found in the workplace during recirculation. Ozone is a reactive gas and therefore undergoes decay after being produced. Depending upon parameters specific to each recirculating exhaust system, such as length of the return air plenum, general ventilation, and the proximity of the worker to the return air distribution plenum, the natural decay rate may or may not be sufficient to eliminate any hazard. Other potential hazards which could also be introduced by the EAFF include:

1. If combustible contaminants are collected, sparking within the electrostatic section could present a fire or explosion hazard.
2. Depending on the contaminant removal and disposal methods employed, overexposure of maintenance personnel could occur.

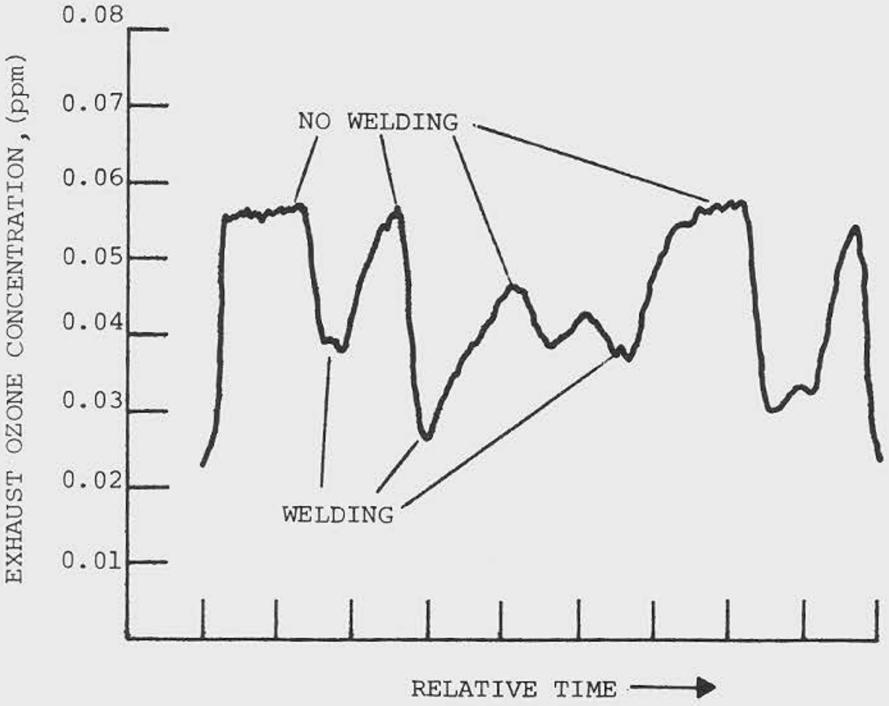


Figure 23. Electrostatically Augmented Fabric Filter - exhaust ozone concentration vs. welding/no welding time periods.

ASPIRATED CARTRIDGE FILTER (ACF)

PRINCIPLE OF OPERATION

The ACF is a fabric filtration device employing pleated filter cartridges for increasing the amount of filtration capacity in a small volume. This feature allows an air cleaner of a relatively small size to be operated at a low filter velocity. Lower filter velocity operation improves air cleaner performance by 1) lowering penetration and, 2) reducing differential pressure resulting in lower operating energy requirements.

The cartridge design also makes filter replacement faster and easier because maintenance personnel are not required to enter the air cleaner housing. It also reduces the likelihood of improper installation of the filters which could result in leaks.

TEST DEVICE DESCRIPTION

The unit tested consisted of six filter elements, each containing 18.6 m^2 (200 ft^2) of fabric area, providing a total filtering area of 111.6 m^2 (1200 ft^2). A photograph of the test unit installed at the testing station appears in Figure 24.

A close-up photograph of a filter element (Figure 25) shows the pleated structure of the filter material. A schematic diagram showing the various components of the ACF during normal operation and cleaning appears in Figure 26.

During normal operation, particulate laden air enters the inlet plenum and is distributed to the various filter elements. This air then passes through the filter elements from the outside to the inside, and the aerosol material is removed and deposited on the external surfaces of the filter element. After passing through the filter element, the clean air moves up the eductor tube into the clean air plenum above and is exhausted.

The filter elements are cleaned without taking them off line, eliminating the need for an extra module to replace the one off line being cleaned. Cleaning is performed by sequentially backflushing each element with air from the clean air plenum induced by short bursts of compressed air directed into the eductor tube (see Figure 26). This sequence is controlled by an air pressure monitor that is adjusted to initiate cleaning whenever the differential pressure reaches some preset level. When the cleaning cycle is energized the bags are pulsed, one by one, over an approximate period of 45 seconds. Material removed from the filter elements drops into a hopper located below.

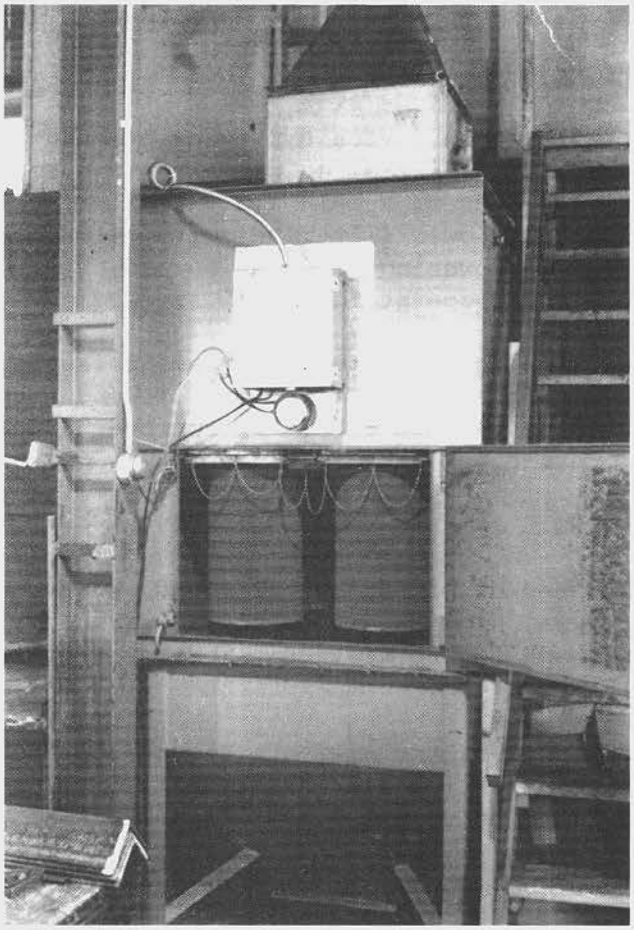


Figure 24. Photograph of the Aspirated Cartridge Filter installed for testing with the access door open showing filter cartridges.

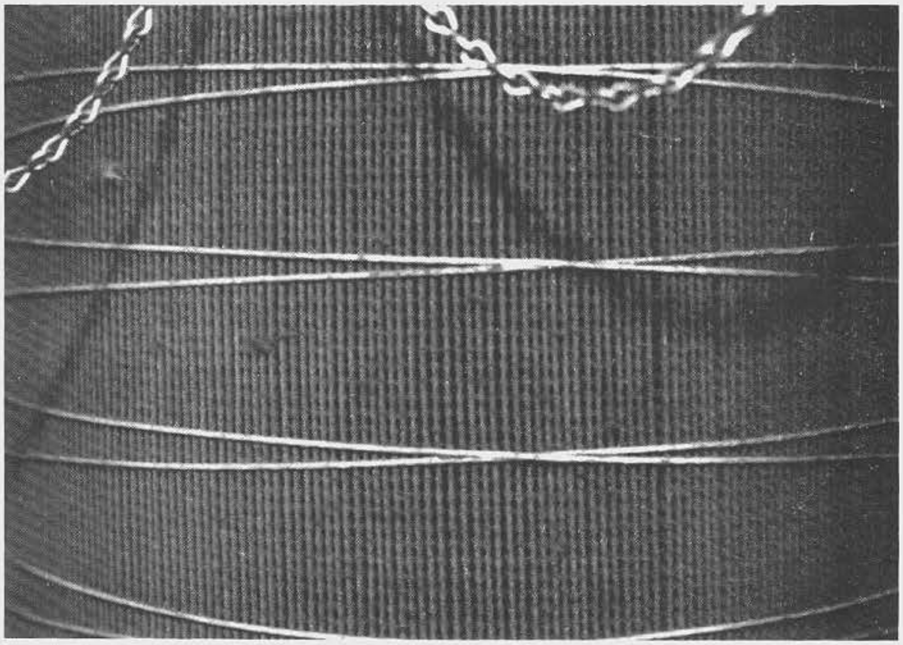


Figure 25. Close-up photograph of Aspirated Cartridge Filter element showing pleated structure.

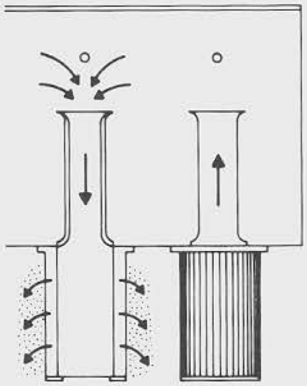


Figure 26. Schematic diagram of Aspirated Cartridge Filter

TEST CONDITIONS AND EXPERIMENTAL VARIABLES

Prior to starting the routine penetration tests, the ACF was operated until differential pressure equilibrium was reached. Equilibrium conditions were rechecked by monitoring differential pressure after any operating variable was changed. The manufacturer's recommendations were followed for setting the cleaning activation pressure. Filter elements with and without a precoat were tested. Filter elements, precoated with Arizona road dust, were supplied by the manufacturer. However, because this material could contain crystalline free silica, other, less toxic materials may be more suitable for this application.

To determine the effect of filter velocity, precoating, and the use of an afterfilter on the ACF performance, penetration tests were conducted under the following operating modes:

1. Low filter velocity [0.25 m/min (0.83 ft/min)] with no precoat on the filter elements.
2. High filter velocity [0.38 m/min (1.25 ft/min)] with no precoat on the filter elements.
3. Low filter velocity [0.25 m/min (0.83 ft/min)] with precoated filter elements.
4. High filter velocity [0.38 m/min (1.25 ft/min)] with precoated filter elements.
5. High filter velocity [0.38 m/min (1.25 ft/min)] with precoated filter elements and an afterfilter.

Other system specifications are presented in Table 19.

Table 19. Aspirated Cartridge Filter specifications.

Number of cartridges:	6
Total fabric area:	111.6 m^2 (1200 ft^2)
Weight:	3175 kg (1,440 lb)
Electrical:	110 v, 60 Hz, 1 amp (for air pressure monitor/controller circuit)
Approximate dimensions of unit tested:	
Height:	3.75 m (11.5 ft)
Width:	1.45 m (4.5 ft)
Length:	1.39m (4 ft)

CONTAMINANT PENETRATION

Total Penetration

Six tests were conducted under each of four operating modes to determine the average penetration and differential pressure for each. A total of three tests were conducted with the afterfilter placed in the air cleaner discharge. The results of these tests, tabulated in terms of averages for each operating mode, are presented in Table 20.

The average penetration varied between 0.193 percent (low filter velocity, precoated filters) and 0.545 percent (low filter velocity, no precoat on filters). The best performance, both in terms of penetration and differential pressure, was obtained with a low filter velocity with precoated filter elements.

Statistical tests performed on each data set to determine if the differences were significant are presented in Table 21.

Effect of Filter Velocity--

When filter elements without precoat were used, changing the filter velocity from 0.25 m/min (0.82 ft/min) to 0.38 m/min (1.25 ft/min) did not significantly change the average penetration, although the average differential pressure doubled. With precoated filter elements, the lower filter velocity resulted in significantly lower penetrations than at the high velocity. The differential pressure increase when going from low to high velocity was 30 percent for the precoated filters. Although significant statistically, the reduction in penetrations was only two-tenths of one percent, which represents a small reduction.

Effect of Filter Element Precoating--

Precoating the filter element with Arizona road dust was effective in reducing the differential pressure under both low and high filter velocity conditions. Precoating also reduced the penetration with a low filter velocity but had no significant effect on the high filter velocity penetration.

The initial penetrations of new, precoated filters and filters without precoat were measured several times before equilibrium differential pressure was reached. For precoated filters, the initial penetration was approximately 0.40 percent, close to the equilibrium penetration of 0.20 percent for the low filter velocity. However, for filter elements without precoat, the initial penetration was almost 5 percent and it took approximately 16 days of operation before equilibrium penetration was reached at 0.50 (Figure 27).

Effect of Adding a Fiberglass Afterfilter to the ACF Air Cleaner Discharge--

The combined penetration of the ACF and SMF was not significantly lower than for the ACF alone, but the combined differential pressure was twice that of the ACF alone. This indicates that the fiberglass afterfilter is characterized by high penetration in the size range of the particles that penetrate the ACF (for further discussion, see section on safety monitoring filter).

Table 20. Aspirated Cartridge Filter total penetration test results.

Operating mode	No. of tests performed	Average inlet concentration, mg/m^3	Average outlet concentration, mg/m^3	Average differential pressure, cm wg	Average penetration, %	Penetration standard deviation, %	CV*, %
Low filter velocity (0.25m/min; 0.82 ft/min) filter elements without precoat	6	13.562	0.074	3.1	0.545	0.241	44.4
High filter velocity (0.38m/min; 1.25 ft/min) filter elements without precoat	6	11.763	0.050	6.2	0.432	0.113	25.6
Low filter velocity (0.25m/min; 1.25 ft/min) precoated	6	26.524	0.048	1.8	0.193	0.112	57.9
High filter velocity (0.38m/min; 1.25 ft/min) precoated	6	14.433	0.059	2.5	0.399	0.131	33.3
High filter velocity (0.38m/min; 1.25 ft/min) precoated with safety monitoring filter.	3	17.717	0.046	4.3	0.240	0.214	87.5

*Coefficient of variation, see Table 6.

Table 21. Aspirated Cartridge Filter statistical test results.

Variable effect tested	F test on variance	F test critical value*, $\alpha = 0.10$	Conclusion concerning variances	t test on mean penetrations	t test critical value*, $\alpha = 0.10$	Conclusion concerning mean penetrations
Uncoated filter elements. High vs. low filter velocity.	4.62	$F_{5,5} = 5.05$	Variances are equal.	1.29	$t_{10} = 1.81$	No difference between mean penetrations.
Precoated filter elements. High vs. low filter velocity.	1.26	$F_{5,5} = 5.05$	Variances are equal.	2.91	$t_{10} = 1.81$	Precoated, low filter velocity resulted in lower mean penetration.
Low filter velocity, precoated vs. unprecoated filter elements.	4.62	$F_{5,5} = 5.05$	Variances are equal.	3.21	$t_{10} = 1.81$	Precoating reduced penetration at low filter velocities.
High filter velocity precoated vs unprecoated filter elements.	0.76	$F_{5,5} = 5.05$	Variances are equal.	0.47	$t_{10} = 1.81$	No significant difference between mean penetrations.
High filter velocity with precoated filter elements; with and without afterfilter.	2.82	$F_{2,5} = 5.79$	Variances are equal.	0.16	$t_3 = 2.35$	Afterfilter did not significantly reduce the mean penetration.

*Upper tail values used ($\alpha/2$).

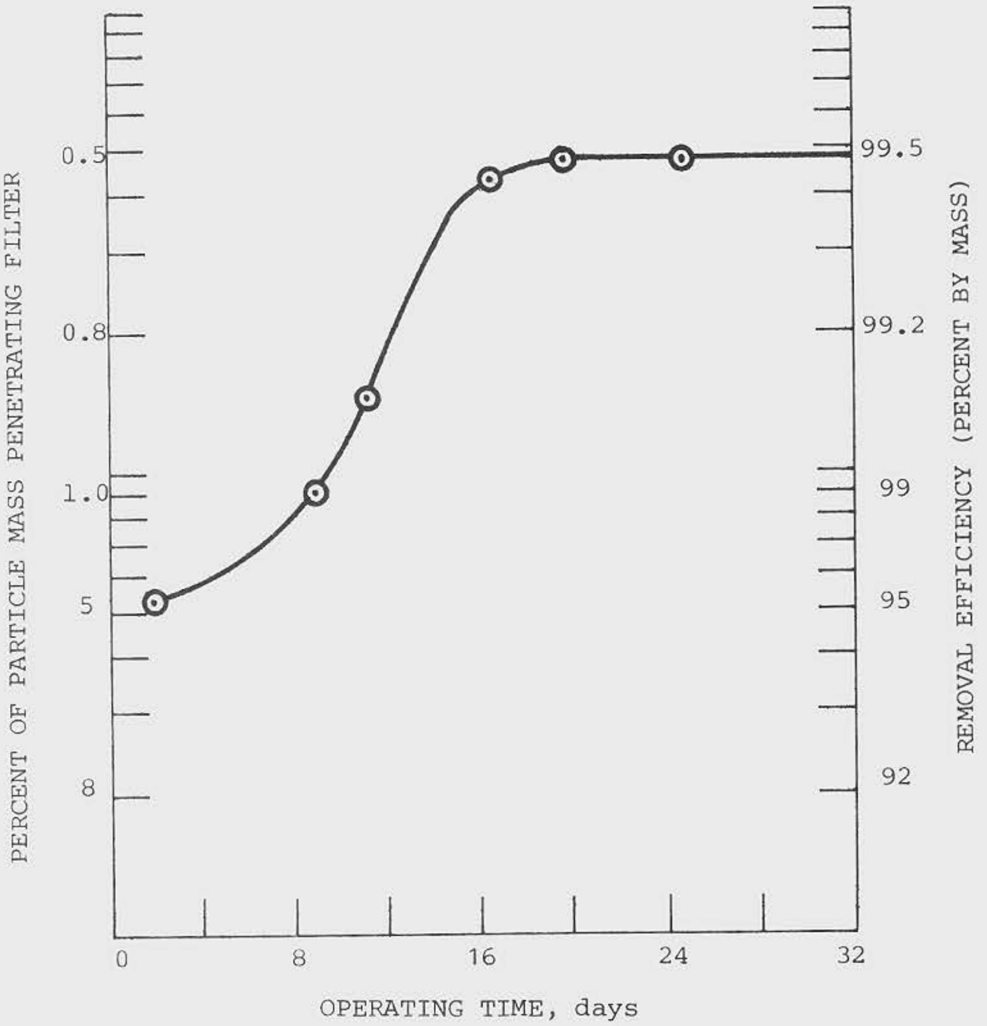


Figure 27. Aspirated Cartridge Filter penetration vs. operating time.

Total Penetration During Cleaning--

Since the ACF cleans while on line, it was of interest to determine if cleaning affected the penetration and exhaust air aerosol concentrations. This was assessed by measuring the aerosol concentration in the exhaust air on a continuous basis with a precalibrated continuous air monitor (RAM-1) before, during and after a cleaning cycle with and without the afterfilter. Plots of typical measurements appear in Figure 28. As can be seen, the aerosol concentration increased from an average of 0.07 to a maximum of 0.50 mg/m^3 during cleaning without the afterfilter and to a maximum of 0.38 mg/m^3 with the afterfilter. The average penetration during the 45 second cleaning period was greatly reduced with the afterfilter. If cleaning would occur often, say every 15 minutes or less (as may occur with a high inlet concentration), these penetration increases could significantly increase the overall, average penetration. However, in this study cleaning only occurred every 60 to 120 minutes and produced little effect on the average penetration. If frequent cleaning caused a penetration problem, an afterfilter may be required or the system may have to be changed to permit shutdown of the air cleaner (or a section of the unit in a full-scale modular system) during cleaning.

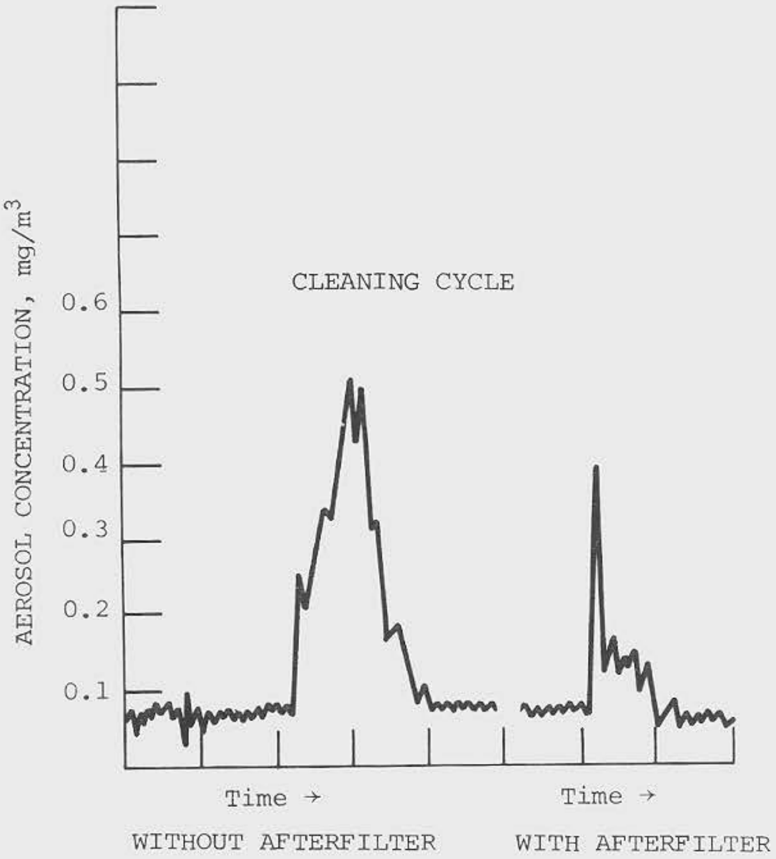


Figure 28. Aspirated Cartridge Filter - typical exhaust air aerosol concentration during cleaning cycle, with and without afterfilter.

Fractional Penetration

Results from fractional penetration tests indicate that the filtering velocities tested affected the fractional penetration only minimally, and that precoating the filter elements generally reduced penetration at all particle diameters, especially above one micrometer.

A summary of the aerodynamic particle sizing tests for both the inlet and outlet air streams for each of the operating modes is presented in Table 22. Based on these measurements, fractional penetrations were calculated and are plotted in Figure 29. Measurements were not conducted with the high filter velocity and precoated filters because of a technical problem that developed with the high volume air sampling train.

The penetration did not increase above 0.70 percent throughout the particle size range tested (0.22 to 7.2 micrometers). For filters not precoated particle size had less of an effect on penetration than the filters that were precoated.

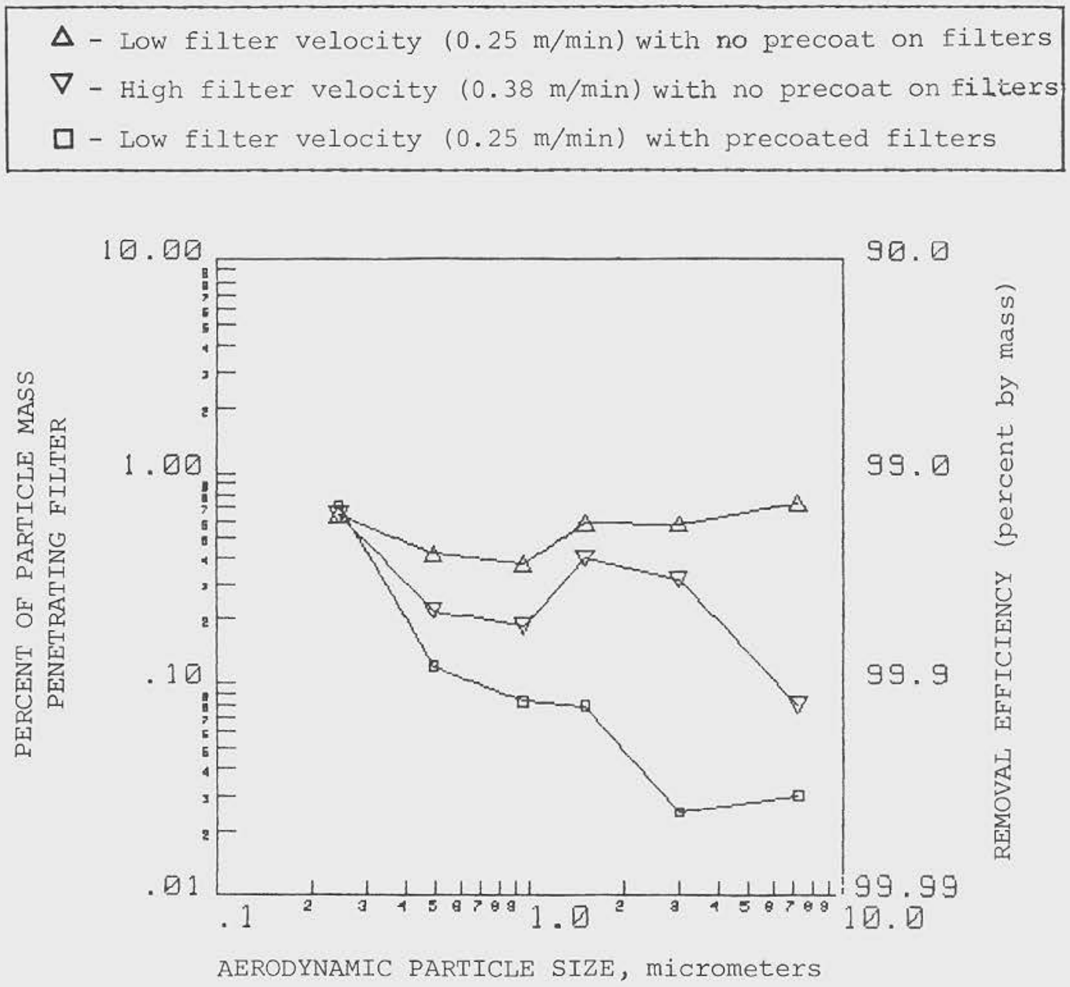


Figure 29. Aspirated Cartridge Filter fractional penetration results.

Table 22. Aspirated Cartridge Filter aerodynamic particle size distribution data.

Sample location	Operating mode	Mass mean diameter (D_{P50}) (micrometers)	Geometric standard deviation(D_{P84}/D_{P50})
Inlet	-	0.35	4.29
Outlet	Low filter velocity, filters not precoated	0.23	4.67
Outlet	High filter velocity, filters not precoated	0.15	4.67
Outlet	Low filter velocity, precoated filters	0.12	3.67

Equilibrium

Equilibrium penetration and differential pressure were found to be reached immediately if the filter elements were precoated. Filters not precoated required approximately 43 days of continuous operation to reach equilibrium differential pressure (Figure 30).

Failure Modes

No failure modes were experienced or identified that were considered to be of concern when using the ACF in a recirculating ventilation system. The two types of failures characteristic of fabric type air cleaners would be blinding and breakthrough. An analysis of possible failure modes and causes affecting the ACF are presented in Table 23. If a fine material is being filtered, such as welding fume, blinding will eventually occur and could be best delayed by precoating the filter elements. If an abrasive material is being filtered, a breakthrough failure caused by a filter leak would be more likely to occur.

Maintenance

The cartridge filter requires very little maintenance to insure proper operation. Cleaning of the filters is performed automatically. The only manual maintenance task would involve changing of the filters when they reach the end of their service life, replacement of any other items that may have a limited service life, and emptying the collection hopper.

New Potential Hazards

No new potential hazards associated with the operation of the ACF were identified. Any ozone produced by the welding process was found to be partially destroyed by the ACF. An ozone destruction rate was calculated and is presented, along with pertinent operating parameters, in Table 24.

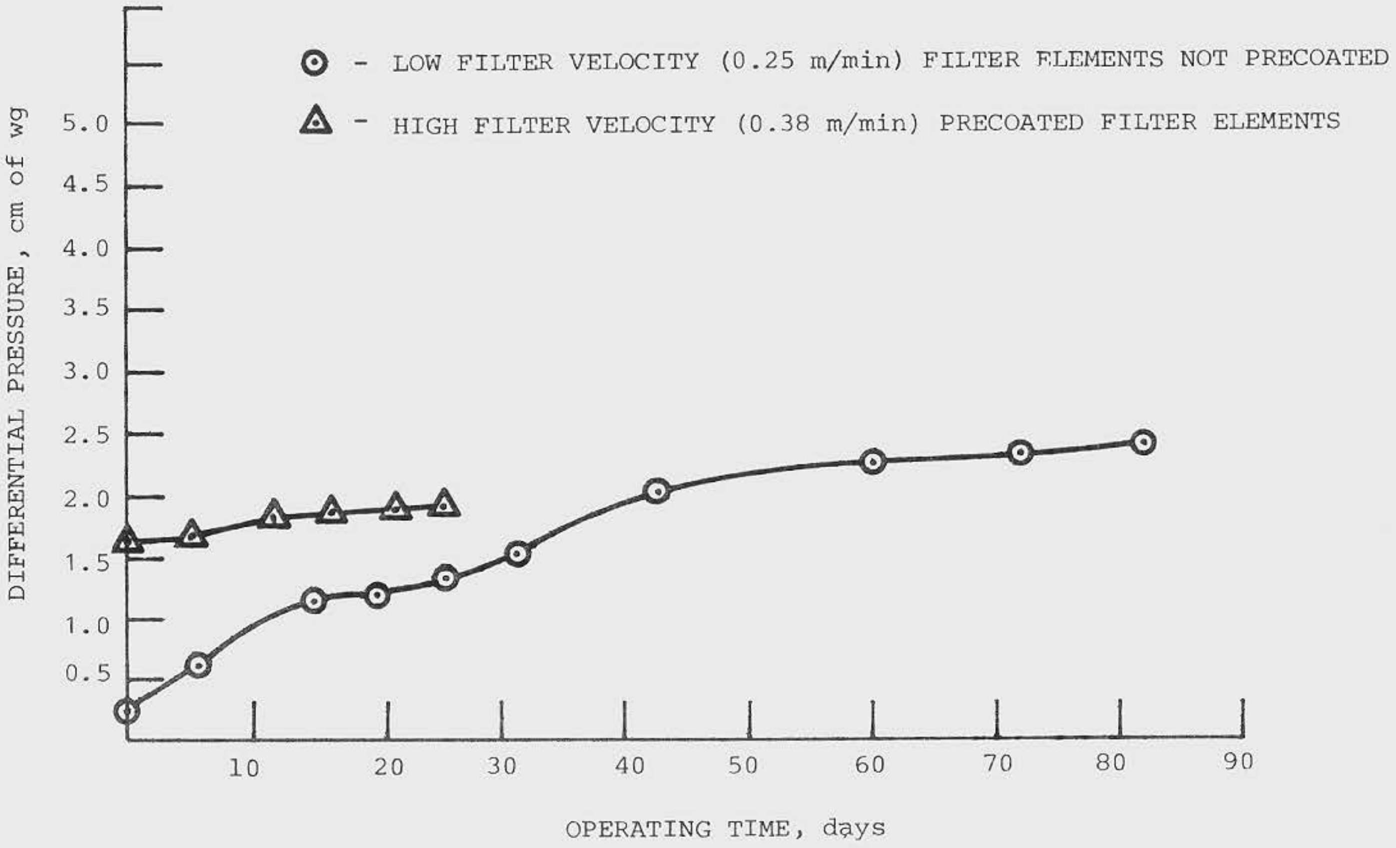


Figure 30. Aspirated Cartridge Filter differential pressure (following cleaning) vs. operating time.

Table 23. Aspirated Cartridge Filter failure analysis.

Failure mode	Effect upon recirculation system					Possible causes	Expected frequence	Was the failure encountered during the evaluation?
	Collector ΔP	Velocity pressure	Work place aerosol concentration	Exhaust aerosol concentration	Hood collection efficiency			
Blinding	↑	↓	$\underline{\uparrow}$	↓	$\underline{\downarrow}$	1. Small particles become embedded in filter media.	Gradual process expected to occur over a long period of time.	No
						2. Compressed air cleaning mechanism failure.	Unexpected component failure which could occur instantaneously.	No
Breakthrough	↓	↑	$\underline{\uparrow}$	$\underline{\uparrow}$	↑	1. Leak in filter cartridge	Probably will occur only if abrasive particles are filtered.	No
						2. Faulty cartridge seal	Most likely to occur at startup, but could occur at any time due to an unexpected component failure or improper installation.	No

↑ ↓ - Arrows indicate direction of relative deviation from steady state.
_ - Denotes failure effect(s) of primary concern.

The potential of overexposure of maintenance personnel while replacing filter elements is greatly reduced because this task can be performed without entering the air cleaner housing.

Table 24. Aspirated Cartridge Filter ozone emission data.

Air flow rate, m^3/min	Inlet ozone concentration, ppm	Outlet ozone concentration, ppm	Ozone destruction rate, mg/min
42.50	0.020	0.010	0.85

EVALUATION OF RETURN AIR MONITORING DEVICES

INTRODUCTION

Eight air monitoring devices were evaluated to determine their suitability for monitoring air cleaner performance and detecting breakthrough failures in recirculating ventilation systems. Seven of the devices tested were extractive type air sampling devices including five particulate and three ozone monitors. The eighth device, termed a safety monitoring filter, was an air pressure monitoring method employing an afterfilter. Most of these devices, particularly the extractive air samplers, are not limited to use in monitoring air cleaner performance; they can also be used to monitor general area levels of contaminants in the workplace. The evaluations performed in this study were limited to monitoring air cleaner performance in the outlet duct from various air cleaners. This type of evaluation has fewer variables to consider than an evaluation involving monitoring of workplace levels.

Only very low concentrations of gaseous contaminants were present in the exhaust gas stream at the welding training center, so the major thrust of the evaluation was directed at particulate monitors, with one exception. Ozone was generated by the electrostatic air cleaners, thus ozone monitors were used in evaluating those devices. Table 25 lists the air monitors evaluated, giving each a reference name which will be used to refer to the device throughout this report. The contaminant monitored, detection method, and output units are also listed.

In this section, evaluation criteria are presented for each of the two general types of monitors evaluated. In the following sections, the evaluations of each monitor are presented individually. Included with the technical discussion is a short discussion of costs, including available options.

Before presenting the evaluation criteria and the findings of the study, a short section is presented to provide an understanding of important monitoring system components and functions.

MONITORING SYSTEM COMPONENTS

Any complete monitoring system can be separated into four basic components: signal transfer, detector/transducer, signal conditioner, and information processor. A schematic diagram of the system formed from these components is shown in Figure 31. The following is a discussion of each of these basic components.

Table 25. Air monitoring devices evaluated.

Monitor	Reference name	Contaminant	Detection method	Output units
Extractive type air sampling devices:				
Thermo Systems, Inc., Model 5500, airborne particulate mass monitor	Piezobalance	Total or respirable aerosol	Piezoelectric balance	Mass concentration, $\mu g/m^3$
GCA Corporation, Model APM aerosol mass monitor	APM	Total aerosol	Beta-attenuation with filtration	Mass concentration, $\mu g/m^3$
Research Appliance Company, Model G1SE, AISI tape sampler	Tape sampler	Total aerosol	Light attenuation	Percent light transmission
GCA Corporation, Model RAM-1 real-time aerosol monitor	RAM	*Respirable aerosol	Near forward light scattering in the near infrared region	Mass concentration, mg/m^3
Mast Development Company, Model 727-2 ultraviolet ozone monitor	UV	Ozone	Ultraviolet absorption	Ozone concentration, ppm
Mast Development Company, Model 724-5 oxidant monitor	OM	Ozone	Coulometric	Oxidant concentration, ppm
Analytical Instrument Development, Inc., series 560 ozone monitor	AID	Ozone	Chemiluminescent reaction with ethylene	Ozone concentration, ppm
Air pressure type devices:				
Farr Company Inc., Riga-flo 200 safety monitoring filter	SMF	Total aerosol	Differential pressure across filter element	Differential pressure, which must be related to a rate of buildup of particulate, (cm wg).

*The RAM measures respirable sized aerosol with the cyclone attachment or particles up to 20 micrometers in diameter without the cyclone.

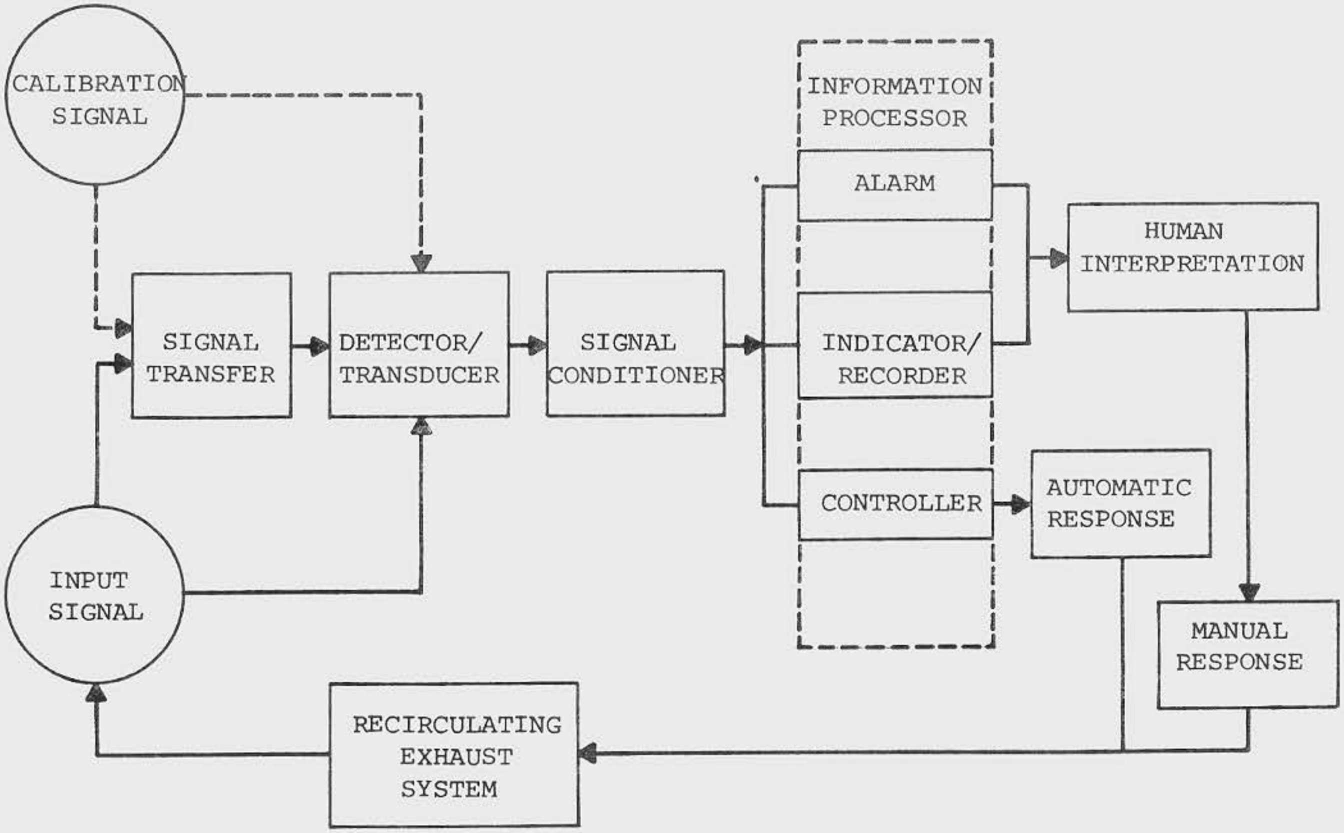


Figure 31. Schematic diagram of a recirculation monitoring system.

Signal Transfer

Input signals can take several forms; the most common include an extracted air sample, air velocity, or static pressure. The function of the signal transfer stage is to transfer an input signal to a detector without distorting or altering it. It is needed where the second stage, detector/transducer, is isolated from the input signal because of space limitations, for ease of operation and maintenance, or to remove the detector/transducer from an unsuitable environment. Input signals are usually transferred with a probe and a length of tubing.

Care must be taken in the design and operation of air sampling systems to insure that the sample extracted is truly representative of the air stream being monitored. The contaminant being transported must not be reduced in quantity because of deposition or changed by reaction with the probe wall material. Clogging is a potential problem with air flow and pressure sensors, as well as air sampling devices.

Detector/Transducer

This stage detects or senses the input signal and transforms it into an analogous signal for further processing. The detector must be selectively sensitive to the desired input and, ideally, insensitive to all other parameters. In reality, most detectors are affected to some extent by changes in the composition and properties of the sampled air and by the external environment in which the detector is operating.

Signal Conditioning

This stage accepts the transduced signal and modifies it so that it is compatible with the information processing stage. This may include amplification, analog to digital conversion, and any other required matching between the second and fourth stages. In addition, one or more basic operations, such as selective filtering, integration, or differentiation, may also be performed on the signal to transform it into more useful information.

Information Processor

The fourth or information processing stage displays the conditioned signal in a form that is comprehensible to one of the human senses, to the controller, or to both. At this point, an interpretation of the signal must be made followed by a decision based on pre-determined criteria as to whether or not the system is functioning properly. Measures to be taken as a result of a detected malfunction include bypassing the exhaust outside the plant, shutting down the process, evacuating the building, or sounding an alarm warning people in the area.

Calibration

Most of the monitors which provide a direct reading of contaminant concentration or a signal proportional to contaminant concentration require periodic calibration checks to insure accurate measurement. The frequency of such checks depends on the calibration stability of the monitor being used. These calibrations must often be performed manually, however, some monitors employ automatic calibration.

SYSTEMS EVALUATED

The schematic diagrams in Figure 32 show the similarities and differences between the two basic methods studied, i.e., extractive air samplers and safety monitoring filters.

Similarities

Although the reasons for using a safety monitoring filter or an extractive type air sampler are the same, i.e., to monitor air cleaner performance and to sense failures, the detection methods are quite different. In the case of extractive air samplers, especially when used in the return air plenum, air cleaner performance is measured by detecting the levels of contaminants in the air stream leaving the air cleaner. In the case of the safety monitoring filter, particulate matter penetrating the air cleaner is caught by an afterfilter. Material buildup on the afterfilter is reflected as a change in differential pressure across it.

Major similarities in the two methods include the fact that they both:

1. Respond to the presence of air contaminants in the exhaust stream of the air cleaner.
2. Are capable of sensing air cleaner failures.
3. Can be utilized with automatic warning and control systems.
4. Can be constructed of commercially available components.
5. Require periodic maintenance to be reliable.

Differences

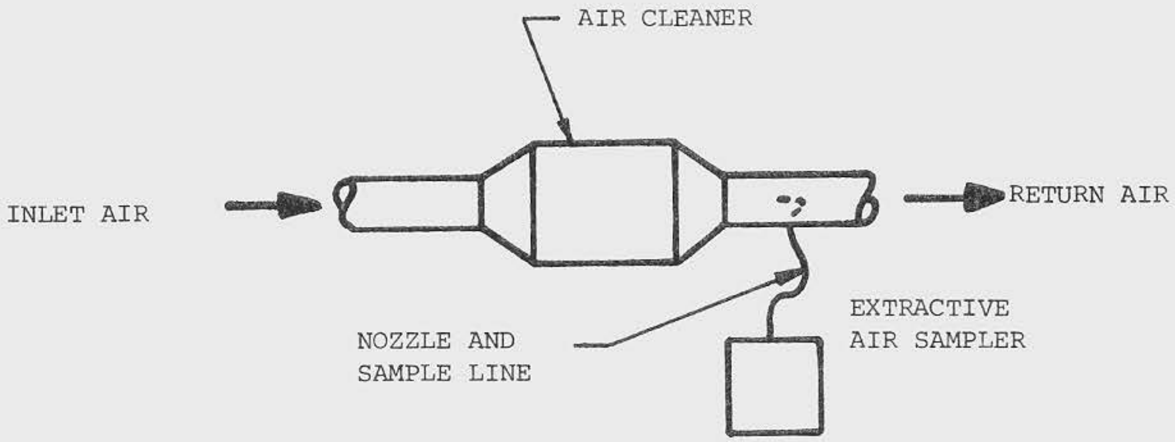
1. The safety monitoring filter is not able to quantify air contaminant levels.

2. Unlike the extractive air sampler which has minimal effect on the pressure conditions in the system, the safety monitoring filter requires a differential pressure to make the method operational.

3. The extractive air sampling method applies to particles and gases whereas the safety monitoring filter is for use with particles only.

4. The extractive air sampler does not change the outlet air quality whereas the safety monitoring filter can improve air quality, depending on the efficiency of the filter utilized.

EXTRACTION AIR SAMPLING (particles and gases)



SAFETY MONITORING FILTER (particles only)

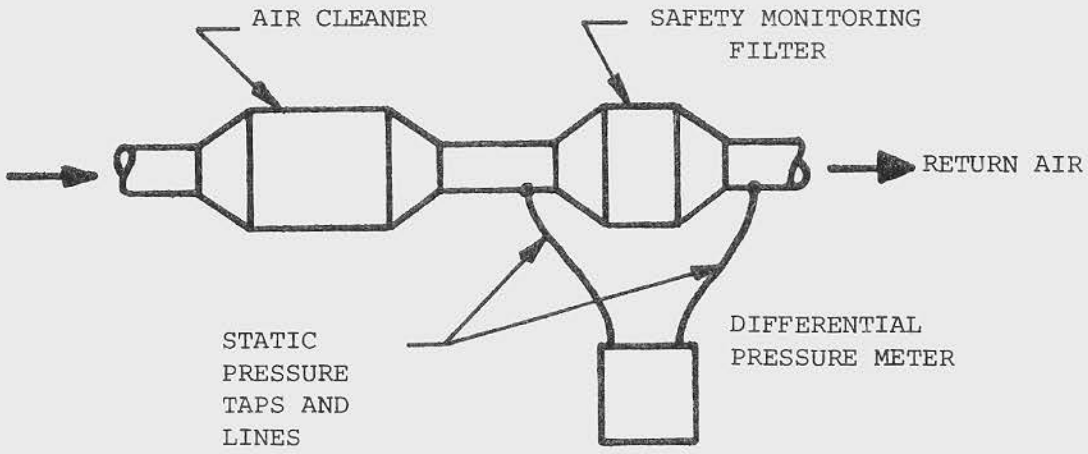


Figure 32. Schematics of the two types of monitors evaluated.

ASSEMBLING A COMPLETE SYSTEM

Most of the commercially available air monitoring devices do not incorporate all four of the previously discussed monitoring stages. Most frequently, these devices consist of a detector/transducer and a partial signal conditioner, although one or more of the other components may also be included. For commercially available devices to be incorporated into complete monitoring systems, custom engineered components must be added, such as sample nozzles, alarm systems, strip chart recorders, integrators, and automatic bypass dampers.

For the evaluations conducted during this study, it was found necessary to add components to each monitoring system to facilitate signal transfer and signal recording. Signal transfer components which were added included nozzles, sampling lines, and signal recording with strip chart recorders.

SIGNAL TRANSFER LOSSES

Nozzle and sample line losses in extractive air samplers can cause a significant reduction in the particulate concentration measured by the monitor in the high concentration range that may occur in the event of a breakthrough-type air cleaner failure. To properly evaluate the accuracy of the various monitors tested, it was necessary to determine the extent of nozzle and sample line losses. This was done under four different conditions: with high and low particulate concentrations, and with long (183 cm) and short (61 cm) sample lines. The low concentration condition (20 to 100 $\mu g/m^3$) was chosen to represent typical outlet concentrations from high efficiency air cleaners and the higher concentration (10 to 15 mg/m^3) represented a breakthrough failure.

The results of these determinations, presented in Appendix A, indicate that there was an undetectably small loss at low concentrations, but that at high concentrations the losses were significant, ranging from 15 - 20 percent. Shorter lines were found to produce lower losses.

EVALUATION CRITERIA

To prevent buildup of contaminants in the workplace and overexposure of workers, a monitor which is suitable for use on a recirculating ventilation system must be capable of:

1. Reliably monitoring the steady state, normal operation (system equilibrium) of the air cleaner, continuously and unattended, for an extended period of time.

2. Quickly and accurately sensing a change of system performance from equilibrium and able to provide a warning if a preselected level is reached at which action is deemed necessary (action level).

To assess a monitor's ability to meet these requirements, its performance was evaluated in terms of predetermined criteria. The criteria list is not intended to be exhaustive but rather to focus only on what are considered to be the most important considerations. The order for presentation of the criteria is as follows:

1. Operational performance of extractive air samplers.
2. Operational performance of safety monitoring filters.
3. Monitor failures and maintenance.

The criteria and the procedures used for evaluating the criteria are presented below.

OPERATIONAL PERFORMANCE OF EXTRACTIVE AIR SAMPLERS

Measurement Accuracy

> The measurement accuracy should be high enough to provide a reliable measurement of a contaminant's concentration when a preselected action level has been reached.

Measurement accuracy refers to how well an instrument's measurements compare to a standard measurement technique. Accuracy is important to assure that action levels are indicated at the proper time. If the instrument reads higher than the actual concentration, the action level will be reached prematurely and the alarm will be, in effect, a false alarm. On the other hand, a low-reading instrument could mask a serious failure and give plant personnel a false sense of security.

Measurement accuracy was evaluated by comparing a monitor's output to measurements made by a standard measurement technique. Unlike the instantaneously reading monitors studied, the standard techniques averaged concentrations over a known period of time. Thus, to compare the output of instantaneously reading devices to these standards, the measurements from the instantaneous devices required recording and integration over the same time span.

An acceptable accuracy cannot be universally specified because it is dependent on how close the action level must be to the equilibrium condition. The action level setting is a function of a number of factors which strongly affect design of the recirculating ventilation system, among them:

1. The toxicity of the contaminants in the air stream.

2. The ratio of fresh to recirculated makeup air introduced into the workplace.

3. The concentrations of contaminants in the general workplace atmosphere prior to recirculation.

4. The location and method of distribution of return air back into the workplace.

Therefore, because an acceptable accuracy cannot be specified, no judgments were made relating to the required accuracy for recirculation monitoring.

Standard measurements for particulate monitors were made with low and high volume sampling trains. Error estimates for each sampling train were calculated for different sampling times and particulate concentrations and are presented in Appendix B.

Tests conducted on one of the aerosol monitors, the piezobalance, indicated that this device's accuracy was ±10 percent or better in the low concentration ranges. After its evaluation the piezobalance was subsequently employed as a standard to evaluate measurement accuracy for several of the other aerosol monitors in this study because this device was found to be very accurate and had the capability of providing average concentration data every two minutes.

The data obtained from the accuracy evaluations was plotted graphically and linear regression analysis by the method of least squares was used to determine the line of best fit. The relative scatter of data points was assessed in terms of the correlation coefficient, R.

For ozone measurements, the Aid® chemiluminescent monitor was used as a standard for comparison after being precalibrated.

Measurement Range

> The measurement range should include both equilibrium conditions and the desired action level.

The measurement range for the monitor lies between the minimum and maximum contaminant concentrations that can be detected by the monitor. As in the case of accuracy, the action level depends on the particular application and no universal action levels can be specified. Thus, the values reported in the monitoring evaluations are those given by the manufacturer of the instrument.

Zero Drift

> Zero drift should be minimal over extended periods of time to reduce the frequency of required re-adjustments and to insure measurement accuracy.

Zero drift is the change in the zero setting after an instrument has operated for a period of time, causing error in the measurements. This was assessed by periodically re-checking the zero setting for possible shifts.

Response Time

> The response time should be as close to instantaneous as possible to provide a fast warning of a change from system equilibrium.

Response time is the time lag that occurs between a change in contaminant concentration and the time it appears on the monitor's output. The response times of all but one of the extractive air samplers evaluated were fast enough (approaching instantaneous measurements) to detect failures in recirculating ventilation systems, so that it was deemed unnecessary to measure them. Instead, the response times reported by the manufacturers are presented. In the one non-instantaneous monitor evaluated, the response time was selectable, the shortest time on the order of several minutes and easily determined experimentally.

OPERATIONAL PERFORMANCE OF SAFETY MONITORING FILTERS

Differential Pressure Limit

> The action level for the safety monitoring filter must be set no higher than the limiting differential pressure which, if exceeded, will cause insufficient indraft into the exhaust hoods, resulting in the escape of contaminants into the workplace and overexposure of workers.

A quantity of particulate matter penetrates every air cleaner, even those with the lowest penetration, resulting in continuous buildup on the safety monitoring filter. The buildup is sensed by a differential pressure sensor. Typical data for a system in equilibrium is shown in Figure 33. The rate at which the filter differential pressure increases from an initial resistance to a final resistance (the rated capacity of the filter) is dependent on the amount of penetration of the primary air cleaner.

The limiting differential pressure for the safety monitoring system is determined during the design of the recirculating ventilation system. It is usually set at the "final resistance" of the filter, which is a design limit set by the manufacturer. Typical final resistances for one manufacturer's line of disposable filters range from 5.1 - 8.9 cm wg (2.0 to 3.5 in. wg). Once the hoods, ductwork, and fan are specified, the limiting differential pressure becomes fixed. If this limit is exceeded during operation, air flow through the system will begin to fall off, resulting in insufficient capture velocities at the exhaust hoods. That condition is as serious a failure as a primary air cleaner failure, which the monitor was installed to prevent.

Safety monitoring filters can be either recleanable or disposable. In this study a disposable filter was evaluated. Differential pressures were continuously monitored up to an action level set at the limiting differential pressure specified by the filter manufacturer.

Contaminant Penetration

> The contaminant penetration of the safety monitoring filter, i.e., the percentage of material that passes through this filter without being retained, should be low enough, especially in the respirable size range (<10 micrometers), to prevent the buildup of contaminants

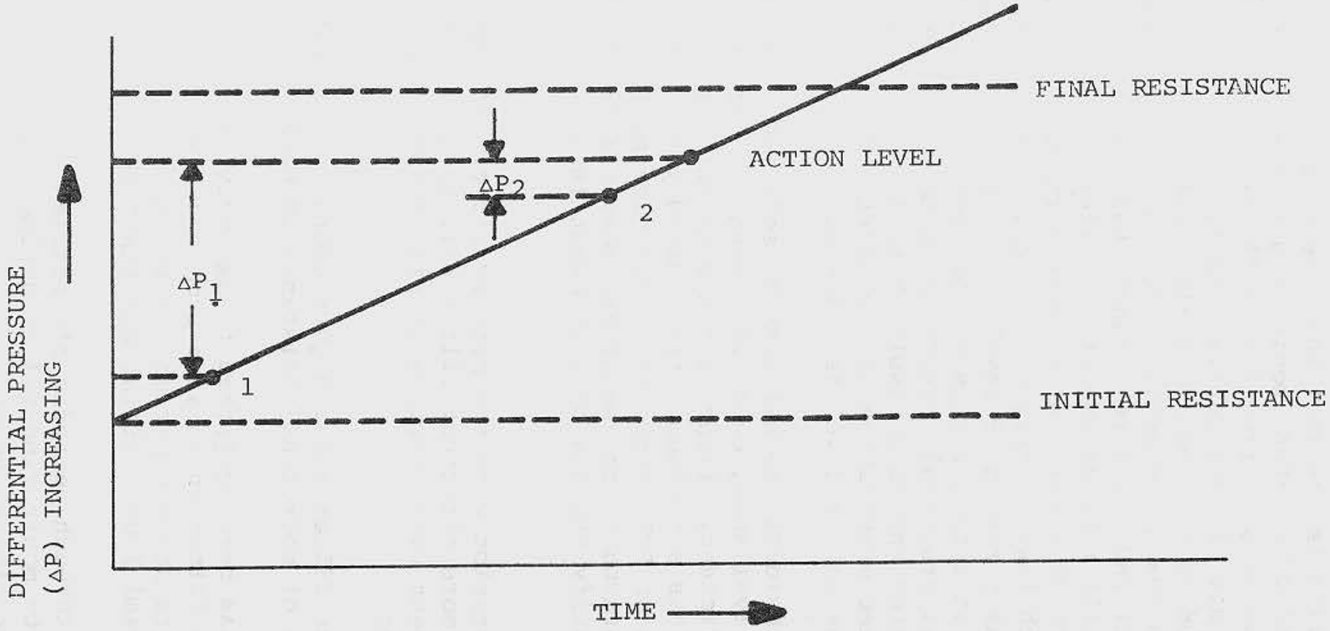


Figure 33. Typical response data for a safety monitoring filter under equilibrium conditions.

in the workplace and overexposure of workers with any increase in the penetration of the primary air cleaner over the equilibrium level, until the action level has been reached.

The basis for this criterion is the fact that there is a practical limit to how close the action level of a safety monitoring filter can be set to the equilibrium point. As can be seen from Figure 33, even equilibrium operation of the primary air cleaner causes a continuous rise in differential pressure, and so the amount of differential pressure at any point in time required to reach the action level is dependent on what percentage between initial and final resistances has been reached. For example, at point 1, it will take an amount of differential pressure equal to ΔP_1, to trigger the action level. At a point further up the curve, point 2, it will take much less to trigger the action level, ΔP_2. It is because of this continuously rising ΔP level which occurs during normal, steady state operation that action levels are not set too close to the operating point. But this practical consideration does increase the time necessary to detect failures and as a result there is a need to utilize an efficient filter to keep penetration of the safety monitoring filter low during a failure until the action level is reached.

The above criterion can obviously be met best by selecting the most efficient safety monitoring filter available, especially when the contaminants are very toxic. One high efficiency filter is the High Efficiency Particulate Air (HEPA) filter, which has a minimum, standardized performance limit of 0.030 percent penetration on DOP particles of 0.3 micrometer diameter. There are, however, two drawbacks to use of the most efficient filter available which could justify the use of a somewhat less efficient filter in certain cases:

1. During normal operation with the primary air cleaner in equilibrium, the more efficient filter will require a more frequent replacement cycle because it will reach final resistance quicker.

2. The more efficient filter has a higher energy requirement because its range of operating resistance is higher.

Because the HEPA filter has been subjected to extensive testing, the present study evaluated a filter which also promised low penetration (0.10 percent at five micrometers and one percent at one micrometer) but a predicted longer replacement cycle and lower initial and final resistance.

Penetration was measured through periodic air samples collected from the inlet and discharge of the safety monitoring filter during equilibrium conditions and during a simulated air cleaner upset.

MONITOR FAILURES AND MAINTENANCE

Malfunction Modes

To insure reliable operation, potential malfunctions should be:

1. Few in number.
2. Easily detectable.
3. Preventable if recommended maintenance schedules and procedures are followed.

There are many possible ways for an instrument to fail. For the purposes of this study malfunction modes have been divided into two classes: common and characteristic. Common malfunctions are those which could happen to any instrument because of such things as misuse, breakage, etc. Typical common malfunctions include: plugged sample line, depletion of indicator/ recorder paper and power failure.

The class of malfunctions of particular interest in this study is the characteristic malfunction which is specific to the individual device. In the maintenance instructions, the manufacturer specifies procedures which are intended to prevent this class of malfunctions. These procedures are a tipoff to the potential malfunctions that could occur. Another source of information is the experience gained during the monitoring tests. The evaluation of malfunction modes includes both types of information since many of the malfunctions may only occur after periods of time much greater than the duration of the tests conducted in this study.

Maintenance

Required maintenance procedures should be simple, infrequent, and not time consuming.

Maintenance requirements affect both operating costs and the reliability of the monitor. Some examples of these requirements would include replenishing expendible items, recalibration adjustments, and cleaning. The maintenance requirements specified for the individual monitors are based on procedures specified by the manufacturer and those determined as necessary through the course of this evaluation.

AIRBORNE PARTICULATE MASS MONITOR (PIEZOBALANCE)

PRINCIPLE OF OPERATION

A prototype of the Thermo-Systems Inc. Model 5500 Airborne Particle Mass Monitor was evaluated as part of this study. The piezobalance is capable of measuring the mass concentration of respirable sized particles on a continuous basis. A photograph of the unit installed for testing appears in Figure 34.

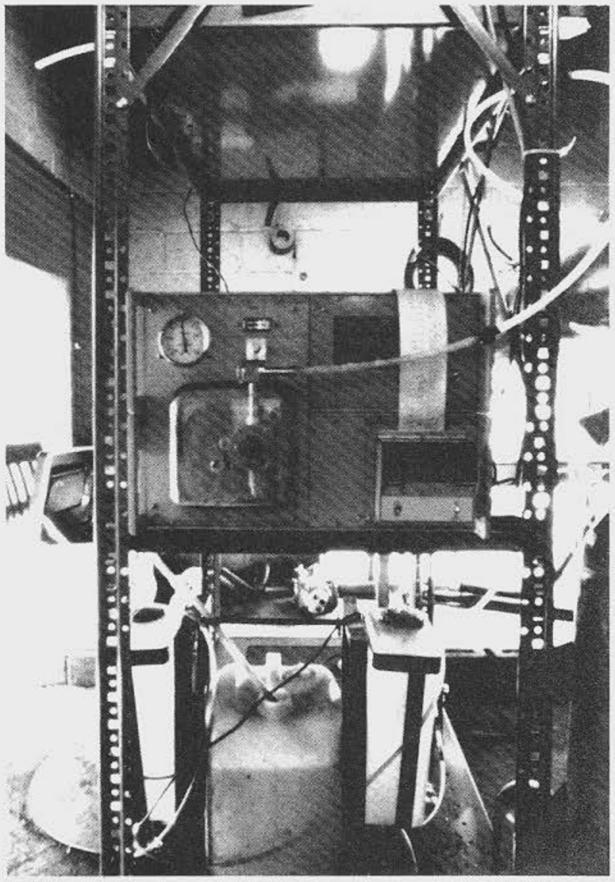


Figure 34. Airborne Particulate Mass Monitor installed for testing.

The piezobalance determines mass concentration of an aerosol by measuring the decrease in resonant frequency of a quartz crystal as particulate matter contained in an incoming air sample is electrostatically precipitated upon the crystal surface. The resonant frequency of the crystal is inversely proportional to the mass of the crystal. The clean crystal has a stable resonant frequency of approximately 5 MHz. Deposition of particulate upon the crystal increases the mass and thus decreases the resonant frequency. The net decrease is proportional to the mass of the adhered particles To facilitate determination of the frequency change, a reference (clean) crystal is utilized, whose frequency is subtracted from the measuring crystal's frequency. The instrument readout displays the absolute value of the frequency change.

Aerosol concentration can be determined from the net frequency change if the sampling interval and the air sampling rate are known. This is expressed by the relationship:

$$C = \frac{1}{S \times Q} \frac{\Delta f}{\Delta t}$$

Where: C = Aerosol mass concentration, $\mu g/m^3$.
S = Mass concentration coefficient, nominally about 180 Hz/μg.
Q = Air sampling rate, m^3/sec.
Δf = Frequency change, Hz.
Δt = Sampling interval, sec.

TEST DEVICE DESCRIPTION

A schematic diagram of the piezobalance is shown in Figure 35. Air is drawn through the impactor/precipitator section at a constant rate of 1 l/min, regulated by a critical flow orifice. The impactor removes particles larger than 10 μm in diameter, thus allowing only respirable-sized particles to reach the precipitator where they are charged by a high voltage corona discharge and precipitated on the crystal surface. The process is continued for 28 minutes during which time cumulative averages of the mass concentration are computed and displayed by the digital readout every two minutes.

At the conclusion of the 28-minute sampling period, the average concentration for the time period is permanently recorded by the built-in printer, and the crystalline element is automatically washed and dried. The cleaning cycle is completed in two minutes after which the measurement cycle is repeated.

SPECIFICATIONS

Manufacturer's specifications for the Model 5500 were not available but they were available for a similar, portable Model 3500 also manufactured by TSI and these are presented in Table 26. The sensor part of the Model 5500 is similar to the portable Model 3500 except that the Model 5500 employs an automatic cleaning system that cleans the sensing crystal on a preset time cycle, thus allowing the unit to operate unattended for extended periods

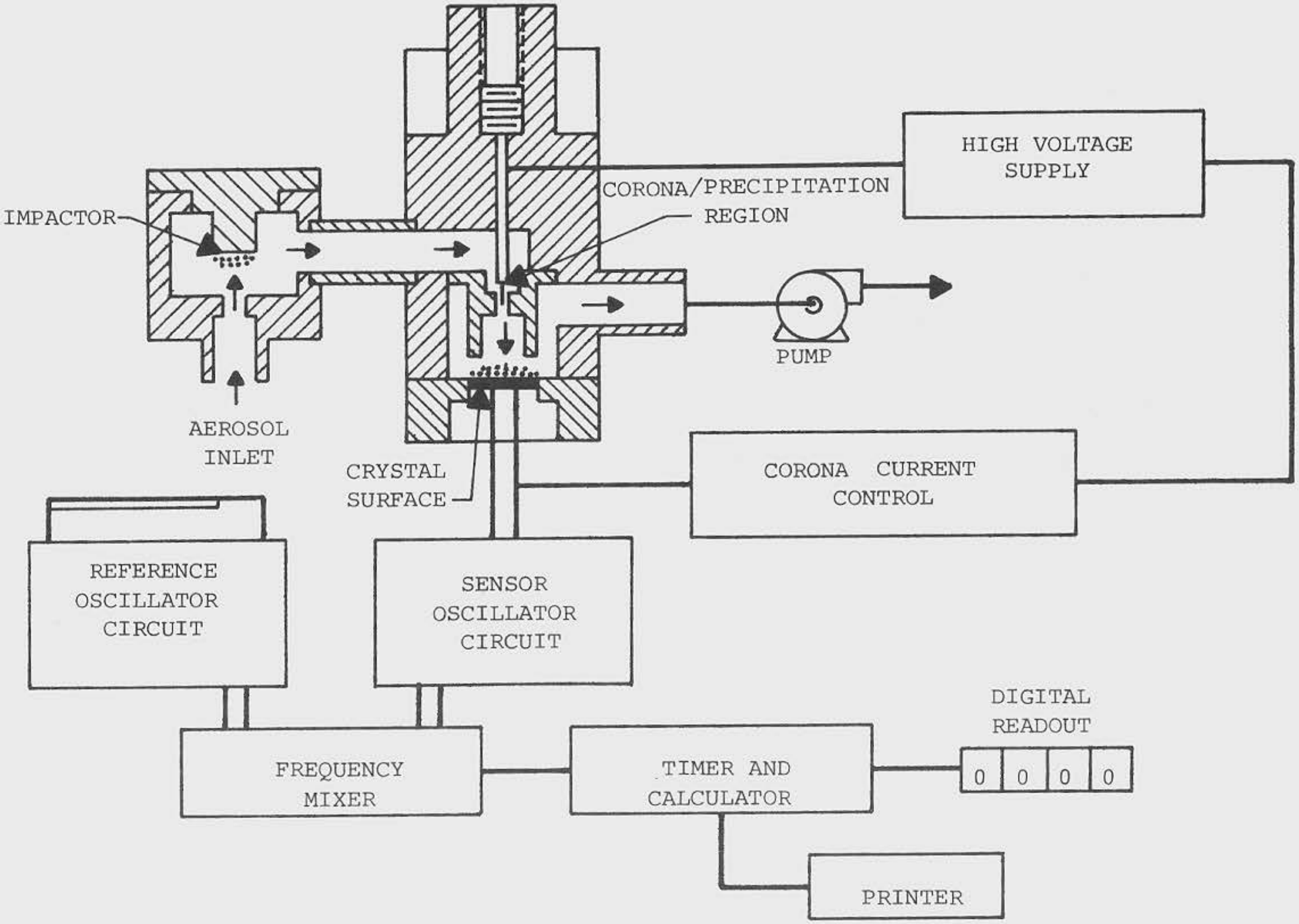


Figure 35. Schematic diagram of the Airborne Particulate Mass Monitor (from manufacturer's instruction manual).

of time. The Model 5500 is also much larger than the portable model, has a built-in printer, and has three reservoirs for storing the cleaning, rinsing and waste fluids.

Table 26. Manufacturer's specifications for the Airborne Particulate Mass Monitor.

Mass concentration measurement range*:	<0.01 – 10 mg/m^3.
Accuracy:	±10% of reading.
Measuring time:	Selectable, 1 to 10,000 seconds.
Sampling air flow rate:	1 l/min (2.12 ft^3/hr).
Particle size range:	0.01 - 10 micrometers. This can be altered by using impactors with different cut diameters.
Environmental limitations:	Temperature 5 to 40°C (41 to 104°F).
Size and weight:	LxWxH, 31.1 cm x 13.0 cm x 17.0 cm (12.3 in. x 5.2 in. x 6.7 in.)
Output and alarm capabilities:	Digital output fed directly to a built-in printer; an outlet is available for an analog signal proportional to frequency shift.

*The measurement range of the piezobalance is dependent upon the measuring time period. The production model's large measuring time range will facilitate a large mass concentration measurement range, probably larger than the range specified.

EVALUATION RESULTS

Measurement Accuracy

Comparisons made between gravimetric and piezobalance measurements indicate that the piezobalance accuracy is approximately ±10 percent or better in the range from 0.02 to 0.30 mg/m^3. Gravimetric and piezobalance measurements agree very well; all of the measurement pairs were within or very close to ±20 percent limits as shown in Figure 36. Experimental error estimates for the high volume sampler used to make the gravimetric measurements indicate that approximately 12 percent of the difference could be attributed to this measurement leaving 8 percent attributable to the piezobalance (see Appendix B). Linear regression analysis indicates that the relationship between the two measurements was linear with minimal scatter.

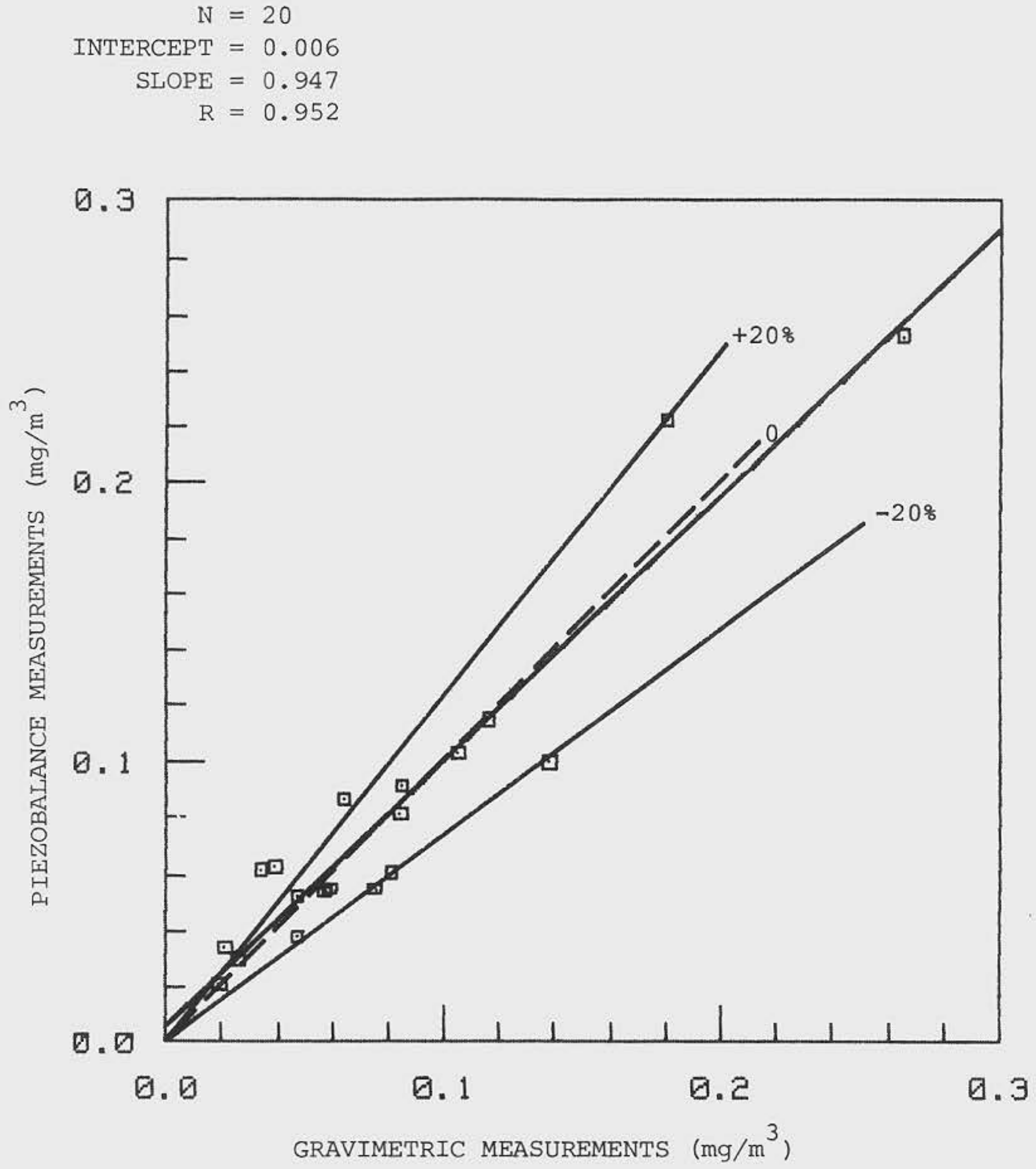


Figure 36. Comparison of Airborne Particulate Mass Monitor (piezobalance) and gravimetric measurements.

The prototype device tested had a fixed measuring time period of 28 minutes, which resulted in a maximum measurable concentration of about 0.5 mg/m^3. Higher concentrations could be measured with shorter measurement time periods. Similar measurement comparisons on welding fume, conducted by the manufacturer on the portable Model 3500 using shorter measurement times (120 and 24 seconds), indicated agreement to within ±15 percent between the piezobalance and simultaneous gravimetric measurements in the 1 to 6 mg/m^3 concentration range.

Measurement Range

The Model 5500 Airborne Particulate Mass Monitor will be capable of detecting concentrations from 1 to several hundred $\mu g/m^3$, as specified by the manufacturer. The sensitivity of the instrument is a function of measurement time. The production model of this instrument will have selectable measuring time periods ranging from 1 to 10,000 seconds, giving the unit the capability of measuring a wide range of concentrations.

Zero Drift

Zero drift does not directly apply to the piezobalance because each concentration calculation is based on a change in crystal frequency, rather than an increase above some set level. This procedure automatically cancels any drift.

Response Time

An analog signal proportional to the crystal frequency provides an instantaneous indication of aerosol concentration except for a 2-minute interruption each half-hour during which the measuring crystal is cleaned.

Malfunction Modes and Maintenance Requirements

Four malfunction modes were identified which would disrupt proper operation (Table 27). The first three of these malfunctions were encountered during the course of this evaluation. Routine inspection and maintenance should be effective in reducing the likelihood of their occurrence.

The malfunction mode of most concern was the base frequency rise: the difference in frequency between the reference and measurement crystals immediately after the reference crystal is cleaned by the automatic cleaning device. This phenomenon was most significant when air was being sampled containing positively charged particles from an electrostatic air cleaner exhaust. The measured frequency shifts for charged and uncharged particles are presented in Table 28.

The base frequency could only be reduced by manually cleaning the crystal. The frequency of cleaning was highly dependent on whether the particles were charged or not.

Table 27. Airborne Particulate Mass Monitor malfunction mode and maintenance schedule.

Malfunction mode	Was the malfunction encountered during the evaluation?	Effect on monitor	Detection method	Preventive maintenance	Maintenance frequency
Shift in crystal base frequency above specified limit.	Yes	Upper frequency limit is reached more quickly, requiring manual crystal cleaning.	-Upper frequency limit alarm. -Base frequency of crystal.	-Check cleaning fluid levels. -Manually clean crystal.	-Dependent upon size of cleaning fluid reservoirs (4 l) of fluid lasts approximately 350 hrs or 700, 30 minute measurement cycles. -As needed*
Upper frequency limit of the measuring crystal is exceeded	Yes	Once the upper limit is reached, the monitor stops measuring until the next measurement period.	-Upper frequency limit alarm light is illuminated.	Adjust measurement time period to accomodate aerosol concentration being measured.	Routine inspection of output data.
Reduced corona voltage.	Yes	Aerosol material contained in air sample would not be precipitated on measuring crystal.	Corona voltage.	Inspect and clean precipitator needle, wiper blade and impactor.	Twice/month
Reduced sample air flow rate.	No	Sampled air flow rate is reduced causing concentration errors.	Pressure across critical flow orifice.	Inspect critical flow orifice and replace filter.	Once/month

*When measuring charged particles from an electrostatic air cleaner, this may have to be done as often as every 2 hours; uncharged particles, every 67 hours of operation.

Table 28. Airborne Particulate Mass Monitor base frequency rise results.

Type of particles sampled	Base frequency rise (Hz/hr)	Operating time before manual cleaning is needed (hr)
Charged particles	224	2 hr
Uncharged particles	7.5	66.8 hr

The base frequency could only be reduced by manually cleaning the crystal. The frequency of cleaning was highly dependent on whether the particles were charged or not.

Although all of the maintenance requirements necessary to assure accurate and reliable operation of the piezobalance are simple to perform, several must be executed routinely and frequently, i.e., every two weeks or less. These include manual cleaning of the crystal and cleaning and inspection of the precipitator needle, wiper blade, and impactor.

Economic and Installation Considerations

Cost--

The estimated cost of the Model 5000 piezobalance is approximately $10,000 as of January, 1980. The first production models will be strictly for single point monitoring, although future models may incorporate a feature which would allow several sensor units to be attached to a single microprocessor section, which reduces the per point cost of a multi-point monitoring system.

AEROSOL MASS MONITOR (APM)

PRINCIPLE OF OPERATION

The Model APM Aerosol Mass Monitor, manufactured by GCA/Environmental Instruments, measures the mass concentration of airborne particulate material in ambient environments. The APM was the most automated monitoring device evaluated, incorporating continuous, automatic measuring and recording of particulate concentrations as well as built-in system diagnosis. It is available as a single channel model which measures total mass concentration and as a two channel option which measures both total and respirable (<10 micrometers) fractions.

Mass concentration is measured using the beta radiation attenuation method. This is accomplished by filtering the sampled air with a teflon, reinforced filter, and determining its mass with beta radiation. The amount of beta radiation transmitted through an area of the filter tape is measured before and after particulate material in the air sample is deposited. The difference between the before and after readings is proportional to the concentration of particles in the air stream.

TEST DEVICE DESCRIPTION

The APM is composed of three components: sensor, controller, and vacuum pump (Figure 37). A microprocessor, located in the controller module, controls all of the system functions including:

Signal conditioning.
Beta count logging.
Mass computation.
Cycle time.
All mechanical operations.
System diagnostics.
Calibration and zero tests.
Data printout.

Normal operation involves the following sequence:

1. A system status check is performed to identify any malfunctions which could render the system inoperable, e.g., broken or depleted filter tape, incorrect air flow rate, depleted printer paper, or incorrect beta-counts. When a malfunction is sensed, the appropriate indicator lamp on the front panel is illuminated and an alarm message is printed.

2. The initial amount of transmitted beta radiation through an area of filter tape is measured by a beta source/detector pair.

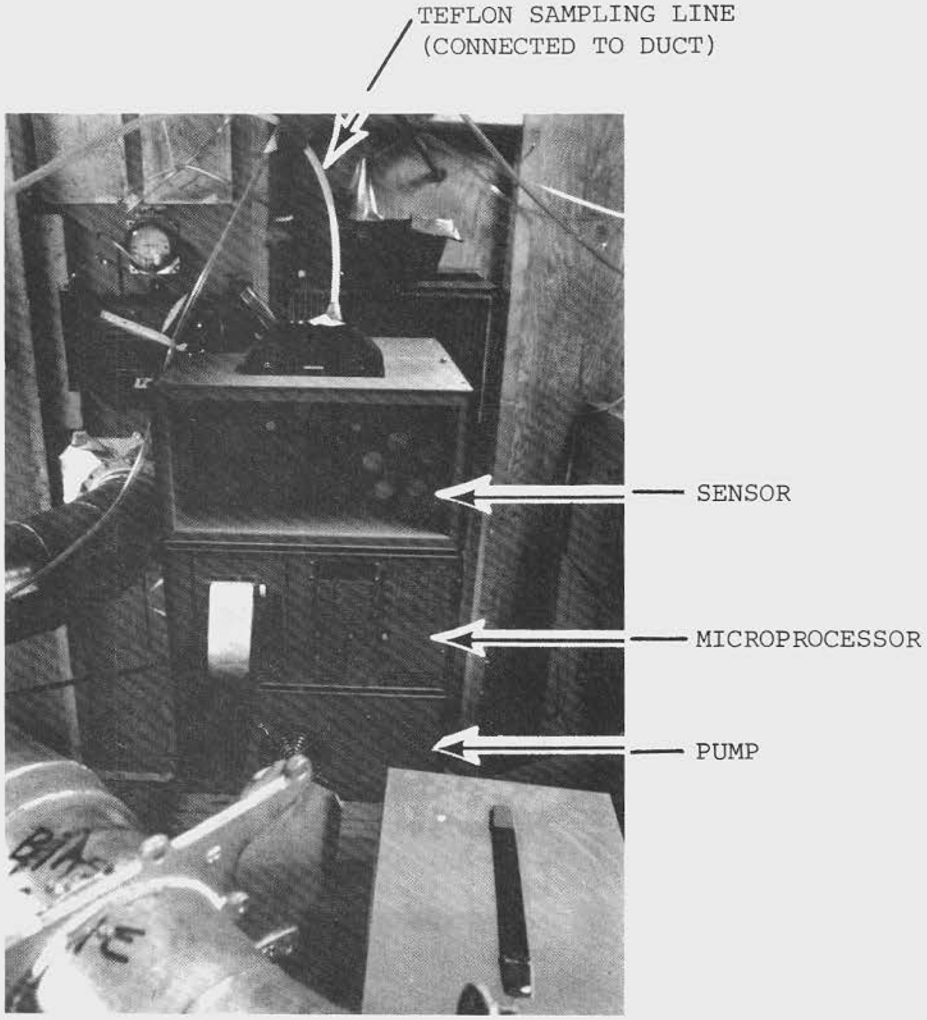


Figure 37. Aerosol Mass Monitor on test stand.

3. The filter tape is advanced to the air sampling port where air is drawn through the filter at a constant flow rate (controlled by a venturi-type critical flow orifice) for a preselected time period.

4. The filter area is returned to the beta source/detector pair where the transmitted beta radiation is re-measured.

5. The beta-count information is relayed to the microprocessor which computes and prints the mass concentration along with the date and the time at which the sample ended.

SPECIFICATIONS

The manufacturer's specifications for the APM monitor are presented in Table 29.

Table 29. Aerosol Mass Monitor manufacturer's specifications.

Total mass concentration measurement range:	18 - 5,000 µg/m^3
Measurement accuracy:	±10% (95% confidence level) dependent on sample time.
Measurement cycle time (time constant):	3 - 999 minutes, selectable in one minute steps.
Maximum duration of unattended operation:	Filter tape: 5,000 measurement periods; e.g., with 5 minute measurement periods, a total of 52 8-hr. shifts. Printer paper: 2,000 measurements or 21 8-hr. shifts (5 minute measurement period) (printer would not need to be used if optional telemetry interface is utilized).
Sampling air flow rate:	9 l/min. (19.1 ft^3/hr), ±3%
Particle size collection range:	Total aerosol 0.1 - 100 µm Respirable aerosol - 0.1 - 10 µm
Power requirements:	115 VAC (230 VAC optional), 60 Hz, single phase, 700 watt maximum.
Temperature limitations for equipment:	Microprocessor 10 - 32°C (50 - 90°F) dry Sensor and pump −18 - 32°C (0 - 90°F) dry
Size, each module:	22.2 cm high (8.8 in.), 42.9 cm wide (16.9 in.), 42.5 cm long (16.7 in.)
Weight:	Microprocessor and sensor module, 15 kg (33 lb) Pump, 21 kg (46.2 lb)

EVALUATION RESULTS

Measurement Accuracy

Because both high measurement accuracy and short response times are in direct opposition to each other with this instrument, the APM is not suitable for an application where high measurement accuracy is needed at low concentrations as well as a near instantaneous response time.

Measurement Accuracy as a Function of Measurement Time--

The measurement accuracy of the APM is dependent upon the selected measurement time* and the aerosol concentration measured. As the measurement time is increased, the APM accuracy improves. In Figure 38, the concentration accuracy is plotted as a function of the measurement time. This information, supplied by the manufacturer, indicates the concentration accuracy for different measurement times at the 95 percent confidence level. For example, for a one hour measurement time, the concentration accuracy from Figure 38 is 8 $\mu g/m^3$, indicating that for any measurement made over this measurement time, one could be 95 percent sure that the APM measurement was within $\pm 8\ \mu g/m^3$ of the true concentration. For a 3-minute measurement time (shortest measurement time possible), the concentration accuracy is approximately 300 $\mu g/m^3$.

Measurement Accuracy Results--

Although it was desired to evaluate all instruments at as close to an instantaneous response time as possible, the tests run during this evaluation were conducted at a measurement time of five minutes (response time of 15 minutes), rather than at the lowest measurement time selectable, in order to improve the concentration accuracy. Comparisons made between gravimetric and APM measurements with a 5-minute measurement time in the 0.3 to 10 mg/m^3 concentration range indicate that APM accuracy was approximately ±40 percent (Figure 39).

A large degree of variability was found between the gravimetric and APM measurements as shown in Figure 39. Approximately half of the measurement pairs agreed within the ±20 percent limits; the remaining pairs differed by as much as 50 percent. About 10 percent of the difference can be attributed to experimental error associated with the gravimetric sampling method, leaving approximately ±40 percent attributable to the APM. Linear regression analysis indicates a linear relationship between the measurements, with the APM measuring lower than the gravimetric method.

Measurement Range

The manufacturer specifies a total mass concentration measurement range of 18 to 5,000 $\mu g/m^3$. However, as previously discussed, shorter measurement times result in larger concentration variations in the APM measurement, thus the lower measurement limit is confined by the degree of accuracy

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*The response time of the instrument, defined as the time lag from the beginning of the measurement until the measured concentration appears on the readout, is three times the measurement time.

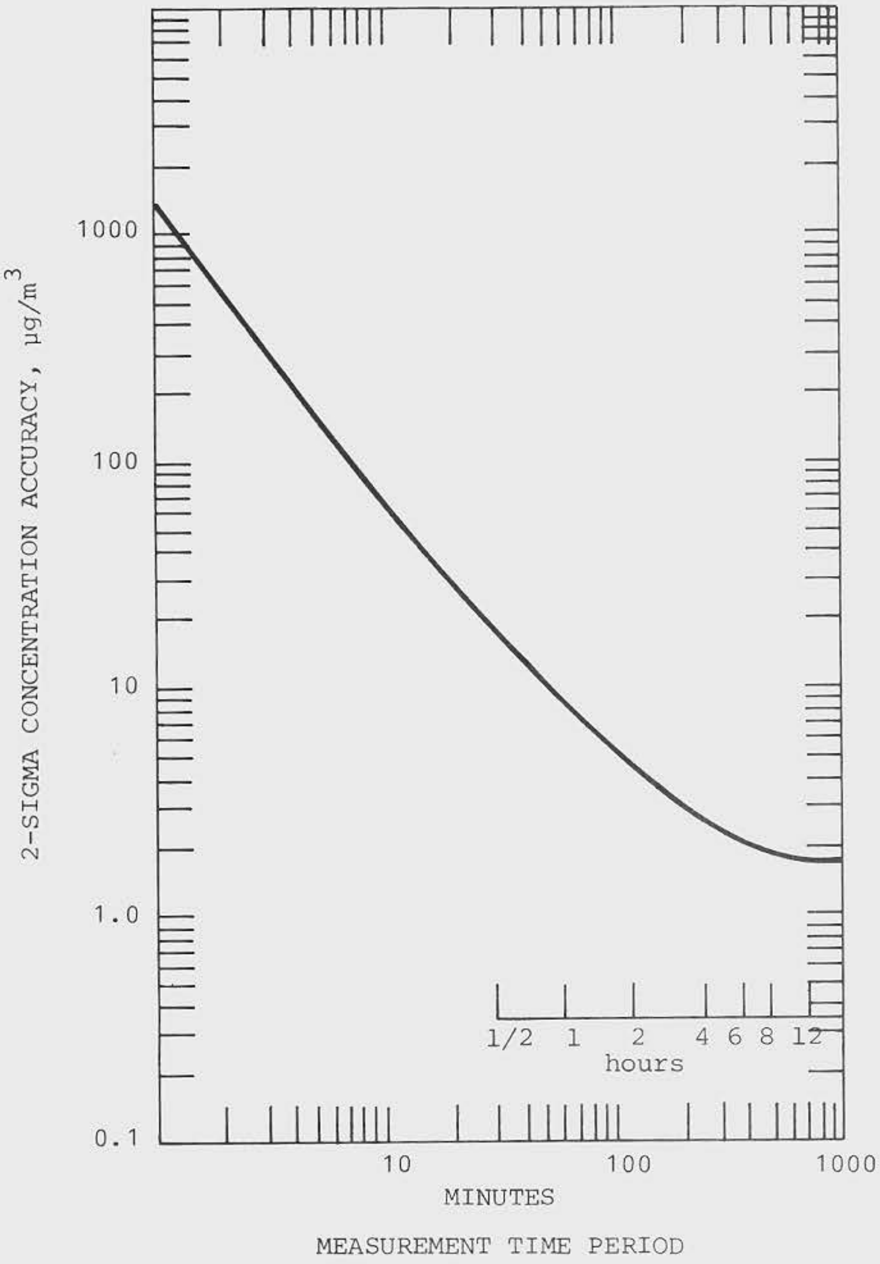

Figure 38. Aerosol Mass Monitor measuring error versus sampling time (from manufacturer's operating manual).

N = 18
INTERCEPT = 0.155
SLOPE = 0.949
R = 0.981

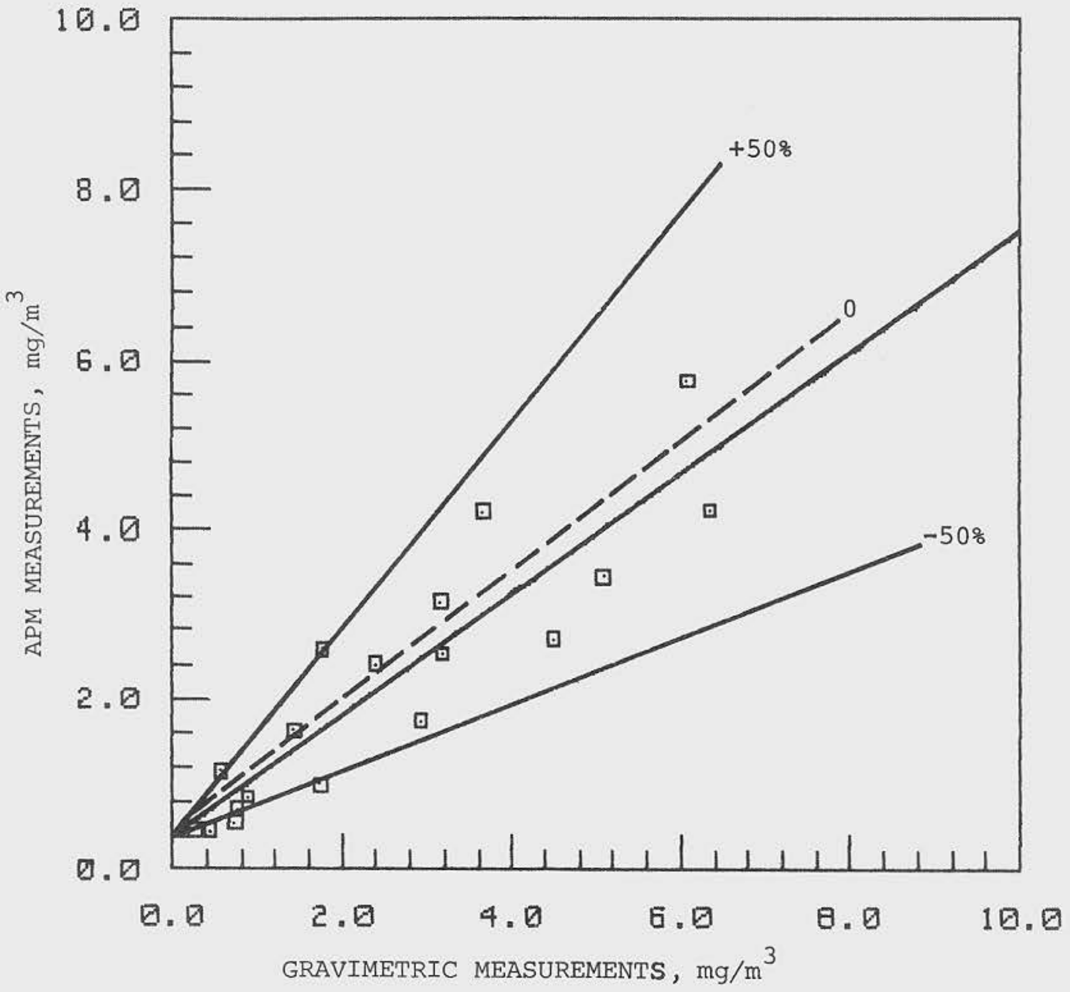

Figure 39. Comparison of Aerosol Mass Monitor and gravimetric measurements using a 5 minute measurement time.

required. For example, at a 5-minute measurement time (concentration accuracy ±150 $\mu g/m^3$) the lower detectable limit would be 1,500 $\mu g/m^3$ if ±10 percent accuracy were desired. The upper limit is determined by the amount of material needed to blind the filter tape and cause a reduction in air flow. Generally, the shorter the measurement time, the higher the maximum detectable limit will be.

Zero Drift

The APM has two zero test functions: static and dynamic. The static test evaluates the stability of the beta detector/sensor and associated electronic hardware. This is performed by taking repeated pre and post beta counts, without advancing the filter paper, over a period of time. The dynamic zero test is performed in a similar manner except that the filter paper is advanced so that any variation in the measurement due to the entire measurement sequence is included. The dynamic zero is referred to as the total error because it includes all factors which could produce drift and is reduced as the measurement time period increases. This is shown by the 2-sigma concentration accuracy curve presented in Figure 38. This curve indicates that, with a measurement time period of five minutes, the dynamic zero readings should fall within ±150 $\mu g/m^3$. Fifty dynamic zero measurements were made at the 5-minute measurement time and they were within the ±150 $\mu g/m^3$ limit, ranging from -102 to +90 $\mu g/m^3$. This indicated that the APM was functioning properly, within the manufacturer's design and specifications.

Malfunction Modes

Automatic monitoring of the four malfunction modes by the microprocessing system increases the overall reliability of the APM and helps prevent malfunctions from going unnoticed. The test unit was operated continuously for five weeks without any serious malfunctions occurring. The APM has incorporated within the microprocessor module an internal failure detection system which routinely inspects vital system functions for possible failures that would render the monitor inoperable. If a malfunction is detected, an alarm is activated and the condition is noted in the output for that time period. A summary of the malfunction modes, along with necessary maintenance requirements, is presented in Table 30.

Maintenance Requirements

The maintenance requirements necessary to insure accurate and reliable operation of the APM monitor are infrequent and easily performed. The only routine maintenance which must be performed regularly is changing the filter tape and the printing paper used in the output interface.

Economic and Installation Considerations

The high cost of the three module system and the inability to adapt more than one sensor module to a microprocessor makes the APM the most expensive

Table 30. Aerosol Mass Monitor malfunction mode and maintenance requirement summary.

Malfunction mode	Was the malfunction encountered during the evaluation	Effect on monitor	Detection method	Preventive maintenance	Maintenance frequency
Flow fault	Yes - due to overloading (aerosol concentration limit exceeded)	Reduction in sampled air flow rate	Automatic warning	--	--
Filter fault	No	No sample will be collected for analysis	Automatic warning	Replacement of filter tape supply at regular intervals	1 Filter tape role lasts for 5,000 measurements
Beta tube source/ detector failure	No	Mass measurements will be incorrect	Automatic warning	--	--
Printing paper failure	Yes	Output will not be recorded	Automatic warning	Replacement of printing paper at regular intervals	1 printer role lasts for approximately 2,000 printouts without diagnostic information
Vacuum pump failure	No	Reduction or loss in sampled air flow rate	Measure static pressure draw of pump	Inspection of vacuum pump	Every 2,000 hours of operation
Clogged critical flow orifices	No	Reduction in sampled air flow rate	Automatic warning	Inspection and cleaning of orifices	Whenever filter tape is replenished
Dirty control module ventilation fan	No	Inadequate control module ventilation	--	Inspection and cleaning of ventilation fan	Every 2 years or sooner in dusty environments

device tested for both single and multi-point operation. A summary of costs is presented in Table 31. High cost may make this instrument prohibitive on many return air monitoring applications. Because the microprocessor and pump modules can only be connected to one sensor, the total cost per monitoring point cannot be reduced by employing several sensors for multiple point monitoring and connecting them to a single microprocessor. The only method that could be employed for multiple point monitoring would be to have several sampling lines tied to a single sensor and sequentially sampled. This arrangement would be likely to cause measurement discrepancies due to probe and line losses.

Table 31. Price list for Aerosol Mass Monitor, January, 1980.

Component	Price
Single channel, 3 module unit.	$12,150
Two channel (total and respirable fractions) unit.	$13,300
Analog output board.*	$1,300

*An optional custom-made analog interface board can be obtained which will transmit the concentrations as analog signals and the APM status as open or closed relay signals. This system could be readily adapted to an alarm.

TAPE SAMPLER

PRINCIPLE OF OPERATION

A Model G1SE Filter Tape Sampler, manufactured by Research Appliance Company (RAC) was evaluated as part of this study. The tape sampler provides a qualitative measurement of particulate concentration by determining the attenuation of visible light through a spot where particulate material contained in the sampled air is deposited.

The tape sampler was selected for evaluation because of its low cost, operational simplicity and flexibility, and its ability to operate unattended for extended periods of time. A drawing of the tape sampler, showing all the major components, appears in Figure 40.

TEST DEVICE DESCRIPTION

A schematic diagram of the tape sampler appears in Figure 41. Air is drawn into the sensor chamber, where the filter tape is positioned, by an internal continuous duty vacuum pump. As the air passes through the tape, particulate material is deposited on the surface as a circular 2.54 cm (1 in.) spot. After a pre-set sampling period has elapsed, the filter tape is automatically advanced by the tape drive system to position a clean area of filter tape for the next sample.

To account for slight variation in the optical density of the filter tape, a potentiometer is provided to adjust the intensity of the light source. For continuous operation, this can be done automatically by employing an automatic standardization option. Both the light source and the detector are located outside of the sampled air stream to prevent contamination due to particles settling on the optical surfaces. A flow meter, mounted on the front panel, is provided for air flow rate adjustment. The output from the photocell detector is routed to an output jack located on the back of the unit. A fully automated tape sampler (Model 5000) is also available from RAC, which incorporates features such as computer interfacing and telemetry as well as alarm capabilities, making the unit easily adaptable to a variety of monitoring applications.

SPECIFICATIONS

Specifications provided by the manufacturer are presented in Table 32.

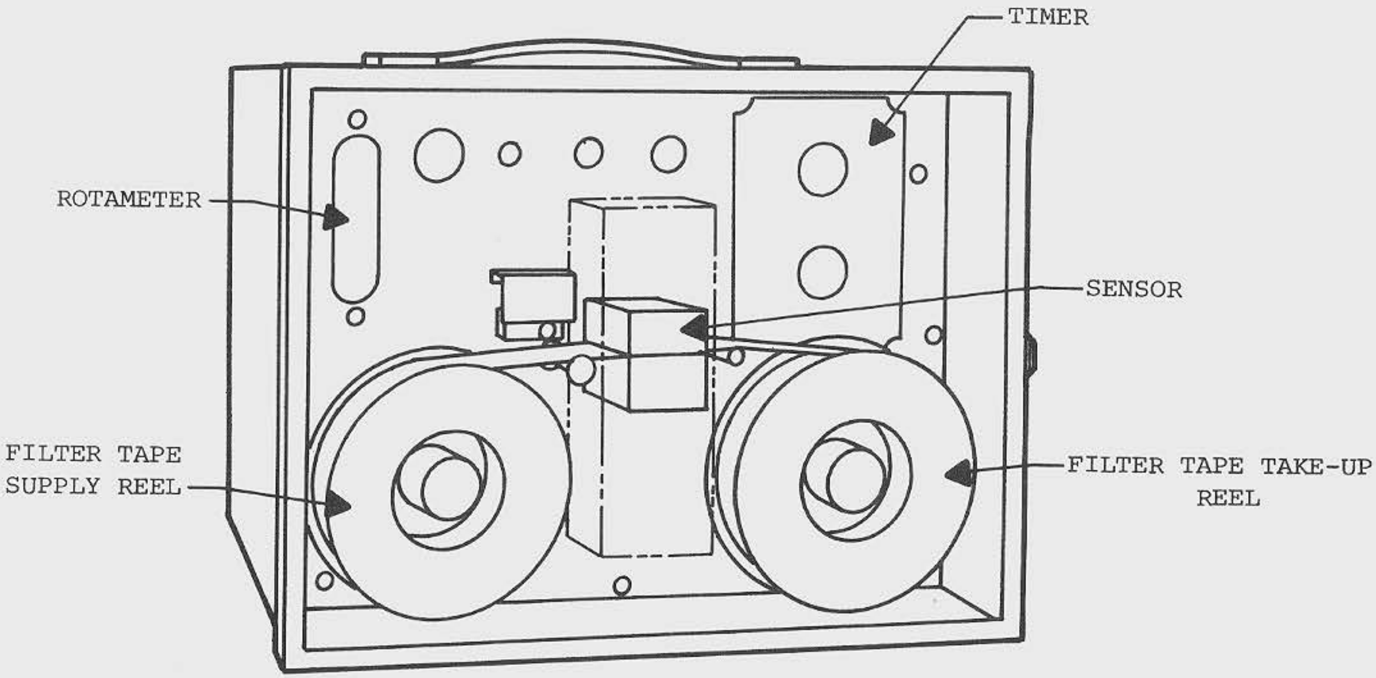

Figure 40. Drawing of Research Appliance Company Model G1SE Filter Tape Sampler.

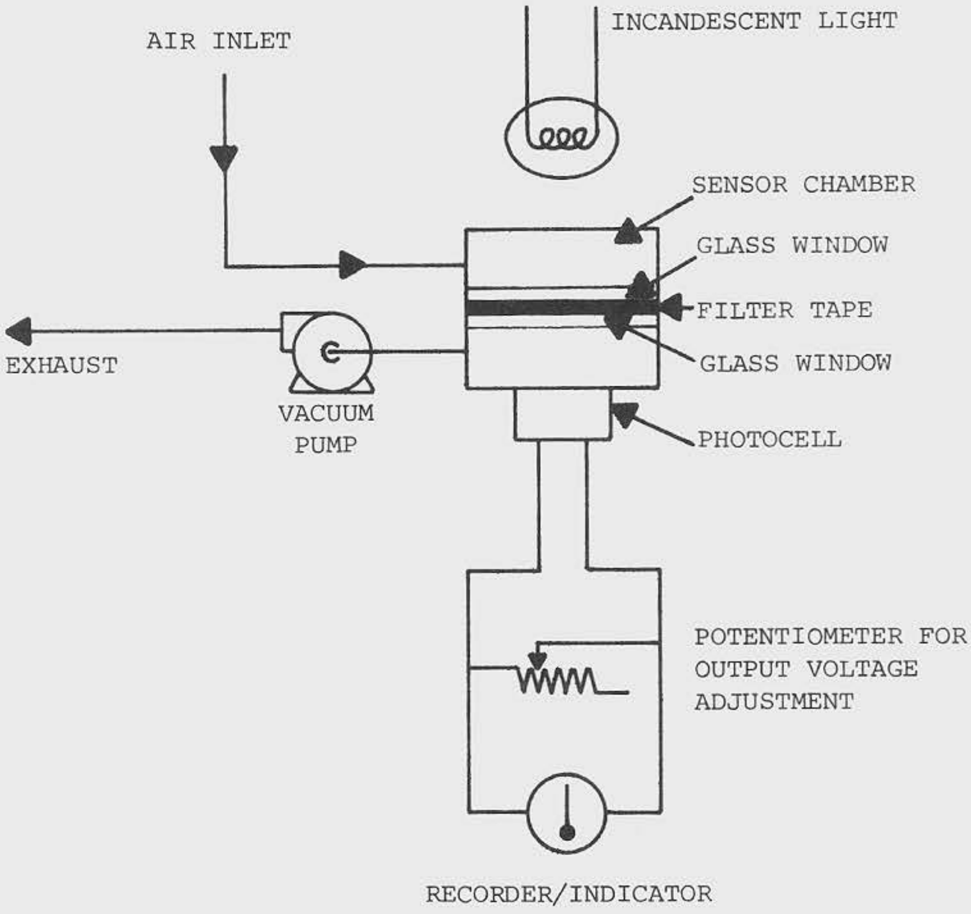

Figure 41. Schematic diagram of Research Appliance Company Model G1SE Filter Tape Sampler.

Table 32. Model G1SE Tape Sampler specifications.

Pump:	14.16 l/min (30 ft^3/hr) free flow.
Flow meter:	2.35 - 9.40 l/min (5 - 20 ft^3/hr).
Sampling cycles:	Standard: 10 min - 3.5 hrs Optional: 0.5 min, 1, 2, 4 hrs
Length of filter tape:	30.5 m (100 ft) Model G2-T-600 will accept 183 m (600 ft) rolls.
Number of samples per roll:	30.5 m, 5 cm center - 600 30.5 m, 3.2 cm center - 960 183 m, - 5 cm center - 3600
Filter tape type:	RAC no. 4, 3.4 micron pore size.
Environmental limitations:	None listed.
Size:	37 cm (14.5 in.) wide x 28.5 cm (11.25 in.) high x 30.5 cm (12 in.) deep.
Weight:	4 kg (8.8 lb).
Output:	0 - 100 mv

EVALUATION RESULTS

Measurement Accuracy

The results of this evaluation indicate that the tape sampler output, in terms of percent transmission of light through a filter spot, can be calibrated against a gravimetric sampling method to provide information in terms of mass concentration. However, this calibration relationship could be altered substantially if:

1. The aerosol being monitored changed in composition, size distribution, or color.

2. Components within the sensing chamber were replaced, such as the light source or photocell.

3. Sampling air flow rate changed.

4. The concentration of the sampled aerosol was outside the range of calibration.

For example, during the course of this evaluation, changes in operating conditions were found to cause large variations in the tape sampler's response. By performing a small amount of arc air gouging, it was found that, on a mass basis, the darker fume generated by the arc air process produced more light attenuation than did the stick welding normally being performed. Since most industrial processes are subject to some variation, the tape sampler would be best suited to providing a qualitative rather than a quantitative indication of air quality, as it was originally intended for.

Tape Sampler Output Interpretation--

The output information provided by the tape sampler is in the form of an analog signal proportional to the amount of light transmitted through the filter tape. As aerosol material is collected on the filter, the light transmission diminishes. An example of the actual output is shown in Figure 42. As can be seen, the total decrease in percent transmission is made up of a series of decreases with varying slopes. The slope is a function of the aerosol concentration being measured at any instant in time; higher concentrations result in steep slopes, lower concentrations in shallow slopes. The percent transmission at any point in time does not provide the observer with the necessary information for assessing the aerosol concentration, rather the change in percent transmission over some period (slope) does.

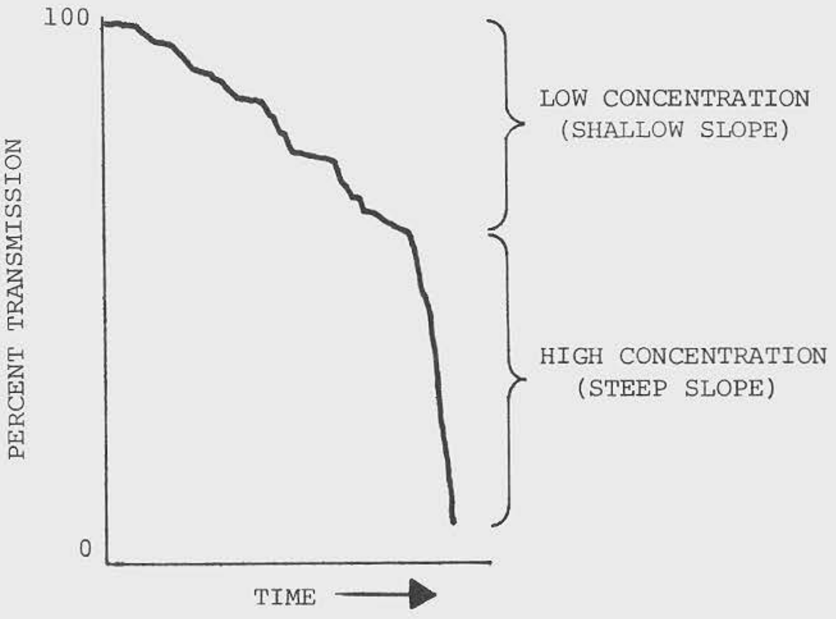

Figure 42. Tape sampler output.

Determination of an Action Level--

Two methods could be employed to determine if the output from the tape sampler is exceeding an action level. One method would involve electronically differentiating the output signal to determine its slope, which, when compared to a calibration curve, would give a measure of the particulate concentration. This would require the use of electronic equipment capable of performing a differentiating operation.

Another way of interpreting the output would be to determine the amount of decrease in transmittance during a set sampling time (say 30 minutes) and comparing that amount to a preset transmittance level. The Model 5000 is equipped with an alarm system which is capable of this type of response. Both of these methods would require that the output be calibrated using a procedure similar to the one employed in this evaluation.

Calibration Results--

The results of this study, conducted under steady-state conditions, indicate that the output from the tape sampler can be related to a mass concentration to within ±10 percent in the 1 to 5 mg/m^3 aerosol concentration range. This was determined by fitting a quadratic model* to the paired measurements and determining the percentage difference between the concentration predicted by the model and what was actually measured gravimetrically. The results are shown graphically in Figure 43. The data were generated by drawing 210 l (7.5 ft^3) of air through a clean filter spot and determining the change in percent light transmission. The decrease in percent light transmission, calculated in terms of percent decrease per ft^3 of air sampled, were then plotted against simultaneous gravimetric measurements.

Measurement Range

The tape samplers available from RAC have options for either a low (0.1 to 1 ft^3/min) or high (0.2 to 2 ft^3/min) sampling flow rate which, coupled with selectable sampling times between 10 minutes and four hours, would provide the potential for a large concentration measurement range, from a few micrograms to several milligrams. However, the exact range would be dependent upon the characteristics of the aerosol being sampled.

Zero Drift

Various changes in the operation of the tape sampler, such as switching the tape sampler on and off and changing filter tapes, were found to alter the initial transmittance by as much as 10 percent. Employing the optional automatic standardization (standard on the Model 5000) would assure 100 percent light transmission at the beginning of each sampling period. If a differentiating signal processor were employed, changes in the initial transmittance reading would be less critical since the change in transmittance with time (slope) would be the warning signal, rather than the actual transmittance value.

Response Time

The response time of the tape sampler is rapid. Because the analog signal is constantly changing as particulate material collected on the filter tape obstructs light, any change in aerosol concentration causes an instantaneous change in the slope of the output signal. The only time lag would be aerosol transport time within the probe and sampling line.

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*Of several methods tried, the quadratic model fit the data best.

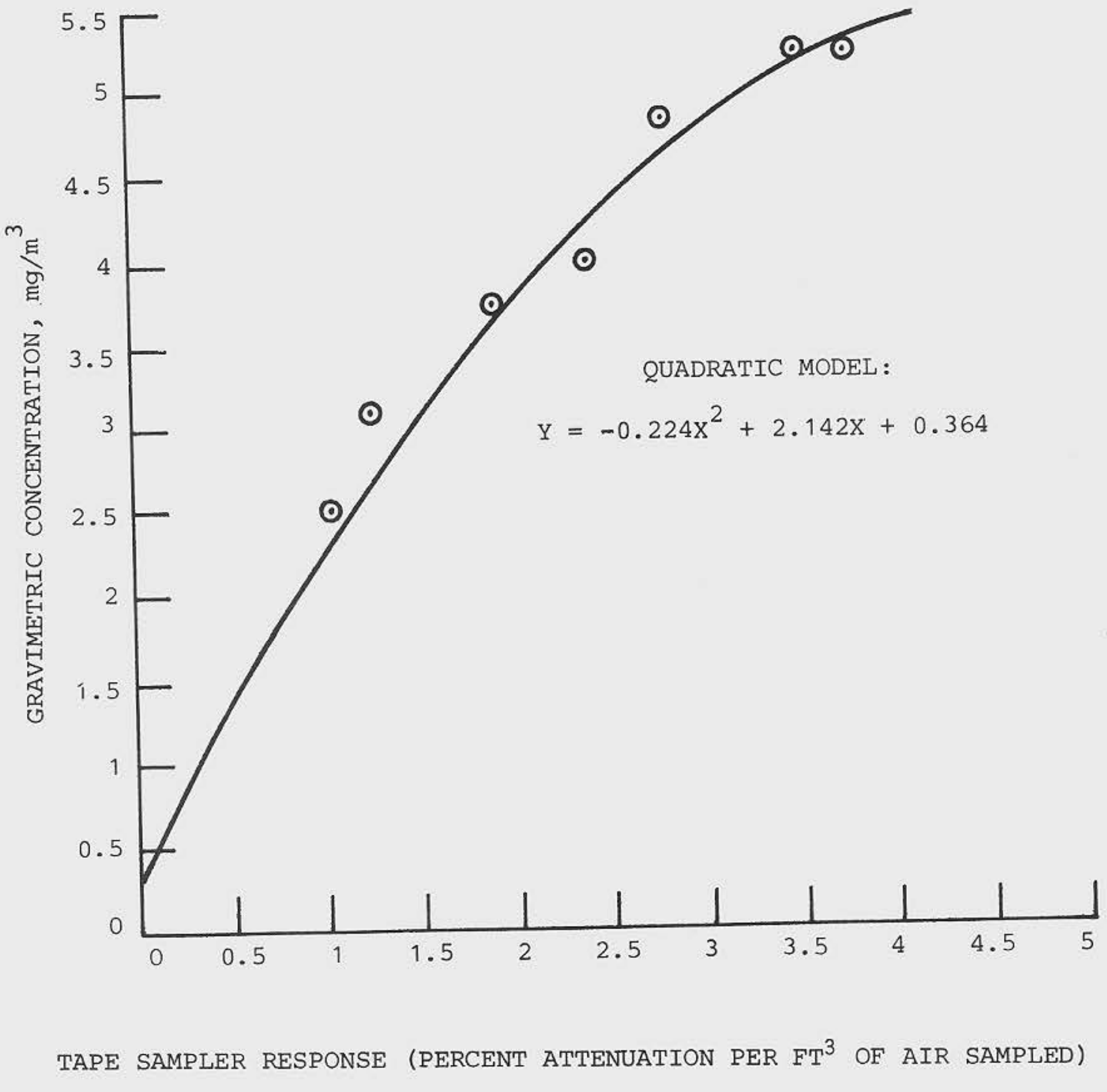

Figure 43. Tape Sampler output vs. gravimetric measurements using quadratic model.

Table 33. Tape Sampler malfunction modes and maintenance schedule summary.

Malfunction mode	Was the malfunction encountered during the evaluation?	Effect on monitor	Detection method	Preventive maintenance	Maintenance frequency
Light source failure.	No	Output would drop to zero.	Visual inspection.	Replacement of light source on routine basis prior to failure	Not known but could be determined from experience.
Depletion of filter tape.	No	Output would remain at 100%.	Visual inspection.	Routine replacement of filter tape.	100 ft standard role lasts for 600 samples.
Dirt buildup on sensor windows.	No	Zero drift.	Zero checks.	Manually clean sensor windows as needed.	As needed, more often in dirty operating environment.

Table 34. Tape Sampler maintenance procedures and schedule.

Task	Method	Schedule
Replace filter tape	Manual	30.5m (100 ft) roll, 5.1 cm (2 in.) center - 600 samples 30.5 (100 ft) roll - 3.2 cm (1.25 in.) center - 960 samples 183 m (600 ft) roll, 5.1 cm (2 in.) center, 3600 samples
Calibration	Gravimetric or other mass specific method	Whenever a parameter changes which could effect the calibration as stated in the text.
Clean sensor windows		As needed.
Clean filter jars	Removed and cleaned with any mild cleaning fluid, and dried.	Every 6 mo. or more often in dirty environment.
Lubricate and inspect take up spool and pump motors.	Lubricate with electric motor oil.	Once per year.

Malfunction Modes and Maintenance Requirements

Three malfunction modes were identified which could disrupt the proper operation of the tape sampler. These, along with necessary preventive maintenance procedures and schedules which would be effective in preventing malfunctions, are presented in Table 33. None of these failures were encountered during the course of these evaluations. All of the maintenance procedures necessary to assure reliable operation of the tape sampler are easily performed and are not required on a frequent basis. A summary of the needed tasks and recommended schedule is provided in Table 34.

Economic and Installation Considerations

The list price of the Model G1SE is $1,122.00 FOB Cambridge,Maryland, September, 1979. The Model 5000, including automatic standardization and an integral alert/alarm system, costs $2,975.00. The low cost and flexibility of application afforded by the standard and optional features make the tape sampler an attractive choice, provided that the output signal is made more useful by appropriate signal conditioning.

Although the manufacturer does not offer a multi-point option, multiple point monitoring using the model G1SE and connecting the outputs to a common signal processor would be inexpensive.

REAL-TIME AEROSOL MONITOR (RAM)

PRINCIPLE OF OPERATION

The Model RAM-1 manufactured by GCA/Environmental Instruments is a portable, self-contained, aerosol monitor. It measures either total or respirable particulate concentration, depending on whether an inlet cyclone is used, although it probably would not be able to accurately measure larger particles*. A photograph of the unit installed for testing appears in Figure 44.

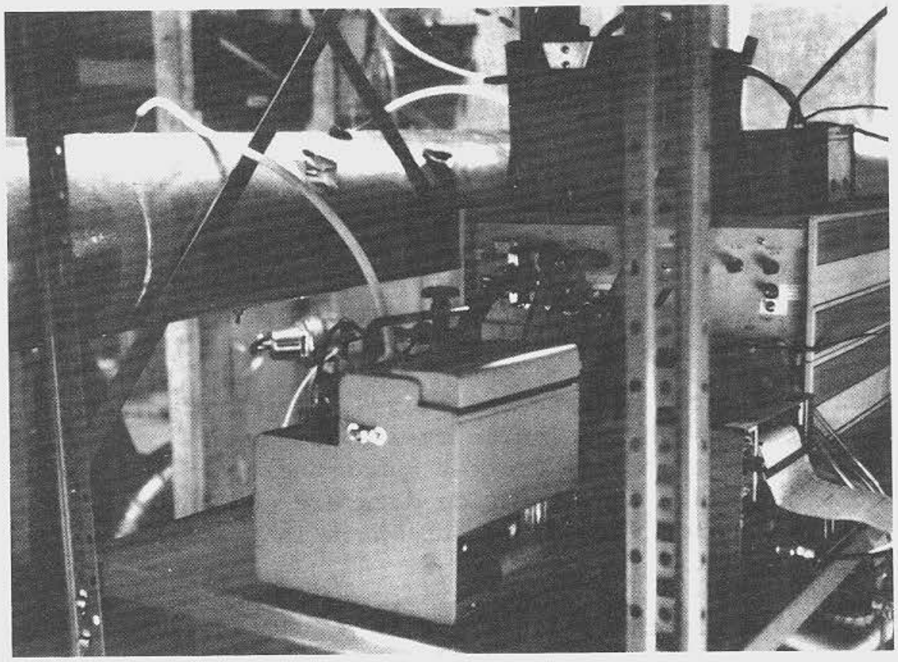

Figure 44. Photograph of the portable Real-time Aerosol Monitor installed for testing. RAM device is located in the foreground with sampling line and probe to the left.

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*Light scattering instruments are typically insensitive to particles larger than 20 micrometers in diameter.

Aerosol concentration is sensed using a principle based on the detection of near-forward scattered light in the near-infrared region. The light source is produced by a pulsed semiconductor light-emitting diode which generates a narrow-band emission centered at 940 nm. The light, scattered by the particles contained in the sampled air stream, is detected by a solid state detector employing an integral low noise preamplifier. The signal produced by the photo-diode detector is processed by state-of-the-art electronic circuitry which reduces drift and noise.

TEST DEVICE DESCRIPTION

A schematic diagram of the air flow system is shown in Figure 45. An air sample is drawn through the optical sensing section of the instrument at a rate of 2 l/min by a double diaphragm pump. At the same time, a secondary, clean (purge) air stream is drawn through the optical assembly, which allows for continuous flushing of the optical surfaces with clean, dry air. This helps to keep the optical surfaces dry and free of particulate material which would distort the signal. The zero reading of the instrument is checked by closing the inlet valve and drawing purge air through the optical chamber. Flow meters are provided for continuous monitoring of the total and purge air flows.

The calibration constant which defines the relationship between the detector output and the digital reading of mass concentration can be adjusted to account for variations in the light scattering characteristics of different aerosols. For example, if simultaneous gravimetric measurements indicated that, on the average, the RAM output was 50 percent lower than the gravimetric measurements for a particular type of aerosol, the calibration constant could be doubled to compensate.

The instrument has three measurement ranges (see manufacturer's specifications, Table 35) for high resolution over a wide range of concentrations. The range and amount of signal scatter can be selected by choosing one of four time constants. Concentration data are continuously displayed in addition to an analog voltage output which is proportional to the aerosol concentration.

Two warning signals are included in the display: a flashing letter "R", which indicates that the reference scatterer used for calibration purposes is inserted, and a flashing "VDC" which alerts the operator of a low battery charge condition during portable operation.

The basic RAM-1 sensor can be employed as part of a multi-point monitoring system designated as the RAM-S, also available from GCA. This system, depicted in Figure 46, consists of a network of RAM sensors at different locations interconnected to a central data acquisition and logging station.

Features incorporated in the multi-point system include alarms for:

1. Sensor malfunction.
2. High particulate concentrations exceeding a preset level.
3. High rate of concentration change exceeding a pre-selected rate of change.

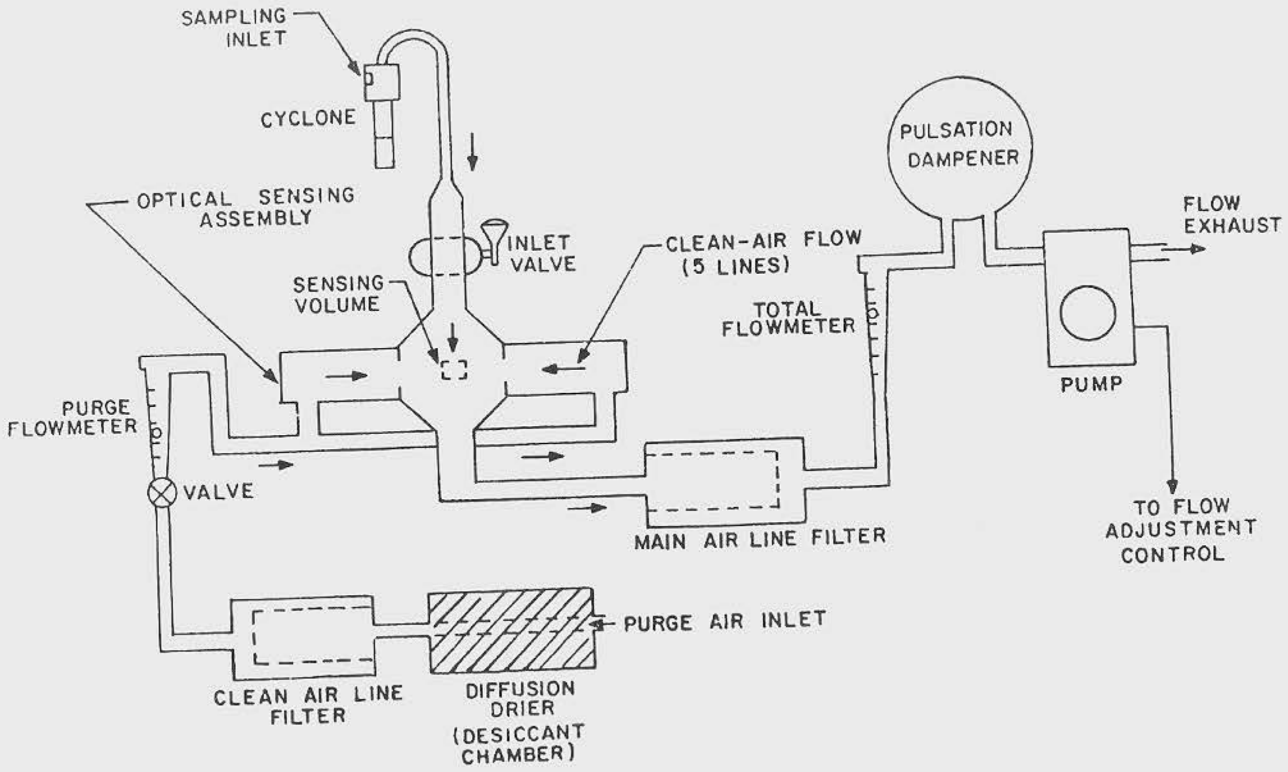


Figure 45. Schematic diagram of the Real-time Aerosol Monitor air flow system. (From manufacturer's instruction manual).

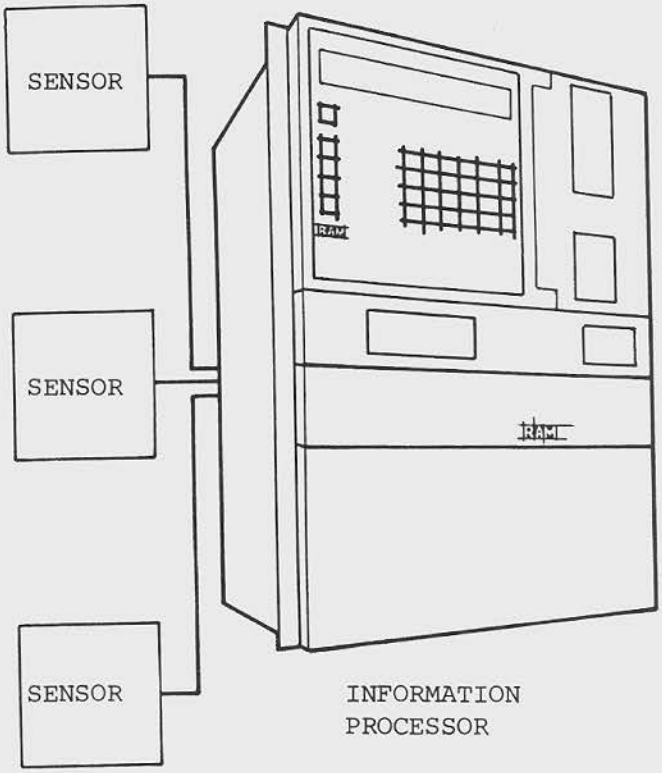


Figure 46. Real-time Aerosol Monitor multi-point monitoring system.

SPECIFICATIONS

Manufacturer's specifications are presented in Table 35.

Table 35. Real-time Aerosol Monitor specifications.

Measurement ranges:	0 - 2, 20, 200 mg/m^3
Measurement time constants:	0.5, 2, 8 and 32 sec.
Display update rate:	3/sec.
Air sampling flow rate:	2 l/min (4.24 ft^3/hr)
Particle size collection range:	Total or respirable (if cyclone is used).
Environmental limitations:	Temperature: 0 - 50°C (32 - 122°F) Humidity: 0 - 95%, uncondensing
Size:	20 cm (7.9 in.) high x 20 cm (7.9 in.) wide x 20 cm (7.9 in.) deep
Weight:	4 kg (8.8 lb)
Power supply:	115 VAC or 6 hrs portable operation using internal battery.
Output:	0 - 10 V analog

EVALUATION RESULTS

Measurement Accuracy

Comparing RAM measurements with gravimetric and piezobalance measurements indicated that the RAM accuracy was approximately ±10 percent in the range of 0.02 - 5 mg/m^3. Comparisons between 30-minute gravimetric measurements and RAM measurements were made in the 1 - 5 mg/m^3 range and between 2-minute piezobalance measurements and RAM measurements in the 0.02 - 0.40 mg/m^3 range.

All of the comparative measurements were made with the monitor's calibration set at the factory value of 2.5. The light-scattering sensing method employed by the RAM appeared to be insensitive to changes in particle size distribution and composition as evidenced by the fact that a calibration setting of 2.5 used for Arizona road dust also provided accurate measurements for welding fume.

Gravimetric Comparisons--

Gravimetric and RAM measurements agreed very well; six of the seven measurement pairs were within ±20 percent limits (Figure 47). About 12 percent of the difference can be attributed to the RAM. Linear regression analysis indicated a linear relationship and minimal scatter. More paired measurement points would be necessary to draw strict statistical conclusions,

N = 7
INTERCEPT = 0.183
SLOPE = 0.880
R = 0.909

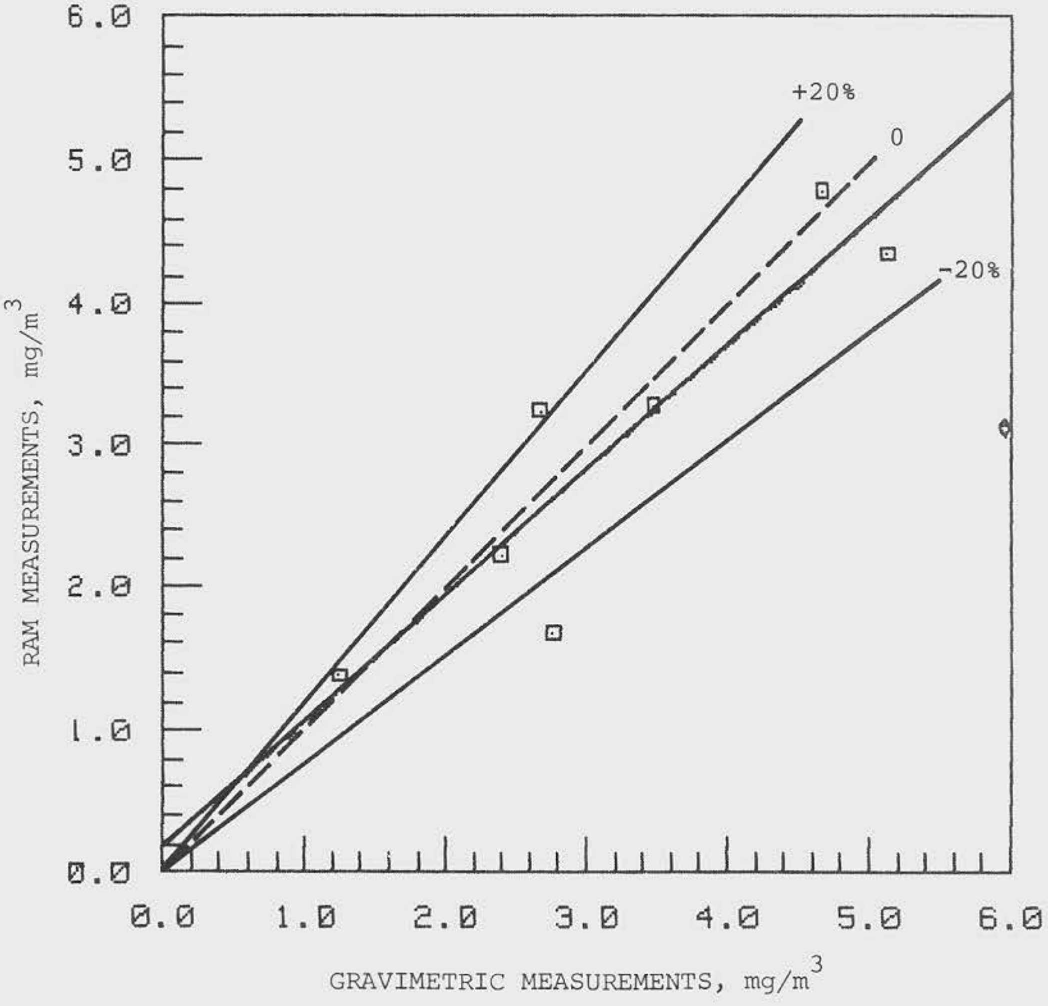


Figure 47. Comparison of Real-time Aerosol Monitor and gravimetric measurements.

however, these data do provide a relative indication of the RAM's accuracy in the 1 to 5 mg/m^3 concentration range. The number of measurements was limited due to a technical problem that developed with the test unit.

Piezobalance Comparisons--

The concentration measured by the piezobalance and the RAM also agreed very well (Figure 48). There was minimal scatter of the data around the regression line and the data was linear. Almost all of the data was within ±20 percent limits. About half of the error could be attributed to the piezobalance, leaving approximately ±10 percent attributable to the RAM.

Measurement Range and Sensitivity

The measurement range specified by the manufacturer is 0 to 200 mg/m^3. In this study, it was found to have been capable of accurately measuring concentrations as low as 40 µg/m^3. The noise level is approximately ±0.005 mg/m^3 at a 2-second time constant and ±0.002 mg/m^3 at a 32-second time constant. The readout resolution is given as follows:

0.001 mg/m^3 on the 0 - 2 mg/m^3 scale
0.01 mg/m^3 on the 0 -20 mg/m^3 scale
0.10 mg/m^3 on the 0 - 200 mg/m^3 scale

Zero Drift

Zero drift was found to be minimal when the instrument was operated continuously over a five day testing period with the RAM sampling air containing both high and low aerosol concentrations (0.02 to 18 mg/m^3).

These results indicate that:

1. The purge air system is an effective method of keeping the critical optical surfaces clean.

2. The lock-in synchronous scheme is effective in reducing circuitry drift and noise.

The manufacturer's specifications indicated that the maximum zero drift should not exceed 0.1 percent or 0.005 mg/m^3, whichever is greater, in a 24-hour period. The results of this study indicate that the device met this criterion. It was operated continuously for five days with low inlet concentrations and for one day with a high inlet concentration with no significant change in the zero reading (Table 36). All of the fluctuations recorded were less than 0.005 mg/m^3.

Response Time

In effect, even with the longest selectable time constant, detection of a rise in aerosol concentration is almost instantaneous. The digital display is updated three times per second. Four time constants can be selected; 0.5, 2, 8 and 32 seconds. Each increasing step of the time constant reduces internal noise fluctuations by 50 percent. More stable readings

N = 23
INTERCEPT = 0.018
SLOPE = 0.816
R = 0.975

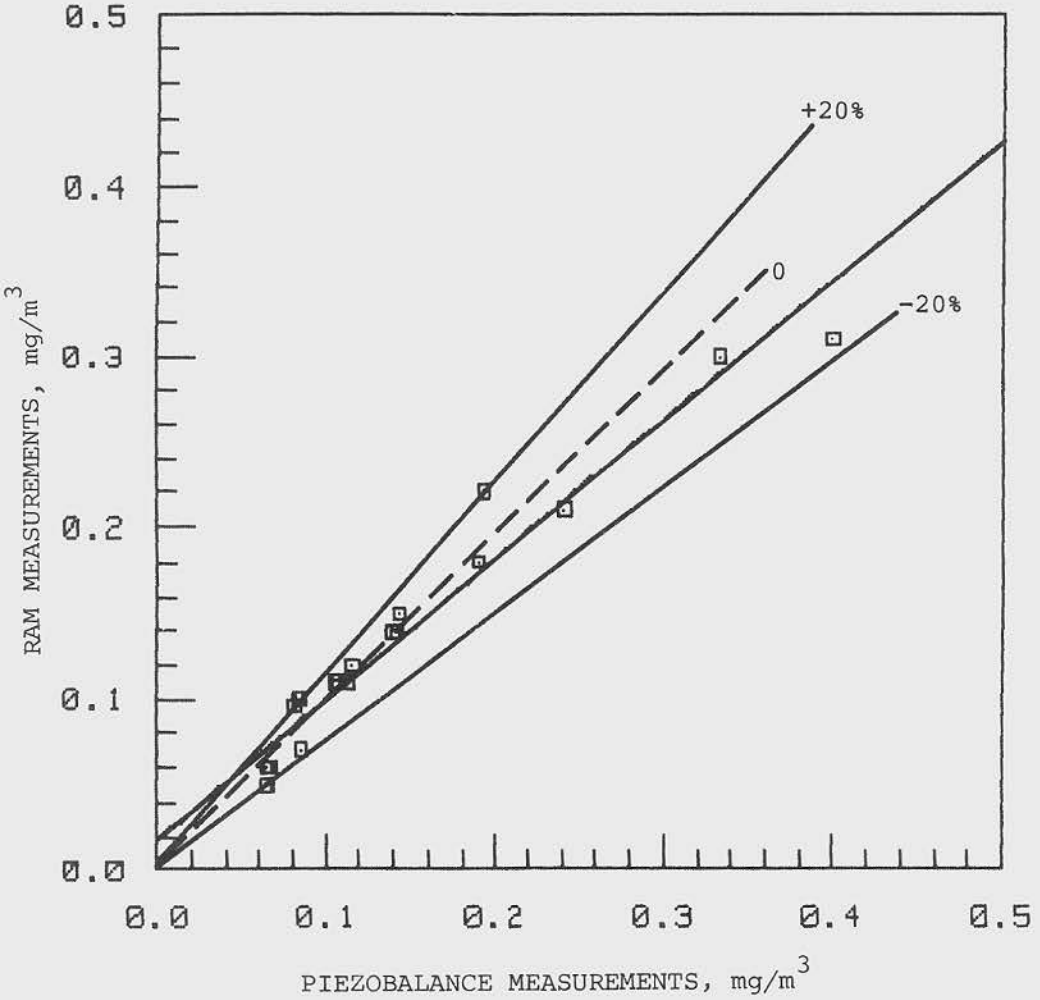


Figure 48. Comparison of Real-time Aerosol Monitor and Respirable Aerosol Monitor (piezobalance) measurements.

Table 36. Real-time Aerosol Monitor zero drift data.

Sample concentration: 0.020 - 0.060 mg/m^3
Measurement range: 0 - 2 mg/m^3
Time constant: 2 sec
Calibration: 2.5

Date, 1979	Time	Zero fluctuations range, mg/m^3	Manufacturer's specified range, mg/m^3
10/25	9:00AM	-0.003 to +0.004	±0.005 $\mu g/m^3$
10/26	8:30AM	-0.004 to +0.003	
10/29	11:00AM	-0.004 to +0.003	
	1:15PM	-0.005 to +0.005	
10/30	8:30AM	-0.005 to +0.003	
	12:45PM	-0.004 to +0.003	

Sample concentration: 5 - 18 mg/m^3
Measurement range: 0 - 20 mg/m^3
Time constant: 2 sec
Calibration: 2.5

10/31	10:00AM	-0.00 stable	±0.020
	11:50AM	-0.00 stable	
	2:45PM	-0.00 stable	
11/1	8:20AM	-0.00 stable	
	11:30AM	-0.00 stable	

are obtained if a longer time constant is chosen, however, the ability to detect rapid changes in concentration is lessened with a longer time constant. This principle applies to both the digital and analog outputs.

Malfunction Modes and Maintenance Requirements

Two preventable malfunctions can occur that would affect the accuracy of the RAM measurements, as summarized in Table 37. Both of these are identified by the manufacturer in the operating manual, but neither was encountered in the course of these evaluations. Neither air flow rates nor filter blinding are monitored automatically by the RAM (air flow rates may be visually monitored) and there are no warning alarms except for low battery and reference scatter. The RAM system incorporates a malfunction monitoring function which sounds an alarm if the analog output deviates from preset boundaries. For example, if the electrical power to the sensor were disrupted, the analog voltage would drop to zero which would cause the alarm

Table 37. Real-time Aerosol Monitor malfunction mode and maintenance summary.

Malfunction mode	Was the malfunction encountered during the evaluation?	Effect on monitor	Method of detection	Preventive maintenance	Maintenance frequency
Dirty or maladjusted optics.	No	Shift in the zero and calibration.	Zero-internal zero check. Calibration-internal reference scatter or reference method.	Check zero and calibration.	90 days
Main air or clean air filters become blinded.	No	Drop in air flow rate causing a shift in the calibration.	Visual check of flowmeters (should be performed every 30 days).	Replace air line filters.	As needed, when flow rate drops by 10% or more. Yearly replacements are predicted under most operating conditions*

*Manufacturer indicates that the filter will hold approximately 200 mg of material. Replacement schedule would be dependent upon the particulate concentrations being measured, with higher concentrations requiring more frequent replacement.

to sound. The maintenance requirements needed to assure accurate and reliable operation of the RAM monitor are relatively infrequent and simply performed. A summary of the needed procedures and a recommended schedule is also provided in Table 37.

Economic and Installation Considerations

The list price of a portable RAM was $4,500, FOB Bedford, Massachusetts, as of December, 1979.

A RAM system, designed for multi-point monitoring incorporates various alarm and telemetry capabilities which the portable RAM tested does not have. These include:

Sensor failure alarm.

High level alarm (i.e., when aerosol concentration exceed a pre-selected value at any given sensor station).

Rate of change alarm (i.e., if the concentration varies more rapidly than a pre-selected rate of change at any given sensor).

Printer and digital display.

Battery powered back-up system to preserve data and program information in case of a power failure.

A graph, showing the cost per point for a RAM system as a function of the number of points monitored is presented in Figure 49. The cost per point ranges from approximately $5,100 for five points to $2,200 for sixty points.

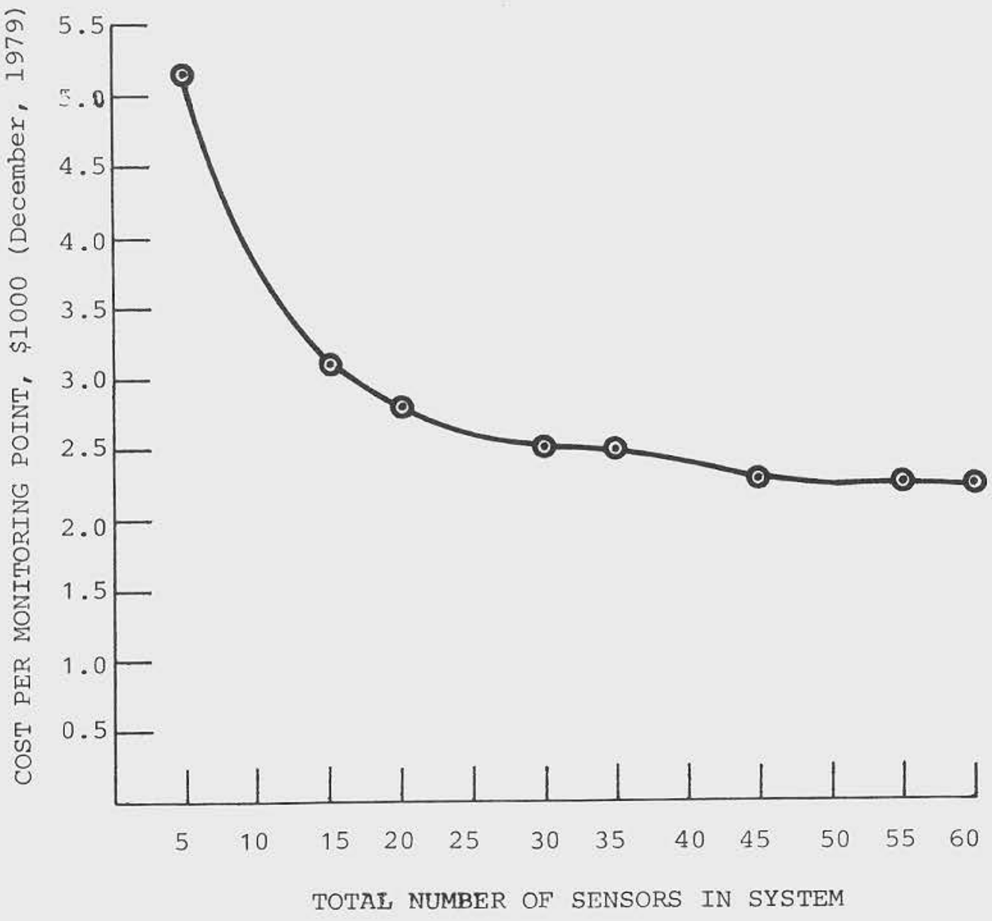


Figure 49. Real-time Aerosol Monitor system costs per monitoring point for a multi-point monitoring system.

ULTRAVIOLET OZONE MONITOR (UV)

PRINCIPLE OF OPERATION

The UV ozone monitor is a self-contained instrument which measures gaseous ozone concentrations by means of ultraviolet light absorption. This detection method is based on the principle of ultraviolet light absorption by the ozone molecule. The degree to which the intensity of the light is attenuated by ozone present in the air sample is described by Beer's law:

$$I = I_o \text{ exp. } (-xLc)$$

Where: I = Light intensity at higher ozone concentration.
I_o = Light intensity at lower ozone concentration.
c = Concentration differences.
L = Path length.
x = Specific absorption coefficient.

The UV method is advantageous because it is not affected by:

1. Presence of other gases, provided their concentration does not change.
2. Air flow rate.
3. Temperature and pressure changes.

In addition, no expendible reagents are required for operation, which allows the UV to operate unattended for long periods of time.

Test Device Description

A photograph of the UV installed for testing appears in Figure 50. Figure 51 is a schematic diagram showing all of the major components and the air flow path during different times in the operating cycle.

To reduce zero drift and improve measurement stability, the UV incorporates an automatic zeroing technique referred to as a zero reference. This is accomplished by drawing an air sample through a catalytic converter to remove any ozone and then drawing the air into the sensing chamber where the UV light attenuation is measured. An electronic circuit then adjusts the UV light intensity to match a preset value of light intensity, I_o. The ozone-containing sample is then drawn into the sensing chamber, light intensity, I, is determined, and the ozone concentration is calculated by the electronic signal processor and displayed digitally. The zeroing phase lasts approximately 20 seconds and the measurement phase 60 seconds, resulting in a total measurement time of about 80 seconds.

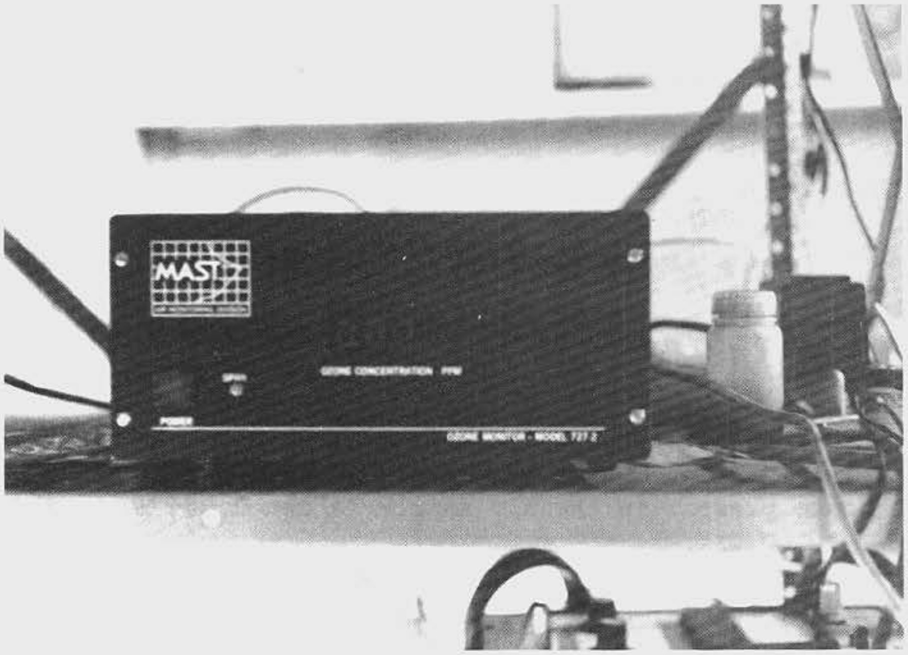


Figure 50. Photograph of Ultraviolet Ozone Monitor installed for testing.

SPECIFICATIONS

Operational specifications provided by the manufacturer are listed in Table 38.

Table 38. Ultraviolet Ozone Monitor specifications.

Measurement range:	0 - 9.99 ppm
Incremental sensitivity:	0.01 ppm
Accuracy:	±4%
Flow rate:	2 l/min
Response time:	90% rise and fall time - 10 sec.
Environmental limitations:	Temperature - 0 - 50°C (32 - 122°F)
Size:	28 cm (11 in.) wide x 15 cm (6 in.) high x 58 cm (23 in.) deep
Weight:	7 kg (15 lb)
Output:	Digital display - 0 - 9.99 ppm Analog 1 mv per 0.01 ppm std. Adjustable to 10 mv per 0.01 ppm
Cost:	$2,500 - January 15, 1980

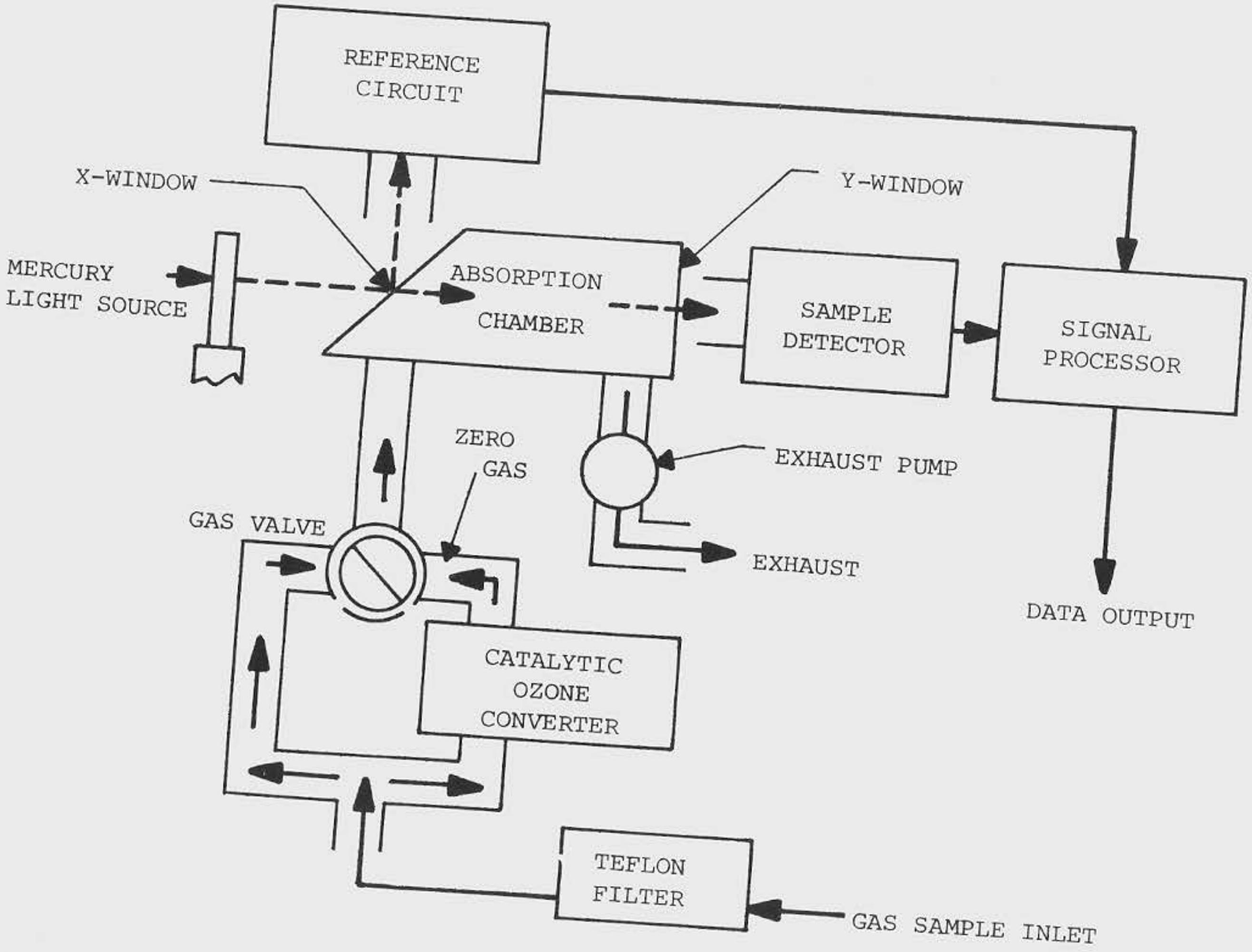


Figure 51. Ultraviolet Ozone Monitor schematic diagram (from manufacturer's instruction manual).

EVALUATION RESULTS

Measurement Accuracy

After being adjusted and calibrated, the response of the UV monitor was found to be linear and stable over a four day test period with the measurements made by the UV being exactly equivalent to the AID measurements. These comparisons were made with a teflon prefilter used to remove particulate material from the sampled air.

When the instrument was first operated at the test site, an inlet air filter was not used. This did not seem to effect the instrument's operation when air was sampled out of the air cleaner's exhaust where aerosol concentrations were extremely low (20 to 80 $\mu g/m^3$). However, it was found that when ambient air from within the testing room was sampled, the light level had to be readjusted almost immediately to compensate for contamination of the optics. Aerosol concentrations in the room air ranged from 2 to 5 mg/m^3 when this phenomenon was observed. The manufacturer suggested that a prefilter be used if aerosol concentrations exceed 500 $\mu g/m^3$, which, from the experience of this evaluation, seems reasonable.

To determine the effect of the teflon prefilter, several measurements were made with and without the prefilter attached to the AID monitor, while sampling air containing a constant concentration of ozone produced by the ozone calibrator. These checks were performed with filters preconditioned with 1 ppm ozone concentration for 30 minutes and with new, unconditioned filters to see if there was a difference. The measurements made under these various conditions are presented in Table 39.

Table 39. Ozone attenuation by teflon prefilter.

Measured concentration without prefilter, ppm	Measured concentration with conditioned prefilter, ppm	Measured concentration with unconditioned prefilter, ppm
0.14	0.12	0.11
0.025	0.020	0.018

Tests were also conducted with teflon filters loaded with fresh welding fume. These results are presented in Figure 52. As can be seen, fresh welding fume further reduces the ozone concentration. The amount of time needed for the fume to completely react and the ozone measurement to reach the actual inlet ozone concentration is a function of the amount of fume on the filter.

These results indicate that the use of a teflon prefilter reduces ozone concentration, even if the prefilter is preconditioned with a high concentration of ozone. Depending upon the rate that the fume is deposited on the

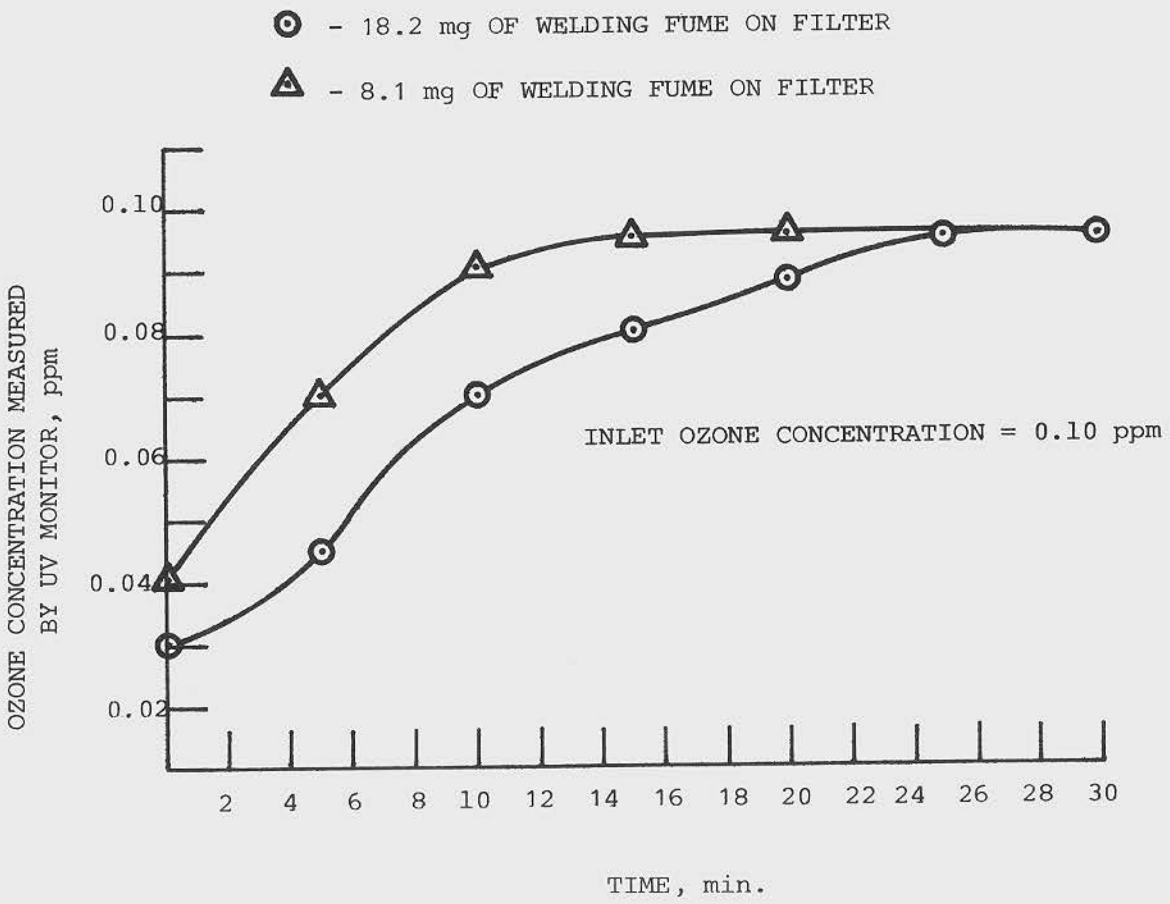


Figure 52. Ozone attenuation by teflon prefilter loaded with fresh welding fume.

filter, reaction of collected fume with the ozone-containing air may also produce artifically low readings.

The results of these tests indicate that if a prefilter is employed, the following procedures should be followed to insure measurement accuracy:

1. The prefilters should be preconditioned with air containing high ozone concentrations (1 ppm for at least 30 minutes).
2. The ozone monitor should be calibrated with a preconditioned filter in place.
3. The filter element should be changed often to prevent accumulated material from reducing ozone concentration measurements.

Measurement Range

The measurement range as provided by the manufacturer is 0 - 9.99 ppm with a lower detectable limit of 0.01 ppm.

Zero Drift

When using a teflon prefilter, the UV monitor was operated for 14 days without any shift in the zero reading adjustment. This indicates that the automatic zero adjustment is an effective means of preventing zero drift.

If the teflon prefilter was not used and air was sampled containing welding fume concentrations in excess of 2 mg/m^3, the optical system would become contaminated almost immediately and the light level would require re-adjustment. Zero drift was assessed by drawing sample air through an activated charcoal filter and recording the instrument output.

Response Time

Response time of the UV is near instantaneous as specified by the manufacturer with 90 percent rise and fall times reported as 10 seconds.

Malfunction Modes and Maintenance Requirements

Two general types of malfunctions were identified that could disrupt operation of the UV ozone monitor: light level maladjustment and failure of a component having a limited service life. Both malfunctions could be prevented by regular inspection, maintenance, and replacement of components. A summary of the UV malfunction modes and maintenance requirements is presented in Table 40.

Required maintenance tasks, necessary to insure accurate and reliable operation, are few, but under high particulate operating conditions, the teflon prefilter would have to be changed frequently.

Table 40. Ultraviolet Ozone Monitor malfunction modes and maintenance schedule summary.

Malfunction modes	Was the malfunction encountered during the evaluation?	Effect on monitor	Detection method	Preventive maintenance	Maintenance frequency
Maladjusted or burned out UV lamp.	Yes	Digital output flashes, and meaningful measurements are discontinued.	Flashing output	Readjust and clean optical surfaces. Replace UV lamp at regular intervals.	Whenever UV lamp is replaced and as needed. (Lamp should be replaced every 12 months).
Failure of sample pump diaphragm.	No	Air sample flow rate drops below 2 l/min.	Manual measurement of sample air flow rate.	Replace pump diaphragm on a regular basis.	Every 6 months of continuous operation.
Failure of solenoid valve.	No	Air leaks resulting in other than sample air being drawn into detection chamber.	--	Replace solenoid valve on a regular basis.	Every 12 months of continuous operation.
Reduced performance of catalytic ozone scrubber.	No	Incomplete removal of ozone from sampled air during zero referencing cycle.	--	Replace ozone scrubber on a regular basis.	Every 24 months, more often if sample air contains high concentrations of sulfur compounds.
Blinded teflon pre-filter.	Yes	Could cause a reduction in measured ozone concentration or reduced sample air flow rate.	Manual measurement of sample air flow rate.	Replace teflon filter element on a regular basis.	As needed, more often in high aerosol concentration environments.

Economic and Installation Considerations

Costs--

The price of the UV ozone monitor, FOB Davenport, Iowa, was $2,500 as of January 15, 1980. Operating costs are minimal, including only labor for readjustments and small costs incurred for replacement parts.

Installation--

The UV is designed for single point monitoring and no options for multipoint monitoring are available from the manufacturer.

COULOMETRIC OXIDANT MONITOR (OM)

PRINCIPLE OF OPERATION

The OM is a self-contained oxidant monitor which measures, on a continuous basis, any gaseous substance capable of liberating iodine from a potassium iodide reagent. The detection method employed by the OM is based upon the oxidation-reduction of potassium iodide which is contained in the sensing solution. This reaction occurs at the cathode portion of an electrode which has sensing solution flowing over it. At the electrode, any ozone in the air sample reacts with the solution and releases free iodine (I_2). At the cathode a voltage is applied which causes a hydrogen layer to be produced by a polarization current. Once equilibrium is reached, the current stops. When free iodine produced by the reaction with ozone is released, it reacts with the hydrogen and reduces it. The removal of hydrogen from the cathode causes a repolarization current to flow in the external circuit until equilibrium is re-established. Thus, for each ozone molecule reacting in the sensor, two electrons flow through the external circuit. The amount of current flowing through the external circuit is proportional to the mass amount of ozone per unit volume entering the sensor chamber.

This same reaction can also occur if the sampled air contains other strong oxidizing gases such as the halogens or nitrogen dioxide. Reducing gases such as sulfur dioxide cause a negative interference. The efficiency of the reaction of these other gases is dependent upon their individual chemical characteristics. Nitrogen dioxide, which could be present in welding exhaust, causes a 10 percent positive interference. Sulfur dioxide, a common ambient air pollutant, causes a negative interference which can be eliminated by using an optional prefilter sold by the manufacturer. However, this prefilter not only removes sulfur dioxide but also converts any nitric oxide that may be present to nitrogen dioxide which causes a positive interference.

Description of Test Device

A photograph of the OM monitor evaluated appears in Figure 53. A schematic diagram of the sensor section is shown in Figure 54. Potassium iodide solution is pumped over an electrode and covers it with a thin film of reagent. The electrode is composed of many turns of a fine wire cathode and a single turn of a wire anode. A small D.C. voltage, supplied by an internal regulated power supply, is applied across the electrode. An air sample is pumped through the sensor where it contacts the reagent film on the electrode and is exhausted through a vacuum pump which controls the air flow rate. The reagent, after passing over the electrode, is directed into a reservoir and stored. The spent solution is recycled through a neutralizing filter which allows the solution to be reused.

Figure 53. Photograph of the Oxidant Monitor installed for testing.

As the air passes over the electrode, any ozone present reacts with the reagent and causes a current to flow in the power supply circuit which is connected to an ammeter for readout. Output from the sensor is in the form of a current output of 0 to 1 ma which can be converted to a millivolt output by employing a 10 ohm resistor in the signal cable, for external recording. An optional alarm circuit is also available which provides a switch closure when the ozone level reaches a preset value.

Specifications

The manufacturer's specifications for the OM are given in Table 41.

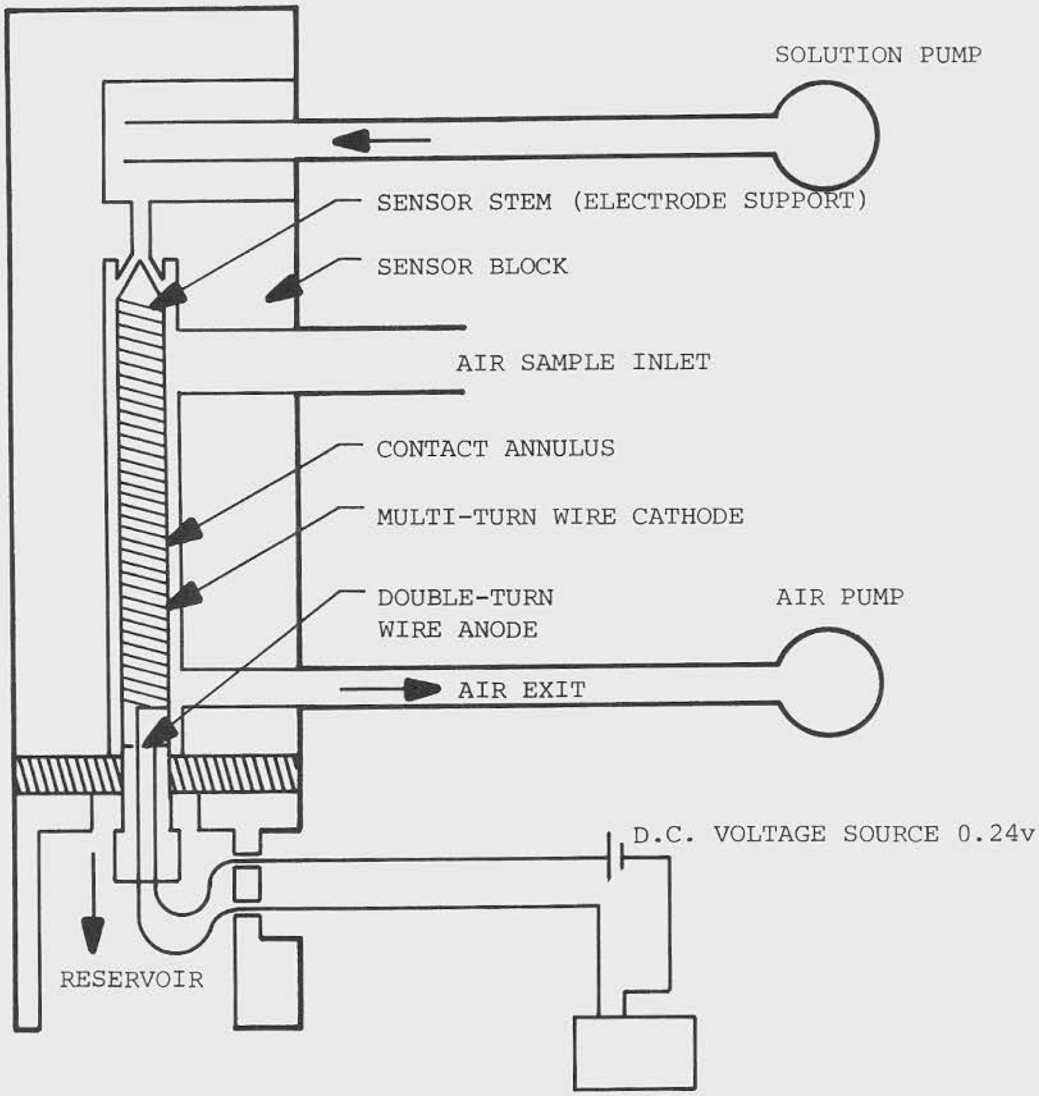


Figure 54. Schematic diagram of Oxidant Monitor (from manufacturer's instruction manual).

Table 41. Oxidant Monitor specifications.

Measurement ranges:	0 - 0.1 ppm 0 - 0.2 ppm 0 - 0.5 ppm 0 - 1 ppm
Accuracy:	±4%
Response time:	Rise time - <1 min. Lag time - <5 sec.
Sampling flow rate:	140 cc/min.
Maximum operating time between maintenance:	30 days continuous operation
Environmental limitations:	Temperature: 0 - 50°C (32 - 122°F)
Size:	19 cm (7.5 in.) wide x 15.2 cm (6 in.) deep x 29.2 cm (11.5 in.) high
Weight:	5 kg (11 lb)
Output:	0 - 1 ma, 0 - 10 mv with 10 ohm resistor in signal cable
Cost:	$1,400, January 15, 1980

EVALUATION RESULTS

Measurement Accuracy

After being calibrated, the OM response to ozone concentrations in the range of 0.07 to 0.14 ppm was linear and stable over a 15-day period of continuous operation. The OM was calibrated against the Chemiluminescent Ozone Monitor (AID) using ozone-containing air extracted from the exhaust duct of the Electrostatically Augmented Fabric Filter (EAFF). Air had to be extracted from the duct with a small blower and exhausted at a low static pressure through a length of duct to avoid exceeding the static pressure limitations of the OM {±5.1 cm wg (2.0 in. wg)]. After 15 days of continuous operation, the measurements of the AID and OM were compared, with both instruments producing identical measurements.

Measurement Range

The measurement range of the OM is stated by the manufacturer as 0 to 1 ppm in the ranges of 0 to 0.1, 0 to 0.2 and 0 to 0.5 ppm, with a lower detectable limit of approximately 0.005 ppm.

Zero Drift

Zero drift over a 15-day continuous operating period was minimal with no change occurring which required re-adjustment. Zero drift was assessed by periodically connecting an activated charcoal filter to the monitor and checking the zero reading.

Response Time

The OM response time, as stated by the manufacturer, is less than one minute on all measurement scales. This small response time is close to instantaneous and should pose no difficulties for recirculation monitoring.

Malfunction Modes and Maintenance Requirements

Four possible malfunctions could disrupt the operation of the OM monitor, none of which were encountered during this evaluation. Because of the simple detection principle, the likelihood of their occurrence is not great. A summary of the malfunction modes and maintenance requirements is presented in Table 42. Six routine maintenance requirements must be performed on a regular basis to insure reliable and accurate operation. Each of these requirements can be performed easily and is not considered to be excessive or prohibitive.

Economic and Installation Considerations

Cost--

The price of the OM, FOB Davenport, Iowa, is $1,400, January 15, 1980. Operating costs consist only of KI solution replacement and electricity, both of which are negligible in cost.

Installation--

The OM is designed for single point, continuous monitoring applications. Recorder output jacks are provided for interfacing with other recorder/indicator devices and an alarm option is available.

Table 42. Oxidant Monitor malfunction modes and maintenance schedule summary.

Malfunction mode	Was the Malfunction encountered during the evaluation?	Effect on monitor	Detection method	Preventive maintenance	Maintenance frequency
Broken reagent film.	No	Unstable and erratic measurements.	Apparent in output data.	Clean sensor with dilute nitric acid solution at regular intervals.	As needed.
Exhausted reagent filter.	No	Zero reading will rise above 0.01 ppm.	Rise in zero reading.	Replace reagent filter when it turns orange.	Dependent upon ozone concentrations being measured.
Depletion of reagent due to evaporation.	No	Incorrect measurements	Visual check of reagent level in reservoir.	Inspect and refill reservoir with distilled water at regular intervals.	As needed to keep reagent level maintained.
Failure of reagent pump diaphragm.	No	Incorrect measurements	Apparent in output data.	Replace pump diaphragm.	As needed.

CHEMILUMINESCENT OZONE MONITOR (AID)

PRINCIPLE OF OPERATION

The AID Series 560 ozone monitor is a portable, self-contained, direct reading instrument that can be used for making continuous measurements. The instrument uses the EPA approved chemiluminescent detection technique which is specific for ozone. A photograph of the AID installed at the test site appears in Figure 55.

Ozone concentration is measured by determining the amount of light that is emitted when any ozone contained in the sampled air reacts with ethylene. This is accomplished by bringing an air sample into direct contact with a regulated supply of ethylene inside of a sealed chamber. Any ozone present in the air sample thus reacts with the ethylene and produces light. A photomultiplier tube located at one end of the chamber detects the emitted light and produces an electrical signal proportional to the intensity of the light.

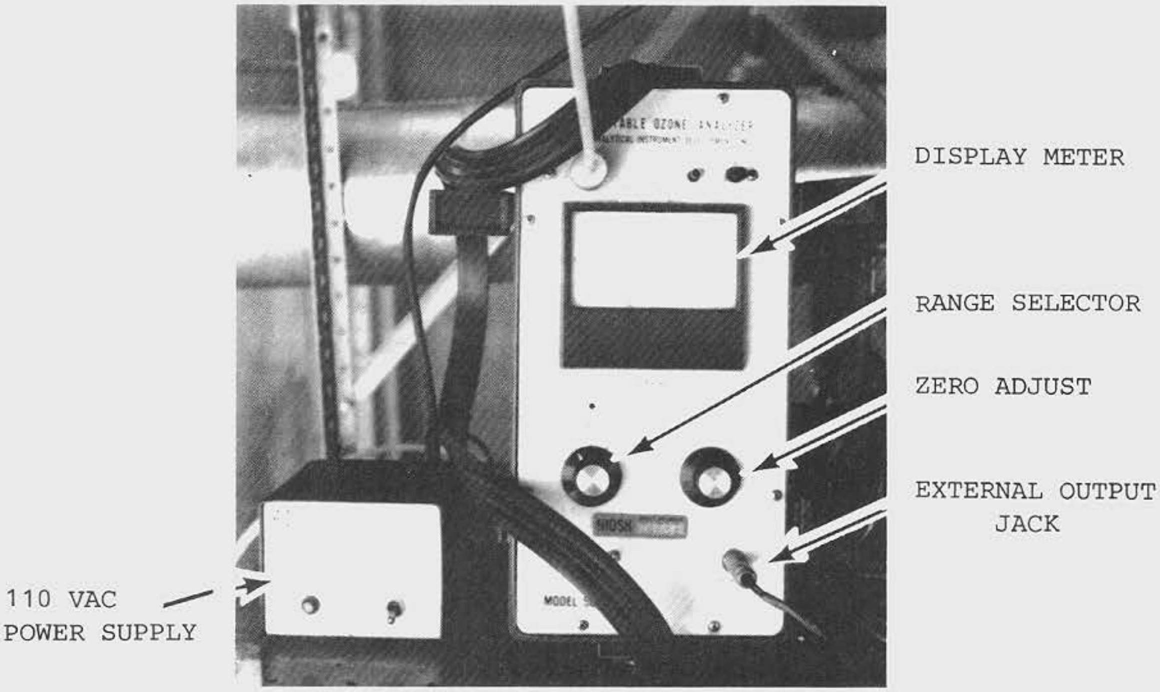
The primary advantage of this detection method is its specificity for ozone which eliminates the possibility of erroneous measurements resulting from interferences from other contaminants present in the sampled air.

A schematic diagram of the flow system is shown in Figure 56. Ethylene is stored in a self-contained cylinder at pressures up to 42.3 kg/cm^2 (600 psig). An external port is provided for recharging the internal cylinder or for continuous operation from an external tank. The ethylene pressure is regulated by a high and low pressure regulating system and controlled by a valve downstream of the low pressure regulator. The flow rate is measured by a flow meter located downstream of the valve. The ethylene control valve, flow meter, recharging port, and gauge are all located on the end panel of the instrument as shown in Figure 55.

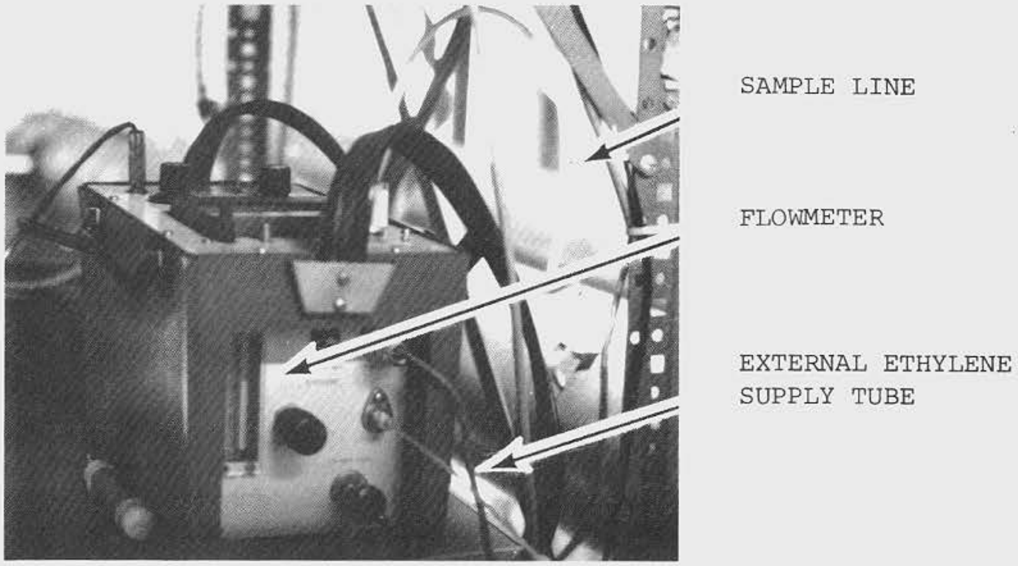
For zeroing purposes, an internal charcoal trap is provided with an external fitting so that a teflon sampling line can be connected and ozone-free air can be sampled. A brushless vacuum pump draws the air/ethylene mixture from the detector chamber and exhausts it outside the instrument housing.

Specifications

The specifications provided by the manufacturer are given in Table 43.



FRONT VIEW



END VIEW

Figure 55. Chemiluminescent Ozone Monitor installed at the test site.

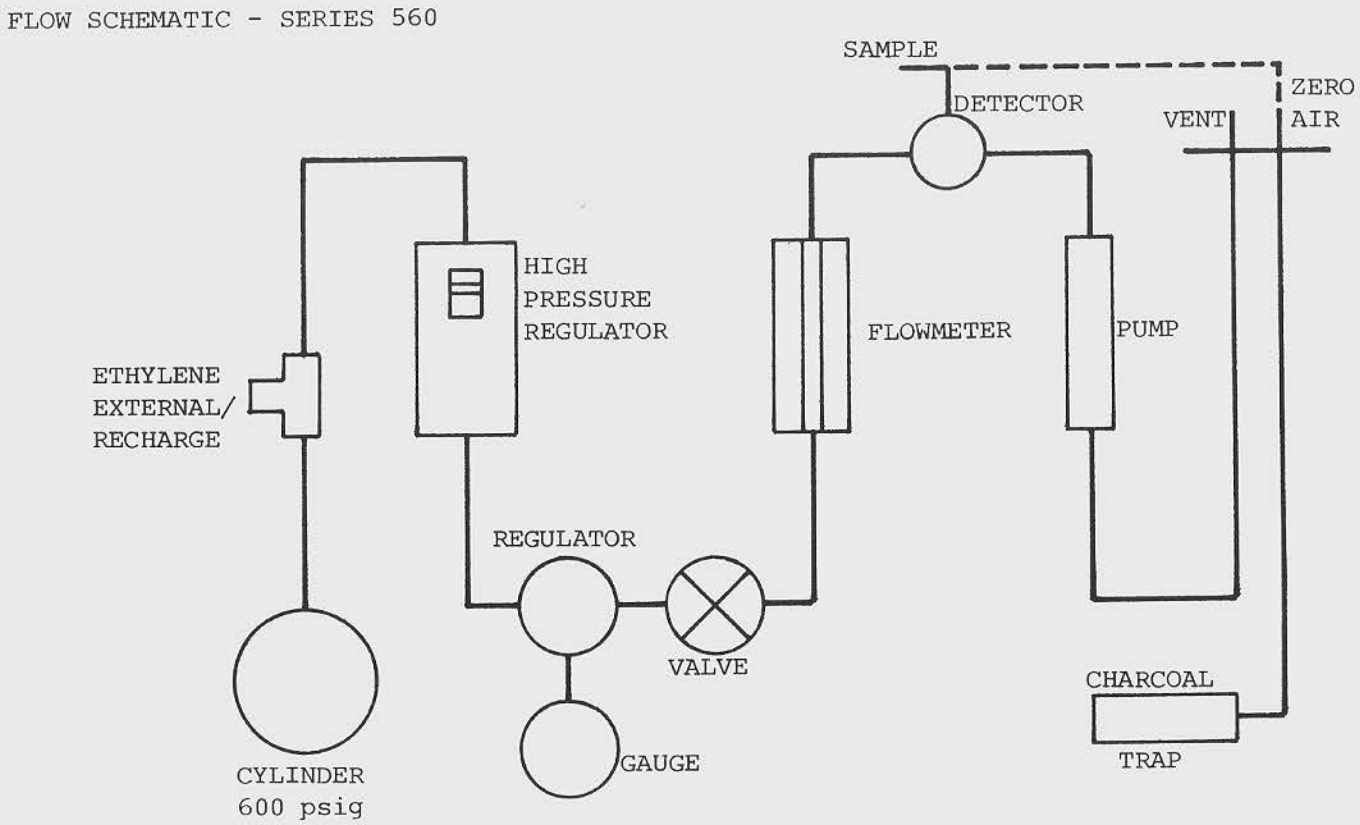


Figure 56. Schematic diagram of the Chemiluminescent Ozone Monitor (from manufacturer's instruction manual).

Table 43. Chemiluminescent Ozone Monitor specifications.

Measurement range: (0 to full-scale)	0 - 0.01 ppm 0 - 0.1 ppm 0 - 1.0 ppm 0 - 10.0 ppm
Response time:	Less than 20 sec. on 0.01 ppm range, less than 5 sec. on all other ranges
Noise:	2% on 0 - 0.1 ppm range
Sampling air flow rate:	1 l/min (2.12 ft^3/hr)
Maximum period of unattended operation:	8 hrs of portable operation Continuous operation limited by capacity of ethylene supply tank.
Environmental limitations:	None specified
Size:	22.9 cm (9 in.) x 36.2 cm (14.25 in.) x 18.4 cm (7.25 in.)
Weight:	33.1 kg (15 lb)
Output:	Analog panel meter and output jack for external indicator/recorder.

EVALUATION RESULTS

Measurement Accuracy

The measurement accuracy of the AID was linear over the 0.03 to 0.7 ppm concentration range tested. Two calibrations performed at the beginning and end of the evaluation indicated that the calibration did not change more than 6 percent over a 6-month period of intermittent operation.

Upon receiving the AID, it was calibrated using the neutral buffered potassium iodide absorption method. Ozone-containing air was generated by a Monitor Labs Model 8500 Ozone Generator. This calibration was then rechecked six months later by the same method. The results of these two calibrations are presented in Table 44. The AID was adjusted at one concentration, and as indicated by the other measurements, was linear in its response with no difference between the AID measurements and the standard measurement. The re-calibration check revealed that the AID calibration changed only slightly, with the AID measurements ranging from 3 to 6 percent lower than the standard measurement.

The manufacturer indicated that the calibration is a function of the ethylene flow rate, as shown in Figure 57. As the ethylene flow rate diminishes, the response of the instrument drops off, causing a lower than actual measurement. To assure accurate measurement, the ethylene flow rate needs to be maintained at the specified rate.

Table 44. Chemiluminescent Ozone Monitor calibration stability data.

Initial calibration, 3/21/79		Calibration, 9/26/79		
Ozone concentration, ppm		Ozone concentration, ppm		
Standard	AID	Standard	AID	Percent change
0.039	0.039	0.57	0.54	-6%
0.14	0.14	0.29	0.28	-3%
0.23	0.23	0.73	0.71	-3%
0.084	0.084	0.053	0.051	-6%

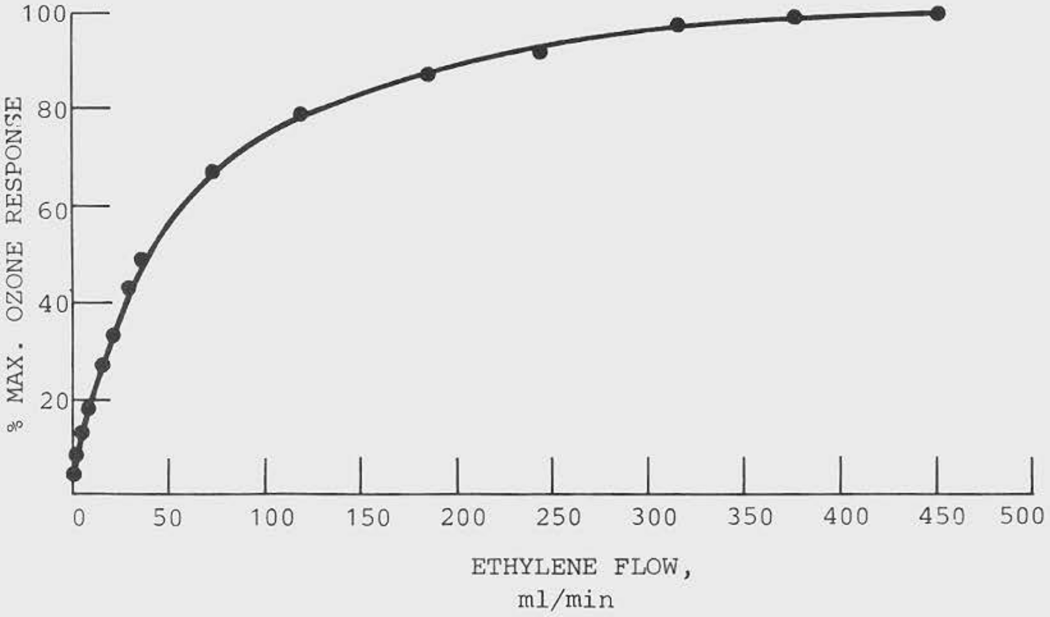


Figure 57. Percent maximum ozone response vs. ethylene flow rate for the Chemiluminescent Ozone Monitor (from manufacturer).

Measurement Range

The measurement range of the AID is 0.001 to 10 ppm, divided into four ranges: 0 - 0.01, 0.1, 1.0, and 10 ppm. This wide measurement range is adequate for measuring ozone concentrations normally occurring in the welding environment.

Zero Drift

The zero setting of the AID is a function of the ambient temperature. It was found that if the ambient temperature was kept within ±6°C, the zero drift was less than 0.005 ppm over an 8-hr time period. Larger variations in temperature did produce larger zero variations because the dark current

(current when there is no signal) of the photomultiplier tube used to detect the light produced by the chemiluminescent reaction is a function of temperature.

Response Time

The response time is close to instantaneous. The manufacturer specified it to be 20 seconds on the 0.01 ppm range and less than 5 seconds on all other ranges.

Malfunction Modes and Maintenance Requirements

Five malfunction modes were identified, four of which were encountered during the evaluation. Each of these could be avoided by regular inspection and maintenance. A summary of the malfunction modes, effects, and maintenance procedures is presented in Table 45.

The only maintenance requirements that are listed by the manufacturer include refilling of the ethylene tank and periodic re-calibration and re-zeroing. The manufacturer recommends re-calibration weekly under continuous operation, although the results of this study show that the calibration remained constant for a 6-month period during which the instrument was periodically used. No other schedules are given or were found to be needed.

ECONOMIC AND INSTALLATION CONSIDERATIONS

Costs

The price of the AID, FOB Avondale, PA, as of April, 1979 was $3,330, including the self-contained, rechargable battery pack, battery charger, and refillable ethylene supply tank. The instrument uses approximately 17.5 l of ethylene per eight hours of operation. A 16.8 kg (37 lb) tank, which costs approximately $75 (January, 1980) would last approximately 750 8-hour shifts or 250 24-hour shifts of operation.

Installation--

The AID output can be read directly off of the meter located on the front of the instrument or it can be transferred to an external recording device from the external output jack located on the front panel. There are no other provisions for interfacing, either standard or optional.

Multi-point monitoring could only be accomplished by connecting a series of sampling lines to the AID and sequentially sampling from each. This type of an arrangement would require a solenoid operated valve system controlled by an electronic timing and switching circuit and would increase the response time, depending on the length of the sampling lines.

Table 45. Chemiluminescent Ozone Monitor malfunction modes and maintenance schedule summary.

Malfunction mode	Was the malfunction encountered during the evaluation?	Effect on monitor	Detection method	Preventive maintenance	Maintenance frequency
Depletion of ethylene supply.	Yes	Monitor response drops off.	Visual check of flowmeter.	Regular inspection and replacement of ethylene supply.	16.8 kg (37 lb) tank of ethylene would last for approximately 6000 hours.
Zero drift which results from ambient temperature variations.	Yes	Changes zero setting which affects the measurement.	Manual zero check.	Control of ambient temperature.	Re-zero as needed, if ambient temperature changes by more than ± 6°C.
Change in ethylene flow rate.	Yes	Causes variations in the measurement accuracy.	Visual check of flowmeter.	Regular inspection and adjustment of ethylene flow rate.	As needed.
Blinding of teflon prefilter that may be required in a dirty environment.	Yes	Reduces sample air flow rate.	Manually check sampled air flow rate.	Regular inspection and changing of the teflon filter.	Dependent upon aerosol concentration of sampled air.
Change in calibration setting.	No	Reduces measurement accuracy.	None.	Recalibration.	Manufacturer recommends weekly recalibration, but the results of this evaluation indicate that the calibration remained constant for 6 months.

SAFETY MONITORING FILTER (SMF)

PRINCIPLE OF OPERATION

As the particulate concentration increases in the air being passed through a filter media, the rate of buildup of particles on the filter increases, causing a parallel increase in the differential pressure across the air filter. This phenomenon is used as the operational principle of a SMF system used to detect an increase in particulate concentration and to prevent contaminants that penetrated the primary air cleaner during a breakthrough failure from entering the workplace.

The SMF system consists of a filter element placed downstream of a primary air cleaner with a differential pressure monitoring device attached across it. The differential pressure monitor is set to activate an alarm when the trigger level differential pressure is reached.

This type of return air monitoring system has three advantages which include:

1. Low cost.
2. Simple and reliable operation.
3. Backup filtration in the event of a penetration failure of the primary air cleaner.

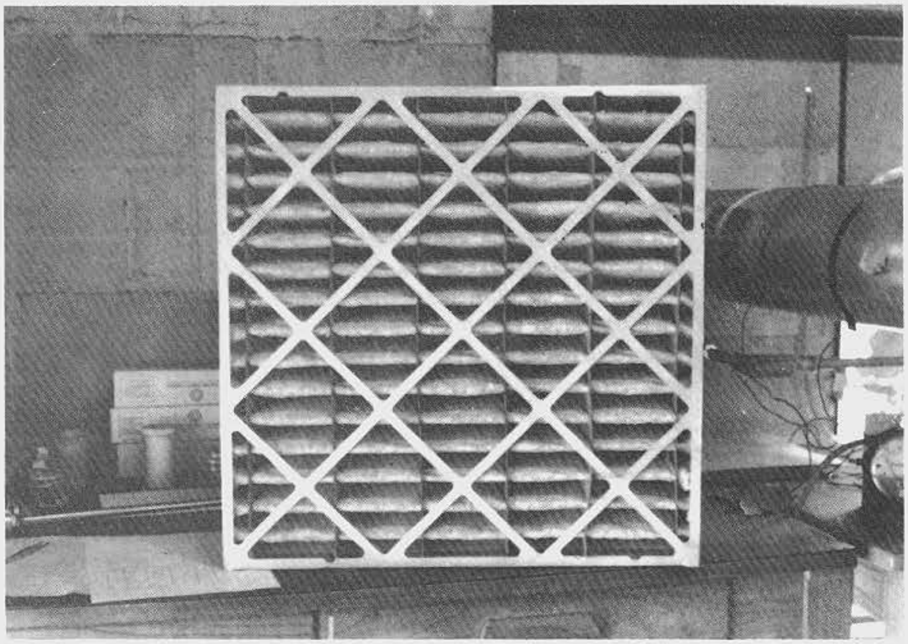
TEST DEVICE DESCRIPTION

A SMF manufactured specifically for return air monitoring by Farr Company Inc. was tested. The Model RIGA-FLO-200® was installed on the discharge of the aspirated cartridge filter as shown in Figure 58. A schematic diagram of the test configuration appears in Figure 59, showing all of the components. The differential pressure was measured with a Magnehelic gauge connected across the SMF. The air flow through the system was 42.5 m^3/min (1500 ft^3/min).

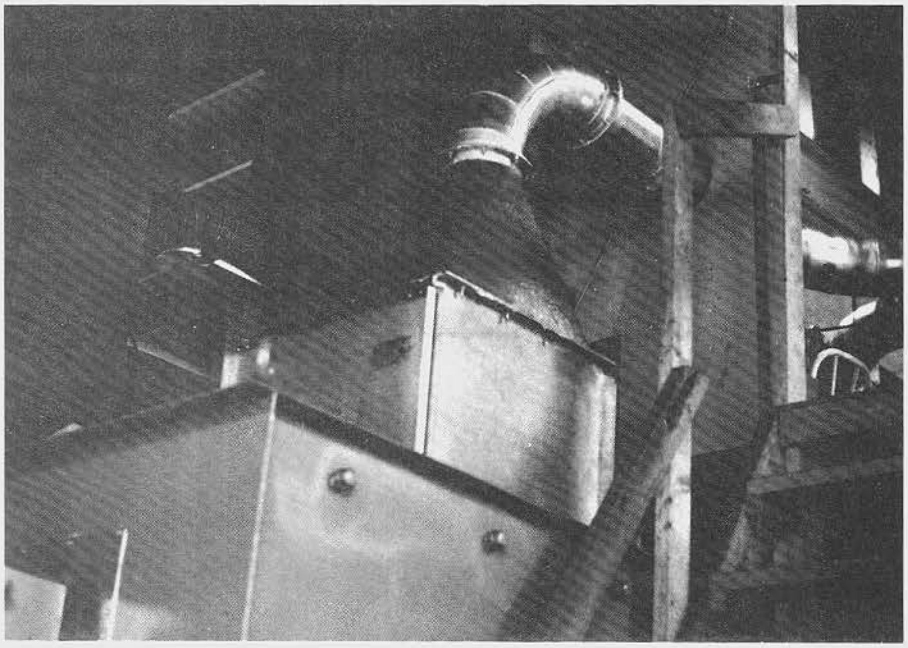
EVALUATION METHOD

The SMF was tested by simulating a breakthrough failure of the primary air cleaner and measuring the penetration and system air pressures as the SMF became loaded with fume. The failure was simulated by removing the filter elements from the aspirated cartridge filter unit and allowing the exhaust air from the welding booths to be introduced directly to the SMF. This was done to determine:

1. The amount of time required for the final resistance to be reached (response time).



FILTER ELEMENT



FILTER HOUSING SHOWN MOUNTED ON
THE PRIMARY AIR CLEANER

Figure 58. Photographs of safety monitoring filter.

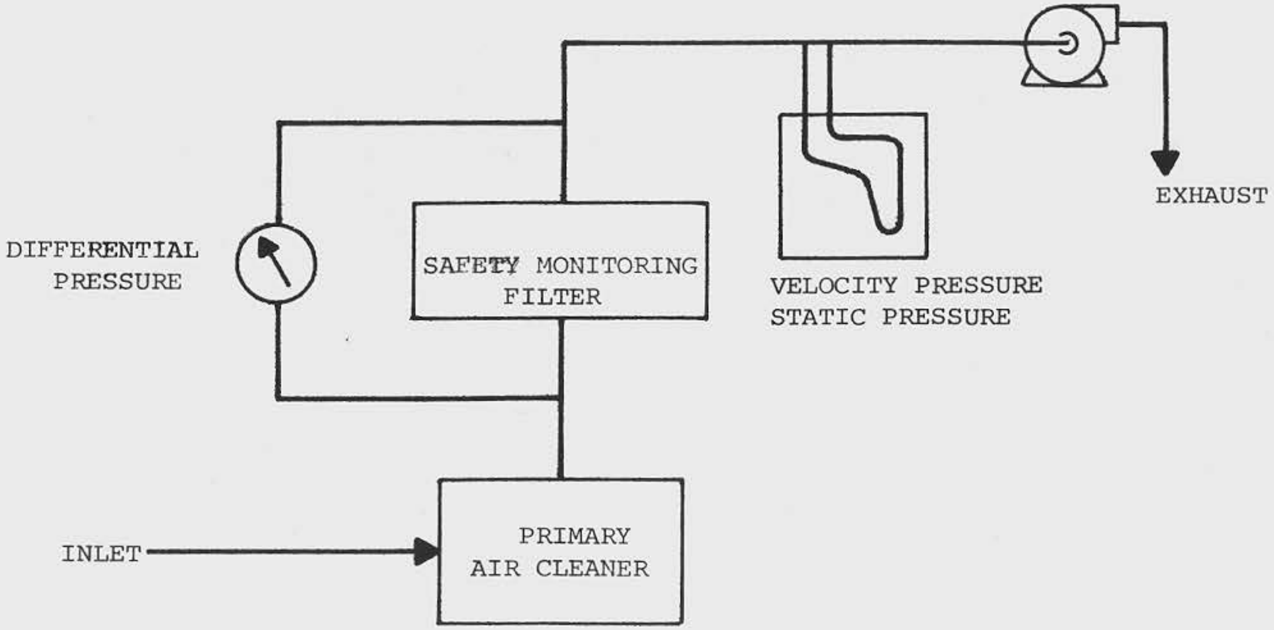


Figure 59. Schematic diagram of Safety Monitoring Filter system.

2. The penetration as a function of differential pressure across the SMF.

3. The effect of rising differential pressure on the air flow rate through the system.

Parameters monitored included:

1. Differential pressure drop across the SMF.
2. Inlet and outlet aerosol concentrations.
3. Velocity and static pressure in the outlet duct.

SPECIFICATIONS

The performance specifications for the SMF tested are given in Table 46 along with specifications for the HEPA SMF also marketed by the Farr Company.

Table 46. Farr Safety Monitoring Filter specifications.

Filter type	Size (cm)	Weight (kg)	Air flow rate, m^3/min (cfm)		Air resistance, cm wg (in. wg)	
			Recommended	Maximum	Initial	Final
RIGA-FLO-200	61x61x30	198	42.5 (1,500)	56.7 (2,000)	1.14-1.65 (0.45-0.65)	5.08 (2.0)
Magna media 100	61x61x29	309	24 (850)	32.6 (1,150)	1.91-2.54 (0.75-1.0)	8.89 (3.5)

EVALUATION RESULTS

Penetration and Differential Pressure

At the outset of a simulated breakthrough, the performance of a new SMF was characterized by high penetration which resulted in a high particulate concentration downstream of the SMF (Table 47).

This caused the outlet concentration to reach 7.07 mg/m^3, which exceeds the current OSHA PEL of 5 mg/m^3 for welding fume. Some 4.5 hours later, as the particles built up on the filter and the differential pressure approached the action level of 5.1 cm wg (2.0 in. wg), the penetration decreased resulting in a lowering of outlet concentration to 1.2 mg/m^3. A plot of penetration as a function of time is shown in Figure 60.

The high initial penetration measured during the period immediately after failure negates the one function that the SMF should perform: that of preventing particulate material that penetrated the primary filter from re-entering the workplace during recirculation. A more efficient SMF, such as a HEPA filter, would be needed in this case to effectively perform this function at the expense of a higher pressure drop, increased capital and operating cost, and reduced service life.

Table 47. Safety Monitoring Filter test results.

Time	Air flow rate, m^3/min (ft^3/min)	Differential pressure, SMF, cm wg	Penetration, %	Particulate concentrations, mg/m^3 Inlet	Particulate concentrations, mg/m^3 Outlet
8:45	42.5 (1500)	1.0	45	15.60	7.07
9:15	42.5 (1500)	1.3			
9:55	42.5 (1500)	1.8			
10:15	42.5 (1500)	2.8	18	15.92	2.85
10:45	41.1 (1450)	5.5			
11:15	41.1 (1450)	5.6			
11:45	40.4 (1425)	5.8			
12:15	40.4 (1425)	5.8			
1:15	40.4 (1425)	6.1	7	16.27	1.20
1:45	40.4 (1425)	6.1			
2:15	40.4 (1425)	6.4			

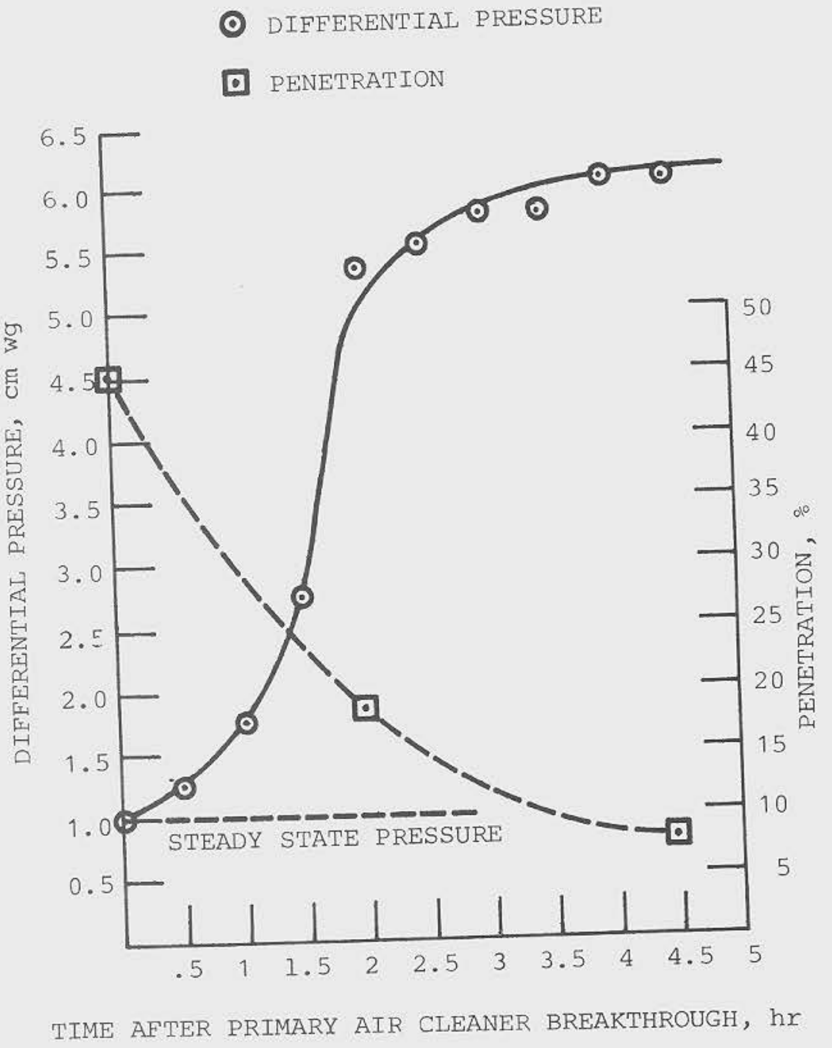


Figure 60. Safety Monitoring Filter differential pressure and penetration vs. time after primary air cleaner breakthrough.

Response Time

If the penetration of the SMF is low, the response time is not critical because a breakthrough of the primary filter would not result in a large increase in contaminant concentration in the return air. Such was not the case for the SMF tested, where the penetration was initially high and, therefore, response time was important.

Starting at an initial differential pressure of 1.02 cm (0.40 in.), it took approximately two hours to reach the action level of 5.1 cm (2.0 in.) with particulate concentrations of 15 mg/m^3 being introduced to the afterfilter during the breakthrough test. This response time represents the longest possible under this particular inlet concentration because the filter was clean at the beginning of the test. Had that filter been used for a period of steady state performance prior to breakthrough, the initial resistance would have been higher and it would have taken less time to reach the action level. The inlet particulate concentration to the SMF is another variable which has an important effect on the time needed to reach the action level.

Differential Pressure

The initial differential pressure across the SMF was low, starting at approximately 1 cm wg (0.40 in. wg). It increased to 5.1 cm wg (2.0 in.), the action level recommended by the manufacturer, during the breakthrough test. Differential pressure was monitored throughout the simulated primary filter breakthrough. These results are presented in Table 47 and shown graphically in Figure 60. It can be seen from the figure that the differential pressure turned sharply upward after about an hour following the outset of the failure, rising 3.5 cm during the second hour.

The test continued for 2.5 hours after the action level was reached and during this period the rate of change of both penetration and differential pressure decreased as these measurements began to level off.

Because the blower was properly sized to handle the increase in pressure associated with particulate buildup on the SMF, the air flow rate through the system decreased only 3.3 percent from 42.5 m^3/min (1500 ft^3/min) to 41.1 m^3/min (1450 ft^3/min) as the filter passed from initial to final (action level) resistances.

Malfunction Modes and Maintenance Requirements

Two malfunctions can occur that would prevent the SMF from functioning as a breakthrough warning device and secondary filter. These are summarized in Table 48 along with pertinent maintenance information. Both of these failures result from a component failure and both are relatively difficult to detect.

Replacement of the filter element when the final differential pressure is reached is another maintenance task associated with the SMF. The replacement schedule is dependent upon the aerosol concentration that is introduced to the SMF, which, in turn, is dependent upon the penetration of the primary air cleaner and the aerosol concentration of the air to be cleaned. Safety monitoring filters that have lower penetrations, such as the high efficiency particulate air (HEPA) filters, require more frequent replacement because they retain a larger percentage of particulate, resulting in a faster buildup rate and differential pressure rise.

Economic and Installation Considerations

Capital costs for both the glass fiber and HEPA SMF systems are listed in Table 49.

The SMF causes additional static pressure loss in the system, requiring more operating energy in the form of horsepower to operate the blower. The electricity costs, based on a 20,000 ft^3/min system operating under the same conditions as the air cleaners are presented in Table 50 for each air cleaner system tested (see cost analysis section and Appendix C).

Table 48. Safety Monitoring Filter malfunction modes and maintenance schedule summary.

Malfunction mode	Was the malfunction encountered during the evaluation?	Effect on SMF	Detection method	Preventive maintenance	Maintenance frequency
Air leak in the filter media or filter gasket.	No	Higher penetration resulting in slower differential pressure rise.	Penetration test.	Periodic leak checks.	As needed or as determined necessary for safety.
Malfunction in the differential pressure sensing device resulting in the alarm sounding either prematurely or late.	No	None	Measuring the differential pressure with an indicator of known accuracy such as a manometer.	Calibration, check differential pressure sensing device.	As needed based on operating conditions.

Table 49. Safety Monitoring Filter costs (January, 1980).

Filter type	Cost per filter element	Cost per ft^3/min for a 20,000 ft^3/min unit
RIGA-FLO 200	$ 50.00	$0.06
Magna Media-100	$150.00	$0.26

Table 50. Additional costs for operation of the Safety Monitoring Filter.

	Differential pressures (cm wg)			Additional electricity costs for fan operation for SMF, dollars per 10^6 ft^3		
Air cleaner	Air cleaner	System	Glass fiber SMF	HEPA SMF	Glass fiber	HEPA
EAFF	14.0	25.4	3.1	5.7	0.11	0.18
ESP	1.3	25.4	3.1	5.7	0.14	0.22
ACF	6.4	25.4	3.1	5.7	0.19	0.26

AIR CLEANER AND AIR MONITOR COSTS

INTRODUCTION

The costs of a recirculating ventilation system, both capital and operating, must be low enough to make the system economically viable. Economic returns may be evaluated in terms of money saved on energy needed to temper make-up air or from lost production time due to the unavailability of energy resources. Before an economic evaluation can be made, the costs for the additional components and maintenance necessary for recirculation must be determined as well as the potential savings that such a system would provide.

A ventilation system being considered for recirculation can take basically two forms as depicted in Figure 61. Configuration 1 represents a system that is exhausted directly to the outdoors without any conditioning of the exhausted air; configuration 2 shows the various components of a ventilation system that, due to ambient regulations on the contaminant being exhausted, requires partial removal of the contaminant prior to being exhausted.

To determine the cost of changing configuration 1 into a recirculating system, the capital and operating costs for the following components must be determined:

No. 4 - Air cleaner providing low enough penetration for recirculation
No. 5 - Bypass damper.
No. 6 - Return air distribution plenum.
No. 7 - Return air monitoring system including alarm.

Changing configuration 2 into a recirculating system would require an addition of the following components:

No. 4 - Air cleaner providing low enough penetration for recirculation. The air cleaner used to clean air being exhausted to the outside may not have a low enough penetration for recirculation. If not, an entirely new air cleaner may be needed or a secondary air cleaner could be added. These additions would result in added capital and operating costs.

No. 5 - Bypass damper.
No. 6 - Return air distribution plenum.
No. 7 - Return air monitoring system including alarm.

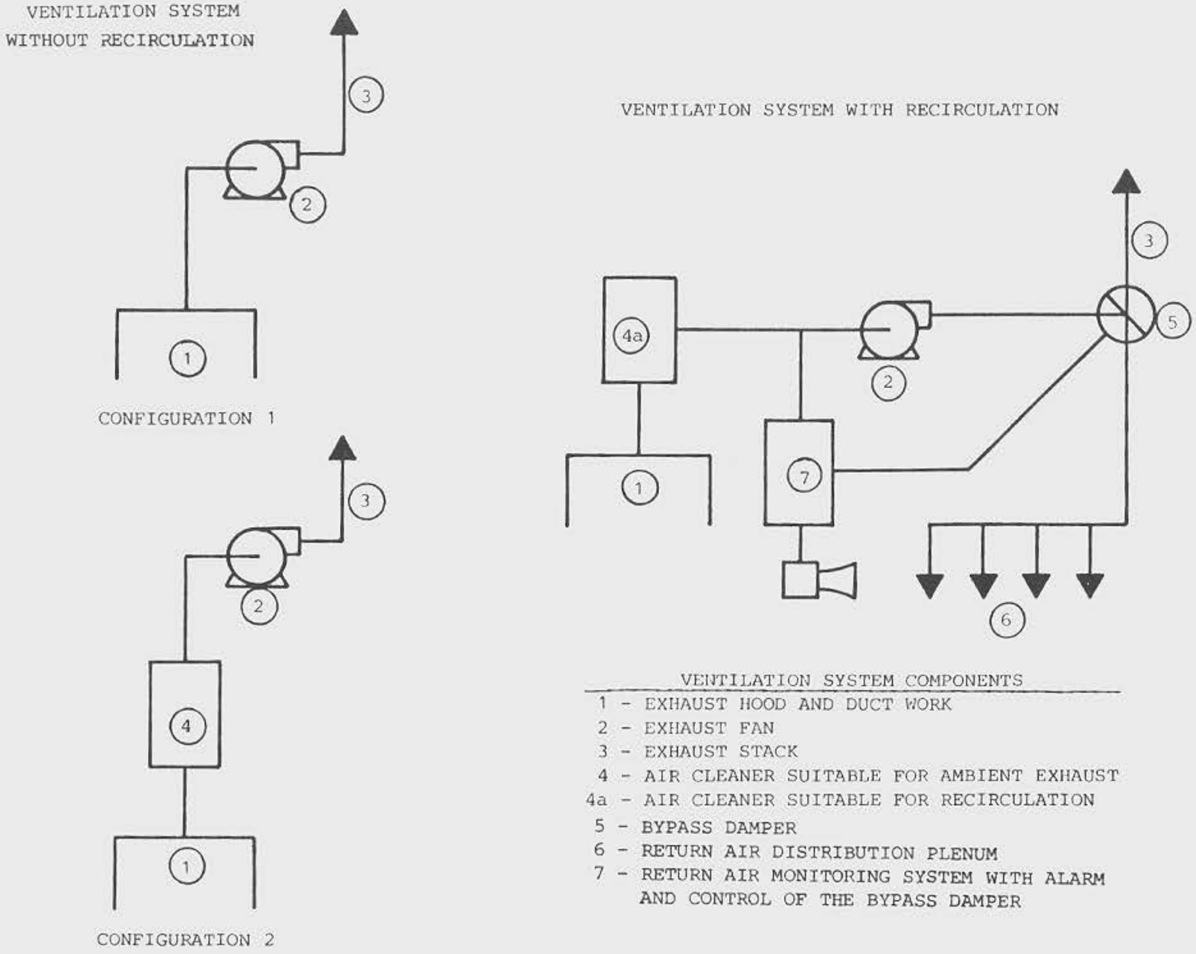


Figure 61. Ventilation system components - with and without recirculation.

RECIRCULATION SYSTEM COST EVALUATION

Wide variations in the magnitude of capital and operating costs are possible because of the circumstances which surround each particular application. The cost of the air cleaner may represent a small or large fraction of the total capital costs, depending in part upon one or more of the following factors (6):

1. Auxiliary equipment - including ductwork, hoods, fan and motor, instrumentation, and air monitoring equipment.
2. New or retrofitted installation.
3. Physical location of the air cleaners with respect to the source.
4. Local code requirements.
5. Plant location.

Operating costs can also vary depending upon such cost factors as:

Raw materials.
Maintenance.
Labor.
Utilities.
Overhead.
Technical and engineering.
Depreciation.
Insurance and property taxes.

These factors can only be assessed on an individual basis, therefore the scope of this economic evaluation was limited to determining only those costs associated with the air cleaning device itself. The actual air cleaners tested as part of this study were pilot sized, so costing information presented here is based on scale-up to a full sized unit with an air flow capacity in the range of 9.44 to 14.17 m^3/sec (20 - 30,000 ft^3/min). Capital and operating costs are based on the assumptions and conditions listed in Table 51. The operating conditions used for costing the EAFF and ACF air cleaners were those which, from this study, were determined to be most efficient. The most efficient operating mode for the ESP was not readily apparent, so costing information for all of the operating conditions tested is presented. A summary of this information is presented in Table 52. Detailed cost calculations for each air cleaner are presented in Appendix C.

AIR MONITOR COSTS

Depending upon the sophistication of the air monitoring system deemed necessary to adequately protect the worker against system failures, the expense incurred could make recirculation economically infeasible. Specific costs which need to be considered include:

1. Capital costs of the instrument including installation.
2. Alarm and telemetry options available and their respective costs.
3. The cost incurred to erect a multi-point monitoring system if needed.
4. Operating costs which would include labor and materials required for such things as zero checks, calibration, and replenishing expendable items.

Table 51. Air cleaner costing method.

Cost description	Items included	Basis of cost calculation	Calculation units	Date
Capital:				
1. Air cleaner	Air cleaner only	ESP - Single and double pass, high and low inlet concentration. EAFF - High filter velocity with electrostatic augmentation. ACF - High filter velocity with precoated filter elements.	Dollars/ft^3/min	FOB factory, January, 1980
Operating Costs:				
1. Electricity	Fan	Horsepower requirements for the fan are based on the differential pressure measured across the air cleaner plus 24.5 cm wg (10 in. wg) added to account for system loses.	Dollars/10^6 ft^3	
	Compressed air	Compressed air costs are based on compressed air requirements specified by the manufacturer. Horsepower use is based on a central air system powered by a 25 Hp motor.	Dollars/10^6 ft^3	
	High voltage for electrostatic devices	Based on electrical requirements specified by the manufacturer.	Dollars/10^6 ft^3	
2. Maintenance	Materials	Based on the materials needed to maintain unit. Estimated schedule is based on manufacturer's data and information obtained from this study.	Dollars/10^6 ft^3	January, 1980
	Labor	Base on manufacturer's estimated time requirements.	Dollars/10^6 ft^3 based on 20.00/ hr for labor	

This study was limited to assessing only those costs associated directly with the monitor itself. The following costs are reported if they were available:

1. List price of the instrument, FOB from the factory.
2. Cost of alarm, telemetry, and other options from the manufacturer.
3. Cost of a multi-point monitoring system.

A summary of the air monitor cost information is presented in Table 53.

Table 52. Air cleaner cost summary.

Air cleaner	Capital cost, $\$$ per ft^3/min	Electricity costs, $\$/10^6$ ft^3			Maintenance, $\$/10^6$ ft^3		Total operating costs, $\$/10^6$ ft^3
		Fan	High voltage	Compressed air	Materials	Labor	
ESP - based on a 9.44 m^3/sec (20,000 ft^3/min) unit.							
- Single pass							
low concentration	1.72	0.87	0.01	0.01	*NR	0.84	1.73
high concentration	1.72	0.87	0.01	0.01	NR	5.56	6.45
-Double pass							
low concentration	3.45	0.87	0.02	0.02	NR	0.84	1.75
high concentration	3.45	0.87	0.02	0.02	NR	5.56	6.47
EAFF - based on a 11.33 m^3/sec (24,000 ft^3/min) unit.	1.38	1.32	0.26	0.01	0.15	0.02	1.76
ACF - based on a 9.44 m^3/sec (20,000 ft^3/min) unit.	1.29	0.97	NR	0.01	0.43	0.01	1.42

* NR - denotes not required.

Table 53. Air monitor cost summary.

Extractive type air sampling devices	List price as evaluated (FOB factory)	Cost of optional equipment	Multipoint system cost (if available)
Aerosol mass monitor	$12,150 (January, 1980)	2 channel (respirable and total fractions) $13,300 Analog output board $1,300.00	* NA
Airborne particulate mass monitor	$10,000 (approximate, January, 1980)	None listed.	NA
Real time aerosol monitor	$4,500 (December, 1979)	See RAM section.	$5,100 per point for 5 points, $2,200 per point for sixty points.
Tape sampler	$1,122 (September, 1979)	$2,975 for model 5000 which includes interfacing and alarm and all other available options.	NA
Oxidant monitor	$1,400 (January 15, 1980)	Alarm - $175.00 30 day Operation - $125.00	NA
Ultraviolet ozone monitor	$2,500 (January 15, 1980)	None listed.	NA
Chemiluminescent ozone monitor	$3,300 (April, 1979)	None listed.	NA
Air pressure type devices			
Safety monitoring filter	$0.06 per ft^3/min (January, 1980, $1200 for a 20,000 ft^3/min unit).	None listed	NA

* NA - denotes not applicable

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APPENDIX A
SIGNAL TRANSFER AND PROBE LOSSES

PARTICULATE SAMPLE EXTRACTION METHOD

All of the extractive type particulate monitors evaluated required that the air sample be extracted from the air duct and transported to the sensing portion of the monitor via a probe and sample line. Ideally, the nozzle portion of the system should be sized so that the sampled air is removed from the duct isokinetically, and shaped and sized so as to minimize losses. Practically, 0.318 cm (1/8 in.) diameter is the smallest probe diameter which can be used. Smaller diameters are easily clogged by large particles. The flow rate of the monitors tested required that a small diameter nozzle be used to approximate isokinetic conditions. The particles being sampled contained a large portion of small particles (90 percent of the mass less than 3 micrometers) so that strict isokinetic sampling was not critical. However, if the air being monitored contained a higher percentage of larger particles, more attention would have to be given to insure isokinetic extraction of the air sample.

A standard extractive technique shown in Figure A-1 was used for each particulate monitor. This consisted of an "s" shaped stainless steel nozzle with a sharpened head, 0.318 cm (1/8 in.) diameter, a 61 cm (24 in.) long 0.64 cm (1/4 in.) ID teflon tube and hardware used to fasten the nozzle to the ductwork. This diameter resulted in near isokinetic sampling rates for the monitors with the highest air flow rates (9 and 10 l/min), but sub-isokinetic sampling rates for the monitors that had lower air flow rates (1 to 2 l/min). Monitor sampling air flow rates were checked with a rotameter with the sampling probe inserted in the duct to insure that the negative duct static pressure did not alter the flow rates of the monitors.

Probe and Line Loss Experiment

An experiment was conducted to determine the percentage of the sampled particles that adhered to the walls of the sampling probes and lines. This was done by connecting two identical probe tips to 47 mm filters, one with a 61 cm (2 ft) and the other with a 183 cm (6 ft) sample line. These lines were free of any sharp bends and relatively straight. A simultaneous air sample was drawn through each system from the inlet duct to the air cleaners at the same air flow rate. The material in the probes and sample line was then removed by backwashing with acetone. The 47 mm filters, along with the backwash samples, were then post desiccated and weighed and the percentages of the total catch calculated.

Initial tests using sample air drawn from the exhaust duct of the air cleaners which contained very low particulate concentration (20 to 50 $\mu g/m^3$) indicated that the probe and line losses were undetectable. Therefore, only the results of the tests using air having a high aerosol concentration are presented in Table A-1.

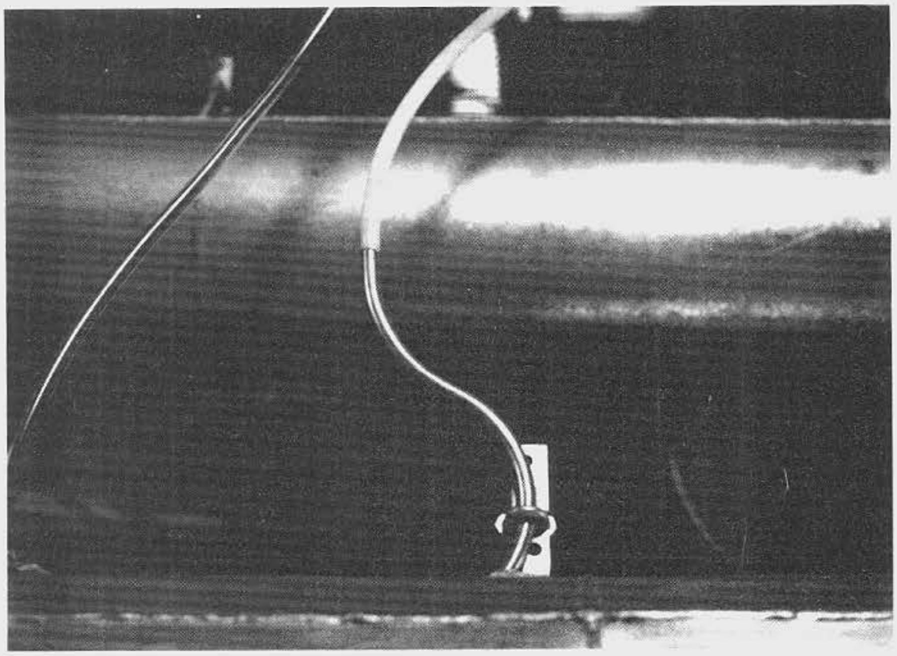

Figure A-1. Photograph of probe and sample line mounted on exhaust duct.

Table A-1. Probe and line loss results.

Air Sample Flow Rate: 10 lpm
Sample Time: 175 min.
Average Particulate Concentration: 11.88 mg/m^3
Probe Tip Diameter: 0.318 cm (1/8 in.)
Percent Isokinetic: 95%

Section	% of Total mass
1.82 m (6 ft) line	12
Probe tip	9
Total	21
0.61 m (2 ft) line	6
Probe tip	9
Total	15

These results indicate that at high concentrations, probe losses are significant, ranging from 15 to 21 percent of the total mass sampled. This also indicates that these losses can be reduced by reducing the sample line length. To keep line losses to a minimum, all of the measurement accuracy tests were conducted with a 61 cm (2 ft) sample line.

Gaseous Sample Extraction Method--
Gaseous samples were extracted from the duct with a 0.64 cm (0.25 in.) ID teflon sampling tube inserted into a hole placed in the side of the duct. As with the particulate monitors, sampling flow rates were checked with a rotameter.

APPENDIX B
GRAVIMETRIC MEASUREMENT ERROR ANALYSIS

Each gravimetric measurement was calculated from the following equation:

$$C = \frac{Sw}{Vm}$$

Where C is the gravimetric concentration in mg/m^3, Sw is the weight of the collected sample, and Vm is the metered volume of air that passed through the filter.

The maximum relative error of the gravimetric concentration measurement can be estimated by summing the absolute values of the relative error associated with each determination made in the gravimetric measurement sequence. This is done by substituting the appropriate values into the following logarithmic differential equation:

$$\frac{dC}{C} = \frac{d\ (Sw)}{Sw} + \frac{d\ (Vm)}{Vm}$$

All of the errors associated with a measurement are usually not additive, as the above equation assumes, therefore, a more accurate estimation of the actual error is best determined by dividing the total absolute error by 2. For each gravimetric measuring technique, the absolute error [d(Sw + d(Vm)] was estimated and then divided by the average value for each measurement. The calculation for each measuring technique is presented as follows:

High volume, 30-minute sampling time, high particulate concentration (<1 mg/m^3):

$$\frac{dC}{C} = \frac{2\ mg}{100\ mg} + \frac{dVm}{Vm} = 2\% + 3\%\ \text{(manufacturer's specifications)} =$$

$$5\% \div 2 = 2.5\%$$

High volume, 120-minute sampling time, low particulate concentration (20 to 500 µg/m^3):

$$\frac{dC}{C} = \frac{2\ mg}{10\ mg} + \frac{dVm}{Vm} = 20\% + 3\% = 23\% \div 2 = 12\%$$

Low volume, 30-minute sampling time, high particulate concentration (5 to 25 mg/m^3):

$$\frac{dC}{C} = \frac{2\ \text{mg}}{10\ \text{mg}} + \frac{dVm}{Vm} = 20\% + 3\% = 23\% \div 2 = 12\%$$

Low volume, 120-minute sampling time, high concentration (5 to 25 mg/m^3):

$$\frac{dC}{C} = \frac{2\ \text{mg}}{15\ \text{mg}} + \frac{dVm}{Vm} = 17\% \div 2 = 9\%$$

APPENDIX C
COSTING METHODS AND CALCULATIONS FOR THE AIR CLEANERS

All capital costs are based on the FOB cost (January, 1980). Operating costs include both utilities (electricity) and maintenance (materials and labor). Electricity costs are based on \$0.03 per kw-hr, labor costs are based on \$20.00 per hour and material costs are based on January, 1980 prices.

Costs for operating the fan were based on horsepower requirements for a Buffalo Forge Company Inc. size 70 MW industrial fan. Horsepower requirements were adjusted to 70°F air temperature and 1,000 ft elevation by multiplying the value found in Table C-1 by 0.96. Compressed air costs are based on horsepower requirements for a Worthington Model 25 BNBR compressor employing a 25 hp motor with 97.1 ft^3/min capacity (Table C-2).

Table C-1. Fan horsepower requirements used in calculations.

Fan type: Buffalo Forge size 70 MW industrial fan.

	Static pressure, in. wg									
Capacity ft^3/min	8 Hp	9 Hp	10 Hp	11 Hp	12 Hp	13 Hp	14 Hp	15 Hp	16 Hp	17 Hp
20,000	40.19	44.15	48.11	52.24	56.24	60.37	64.61	68.98	73.73	77.78
24,000	52.95	57.51	62.25	67.00	71.74	76.48	81.25	86.08	91.06	95.88

Table C-2. Compressor horsepower requirements used in calculations.

Type: Worthington Model 25 BNBR

RPM	Actual capacity, ft^3/min	Maximum discharge pressure, $lb/in.^2$	Motor Hp
1490	97.1	125	25

EAFF COST CALCULATIONS

A. Capital Costs

24,000 ft^3/min unit	\$24,000
High voltage power supply (could be used for 10 modules)	9,000
Total	\$33,000
Capital cost per ft^3/min =	\$1.38

B. Operating Costs

Electricity:

Fan, based on 14 cm wg (5.5 in. wg) differential pressure across the unit and 25.4 cm wg (10 in. wg) system loss. Horsepower requirements based on fan manufacturer specifications are 85.03, converting this to kw-hr used for each 10^6 ft^3 of air cleaned gives:

$$85.03 \times 0.746 \frac{\text{kw}}{\text{hp}} \times \frac{0.694 \text{ hr}}{10^6 \text{ ft}^3} = \frac{44.02 \text{ kw-hr}}{10^6 \text{ ft}^3}$$

@ \$0.03/kw-hr yields \$1.32/10^6 ft^3

High voltage, based on 1 ma per tube, and a 50 percent efficiency of the power supply:

$$2 \times \frac{1 \text{ ma}}{\text{tube}} \times 200 \text{ tubes} \times 31{,}000 \text{ V} \times \frac{1\text{kw}}{1000\text{W}} = 12.4 \text{ kw}$$

Converting to kw-hr @ \$0.03 kw-hr yields:

$$12.4 \text{ kw} \times \frac{0.694 \text{ hr}}{10^6 \text{ ft}^3} = \frac{8.606 \text{ kw-hr}}{10^6 \text{ ft}^3} = \frac{\$0.26}{10^6 \text{ ft}^3}$$

Compressed air, based on 2 ft^3 per bag at 100 psi with 1 cleaning per 8-hour shift yields:

$$\frac{2 \text{ ft}^3}{\text{bag}} \times 200 \text{ bags} \times \frac{25 \text{ hp}}{97.1 \text{ ft}^3 \text{/min}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{0.746 \text{ kw}}{\text{hp}}$$

$$\times \frac{1 \text{ clean}}{5.55 \times 10^6 \text{ ft}^3} \times \frac{\$0.03}{\text{kw-hr}} = \$0.01/10^6 \text{ ft}^3$$

Maintenance, based on bag replacement every five years, operating 240 - 8-hr shifts per year.

Materials

200 bags @ \$10.00/bag = \$2,000.00

$$5 \text{ yrs} \times \frac{2765 \times 10^6 \text{ ft}^3}{\text{yr}} = 13{,}825 \times 10^6 \text{ ft}^3$$

$$\text{Costs per } 10^6 \text{ ft}^3 = \frac{\$2,000.00}{1,382.5 \times 10^6 \text{ft}^3} = \$0.15/10^6 \text{ ft}^3$$

Labor, based on 16 hrs to change 200 bags:

$$16 \text{ hr} \times \frac{\$20.00}{\text{hr.}} \times \frac{1}{1,382 \times 10 \text{ ft}} = \$0.02/10^6 \text{ ft}^3$$

TOTAL OPERATING COSTS: $\$1.76/10 \text{ ft}^3$

ESP COSTS CALCULATIONS

A. Capital Costs
TEPCO, Inc., Model 2001-ST, with self-cleaning and timer options for 20,000 ft^3/min air flow rate.

Operating mode	No. of units	List price per unit	No. of marriages	Cost per marriage	Total cost	Cost per ft^3/min
Single pass	10	\$3,356	9	\$100.00	34,460	1.72
Double pass	20	\$3,356	19	\$100.00	69,020	3.45

B. Operating Costs
Electricity:
Fan, based on 1.3 cm wg (0.5 in. wg) differential pressure across the ESP and 25.4 cm wg (10 in. wg) system loss. Horsepower requirements, based on fan manufacturer's specifications, is 46.38 hp. Converting this to kw-hr used for each 10^6 ft^3 of air cleaned gives:

$$46.38 \text{ hp} \times \frac{0.746 \text{ kw}}{\text{hp}} \times \frac{0.833 \text{ hr}}{10^6 \text{ ft}^3} = \frac{28.82 \text{ kw-hr}}{10^6 \text{ ft}^3} \text{ @ } \$0.03/\text{kw-hr}$$

$$= \$0.87/10^6 \text{ ft}^3$$

High voltage, based on 50 watts per unit:

$$\text{Single pass:} \quad 0.050 \text{ kw} \times \frac{0.833 \text{ hr}}{10^6 \text{ ft}^3} \times \frac{\$0.03}{\text{kw-hr}} \times 10 \text{ units} = \$0.01/10^6 \text{ ft}^3$$

$$\text{Double pass:} \quad 0.050 \text{ kw} \times \frac{0.833 \text{ hr}}{10^6 \text{ ft}^3} \times \frac{\$0.03}{\text{kw-hr}} \times 20 \text{ units} = \$0.02/10^6 \text{ ft}^3$$

Compressed air based on 52.8 ft^3/min consumption per unit and a 1-minute cleaning time, every 8 hr of operation:

Single pass: $52.8\ \text{ft}^3/\text{min} \times \frac{25\ \text{hp}}{97.1\ \text{ft}^3/\text{min}} * \frac{0.746\ \text{kw}}{\text{hp}} \times \frac{1\ \text{hr}}{60\ \text{min}}$

$\times \frac{1\ \text{minute operating}}{\text{time}/9.6 \times 10^6\ \text{ft}^3} \times \frac{\$0.03}{\text{kw-hr}} \times 10\ \text{units} = \$0.01/10^6\ \text{ft}^3$

Double pass: $\$0.02/10^6\ \text{ft}^3$

Maintenance

Materials - None used.

Labor: The maintenance schedule is dependent upon the particulate loading of the incoming air stream.

High loading - washed cleaned every 3 eight-hour shifts:

$$8\text{-hr labor} \times \frac{\$20.00}{\text{hr}} \times \frac{1}{28.8 \times 10^6\ \text{ft}^3} = \$5.56/10^6\ \text{ft}^3$$

Low loading - washed cleaned every 20 eight-hour shifts:

$$8\text{-hr labor} \times \frac{\$20.00}{\text{hr}} \times \frac{1}{192 \times 10^6\ \text{ft}^3} = \$0.84/10^6\ \text{ft}^3$$

TOTAL OPERATING COSTS:

Single pass, high loading = $\$6.45/10^6\ \text{ft}^3$
Single pass, low loading = $\$1.73/10^6\ \text{ft}^3$
Double pass, high loading = $\$6.47/10^6\ \text{ft}^3$
Double pass, low loading = $\$1.75/10^6\ \text{ft}^3$

ACF COSTS CALCULATIONS

A. Capital Costs
20,000 ft^3/min (80 cartridge) unit - $25,800
Capital cost per ft^3/min - $1.29

B. Operating Costs
Electricity:
Fan based on 3.8 cm wg (1.5 in. wg) differential pressure across the air cleaner and 25.4 cm wg (10 in. wg) system loss.

Horsepower requirements based on fan manufacturer's specifications are 52.07. Converting this to kw-hr used for each $10^6\ \text{ft}^3$ of air cleaned gives:

$$52.07\ \text{hp} \times \frac{0.746\ \text{kw}}{\text{hp}} \times \frac{0.833\ \text{hr}}{10^6\ \text{ft}^3} = 32.36\ \text{kw-hr @ } \$0.03/\text{kw-hr}$$

$= \$0.97/10^6\ \text{ft}^3$

Compressed air, based on 0.7 ft^3 of compressed air at 100 psig used per cartridge cleaned with the unit operating on a once per hour cleaning cycle:

$$\frac{0.7\ \text{ft}^3}{\text{cartridge}} \times 80 \text{ cartridges} \times \frac{1 \text{ clean}}{1.20 \times 10^6\ \text{ft3}} \times \frac{25\ \text{hp}}{97.1\ \text{ft}^3\ /\text{min}}$$

$$\times \frac{1\ \text{hr}}{60\ \text{min}} \times \frac{0.746\ \text{kw}}{\text{hp}} \times \frac{\$0.03}{\text{kw-hr}} = \$0.004/10^6\ \text{ft}^3$$

Maintenance, based on cartridge replacement every four years, operating for 240 8-hr shifts per year.

Materials:

80 cartridges @ \$50.00 ea. = \$4,000

$$4 \text{ yrs} \times \frac{2304 \times 10^6\ \text{ft}^3}{\text{yr}} = 9216 \times 10^6\ \text{ft}^3$$

$$\$4{,}000 \div 9216 \times 10^6 \text{ft}^3 = \$0.43/10^6\ \text{ft}^3$$

Labor, based on 2 hrs to change 80 cartridges:

$$2\ \text{hr} \times \frac{\$20.00}{\text{hr}} \times \frac{1}{9216 \times 10^6 \text{ft}} = \$0.004/10^6\ \text{ft}$$

TOTAL OPERATING COSTS:

$\$1.42/10^6\ \text{ft}^3$

ADDED OPERATING COSTS FOR SAFETY MONITORING FILTERS

The added electricity costs for operating the fan for each air cleaner tested were calculated by determining the extra horsepower needed to compensate for the additional pressure of the SMF. These calculations are based on the following system pressures:

EAFF = 14 cm wg (5.5 in. wg)
ACF = 3.8 cm wg (1.5 in. wg)
ESP = 1.3 cm wg (0.5 in. wg)

Ductwork = 25.4 cm wg (10 in. wg)

Glass fiber SMF = 3.1 cm wg (1.22 in. wg) average

HEPA SMF = 5.7 cm wg (2.24 in. wg) average

EAFF
Glass fiber SMF:

Hp = 92
Additional cost for SMF = $\$0.11/10^6$ ft^3

HEPA SMF:

Hp = 96
Additional cost for SMF = $\$0.18/10^6$ ft^3

ESP
Glass fiber SMF:

Hp = 54
Additional operating cost for SMF = $\$0.14/10^6$ ft^3

HEPA SMF

Hp = 58
Additional operating cost for SMF = $\$0.22/10^6$ ft^3

ACF
Glass fiber SMF:

Hp = 62
Additional operating cost for SMF = $\$0.19/10^6$ ft^3

HEPA SMF:

Hp = 66
Additional operating cost for SMF = $\$0.26/10^6$ ft^3

GLOSSARY

C	- Measured concentration, mg/m^3.
cc/min	- Volume, cubic centimeter per minute.
CI	- Confidence interval used in statistical evaluations.
cm wg (in. wg)	- Pressure, centimeters of water (in. of water), water gauge
CV	- Coefficient of variation, equal to the standard deviation divided by the mean.
Dp_{50}	- Aerodymic diameter - 50 percent or mass median diameter.
ft^3	- Cubic feet.
ga	- Gauge.
hp	- Horsepower.
KVDC	- Kilovolts, DC.
l/min	- Liters per minute flow rate.
ma	- Milliaperes.
mg	- Milligram.
m^3	- Cubic meter.
MV	- Voltage, millivolts.
NIOSH	- National Institute for Occupational Safety and Health.
OSHA	- Occupational Safety and Health Administration.
p	- Pressure.
Δ	- Change in a variable.
PEL	- Permissible exposure limit (OSHA).
ppm	- Parts per million.
R	- Correlation coefficient.
Sw	- Sample weight, mg.
TLV	- Threshold limit value (ACGIH).
μg	- Microgram.
V_m	- Metered volume of air, m^3.

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