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PROCEEDINGS: SYMPOSIUM ON THE USE OF FABRIC FILTERS FOR THE CONTROL OF SUBMICRON PARTICULATES (APRIL 8-10, 1974, BOSTON, MASSACHUSETTS)

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by

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ABSTRACT

This document provides the papers presented at the Symposium on the Use of Fabric Filters for the Control of Submicron Particulates, which was jointly sponsored by the Environmental Protection Agency and the GCA/Technology Division. The primary purpose of the symposium was to better define the role of fabric filter systems for the control of fine particle emissions.

The effectiveness of fabric filter systems for controlling particulate emissions from industrial sources is well accepted in the pollution control field. However, the vast majority of available performance data depict overall weight recoveries with only minimal information on the capture efficiencies for particles in the ≤ 1 micrometer size range.

Experts from Government, Industrial and University groups discussed the theoretical and practical aspects of filtration and important related areas such as particle behavior, fabric selection and system evaluation. The technical presentations were aimed at describing the fine particulate control potential of existing fabric filter systems for the benefit of regulatory and user groups and suggesting to manufacturing and research organizations those areas where performance levels most need improvement.

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ACKNOWLEDGEMENTS

The editor, and General Chairman of the Symposium, wishes to acknowledge the capable assistance of Dr. Dennis C. Drehmel of the Environmental Protection Agency and Mr. Richard Dennis of the GCA/Technology Division in formulating the symposium program and carrying out its implementation.

THE SIGNIFICANCE OF PARTICULATE EMISSIONS

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INTRODUCTION

Fine particulates, those solid or liquid aerosols less than 3 microns in diameter, are the subject of increasing concern as one of the major air pollutants. Compared to coarse particulate their greater capacity for obstructing light and their slow settling rate in the atmosphere cause the limited visibility typical of air pollution haze and smog. More importantly, fine particulates constitute a health hazard, since they can bypass the body's respiratory filters and penetrate deep into the lungs. Further, because these particles can act as transport vehicles for gaseous pollutants, both adsorbed and reacted, the resultant synergistic effects can be harmful to human health. These problems associated with fine particulates are intensified by the tendency of some metallic materials to be highly active, both chemically and catalytically.

Emissions of fine particulates typically result from physical or chemical processes, which may include condensed gaseous products or products of chemical reactions. High temperature processes such as metallurgical operations and combustion of fossil fuels are major sources. Metallurgical operations are major producers of metal fumes unique to the process, such as lead, zinc, copper or iron oxide, while combustion processes produce fuel ash containing a wide spectrum of materials. Combustion of residual oil, for example, produces vanadium, chromium, nickel, iron, copper and other highly reactive and catalytic metals. Some processes emit solid and liquid hydrocarbons such as organic condensibles, tars, and carbon particles capable of sorption of more volatile constituents. Such processes include pyrolysis, incomplete combustion, vaporization of lubricating or process oils, and chemical operations related to the textile, refinery, petrochemical, and plastics industries. Forest fires, as well as controlled agricultural and slash burning, also are sources of fine particulates.

HEALTH EFFECTS

As is frequently the case with non-infectious pollutants and toxicants, the health effects case against fine particulates is not absolutely clear cut. First it must be remembered that fine particulates are not a single pollutant but a large category of pollutants with a common set of size, transport, and behavioral characteristics. Once dispersed, fine particulates behave, depending upon their size, like something between a coarse particle and a gas. They remain suspended and diffuse, are subject to Brownian motion, follow fluid flow around obstacles, and can penetrate deep into the respiratory system.

The moderate amount of information that is available concerning this deposition of particles is based upon mathematical models and experimental data. Particles larger than 5 microns are deposited in the nasal cavity or nasopharynx, while increasing numbers of smaller particles are deposited in the lungs. Over 50 percent of the number of particles between 0.01 and 0.1 microns that penetrate into the pulmonary compartment will be deposited there. This ability of particulates to penetrate into the respiratory system and be captured, is principally a function of their geometry and is relatively independent of the chemical properties of the particle.

On the other hand, the health effects of the fine particulates that have penetrated the respiratory system and been captured, are almost completely dependent on their chemical or toxic nature. It is, therefore, not possible to generalize on health effects; specific materials must be considered. Here the data become sparse and it becomes necessary to draw on our knowledge of toxic characteristics of specific substances gained from other information sources, and on our understanding of physiological mechanisms that work to dispose of collected materials.

The principal effect on health is through inhalation and direct attack on the respiratory system. This may result in short term irritant effects, or longer term damage such as silicosis, asbestosis, chronic bronchitis, and emphysema. In all these cases the respiratory system is directly impaired.

A second mechanism of adverse effects involves the respiratory system indirectly as a significant route of entry for non-respiratory toxicants. In this case, substances which are deposited in the respiratory system are translocated to the gastro-intestinal system by muco-ciliary transport and are swallowed. They may then exert a primary toxic effect directly or be absorbed and translocated to other tissues to exert adverse health effects.

Because of the present scarcity of knowledge concerning the health effects of specific pollutants and combinations of pollutants, it will take years to develop the data base necessary to quantify the exact dose-response characteristics of fine particulates. Sufficient information does exist, however, to conclude that fine particulates must be controlled to fairly stringent levels if public health is to be properly protected.

PARTICULATE EMISSION SOURCES

In 1971, under a project carried out by Midwest Research Institute, EPA published a systems study of particulate pollutants covering mass emissions from U. S. industry. It was estimated that gross particulate emissions in the U. S. totaled 18 million tons per year from various major industries. These emission figures, based on 1968 production data, took into account the degree of application of control devices and their average efficiency.

This study also included estimates of the mass and number of fine particles emitted, although analysis of the particle size distribution data then available, indicated that almost all had been obtained using sampling and sizing procedures that are just not suitable for particles smaller than about 2 microns. Accurate data on the fractional efficiency of commercial control systems were either completely lacking or too generalized in nature.

Since reliable particle-size distributions were not available in the 0.01-2 micron range, it was necessary to extrapolate from the available data for larger particles. This extrapolation was the basis of estimates for fine particulate emissions, both mass and number data, from the major industrial sources. (Inadequacy of data made it impossible to make these calculations for agricultural operations, forest products, clay products, and primary non-ferrous metals, and consequently these important sources of particulate were not included.)

These mass and number estimates led to the following preliminary priority ranking of major industrial sources of fine particulate:

1. Ferro-alloy furnaces.
2. Steel-making furnaces.
3. Coal-fired power plants.
4. Lime kilns.
5. Kraft pulp mill recovery furnaces.
6. Municipal incinerators.
7. Iron foundry cupolas.
8. Crushed stone plants.
9. Hot-mix asphalt plants.
10. Cement kilns.

During this study, it became obvious that the severe lack of sub-micron particle size data was the result of not having adequate sampling, sizing, and particle measurement techniques in the sub-micron range. As a result, the Control Systems Laboratory of EPA set out to sponsor the development of such capability. Emphasis was placed on inertial impactors as the most practical approach. This development culminated in a recent comparison of available inertial impactors in a series of 192 individual measurements on one power plant; this comparison showed that, when properly used, inertial impactors are reliable for measurement down to about 0.2 micron. They are now used routinely by EPA personnel and contractors; more than 50 sets of particle size distribution data have been generated in the last few months.

In an effort to extend our measurement capabilities to even smaller particulates, Southern Research Institute, under EPA sponsorship, recently used a series of diffusion batteries coupled with condensation nuclei counters, to provide concentration and size distributions by number over the size range from about 0.01 to 0.3 micron.

FINE PARTICULATE CONTROL

We are already learning some interesting facts about control of fine particulate using these new measurement techniques. Four tests on high-efficiency electrostatic precipitators, three on utility boilers and one on a paper mill recovery boiler, have shown fractional efficiencies better than 90 percent (in some cases better than 98 percent) all the way down to 0.1 micron. We have also found some high-energy scrubbers that show good collection capability.

Of particular interest to this fabric filtration oriented group are the results of testing two baghouses (both with reverse air cleaning) installed on coal-burning sources. The first is installed on a utility boiler burning a mixture of anthracite coal tailings and metallurgical coke. Tests made under standard operating conditions showed greater than 99 percent removal of all particulate down to 0.1 micron. This baghouse has operated efficiently and relatively trouble-free for over 1 year with no bag failures.

The second unit is a pilot scale baghouse installed on a slip stream of an industrial boiler burning bituminous coal and operated at a high gas-to-cloth ratio. Initial testing again showed greater than 99 percent efficiency down to 0.1 micron.

These tests indicate that certain currently available devices--including fabric filters--can effectively control fine particulates under the right conditions. However, it should be emphasized that the range of applicability of conventional baghouses, precipitators, and scrubbers to control fine particulates is limited. Baghouses cannot be used for high temperature clean-up, or in gaseous atmospheres which degrade the fabric, and their size limits applicability in many retrofit situations. Precipitators are most effective on particulates of a fairly narrow range of electric resistivity; at both higher and lower resistivities, control efficiency drops off. Unfortunately, most low sulfur coals produce high resistivity fly ash, so that switching to low sulfur western coals decreases the sulfur oxides problem but increases the particulate control problem.

EPA is intensively studying all facets of the problem of fine particulates which, of course, is a very complicated one. This includes characterization of the chemical composition and toxicology of particulates as a function of particle size and industrial source. As would be expected, chemical composition varies dramatically depending on source. For example, particulate emissions from an open-hearth furnace have been found to be about 90 percent iron oxide, with the remainder being other metallic oxides and compounds depending on the source of ore and fluxes used. In contrast, particulate from a cement plant was 40 percent calcium oxide, 20 percent silicon dioxide, 10 percent iron oxide, and the remainder primarily other metallic oxides.

Fly ash from fossil fuel burning varies markedly in composition depending on the source of coal and degree and type of combustion. In addition to substantial quantities of oxides of silicon, aluminum, iron, and calcium, as many as 30 to 40 additional elements are present in trace to significant quantities. Most exist at constant levels in all particle sizes, although some of the more toxic elements appear in increasing concentrations with decreasing particle size.

The complexity of sources of fine particulate emissions, and the physical and chemical characteristics of the particles, as well as of the off-gases bearing them, complicate the development of adequate control technology. In addition to studying the application of currently available control techniques, we are continuously evaluating numerous new concepts and novel devices. In the long run, we believe it will be necessary to develop a number of different techniques for control of the wide diversity of sources, and wide variety of types, of fine particulate.

CONCLUSIONS

You may wonder if we are making any real progress in our goal to decrease air pollution. In the 4th Annual Report of the Council on Environmental Quality published in September of 1973, the statement is made that of the 10 major cities with detailed particulate information available, six have shown a general trend toward improved levels of particulate. These improvements are due to the use of less polluting fuels, as well as the installation of control devices. However, the report goes on to state that, although there have been significant improvements, a massive effort is still needed to meet air quality standards. Many areas of the country have ambient levels which still exceed the primary standards for the six "criteria" pollutants; this situation is worse for particulates than for any other major pollutant. Combined with the special problems of control of fine particulate, it is clear that EPA, industry, and the control equipment manufacturers, working together, have a difficult and challenging task to accomplish in this area. Improved fabric filtration will be an important step toward the successful accomplishment of this task.

EMISSION STANDARDS FOR PARTICULATES

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The Emission Standards and Engineering Division is responsible for the promulgation of standards of performance under Section 111 and national emission standards for hazardous pollutants under Section 112 of the Clean Air Act. The Division also serves as a primary source of technical expertise in defining stationary source control measures for State implementation plans. Different criteria are applied when defining stationary source emission standards, depending on which Section of the Clean Air Act is being implemented. For State implementation plans we are, for example, generally concerned with reasonably available control for existing sources. Under Section 112, the criteria is one of providing an ample margin of safety to protect public health. In any case, a major deficiency in developing emission standards is the lack of predictive capability when baghouses are intended as the control device. This is best illustrated by confining this discussion to standards of performance for new stationary sources. For purposes of orientation, let me briefly review this Section of the Clean Air Act.

As defined in the Act, standards of performance are restricted in application to new facilities, and must "reflect the application of best system of emission reduction." The term "best system of emission reduction" was chosen to emphasize the concept that pollution control includes the selection of raw materials, the manufacturing process, and performance of the control device. Therefore, the potential exists for the application of new technology, provided one can demonstrate that the standards are achievable. Cost is a factor to be considered, but a cost/benefit analysis is not mandatory. According to Congress, the costs must be reasonable in terms of the economics of the industry for which standards are being set. To date, except for standards on sulfur oxides from fuel combustion, consideration of raw materials has been minimal. Indeed, when faced with issues on the impact of raw materials on control system performance, we have generally tended toward a relaxation of the standards. This has occurred because relationships between raw material characteristics and system performance are not generally available.

Since standards of performance must reflect "the best system of emission reduction," our data base is always limited. A purist philosophy leads to the conclusion that the standards should be based on a single system. The word "reflects," however, provides some relief and the "necessary consideration of costs" provides increased maneuverability. Nonetheless, we are clearly not attempting to define averages of the most probable emission rates given the application of some generic control device to a large number of sources.

With the goal being a definition of best technology, it should be clear that highly detailed design and operating characteristics are important. For example, fabric structure, bag length-to-diameter ratio or filter spacing may affect performance in a subtle but significant manner. Given the range of variables, it is an almost impossible task for our engineers to identify which details are important. Without such an identification, however, we are constantly faced with the need to relax our recommended standards. This, in turn, does not force technology to any great degree. Some basic field investigations are needed, therefore, which would define which parameters are critical to performance and which are important only from a manufacturers viewpoint.

The need to better delineate control system performance as a function of raw material characteristics, process variables, and collector design parameters can be better appreciated by examining the full standard-setting process.

In addition to the collection and analysis of hard data to arrive at some suitable recommended number, the standard-setting process involves an examination of energy consumption, economics and environmental impact. All of this information is then subject to review, both in and out of EPA. As you can imagine, the review process is generally one of destructive criticism. To off-set the questions raised, many of which refer to conditions not experienced at test sites, more and better defined correlations are needed between equipment design, process variables, and raw material characteristics. For example, in setting standards of performance for asphalt plants a major issue was the influence of raw material size on baghouse efficiency. Three size distributions come into play: (a) the size distribution of the sand before the drier, (b) the size distribution of entrained particles leaving the drier; and (c) the size distribution of the particulate matter as it approaches the fabric itself. It is generally accepted that significant differences can exist from one point to another. It can also be theorized that the geometry of the baghouse is important in determining what the filter actually sees. Some quantification in this area would be extremely helpful so we can better define system capability under a variety of conditions.

The problem of adequately defining baghouse efficiency still haunts us. Many of the systems we investigate emit gas streams that follow a cyclical pattern. Without some predictive capability our testing must include the entire cycle. With such general data we are never sure what happens when the process is changed, when the filter cleaning cycle is altered, or when testing time is different. Basic oxygen furnaces and electric arc furnaces are good examples of this problem.

Increased knowledge about fabric filter performance is also important if we are ever to be able to set standards on similar processes without testing. Why, for example, can we not establish an emission standard for lime kilns based on our knowledge of how to control cement kilns? The answer, of course is that we cannot demonstrate that the standards would be achievable. Therefore, each source represents a new problem and the rate of standard setting is decreased.

Our ability to predict collector performance is very important to the issuance of modifications. The definition of a new source in Section 111 of the Clean Air Act includes construction (which is obvious) and modification (which is not so obvious). A modification is defined as any "physical change or change in method of operation which increased emissions."

The question which must be answered is the impact of physical changes or changes in method of operation on emissions from an existing collector. If the emissions are predicted to increase, then the source will be modified, and the standards of performance applied. This, in turn, raises a second question of how to upgrade collector performance so that emissions will not increase or to achieve the standard of performance. As you can imagine, answers to these questions are important to both the regulated and the regulator.

Although a great amount of effort has gone into particulate control, and even though a majority of the standards of performance are concerned with particulates, we have not achieved any great degree of expertise in setting standards. We tend to rely on broad categories of equipment, and have not yet really been able to project the difference between baghouse A and baghouse B. This ability, however, is of great importance when dealing with modifications to existing plants which are already controlled. In such a situation we like to know how the existing equipment can be up-graded to comply with the standards of performance. This knowledge will be indispensable in deciding what is and what is not a modification and who should and who should not be subject to Section 111 of the Act. Our ability to predict collector performance must also be increased to better answer the many questions raised during the standard setting process and to enable a transfer of performance from one source category to another.

PERFORMANCE AND COST COMPARISONS BETWEEN FABRIC FILTERS AND ALTERNATE PARTICULATE CONTROL TECHNIQUES

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INTRODUCTION

A study was conducted to evaluate performance and cost comparisons of fabric filters and alternate fine particulate control techniques. In relating the removal of fine particulate to costs, due to the lack of fractional efficiency data, it was found necessary to treat a specific application in order to make the study manageable. The case chosen is that of the coal fired industrial boiler since Enviro-Systems has a pilot program in this application area.

Thus, as a preamble to the economic comparisons a brief discussion of the pilot plant activity and related economics will be made. This discussion will be followed by a treatment of the particulate removal capabilities of electrostatic precipitators, fabric filters and venturi scrubbers. Then, on the basis of the specific application of interest, a comparison of the capital, operating and annualized costs will be made for these three conventional methods of dust removal. Presently very little actual field data is available on the fine particulate removal capability of the above mentioned control techniques. Therefore, it is necessary to base the economic comparisons upon a severely limited amount of existing fractional efficiency data combined with extrapolations of performance at larger particle sizes as suggested by Craig.[1]

PILOT PLANT ACTIVITY

As previously reported,[2,3] the Enviro-Systems & Research fabric filter pilot plant was installed at Kerr Industries in Concord, North Carolina. This effort was jointly sponsored by the Environmental Protection Agency, Kerr Industries and Enviro-Systems & Research. A slip stream for the pilot facility was installed on a Babcock and Wilcox boiler with a design capacity of 60,000 lb/hr. steam. Stack sampling conducted in January, 1973, indicated emission rates of 130 lb/hr. Gas volumes were determined to be around 35,000 acfm per boiler, at a temperature of 355°F which gives a grain loading of 0.4 gr/acfm. Neither the slip stream duct nor the baghouse was insulated. Orsat analysis indicated 9.5 percent CO_2, 10 percent O_2, 0 percent CO and 80.5 percent N_2. Coal analysis showed a sulfur content of about 0.6 percent. Analysis of inlet flue gas to the pilot unit indicated SO_3 concentrations between 3 and 8 ppm and SO_2 concentrations between 240 and 370 ppm.

The pilot plant was capable of handling 11,000 acfm of flue gas when operating at an air-to-cloth ratio of 6/1. The baghouse is divided into four cells, each containing 54 bags. The bags are 5" in diameter by 8' 8" long giving 11.5 square feet per bag, 620 square feet per cell and 2,480 square feet for the house. The bags are set into a tube sheet located at the top of the house by two snap rings incorporated into the bag itself. A spiral cage is set inside the bag to prevent collapsing. The dirty gases enter one end of the unit, see Figure 1, pass thru the tapered duct, into the classifier, then through the bags. The classifier forces the dirty gases to change direction 90°, then 180°. This quick directional change forces the larger and heavier particles out of the flow so they fall directly into the hopper. Gases are forced thru the fabric filter into the center of the bags, leaving the particulate on the outer surface of the bags where it is removed periodically during the cleaning cycle. The cleaned gases are drawn up and out through the center of the filtering bag into a center exit plenum via an open damper in the cell above the tube sheet. The bags are

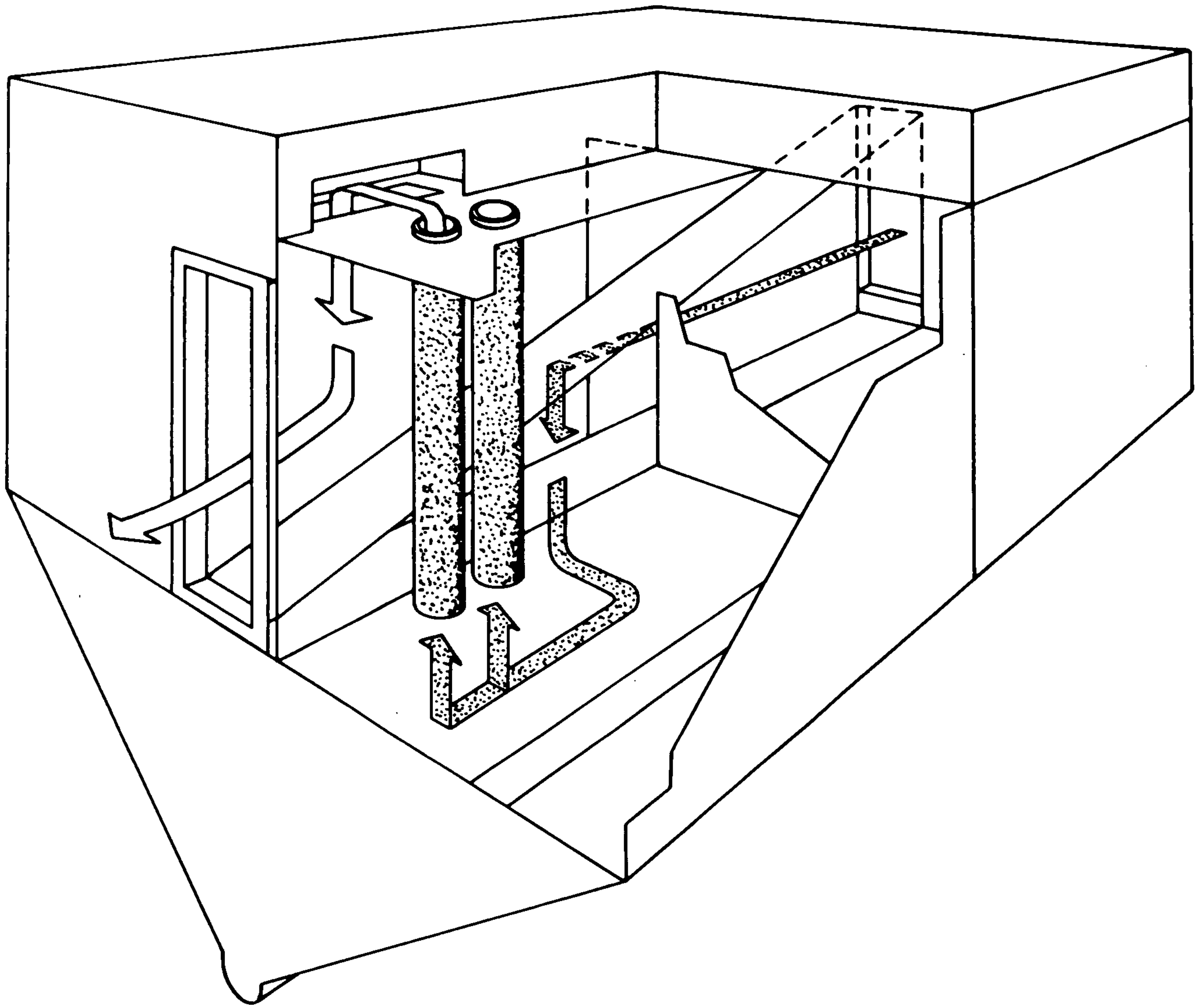

Figure 1. Baghouse flow and collection diagram

cleaned one cell at a time by closing off the cell damper to the exit plenum and at the same time opening a reverse air damper. As the solid matter collects on the outside of the filter bag, it builds a cake or crust which begins to restrict the flow of the gases. During the cleaning cycle, clean air enters the cell thru the reverse air damper. The clean air is forced down the filter bag, opposite to the normal flow direction. Damper system and control panel arrangements allow for variations in main gas volume, reverse air volume duration of cleaning and frequency of cleaning. The existance of four cells allows for repetitive sequential testing of different bag types without the need to change bags.

Inlet particle size and analysis was obtained by the use of Anderson and Pilat (University of Washington) in-situ particle size analyzers. The results of these tests are shown in Figure 2.

Outlet particle size analyses were conducted at two air-to-cloth ratios of approximately 3 and 6 ft./min. These results are shown in Figure 3. Raising the A/C from 3 to 6 increased the outlet loading from .03 mg/SCF to .06 mg/SCF. Table 1 shows that even at the higher gas velocity the overall efficiency was still greater than 99.5 percent.

Installed costs were determined for a fabric filter dust collector sized for 70,000 ACFM at 250^{o}F and using Nomex felt as the filter material. It was assumed that the house and hopper would be insulated and the bags would be continuously coated with lime to prevent filter media deterioration due to acid dew point excursions. Air-to-cloth ratios considered were 4.3, 6.3 and 7.5. As shown in Figure 4, the corresponding costs were found to be $164,000, $141,700 and $104,000 or on the basis of $/ACFM, they are $2.34, $2.02 and $1.48 respectively. These estimates were based on a bag price of $15.50 each.

Annual operating costs were also determined based on 25 percent bag replacement per year and a pressure drop of 5 inches of water. These were

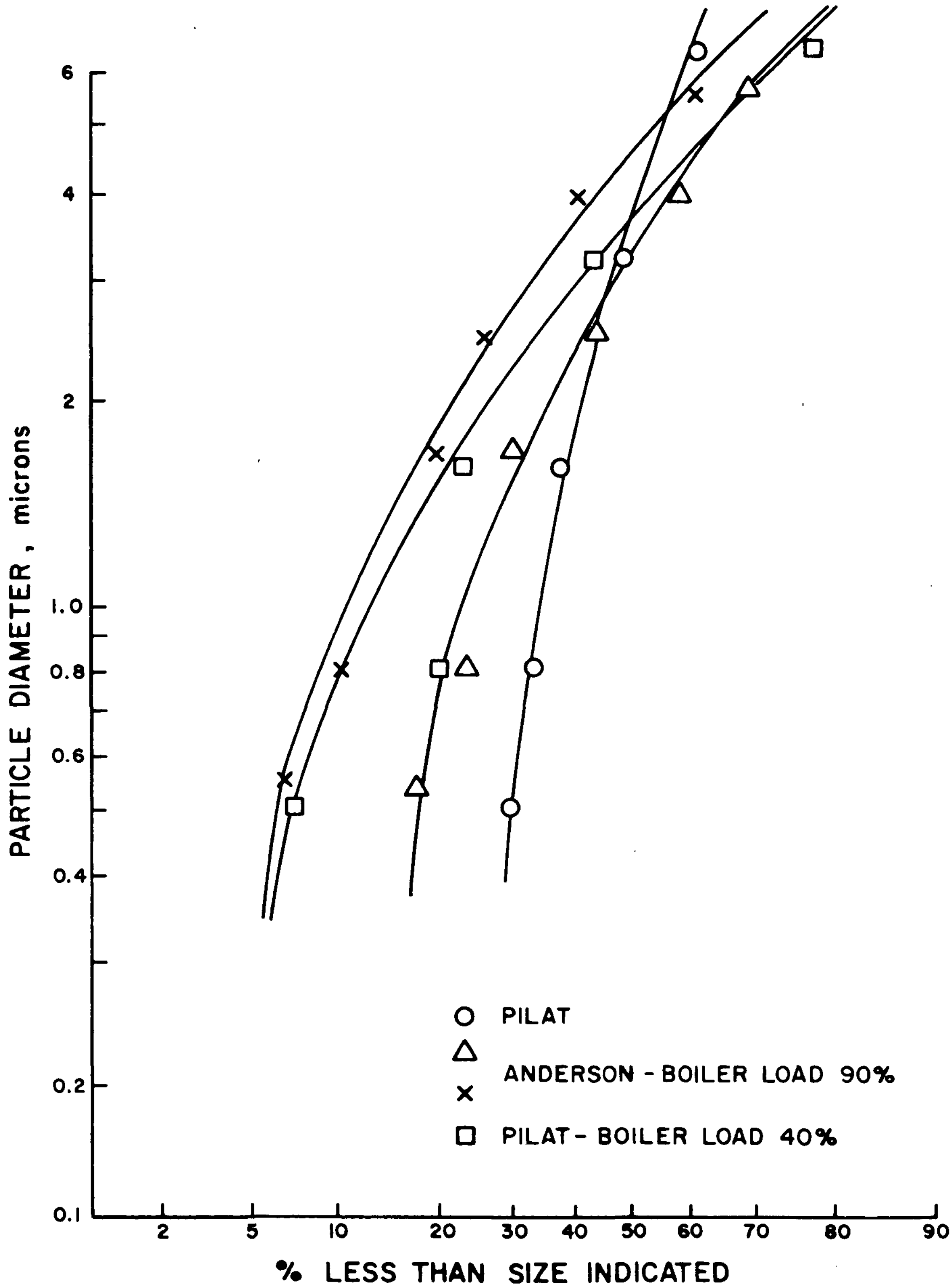

Figure 2. Inlet particle size distribution

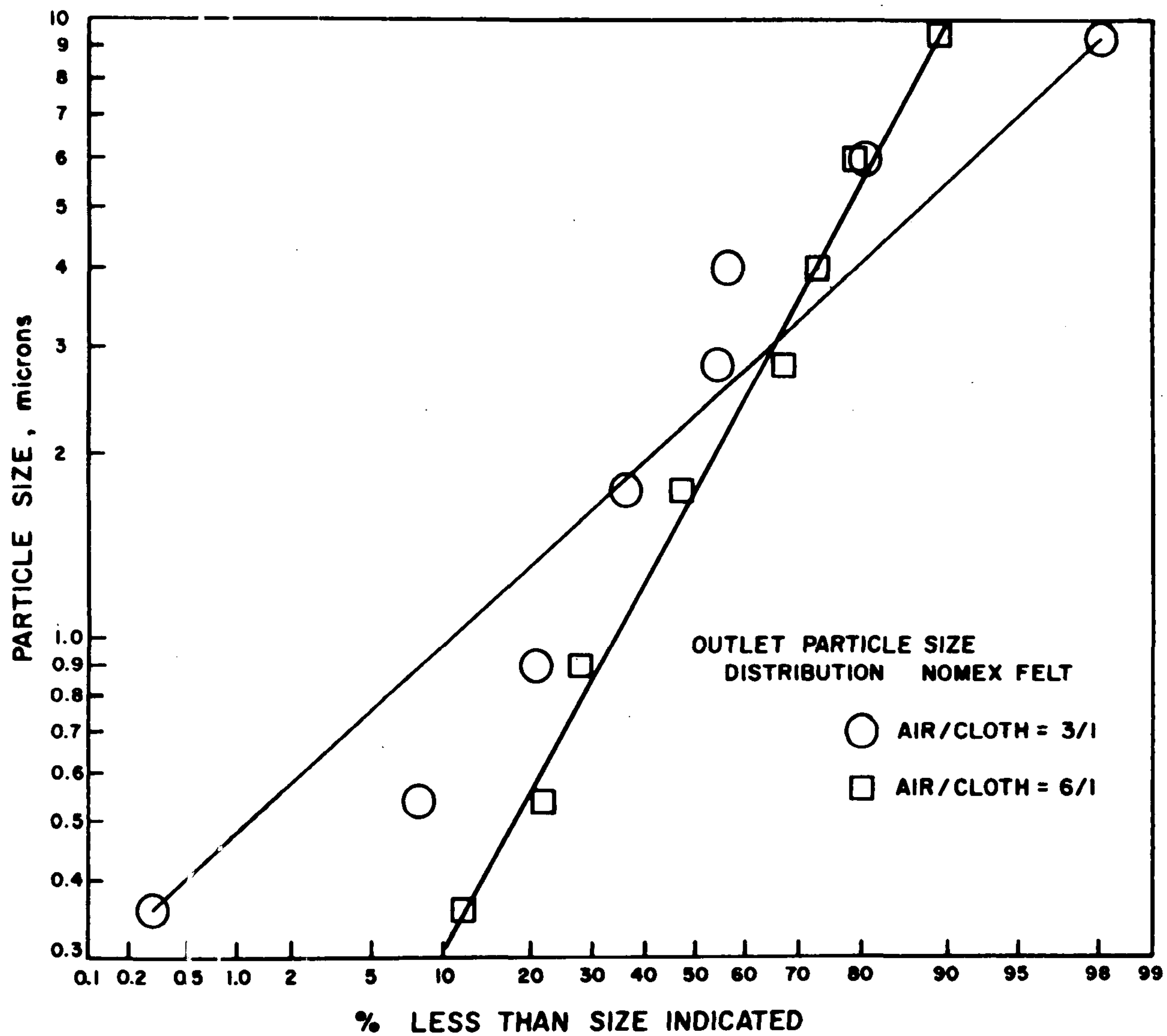

Figure 3. Outlet particle size as a function of air-to-cloth ratio

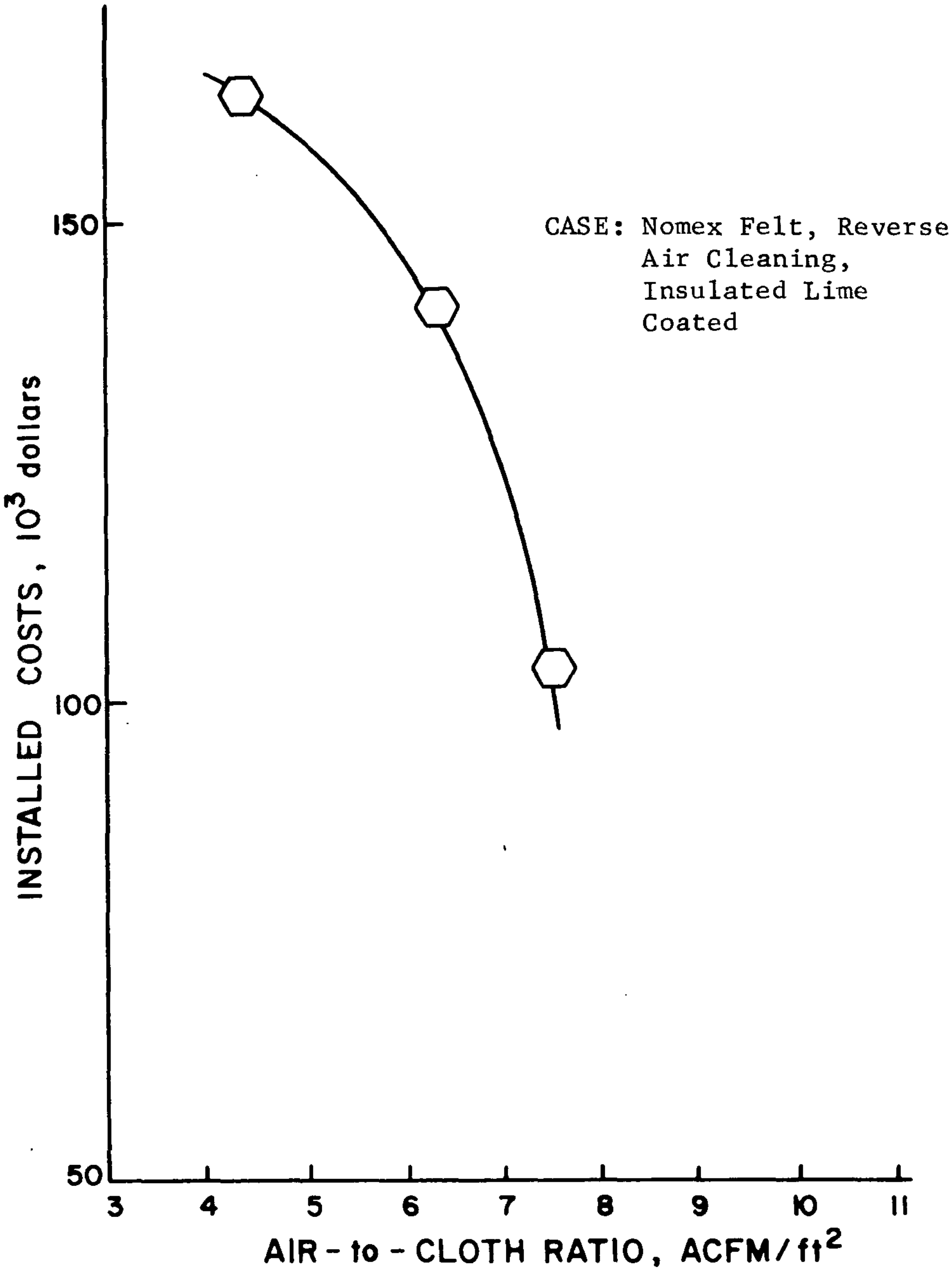

Figure 4. Installed cost vs. air-to-cloth ration, Nomex felt

Table 1. DUST REMOVAL EFFICIENCIES

Filter Media Nomex Felt Air-to-Cloth Ratio ≈6			
Particle Diameter	Inlet Load mg/scf	Outlet Load mg/scf	Removal %
> 9.5	4.221	.0068	99.84
6	2.292	.0060	99.74
4	1.482	.0033	99.78
2.8	1.254	.0039	99.69
1.75	0.8893	.0175	98.03
0.9	0.6844	.0054	99.21
0.54	0.4179	.0035	99.16
0.36	0.1920	.0060	96.88
< 0.36	0.7062	.0072	98.98
Total	12.140	.0596	99.51

found to be $13,270, $11,620 and $10,770 for air-to-cloth ratios of 4.3, 6.3 and 7.5 respectively. The operating costs vs. air-to-cloth ratio are shown in Figure 5.

Annualized costs were computed from installed and operating costs, see Figure 6. These were $35,000, $30,460 and $24,600 for the same air-to-cloth ratios.

Development of the operating and annualized costs for the foregoing fabric filter case, as well as the subsequent cases for electrostatic precipitators and wet scrubbers, employed the formulae published by Edmisten and Bunyard.[4]

Capital costs for the fabric filter and venturi scrubber were based upon Enviro-Systems & Research selling prices as of March, 1974. Electrostatic precipitator capital costs were based upon two independent vendor quotations obtained in March, 1974.

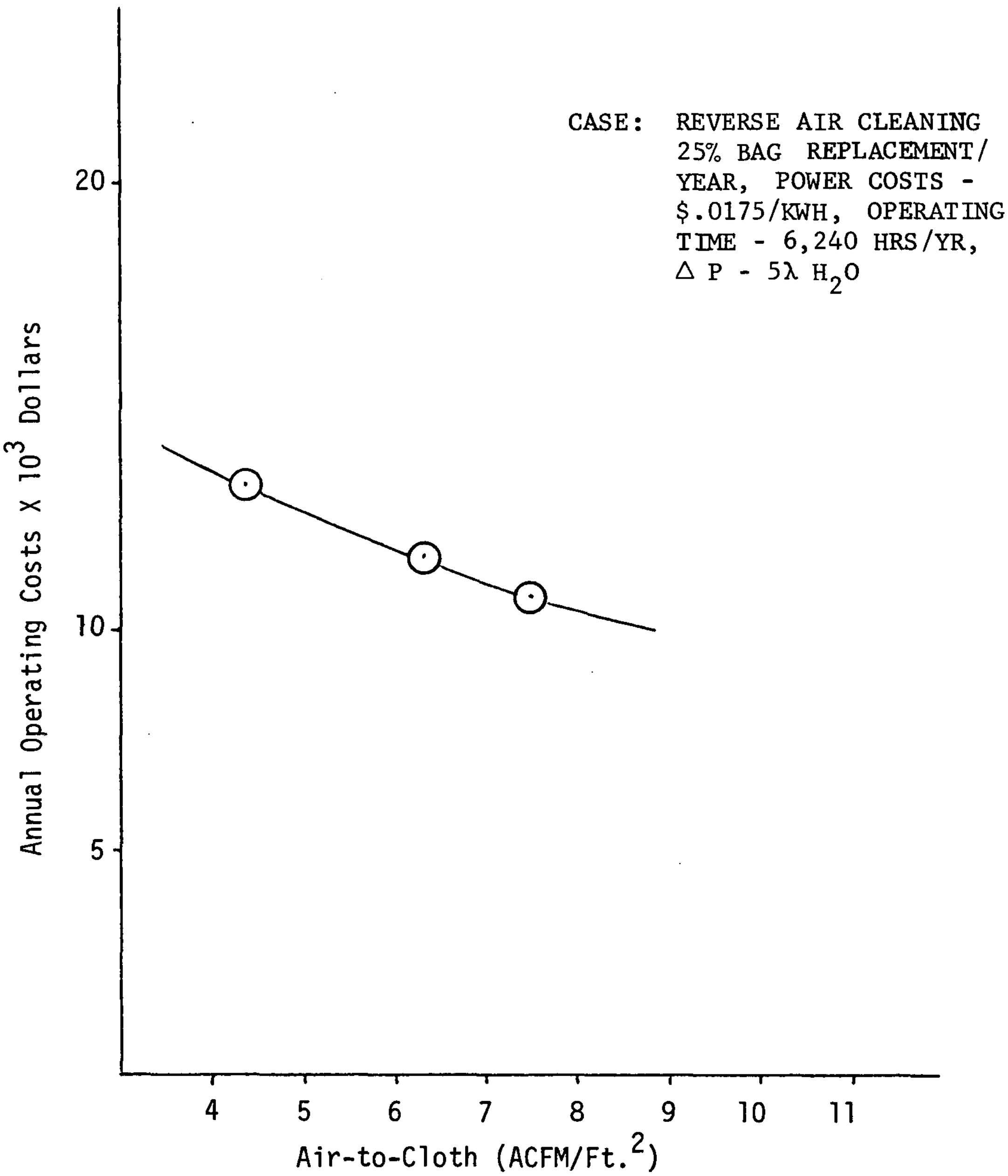

Figure 5. Annual operating costs versus air-to-cloth ratio for Nomex felt

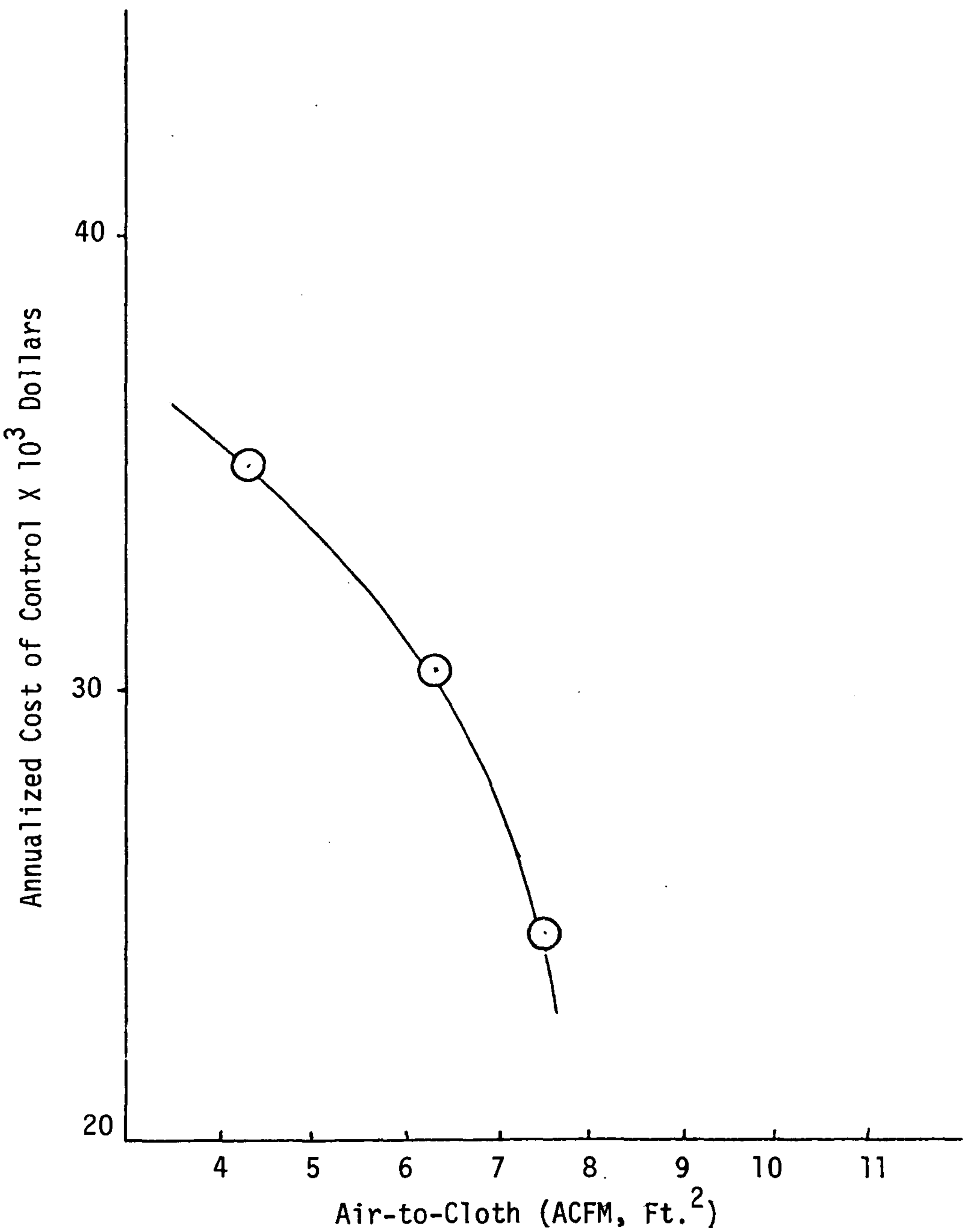

Figure 6. Annualized cost versus air-to-cloth ratio for Nomex felt

EFFICIENCY VERSUS PARTICLE SIZE

Fabric filters, electrostatic precipitators and high energy scrubbers are capable of achieving greater than 99 percent overall efficiency for removal of fly ash particulates. There is, however, a significant difference in removal efficiencies when considering fine particles; i.e. those less than 2 microns.

In removal of submicron particulate by fabric filtration, mechanisms different from those which control removal of larger particles dominate.[5] The removal of particles greater than one micron is considered to be controlled by impaction and interception while in the submicron region diffusion and electrostatic attraction are considered the important factors.

The efficiency of the fabric filter vs. fly ash particle diameter at air-to-cloth ratios of 3/1 and 6/1 is shown in Figure 7. This curve shows highest efficiencies at either end of the particle size range. This difference is explained readily by classical filtration theory; that is, different filtering mechanisms are responsible for entrapment of fine particles as opposed to large particles. Particles less than 0.36 microns were removed at efficiencies greater than 99.9 percent. This is an extremely important consideration when attempting to control hazardous particles in the respirable range. It is notable that both diffusion mechanism controls in the range below about 0.2 microns and that for this mechanism the efficiency is inversely proportional to the gas velocity. As seen in Figure 7, the removal efficiency at the size range below 0.36 microns shows a sharp decrease as the velocity increases. Unfortunately, very little data is available at this time, and therefore confirmation of Figure 7 is presently underway. Increasing the air-to-cloth ratio from 3/1 to 6/1 increased the outlet loading, however, overall efficiency remained greater than 99.5 percent.

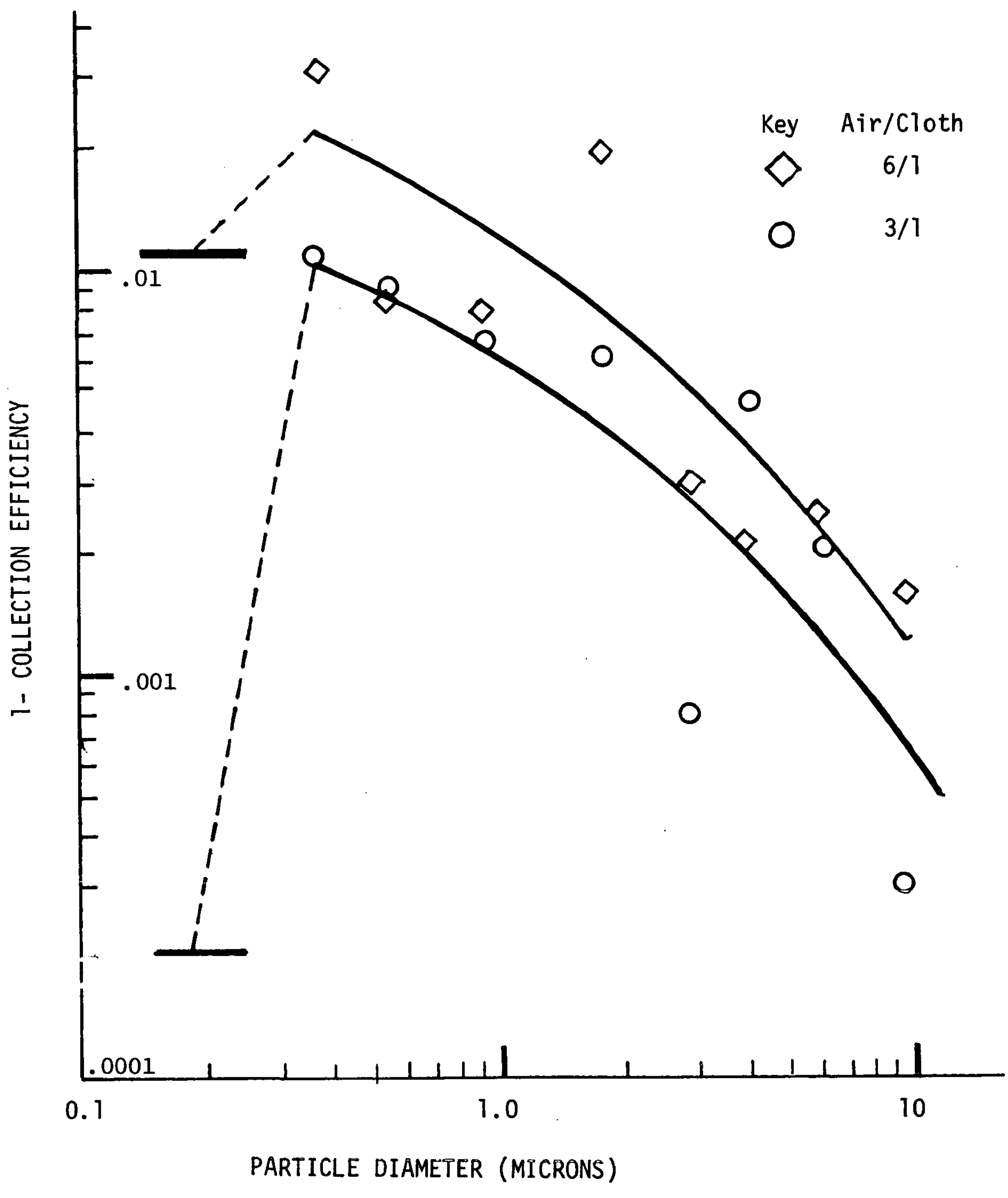

Figure 7. Fabric filtration collection efficiency versus particle diameter

The efficiency of an existing electrostatic precipitator is a function of the precipitator size (collection area) as well as the charge on the dust and the electric field of collection. The particle size and the electrical resistivity of the dust, the gas composition and the temperature, all influence the precipitator efficiency. Of these, for the case considered, the most influential is the resistivity of the fly ash. The highest precipitator efficiency is obtained in the range of 1×10^{8} to 1×10^{10} ohm-cm. For the case considered here, the sulfur content of the coal is very significant since the resistivity of low sulfur coals is generally higher than the optimum range and therefore difficult to control. A problem encountered in this study is that sizing a precipitator is difficult, for as Oglesby[6] points out, for fly ash precipitators the size required for 99 percent collection efficiency can vary from 150 $ft.^2$/1000 cfm to about 450 $ft.^2$/1000 cfm, depending upon the properties of the fly ash. As is known for the case of coal fly ash, the composition varies greatly, depending upon a number of source and operating factors. Thus, generalization of the economics and performance and electrostatic precipitators as applied to industrial boilers is a more difficult problem than either fabric filters or venturi scrubbers, applied to the same case.

The efficiency of electrostatic precipitators for fly ash particulates as projected by Oglesby[7] from the Deutsch equation is given in Figure 8. As he notes: "Some of the limitations of using the Deutsch-Anderson equation become apparent as one attempts to extrapolate to the required size from lower efficiency tests that use constant precipitation rate parameter." Figure 9 shows actual field data for electrostatic precipitator efficiency here are significantly higher than that in Figure 8; it is still not as high as the fabric filter case. This curve does, however, show an increase in efficiency for the smallest particle diameter. Craig[8] also noted this and reported the existence of a bimodal distribution. Similarly, he reported 99 percent for greater than 2 microns, down to 92 percent in the 0.2 to 0.5 micron range then increasing to 95-97 percent in the 0.05 to 0.1 micron and then falling off again.

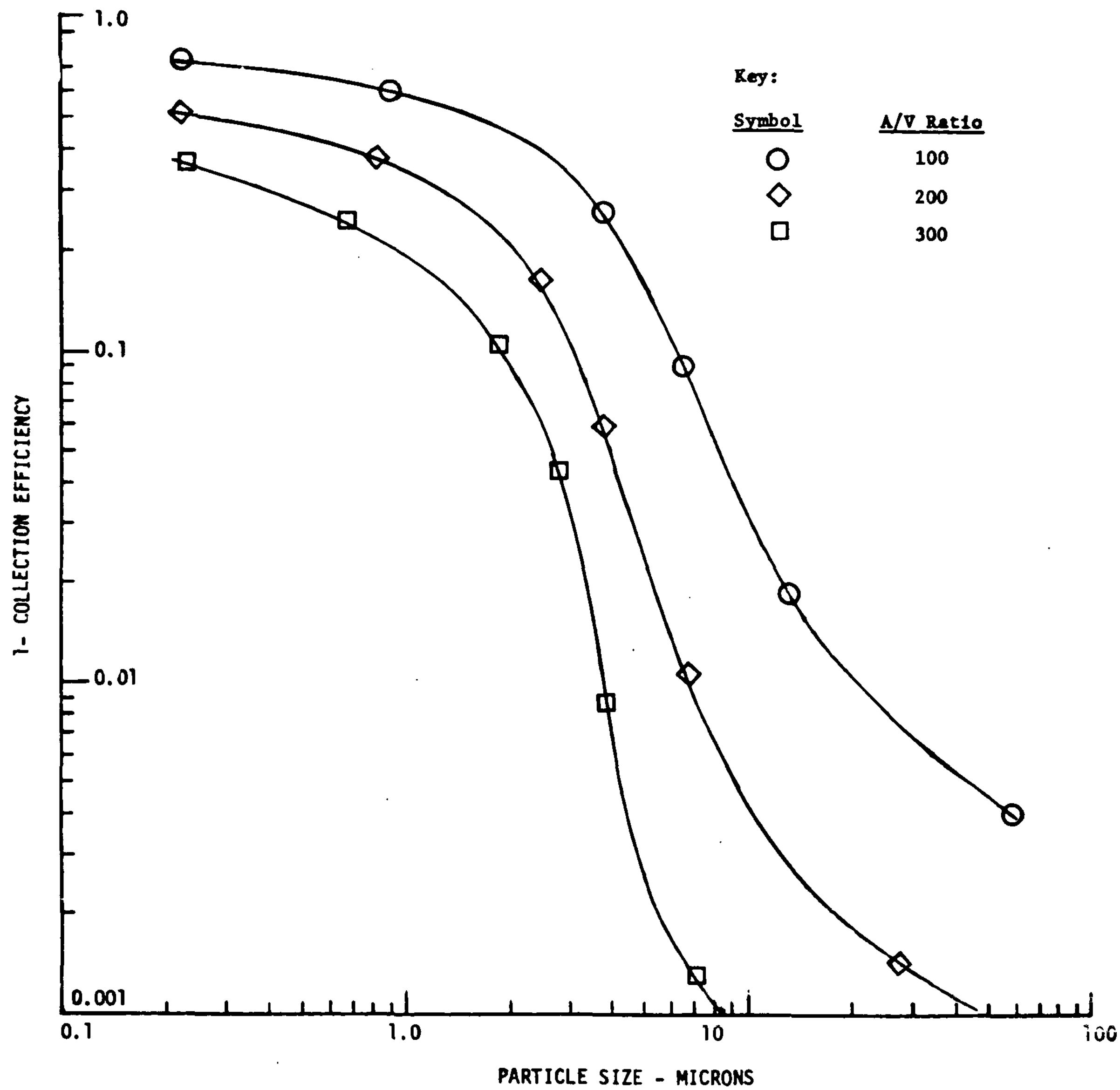

Figure 8. Electrostatic precipitation fly ash collection efficiency versus particle diameter

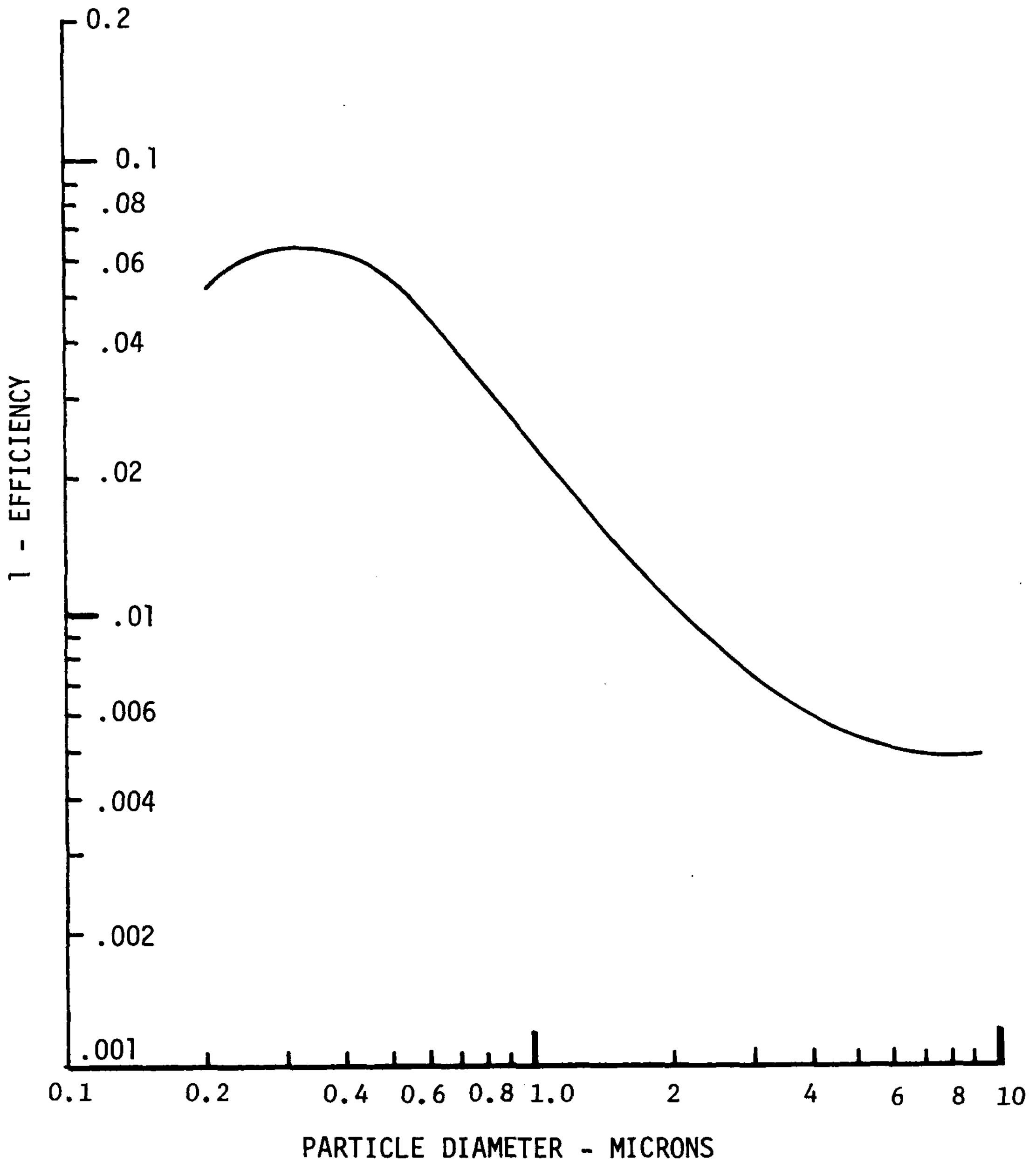

Figure 9. Electrostatic precipitation field data collection efficiency versus particle diameter

For venturi scrubbers, the dust removal efficiency is mainly a function of the energy consumed in the dust to liquid contact. Since this contact is achieved by passing the liquid and dust laden gas through the venturi throat or orifice where the velocity is increased dramatically, the efficiency is primarily a function of the pressure drop across the throat. While there is some difficulty in establishing a purely theoretical model, good empirical correllation of efficiency and pressure drop exist and take into account particle size distribution and density. For a given pressure drop and particle density, the smaller the particle the lower the removal efficiency. Figure 10, Scrubber Efficiency vs. Particle Diameter, shows efficiencies for fine particulates dropping off to the order of 90-95 percent, even at high energy levels.

ECONOMICS VERSUS EFFICIENCY

As stated previously, in order to make economic comparisons between particulate control techniques, a specific area of application was chosen. That application is the coal fired industrial boiler. All costs were based on facilities sized for a stoker fed industrial boiler burning 0.6 percent sulfur coal. The gas volume chosen is 70,000 acfm (two boiler basis) at a temperature of 250^{o}F. An attempt will be made to compare capital, operating and annualized costs and to discuss the pertinent factors affecting each for the three methods of control being considered.

Figures 11, 12 and 13 show capital, operating and annualized costs for a fabric filter at two levels of efficiency, 99.5 and 99.75 percent, based upon the assumption that the pilot plant data can be confirmed. These efficiency levels correspond to air-to-cloth ratios of 6/1 and 3/1 respectively. To go from 99.5 to 99.75 percent efficiency, assuming the relationships between air-to-cloth ratio and removal efficiency, the size of the baghouse increases as well as the number of bags employed; thus, capital cost increases accordingly. Annual operating costs were

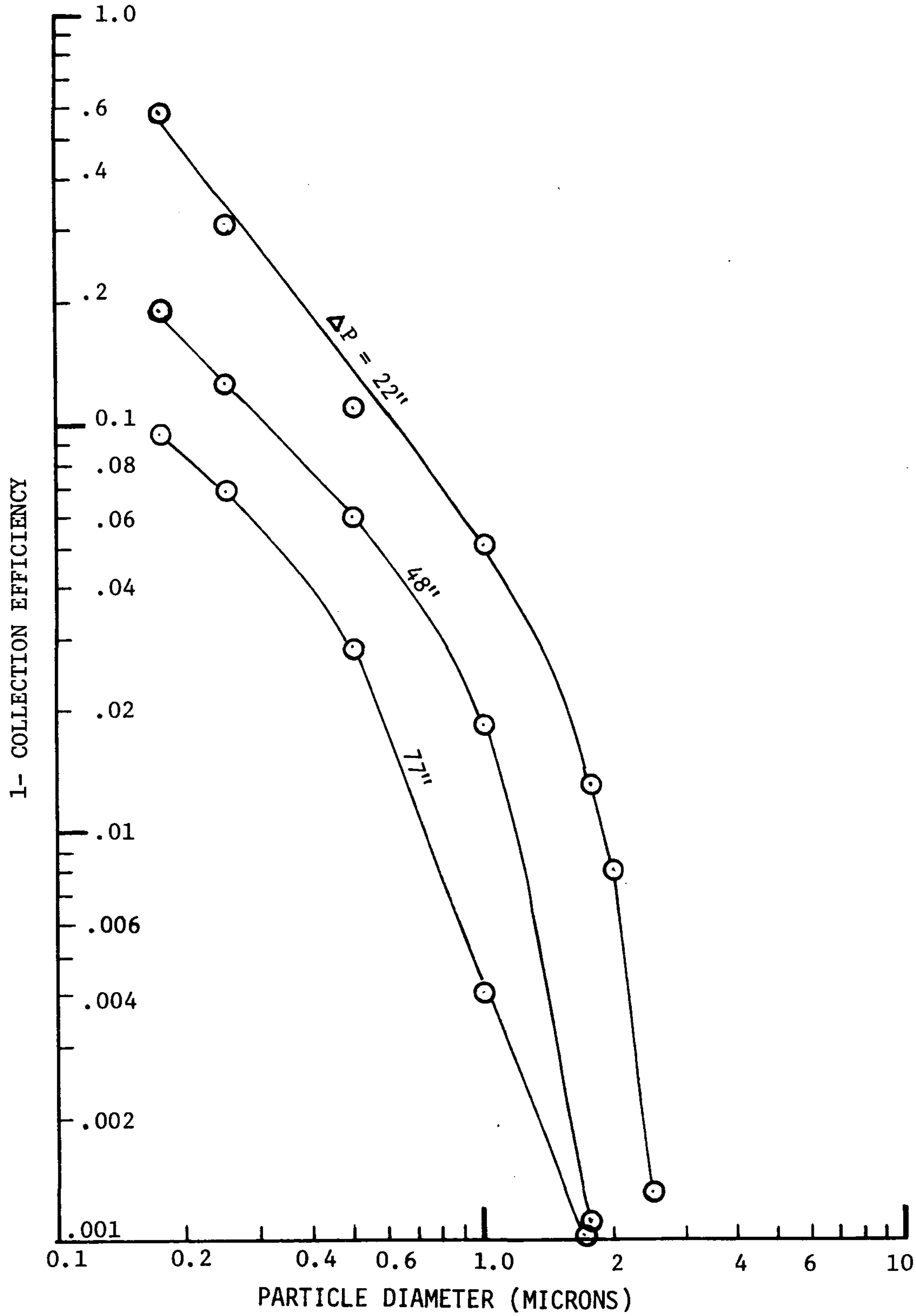

Figure 10. Venturi scrubber collection efficiency versus particle diameter

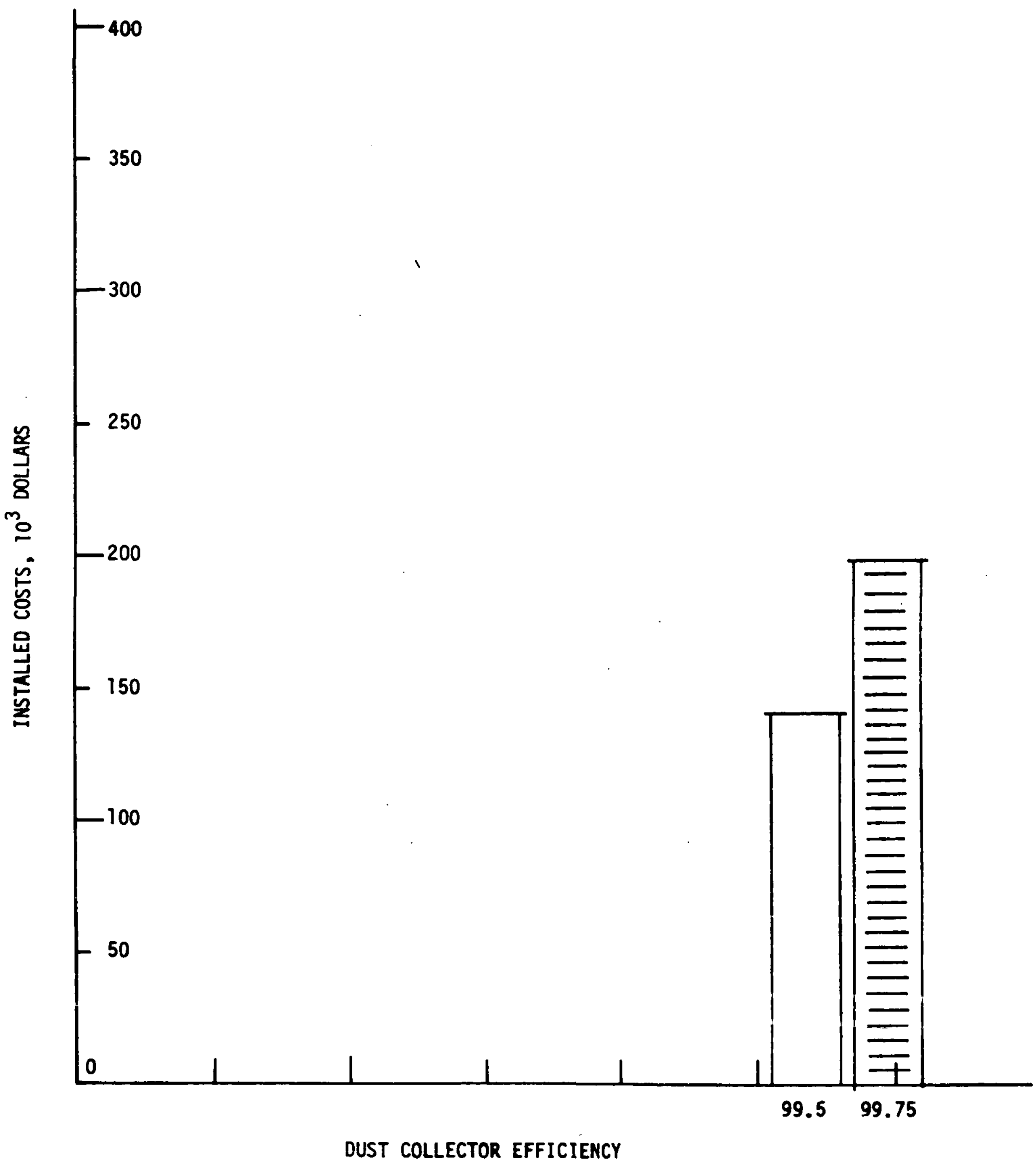

Figure 11. Fabric filter installed costs

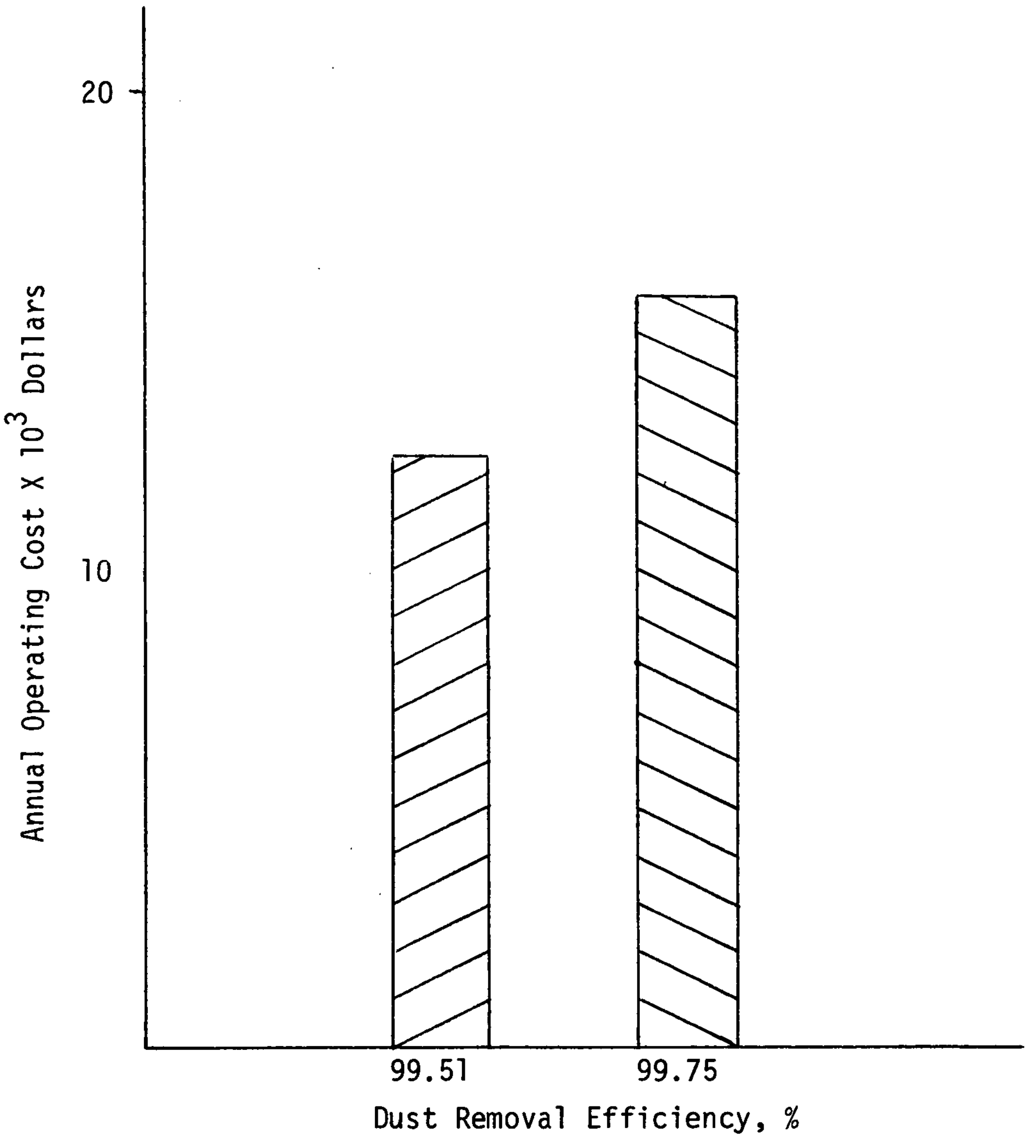

Figure 12. Fabric filtration operating costs

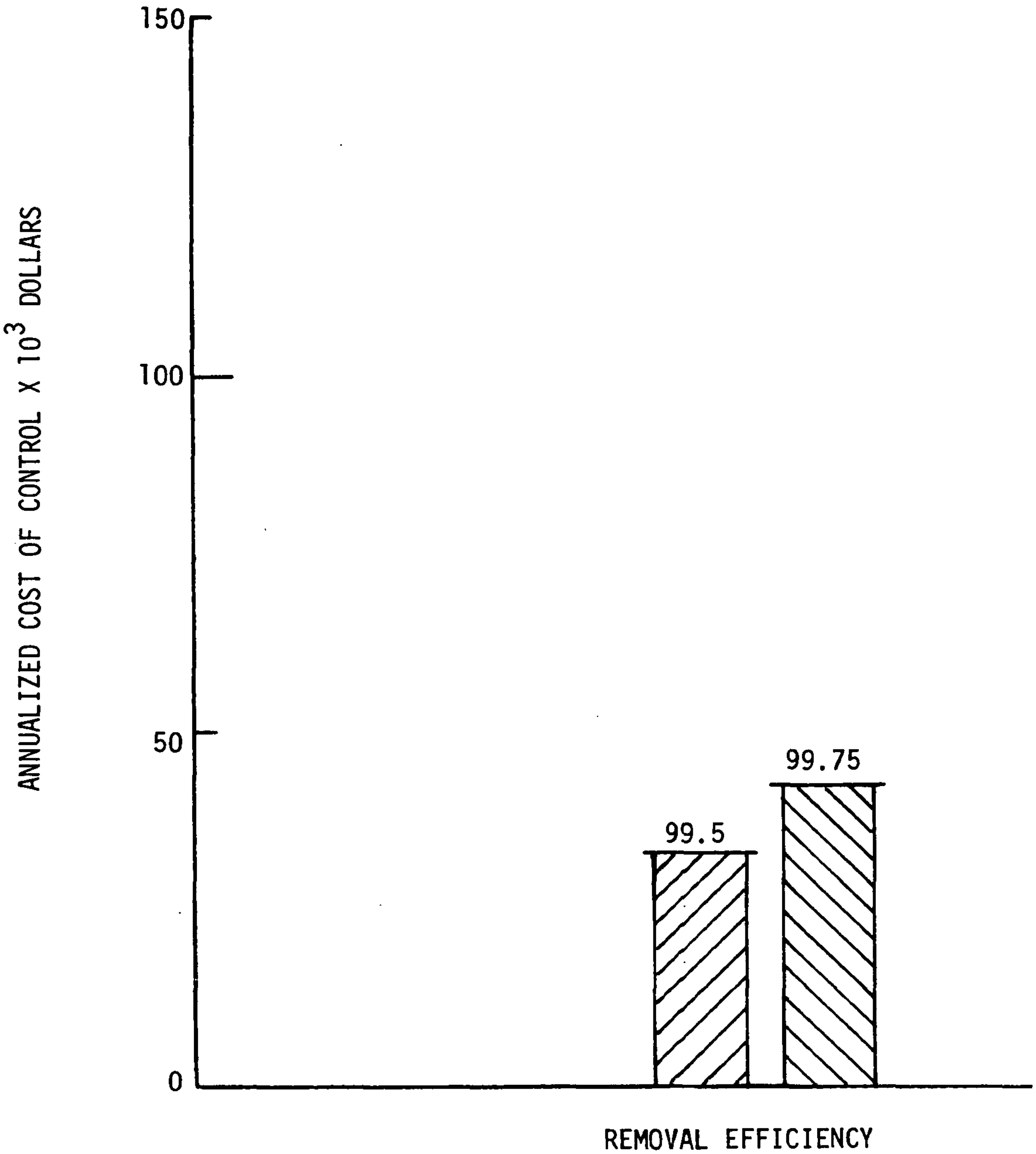

Figure 13. Fabric filtration annualized cost of control

computed on the basis of 25 percent bag replacement per year and operation at a pressure drop of 5 inches of water. The cost of bag replacement is the most significant factor in operating costs. Annualized costs were based upon 15 year straight line depreciation.

Figures 14, 15 and 16 show capital, operating and annualized costs for an electrostatic precipitator at different efficiency levels. The levels of efficiency are a little different between cases but are still useful for the sake of comparison. Installed or capital costs are proportional to the size of the electrostatic precipitator which is in turn dictated by the efficiency required. Annual operating costs were based on operating 6,240 hours/year, power costs of $0.0176/kw-hr and precipitator power required of 0.004 kw/ACFM. The cost of power is the most significant factor here. Annualized costs were again based upon a 15 year depreciation period.

Figures 17, 18 and 19 show capital, operating and annualized costs for a venturi scrubber at two levels of efficiency -- 97 and 99 percent. These efficiency levels correspond to 20" and 60" of pressure w.g. respectively. Fan size is obviously an important capital cost element in attaining the higher efficiency. Both sizes are based on using 316 stainless steel due to the abrasive and corrosive nature of the source. The cost of attaining higher efficiency is more than twice that of the lower efficiency. Annual operating costs were based on operating 6,240 hours/year and power rates of $0.0176/kw-hr. Here the cost of power dramatically increases operating cost as one goes to the higher efficiency level. This is due to the large increase in pressure drop required for high efficiency removal of fine particles. Annualized costs, based upon 15 year straight line depreciation, also show the high cost required to achieve 99 percent efficiency.

Installed, operating and annualized costs for the three particulate control methods are consolidated in Figures 20, 21 and 22. The same costs are also presented in Table 2 for easier reference. The fabric filter

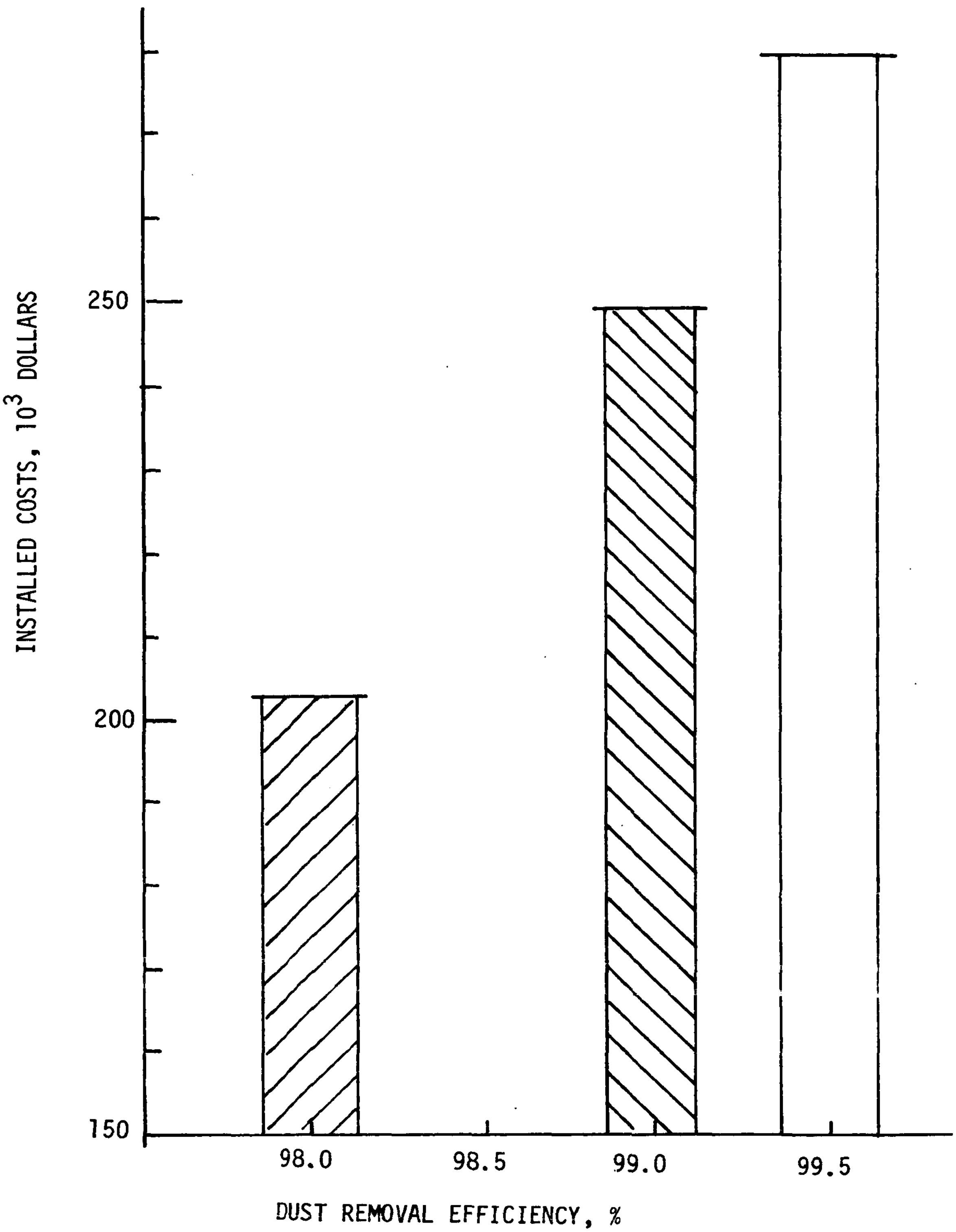

Figure 14. Electrostatic precipitator installed cost

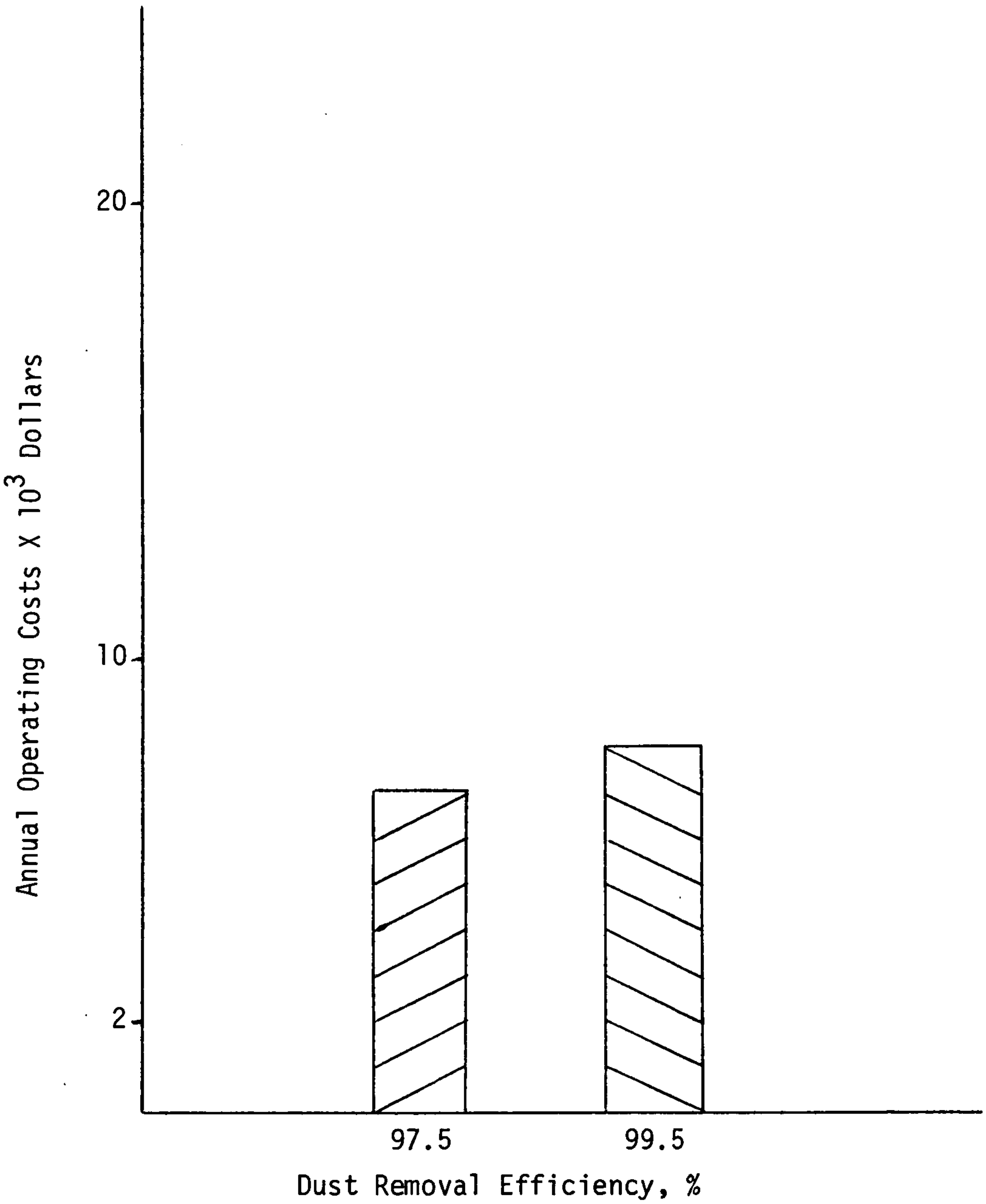

Figure 15. Electrostatic precipitator operating costs

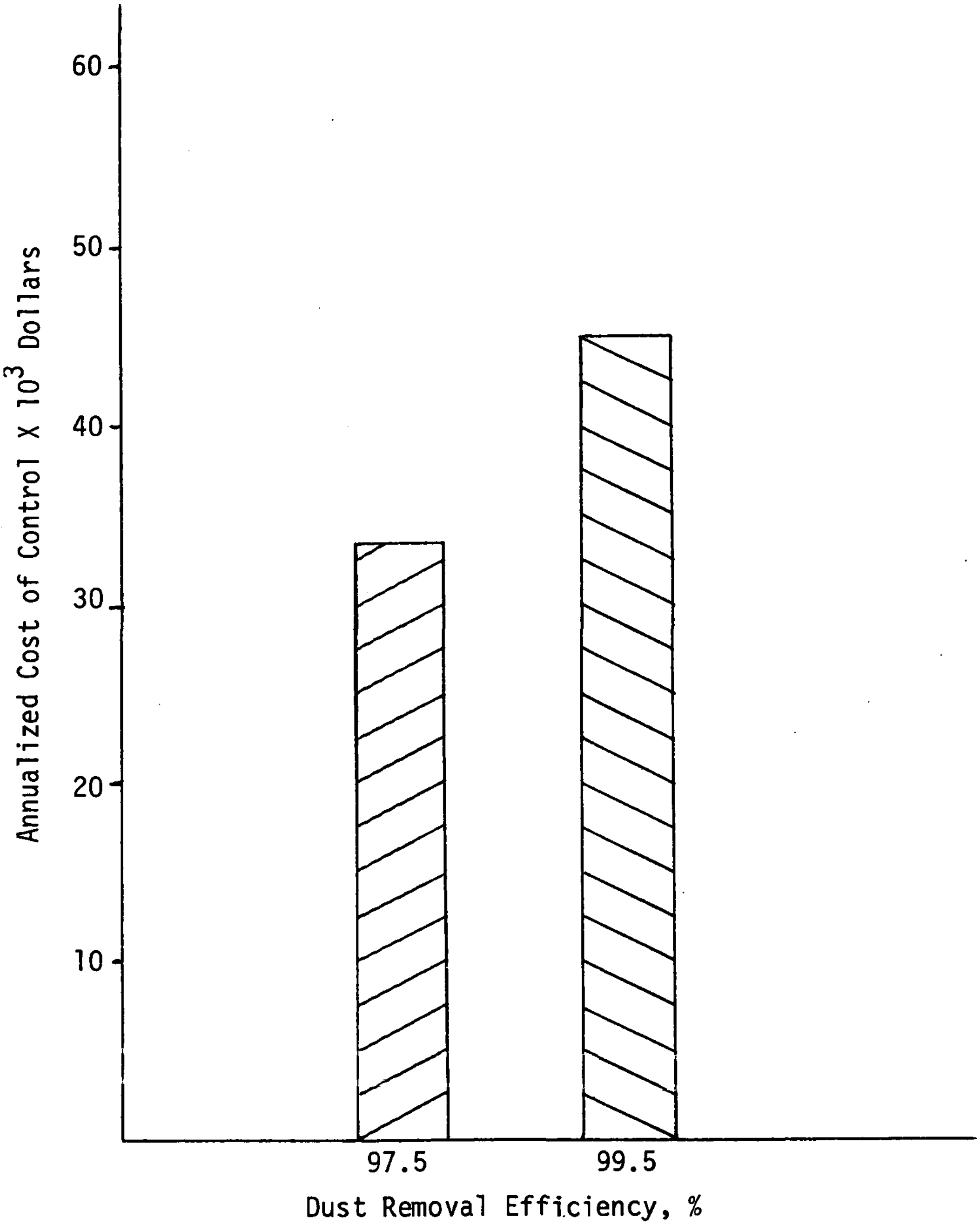

Figure 16. Electrostatic precipitator annualized cost of control

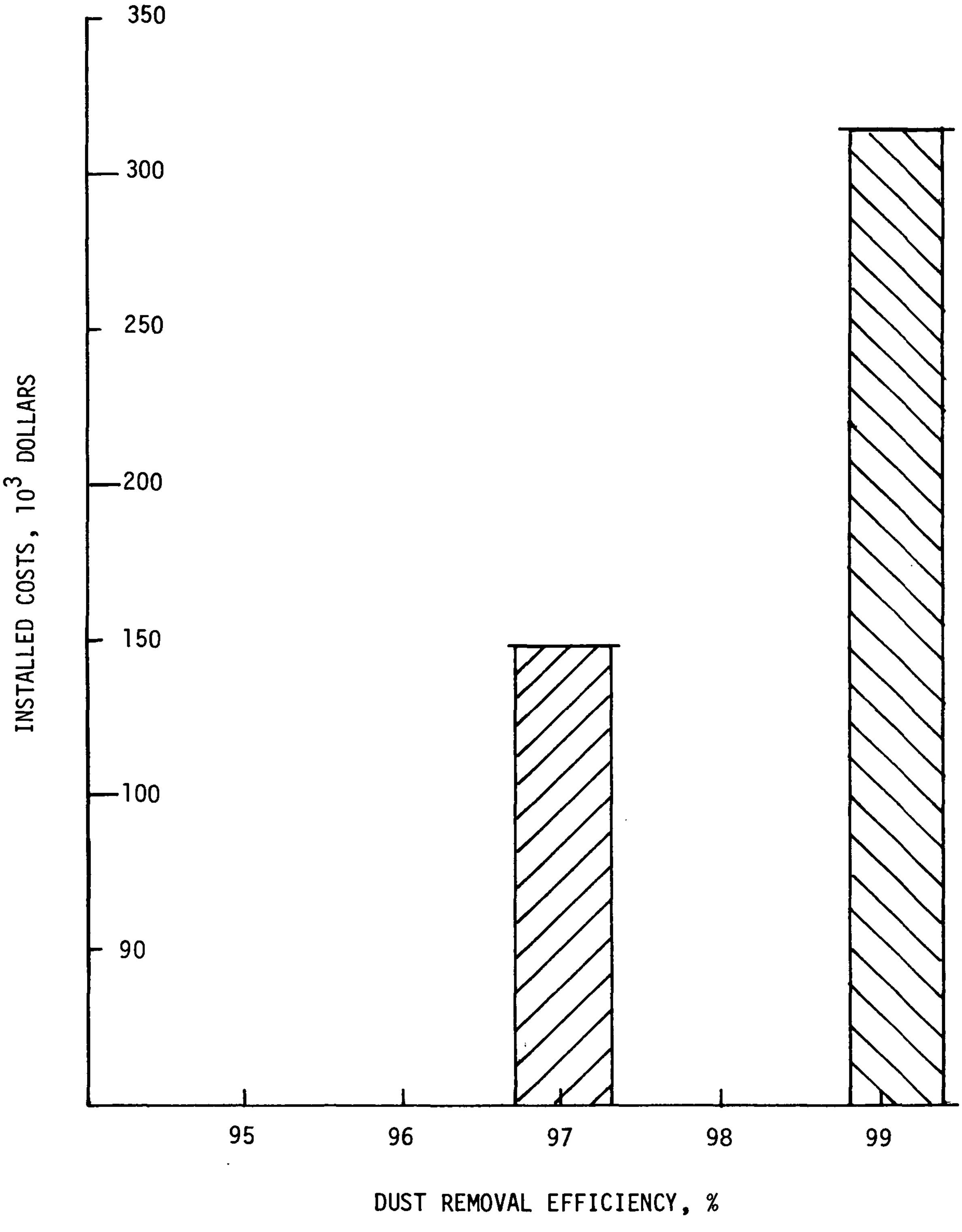

Figure 17. Venturi scrubbing installed costs

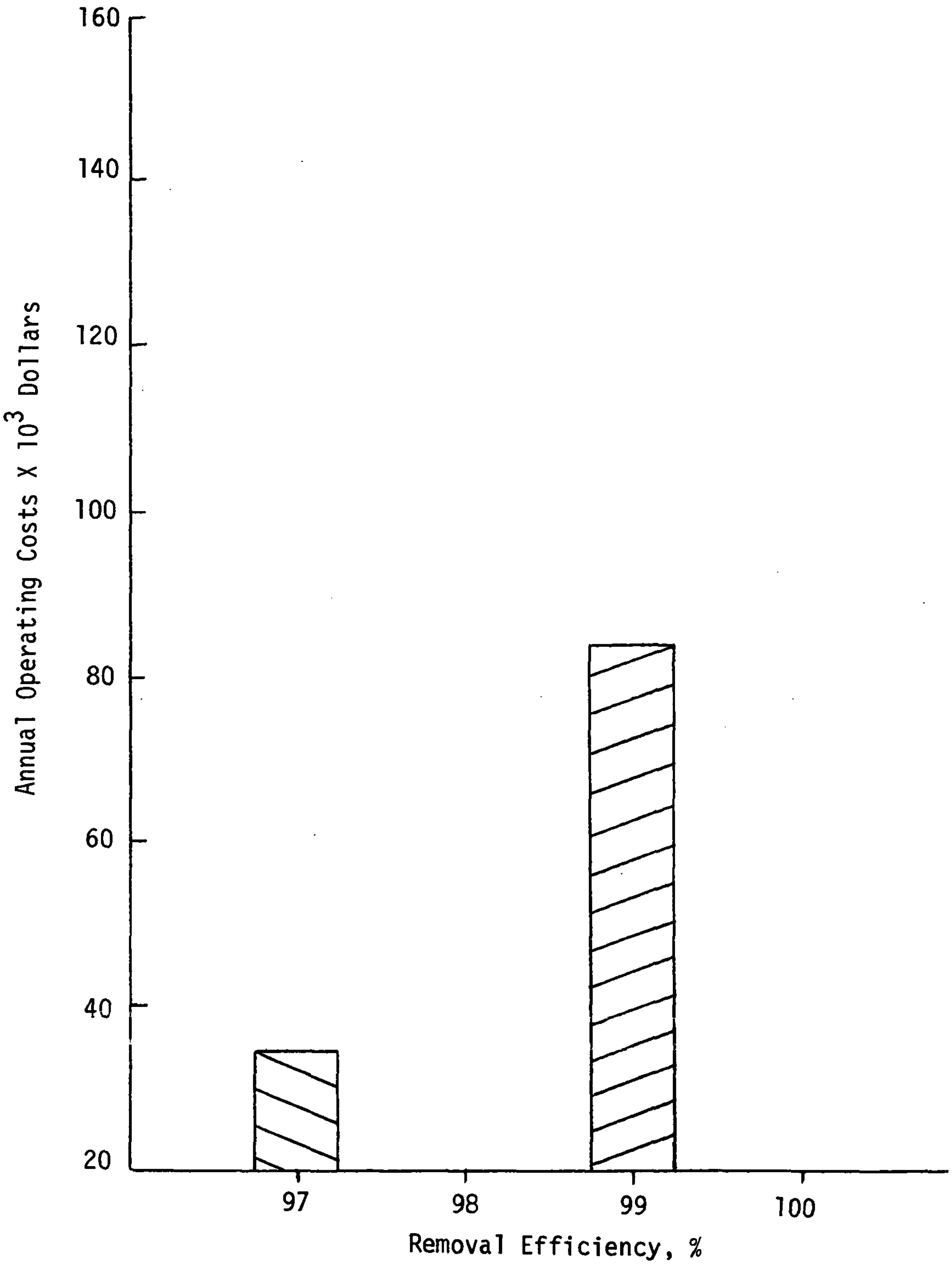

Figure 18. Venturi scrubbing stoker fly ash operating costs

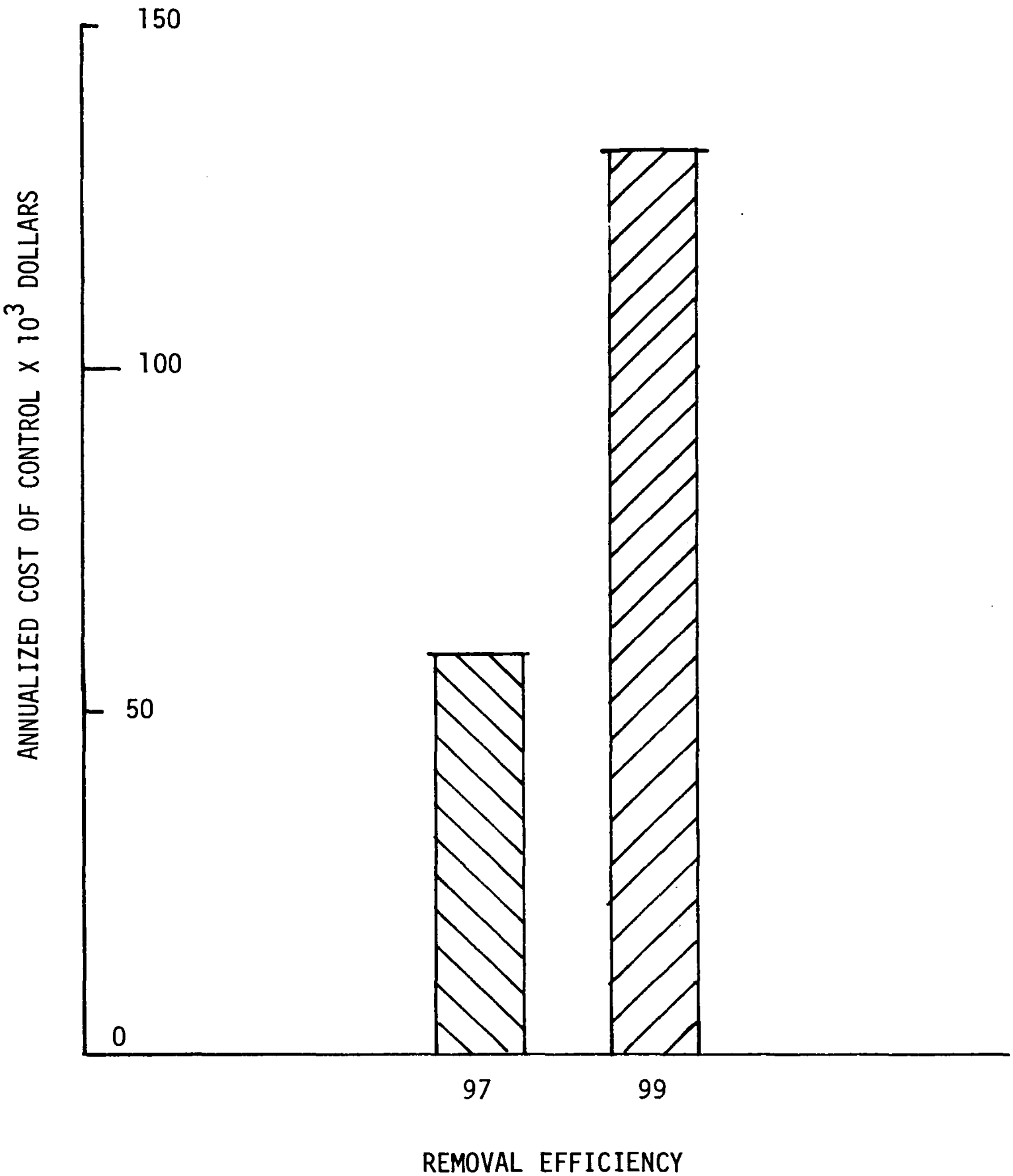

Figure 19. Venturi scrubbing annualized cost of control

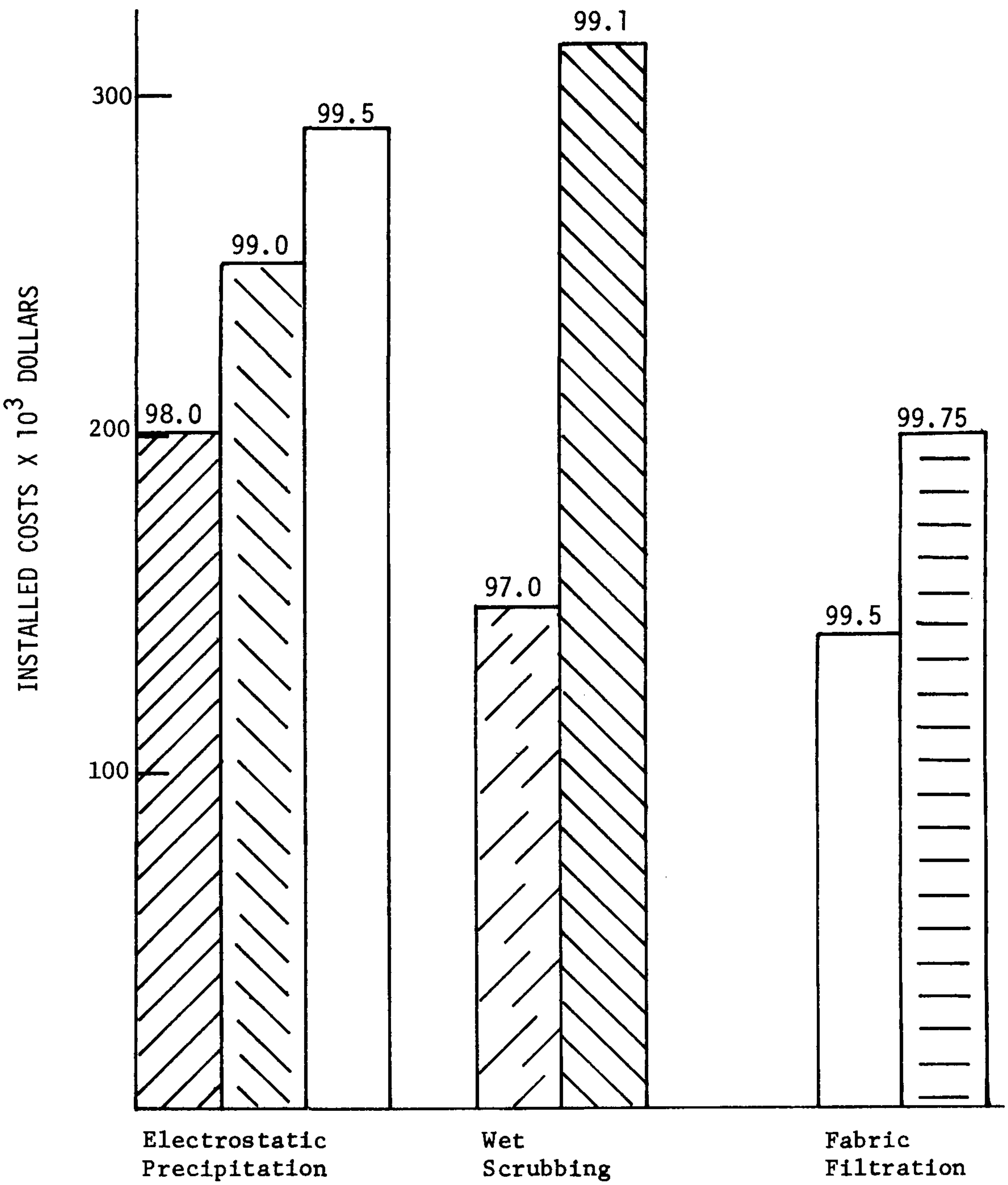

Figure 20. Installed cost comparisons at varying efficiencies

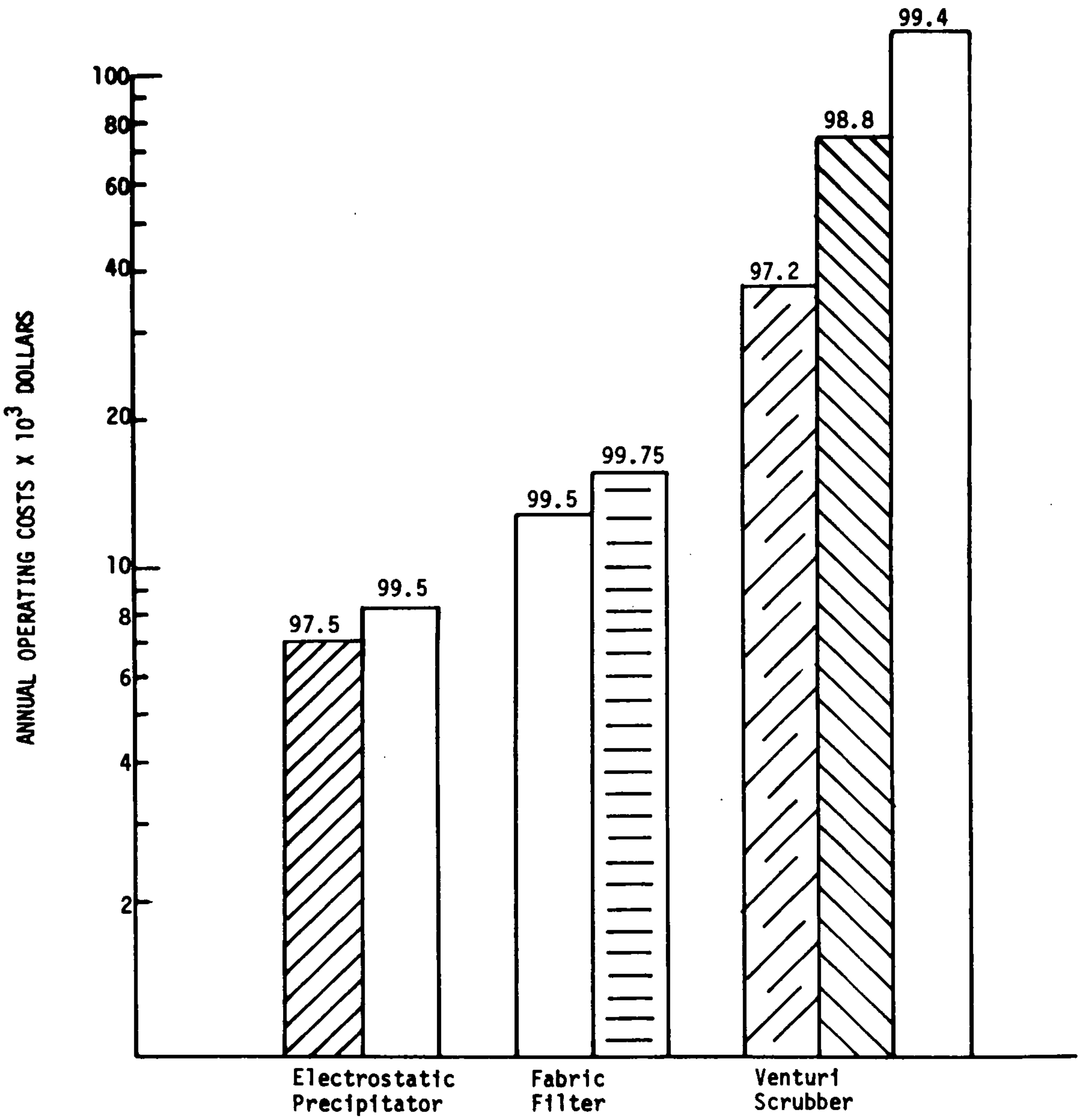

Figure 21. Operating cost comparisons for varying efficiencies

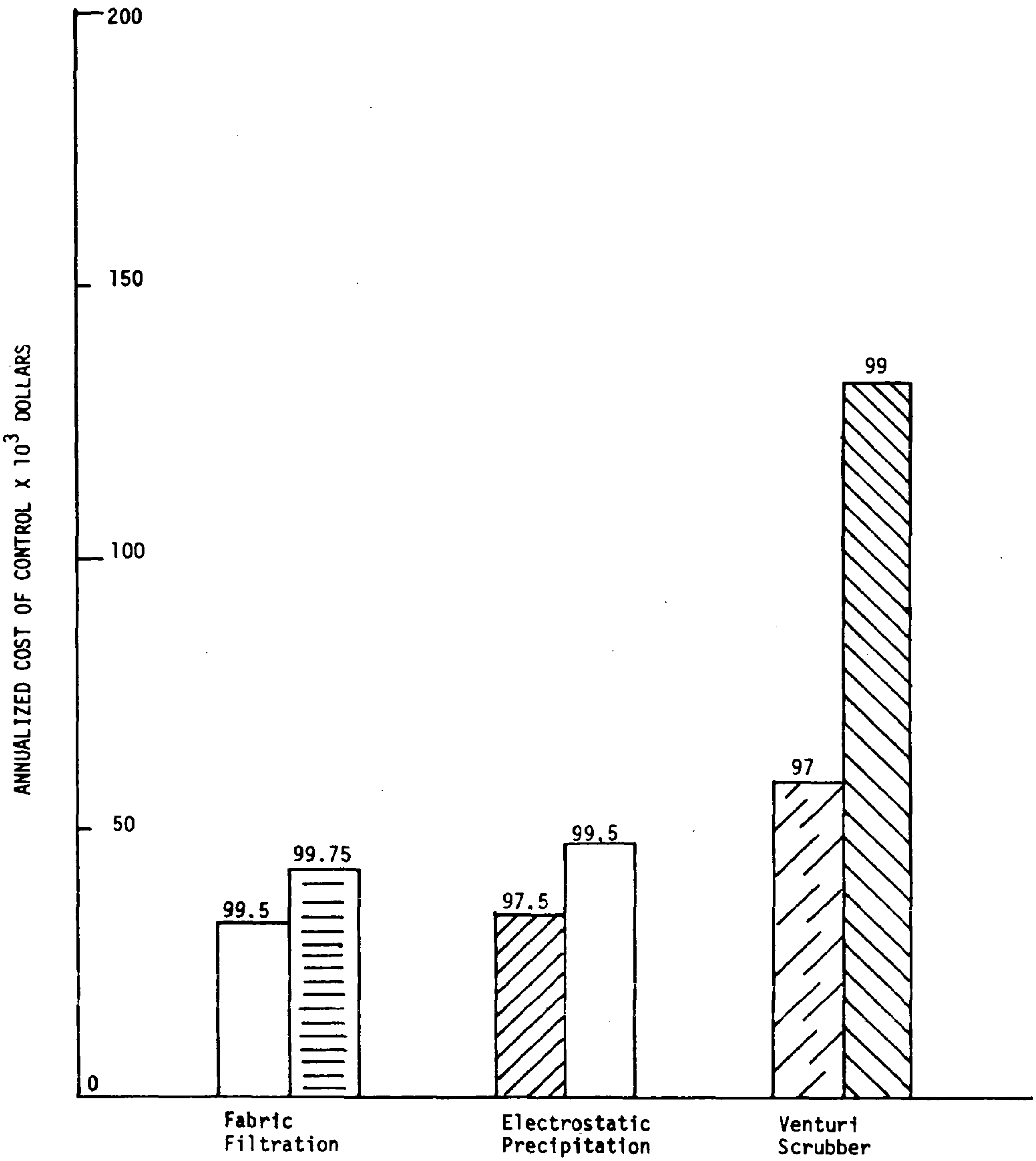

Figure 22. Annualized cost for varying efficiencies

Table 2. CONTROL COSTS

Control method	97 %	97.5 %	98 %	99 %	99.1 %	99.5 %	99.75 %
Fabric filter							
Capital						140,000	200,000
Operating						12,700	15,750
Annualized						35,000	---
Electrostatic Precipitator							
Capital		200,000	202,300	250,000		279,200	
Operating		7,084				8,155	
Annualized		33,684				45,289	
Venturi scrubber							
Capital	147,500			316,000			
Operating	35,315			94,941			
Annualized	54,933			136,969			

has the lowest capital cost while achieving the highest efficiency. The electrostatic precipitator is second best with respect to capital cost and efficiency. Scrubbers would appear to be a poor choice due to both high capital costs and lower efficiency.

Considering annual operating costs, the positions of the fabric filter and the electrostatic precipitator are reversed. Electrostatic precipitators cost approximately 25 percent less to operate at the 99.5 percent efficiency level than fabric filters. Scrubbers again appear to be a poor choice with high operating costs due to large power requirement. The scrubber operating costs are two to three times those for either electrostatic precipitators or fabric filters.

Looking at the overall picture given by annualized costs, we find fabric filters roughly 20-25 percent less expensive to install. Here again the fabric filter not only compares best with respect to annualized costs, achieves higher overall efficiency, and as we have seen higher efficiency for removal of fine particulates. The annualized cost of scrubbers only serve to demonstrate again their inability to compete with the other control methods in the control of fine particulates.

CONCLUSIONS

Generalizations of the cost of fine particulate removal are inherently dangerous. It does appear, however, that of the conventional routes to particulate control, only fabric filters and electrostatic precipitators are suitable to fine particulate removal. Venturi scrubbing, because of the high energy required, does not compete economically. The particular case studied probably exaggerated the economic shortcomings of the venturi since the scrubber needed to be stainless steel. No consideration is given here to the application of steam ejector venturis which have demonstrated the ability to achieve higher efficiencies than the conventional venturi scrubber.[9] This and other high energy scrubbing[10] techniques in the development stage have not been considered in this paper due to the uncertain economics at this point in time.

The case of the fabric filter chosen, Nomex felt with lime injection, is yet unproven and if the more expensive Teflon bags are required the electrostatic precipitator will look even better. On the other hand, if a filter media innovation such as Gore-Tex allows for the use of higher air-to-cloth ratios, a dramatic reduction in the capital and annualized costs of employing fabric filtration can be realized. Since the economics of the electrostatic precipitator turn out to be very sensitive to the resistivity of the dust one must employ caution when generalizing on economic comparisons from this specific case.

Very little fine particulate data is available at this point; therefore, the cost developments had to be based on a number of assumptions. Ideally, in order to develop these economic comparisons an electrostatic precipitator and a venturi pilot plant should be run on the same slip stream and the in-situ particle size measured on the outlet from each.

We hope to answer some of the questions remaining with respect to fabric filtration with an EPA sponsored pilot plant now getting underway at Kerr Industries.

All of the foregoing economics will need updating shortly for two reasons. Firstly, at the time of this writing the first major effort is underway to collect fractional efficiency data on field installations of all three conventional dust control techniques. Secondly, these economics have been executed in a period of unusually high inflation rates and therefore are subject to significant upward fluctuations in price.

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TYPES OF FABRIC FILTER INSTALLATIONS

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The market for fabric filters is currently running at the rate of approximately 90 million dollars per year, flange to flange, based upon IGCI Statistics, which represents approximately 90 percent of the total manufactured. This breaks down into approximately 45 million of high energy cleaned collectors and 45 million of low energy collectors. The definition of high energy means that the cleaning is done with high energy and primarily consists of Pulse Jet configurations such as depicted in Figure 1. The low energy methods of cleaning are shaking and reverse flow. Figure 2 shows a shaker system operating in a grinding booth application. While the Pulse Jet or other similarly configured units make up the high energy portion, the low energy portion is split approximately 50-50 between continuous and intermittent collectors. The continuous portion includes approximately 15 million dollars of large structural baghouse work, while the intermittent portion contains approximately 10 million dollars of in-plant size collectors. The remainder are made up of medium size types.

Table 1 provides a basic classification scheme for Fabric Filters.

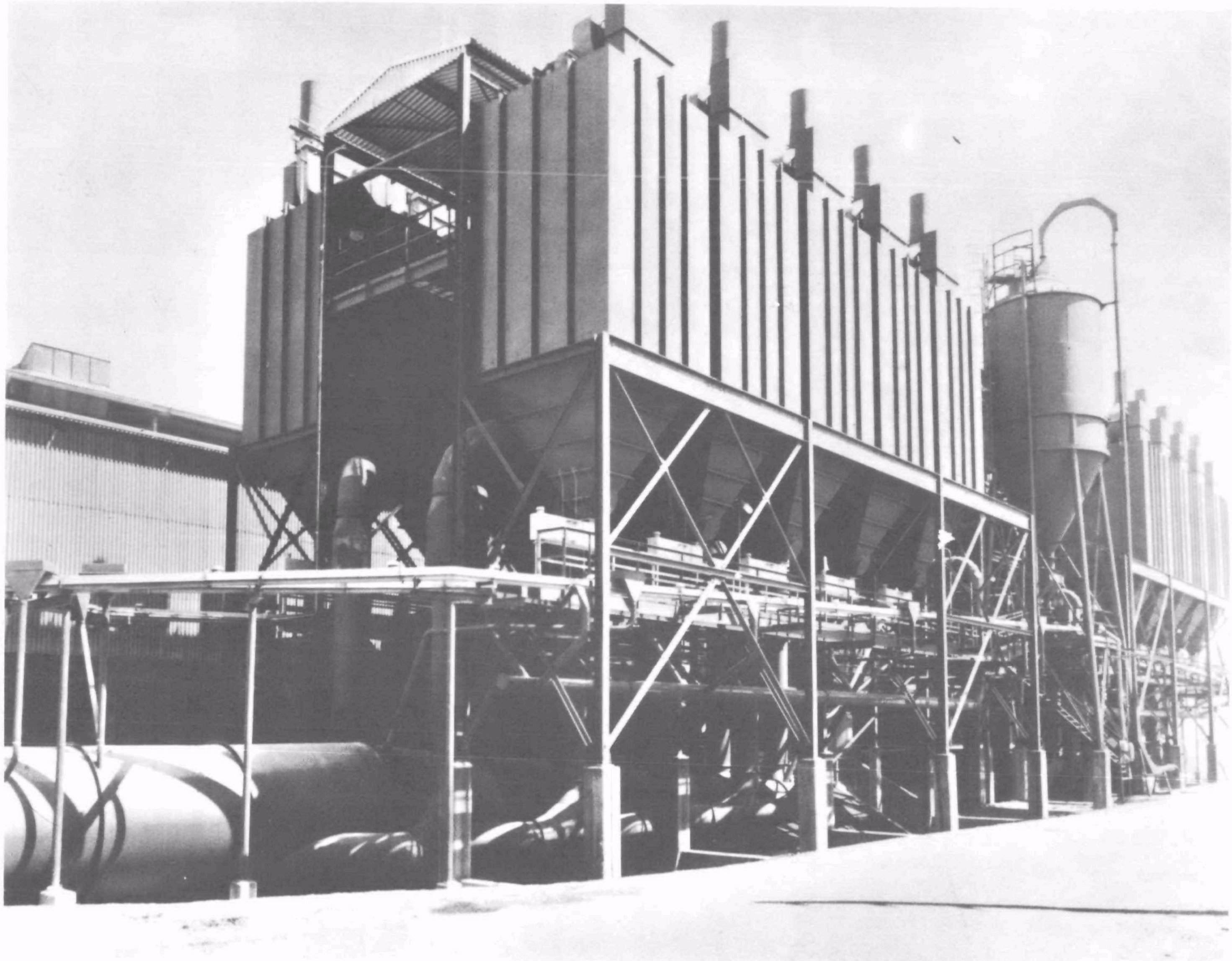

Figure 1. Large pulse-jet installation

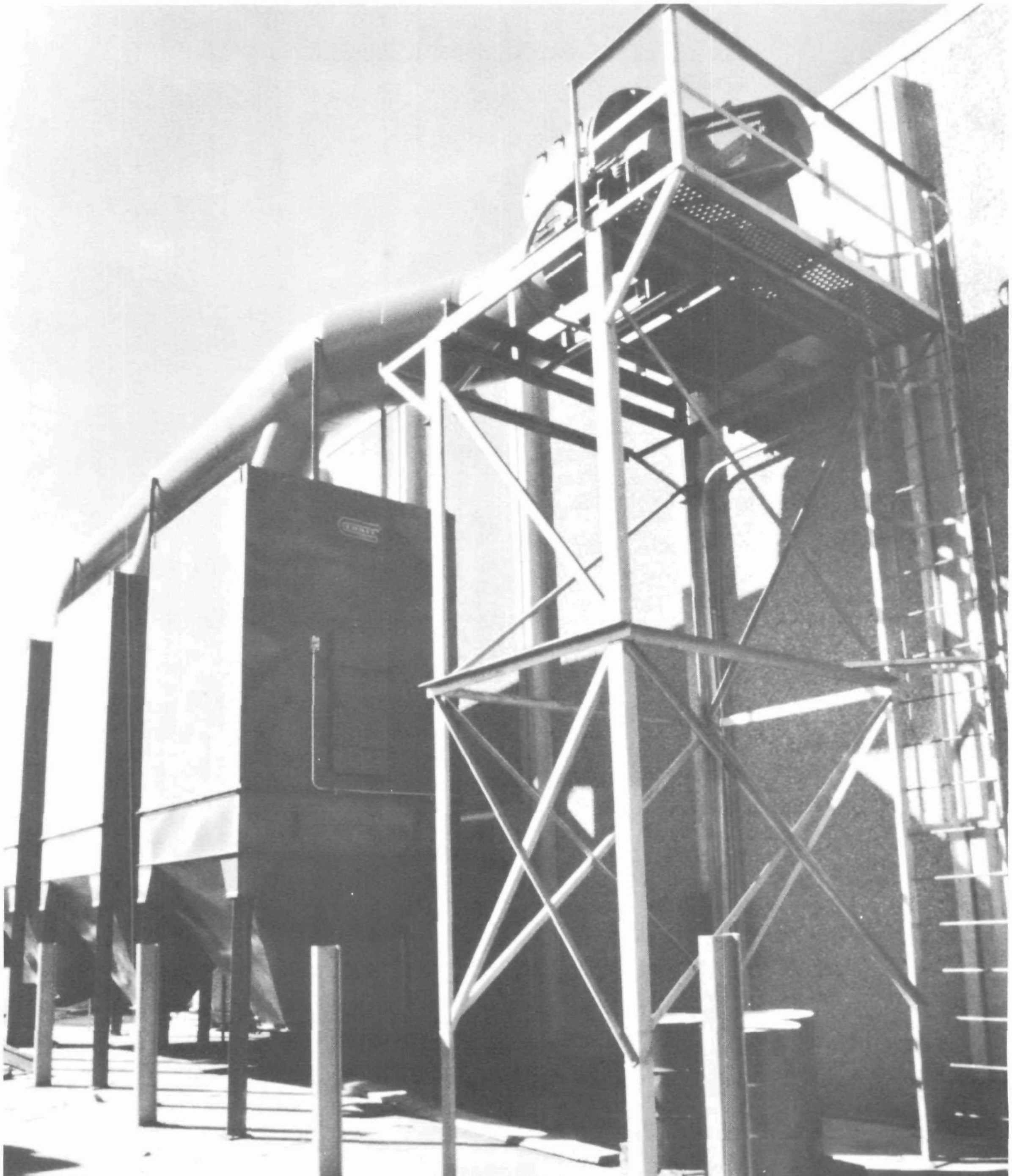

Figure 2. Torit tube house dust collectors serve huge grinding booth inside Allis-Chalmers Plant

Table 1. TYPES OF FABRIC FILTERS

1. Cleaning energy level
   - A. High
   - B. Low
   - C. None
2. Fabric
   - A. Felt
   - B. Woven
   - C. Other
3. Duty
   - A. Continuous
   - B. Intermittent
   - C. Fail safe
4. Service
   - A. Particulate removal
   - B. Gaseous control (adsorption)
   - C. Process
   - D. Non-process (nuisance dust)
5. Application factors
   - A. Temperature
   - B. Dust loading
   - C. Moisture level
   - D. Housing suction or pressure
   - E. Size
   - F. Efficiency

The first classification of cleaning energy level follows the IGCI figures and breaks it down into high and low energy cleaning methods. In addition, we add a third category of cleaning energy which is 0, this applies to units that are designed for a disposable media situation. The second classification is fabric and the basic types are: a) felt and b) woven. The felt media is normally connected with the high energy cleaning system, whereas, the woven media or woven cloth is connected with the lower energy of cleaning. The felt material is a true filter media and may be kept as clean as possible, hence the application to the higher energy system, whereas, the woven fabric is only, in general, a site upon which the true filter media or the dust cake builds. A third classification of fabric would be an "other" category where the media is a non-woven disposable configuration.

Another important classification is the duty. Under this we have the basic split between continuous and intermittent collectors. Figure 3 shows the performance of an intermittent collector versus time, compared to a continuous automatic unit.

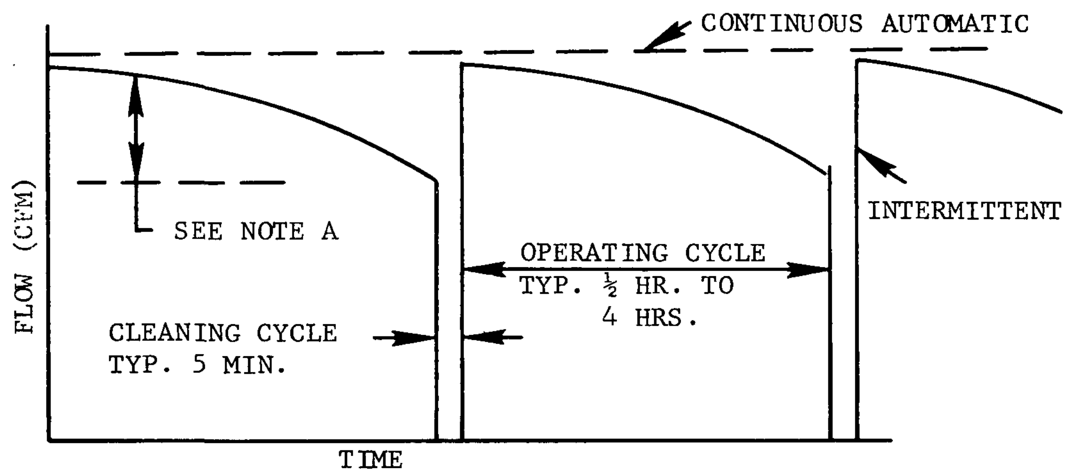

Figure 3. Performance of an Intermittent collector versus time compared to a Continuous Automatic Unit

Note A - Reduction of cfm during operating cycle is a function of the air moving device performance curve.

The third basic type of duty would be considered a fail-safe configuration, where a maintenance spare compartment is provided so that cleaning and repairs will take place during normal operation, and the unit has full 24-hour, 7 day a week availability under all conditions.

The fourth major classification of fabric filters is the service. There are two categories of service and the first is for particulate removal or for gaseous control by way of adsorption. This technique is well proven in industries, such as, primary aluminum where alumina is used quite successfully to adsorb a gaseous fluorine, which otherwise would go to the atmosphere. In addition, other gaseous control situations would involve the use of activated carbon in a fluid bed or dry scrubber to remove odors.

The second basic distinction under the service is between process and non-process work. The process function of a fabric filter may be such applications as venting of dryers, where the full product is handled or perhaps the use as an air conveying receiver, again where product collection is the primary function. The non-process applications are the typical nuisance dust venting jobs where mechanical conveyors and other dust producing sources are properly hooded and then ducted to a fabric filter.

It is interesting to note that with today's emphasis on pollution control, even non-process collectors must receive the kind of care and attention that only process collectors received in years past, so that the plant emissions are held to an absolute minimum. In effect, the non-process nuisance dust collector is a license to operate the plant and must be kept operating properly.

The final classification would be by application factors and these are temperature, dust loading, moisture level, housing rating, size and efficiency. The current maximum temperature limit for fabric filters is in the range of 550^{o}F with the use of fiberglass media, although work is currently proceeding to develop higher temperature medias. It should be pointed out that a significantly higher temperature media may not be too practical, since fabric filters are sized on an actual cfm basis. Therefore, the current practice of conditioning the gases to some temperature below 550^{o}F may, in fact, prove to be the most economical solution for most applications rather than attempting to handle the stream at much higher temperatures. Exceptions to this, of course, would be cases where energy may be recovered following filtration at much hotter gas temperatures, assuming the media to be available.

The dust loading factor is one that is often misunderstood. The pros and cons of using a mechanical collector or cyclone ahead of a fabric filter are somewhat complex. In the case of an intermittent collector, it is often necessary to use a mechanical collector prior to the bag filter in order to keep the dust load with time to an absolute minimum and enable the unit to run a reasonable number of hours before the shutdown and cleaning occurs. However, it must be born in mind that a mechanical collector will remove most coarse material leaving only the fine material for the fabric collector. This may result in changed performance, since fine material only is more difficult to filter. In the case of Pulse Jet Collectors, there is a singular insensitivity to dust load above a certain level. In other words, any amount of dust capable of being carried by the air can be handled in the collector without resorting to a primary separator.

The next major application factor would be the moisture level and here it should be pointed out that fabric filters can be engineered to operate at extremely high moisture levels up to the greater than 90 percent moisture vapor range, as long as the proper engineering precautions are taken. Included among these are insulation, addition of heat and proper control so that the moisture is always kept in vapor form and the bags will remain in good condition for filtration. If a standard collector is put on a high moisture situation without proper design of the system, the bags are quite likely to turn into architectural columns and be totally useless in a short while.

Housing suction and/or pressure becomes a rather obvious classification affecting the size and shape of the housing and, of course, fabric filters can be designed to operate at pressure in excess of 200 psi and quite commonly at vacuums of half an atmosphere or 15 inches of mercury. The normal collector is designed and operated for typical suctions produced by industrial exhaust fans and this is in the range of plus or minus 20 inches of water.

The subject of fabric filter efficiency is generally an academic problem, because properly applied fabric filters approach 100 percent efficiency in most cases and will perform at highly satisfactory efficiency levels, assuming the proper maintenance is performed. Efficiency problems with fabric collectors are generally associated with installations that are of inadequate cloth area to do the job properly. This results in poor operation from a differential pressure standpoint and may cause considerable seepage because of the higher than proper filtration velocities.

COMPARISON OF FINE PARTICLE CAPTURE IN FIBER STRUCTURES AND FILTER CAKES

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PAPER NOT AVAILABLE AT TIME OF PUBLICATION

OPTIMIZING FILTRATION PARAMETERS

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INTRODUCTION

The pulse-jet type of dust filter was invented and developed by T. V. Reinauer of MikroPul (formerly Pulverizing Machinery) and introduced on the market in the late 1950's.[1] Since then, pulse-jet collectors have been applied to hundreds of applications and MikroPul now has more than 40,000 installations all over the world. The basic patent on the device has expired and there are now many manufacturers of the pulse-jet type of collector. According to Industrial Gas Cleaning Institute (IGCI) statistics, the sale of pulse-jet collectors is now approximately the same in dollars as for the shaker type of collector.

The operating principle for the shaker type of collector is relatively well-known and documented;[2] however, this is not the case for the pulse-jet type of collector. In this paper, the fundamental operating principle of the pulse-jet collector will be explained with a series of performance curves, since, in order to optimize the collector, every detail of its performance must be fully understood.

The operating principle of the pulse-jet collector is based on the use of an air ejector for dislodging dust from the bags. The air ejector or jet pump produces a short pulse of compressed air in the opposite direction of the gas being filtered. Since the energy level of the cleaning pulse is much higher than the energy used in shaker or reverse air types of dust collectors, the filter media must inherently have a high dust particle collection efficiency, and the deposit of dust on the bags is not relied upon for producing high removal efficiency. The filter media used for the bags is therefore needled felt, where the fibers are held together in a random fashion on a scrim or open woven matrix.

The pressure drop through the collector will depend upon the bag permeability, i.e., the filtration rate per square foot of filter media at a certain pressure drop across the filter media. The consumption of compressed air for cleaning off the collected dust indicates the cleaning energy required to operate the dust collector at a steady state.

THEORY OF OPERATION AND DESCRIPTION OF PULSE-JET FILTER

The principle of bag cleaning is based on the theory of the ejector or jet pump. A primary jet of high velocity fluid is used to create a low pressure zone and transfer momentum to the surrounding fluid, thereby inducing a secondary flow which will mix with the primary fluid in a constricted zone or Venturi placed some distance downstream of the source of the primary jet. In the case of a pulse-jet collector, the jet of air is directed upstream into the bags, against the normal flow of filtering gas.

The jet must accomplish three things:

1. Stop the normal filtering flow.
2. Transmit a burst of air to the filtration media which will physically give the media a vibratory shock.

3. Create enough pressure in the bag to ensure a reversal of the flow from the clean side to the contaminated side of the bags.

Figure 1 shows a schematic of a typical pulse-jet collector. In this unit, the contaminated air enters into the hopper or a bottom inlet. The coarser particles are removed by the "knock-out" effect, while the finer particles flow upward and collect on the outside of the bags. The bags are prevented from collapsing by a cylindrical wire cage (retainer) which is fastened to a tubesheet and collar-Venturi combination. The filtered gas then flows upward inside the bags, through the Venturi, into the plenum and out through the exhaust duct. The bags are cleaned row by row from a series of compressed air distribution pipes.

A short burst of compressed air controlled by a solenoid (pilot) valve is released by the diaphragm valve, and the air then flows into the header or blow pipe. Small nozzles or orifices in the blow pipe direct jets of air at critical conditions (sonic velocity) axially into the upper bag openings and the jets induce secondary air from the plenum as shown. To convert the energy of the high velocity jet into pressure and facilitate the induction of secondary air, the jet flows through the throat of a Venturi which is attached to the tubesheet and extends into the bag. The burst travels down the bag and stops the normal flow of air, transmitting a shock on the filter media and giving a back-wash of air through it. The pressure developed in the bag depends on the jet pump characteristics of the nozzle and Venturi configuration and on the permeability of the bag to be cleaned, i.e., the combined permeability of the dust collected on it and the filter media. The bag cleaning is done row by row while the unit is onstream. The other rows of bags, still onstream, take the excess flow during the cleaning and the bag pressure drop is therefore constant at all times.

Figure 2 shows the jet pump curve for the standard Venturi. The pressure developed at no flow is the static no delivery of the ejector, which

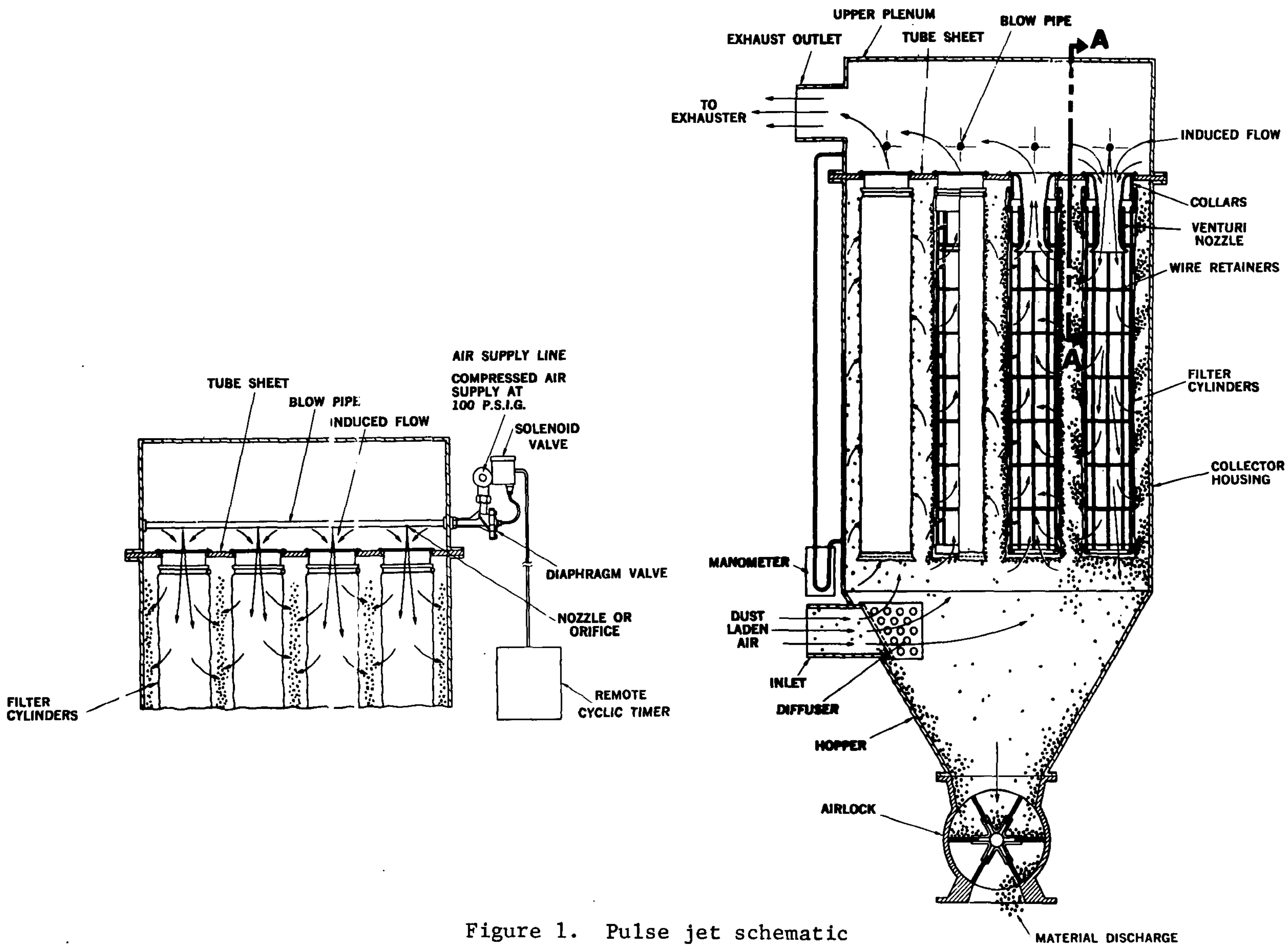

Figure 1. Pulse jet schematic

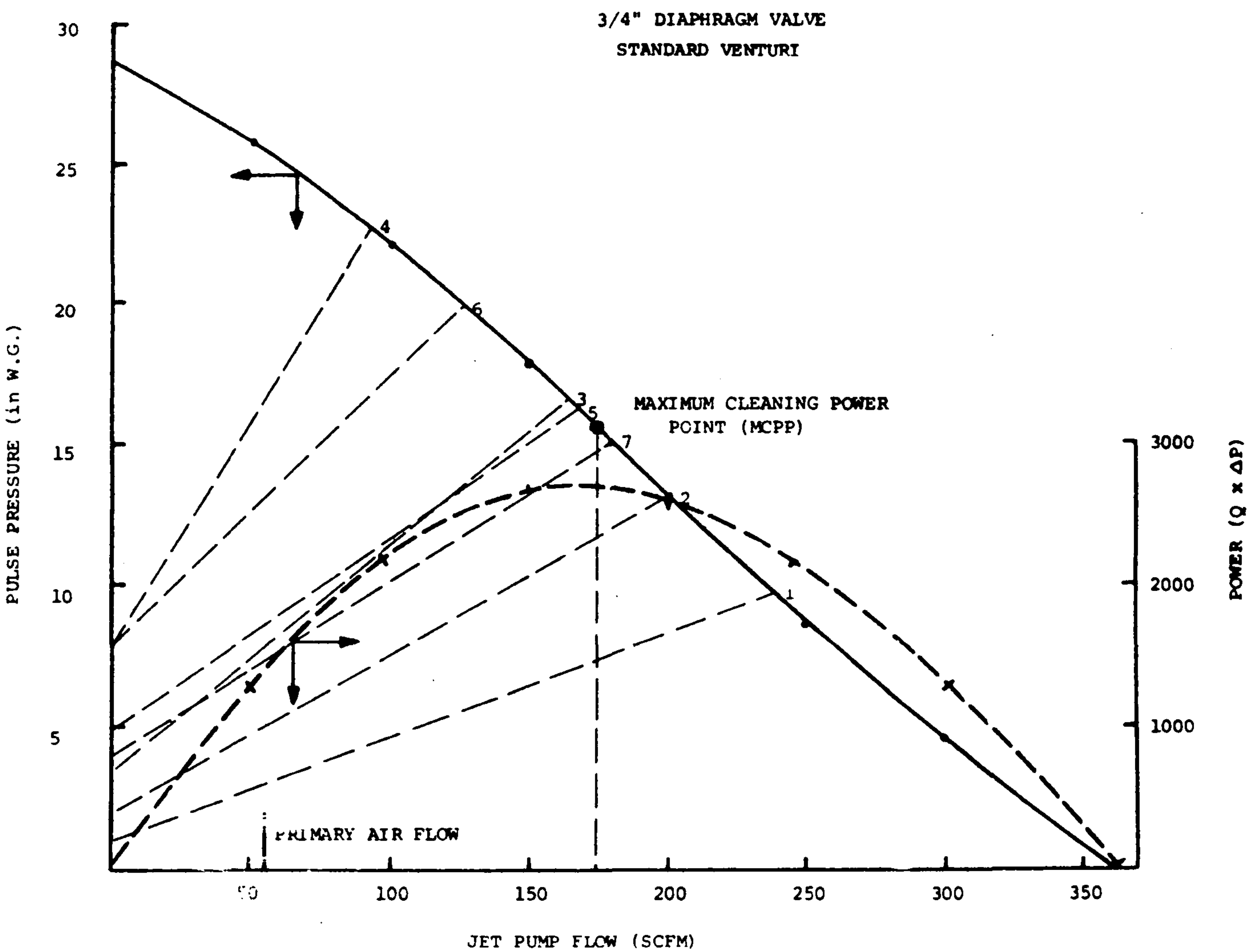

Figure 2. Jet pump and cleaning energy curves

corresponds to blowing into a bag with zero permeability or into a closed chamber. The dotted diagonal lines show the pressure drop curves of operating bags with different permeabilities. The intercept of these lines above the abscissa is the bag pressure drop under normal operation which the air pulse must overcome before a flow from the clean side to the contaminated side of the filter media can take place. The crossing of the jet pump curve and the bag pressure drop curve is the operating point during cleaning. A certain amount of primary and secondary cleaning flow is developed at a certain pressure build-up in the bag. Since the primary air is constant, the entrainment ratio, i.e., the ratio of secondary-to-primary air, increases with increasing total flow, i.e., increasing bag permeability.

When there is a continuous increase in the pressure drop across the bags, as is the case during start-up, the operating point will move upward on the jet pump curve until the steady state operating point has been reached.

If the power of the cleaning pulse, i.e., the product of the jet pump flow and the developed pressure, is considered, a point of maximum cleaning energy can be established (as shown in Figures 2 and 3). From these graphs, the maximum point can easily be picked out. If the bag pressure drop curve is assumed to be linear with respect to gas flow (constant permeability), any bag operating condition can be laid out on the jet pump curve by a line from the steady state pressure drop on the ordinate with a slope equal to bag pressure drop divided by the filtering flow through the bag (the inverse of the bag permeability). If this line intersects the point of maximum cleaning, bag operation should be most efficient.

A typical static pressure pulse measured by a high frequency response pressure transducer connected to the bag is shown in the insert of Figure 4. The peak pressure corresponds to the intercept point of the jet pump curve and the bag pressure drop curve. The electrical on-time

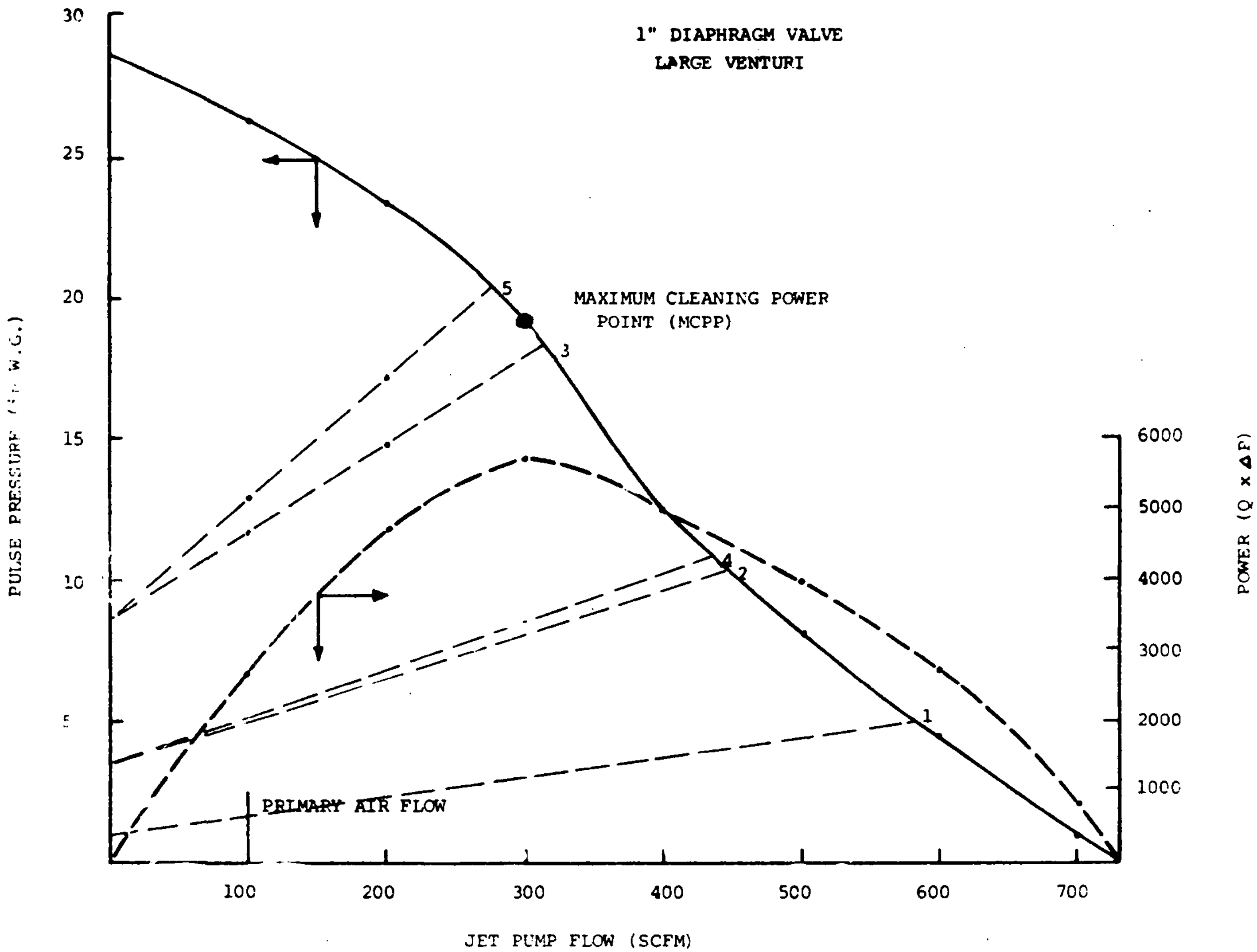

Figure 3. Jet pump and cleaning energy curves

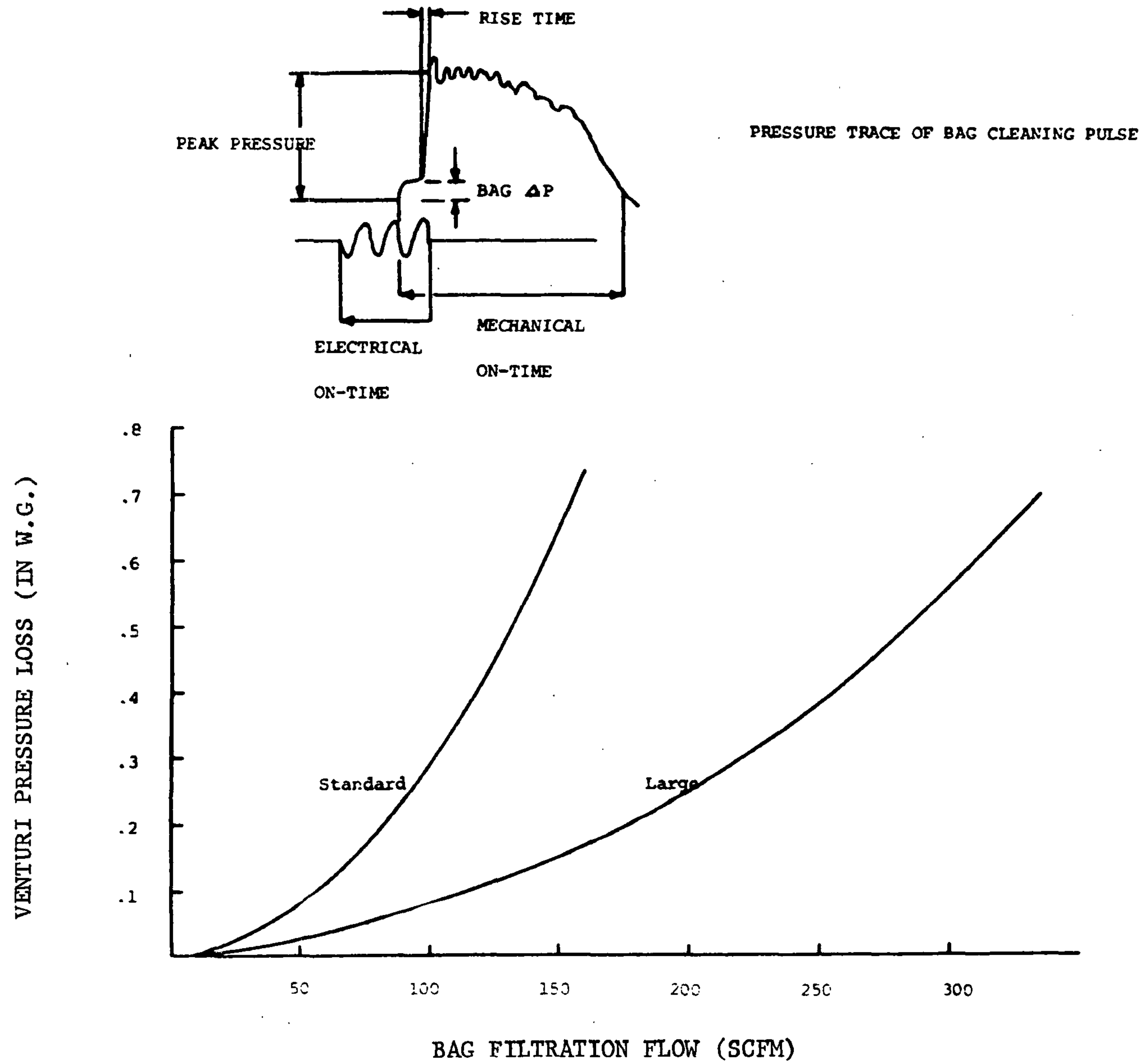

Figure 4. Venturi pressure loss curves and cleaning pulse trace

is the on-time of the electronically controlled pilot valve; the mechanical on-time is the on-time of the diaphragm valve. This on-time, together with the valve cycle time (the time for firing all valves), determines the air consumption needed for cleaning all bags. The relationship between electrical and mechanical on-time is dependent on the drain characteristics of the main valve, the compressed air capacity, volume of blow pipe, and losses downstream of the valve.

Also shown in Figure 4 are two Venturi pressure loss curves for the standard Venturi and for the larger Venturi for high filter rate applications. The larger Venturi is used when the loss through the standard Venturi becomes too high.

To describe the operation of a dust collector on a specific dust, two curves are normally used. The first is a filter rate (flow rate/bag area) versus grain loading curve at a given bag pressure drop. The second is a filter rate vs. bag pressure drop at a given grain loading. The first curve is most useful for product recovery or pneumatic conveying where the grain loading is a variable. In the case of air pollution control, the second type of curve is the most useful, since in this case the loading is relatively constant and the filter rate and bag pressure drop relationship is of greatest interest. However, both curves are needed to give an overall picture of the dust collector performance.

OPTIMIZING PARAMETERS

When the performance of a pulse-jet type of dust collector is to be optimized, the following parameters are used as the gauge for success:

Maximum filter rate at minimum pressure drop
(i.e., minimize collector size and fan horsepower)

Minimum outlet dust loading or maximum collection efficiency

Maximum bag life

The following variables should be considered to reach the optimizing objectives:

Jet pump characteristics

Dynamic response of cleaning valves

Cleaning energy and air consumption

Operating bag pressure drop

Bag size and baghouse configuration

Filter media

In an optimizing program, these parameters can usually be varied, but there are many parameters that are fixed for a given application that will have a significant influence on performance. Some of these are:

Grain loading

Particle size distribution

Dust characteristics (sticky, hydroscopic, corrosive, etc.)

Gas temperature and humidity

Corrosive components in gas

Electrostatic charges on the dust particles

By considering the variables one by one, their effect on performance can be established. In order to obtain a relatively complete picture of the effect of the different variables, one usually has to resort to laboratory studies, since some of the variables are very difficult to change on operating units. The variables most easily evaluated in the field are the effects of cleaning energy, air consumption, and total flow.

EXPERIMENTAL APPARATUS AND METHODS

During 1972, an intensive pulse-jet test program took place in the Research and Development Laboratory at MikroPul. The objective of the program was to determine the effect of the different variables and parameters mentioned above.

A schematic of the test setup is shown in Figure 5. The test unit was a cylindrical unit with 28 bags, 4-1/2 inches in diameter and 8 feet long. Each Venturi had a pressure tap in the throat area, and by connecting to inclined manometers the flow through each bag could be measured. By installing different bags with various filter media, their relative performance in terms of filter rate could be established by measuring the flow through each bag. The total flow through the unit could be varied and measured. A sampling train was connected to a sampling probe in the outlet duct for measurements of outlet concentrations of dust.

The dust was recycled by feeding it into a mixing box with a variable speed rotary feeder. By changing the speed of the feeder, the inlet loading could be adjusted. A fan connected to the box would disperse the dust and air convey it through a duct back to the inlet. Air dispersing rings used in the conveying duct were installed to break up dust agglomerations. Two types of inlets were tested, a radial hopper (bottom) inlet, and a tangential top inlet. These two types of inlets gave very different flow conditions inside the unit; the hopper inlet provided some knock-out of the coarser particles and created very turbulent motion in the hopper and a counterclockwise secondary motion (see Figure 5) in the housing. The top tangential inlet gave downward spiral motion of gas and dust, with the finer dust particles being sucked into the bag area. The turbulence was less and the flow much more orderly.

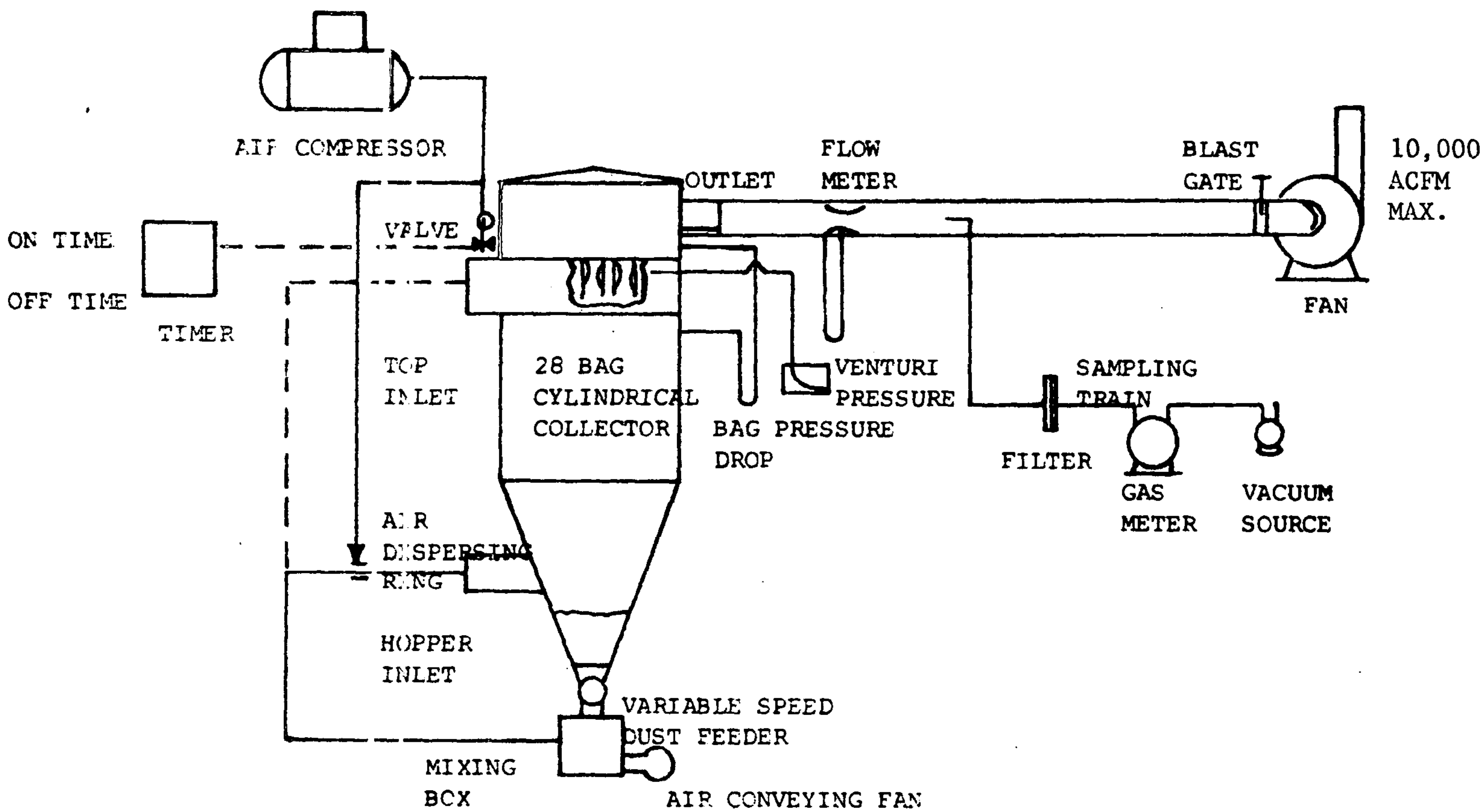

Figure 5. Schematic of test set-up

The cleaning energy was adjusted by changing air pressure, adjusting solenoid valve on-time and off-time, changing pneumatic valves (changing the flow coefficient of the valve), and changing the diameter of the orifices in the blow pipes. Two types of Venturis were tried, the standard for lower filter rates, i.e., less than 15 cfm/ft^2, and the larger for higher filter rates.

Two different dusts were used: magnesium silicate (talc), with a mean particle size of 1.8 microns with 25 percent less than 1 micron, and wood sander dust with a mean of 26 microns. These two dusts enabled us to optimize the dust collector performance on very fine and relatively coarse dusts.

Several types of felt media were tested in groups, with 15 oz/yd^2 wool felt as the base material. The average flow through each group was then determined by reading the Venturi pressure and converting to flow with the help of a calibration curve.

By maintaining a constant inlet grain loading (always 10 gr/scf), by adjusting the dust feed rate and changing the flow through the unit, a filter rate vs. pressure drop curve was generated. By reading the Venturi throat pressure for each group of bags, their relative performance was determined. Then, by maintaining a constant bag differential pressure (always 3.5" w.g.), and varying the inlet grain loading, its effect on filter rate was measured.

DISCUSSION OF RESULTS

The first part of the program consisted of exploratory work on the fine particle size dust (magnesium silicate or talc) with 15 oz/yd^2 wool felt bags having a permeability of approximately 35 cfm/ft^2 at 0.5" w.g. pressure drop. First the hopper inlet was evaluated with standard diaphragm valves of 3/4", using standard cleaning with 45 msec. electrical on-time and a 60 second cycle time. The filter rate curves are shown in Figures 6 and 7. Figure 6 shows that a filter rate of 4.45 cfm/ft^2 was measured at 3.5" w.g. bag pressure drop with an inlet loading of 10 gr/scf. By changing the inlet to the top entry, the filter rate increased to 5.20 cfm/ft^2. Then larger 1" pneumatic valves were installed which gave an increased air consumption from approximately 1 scf/burst for the 3/4" valve to 1.3 scf/burst for the 1" valve. The supply pressure in both cases was 90 psig. The blow pipe orifice diameter was maintained at 0.25", which gave an increased filter rate of 5.75 cfn/ft^2, still at 3.5" w.g. pressure drop, and 10 gr/scf inlet loading. The blow tube orifice was then increased to 0.3285" (21/64"), which increased the air consumption by a factor of 1.73, to approximately 2.2 scf/burst and the filter rate increased to 7.2 cfm/ft^2. Figure 6 shows that for this condition the filter rate was independent of the grain loading between 0.3 gr/scf and 10.5 gr/scf. However, for the other curves with top entry, there was more dependency of filter rate on grain loading than for bottom (hopper) inlet, which is normally the case.

Figure 7 shows the dependency of bag pressure drop on filter rate for an inlet loading of 10 gr/scf. This figure shows that as the inlet was changed from bottom to top and the air consumption increased, the curves straightened out and one could go to higher bag differentials and still get increases in flow. As illustrated by the curve for bottom inlet, the curve eventually turns vertical and no gain in flow can be achieved by increasing the pressure drop. In other words, if the unit were undersized, increasing the fan speed would not result in an increase in flow because the bags would be overloaded with dust.

Figure 8 shows the effect of increased filter rates on collection efficiency. The curves show the relationship between collection efficiency of talc and bag pressure drop for the different modifications made. The inlet loading of dust was 10 gr/scf. For the hopper entry, no material could be measured on the sampling filter paper after a two-hour sampling period, and therefore was considered essentially 100 percent

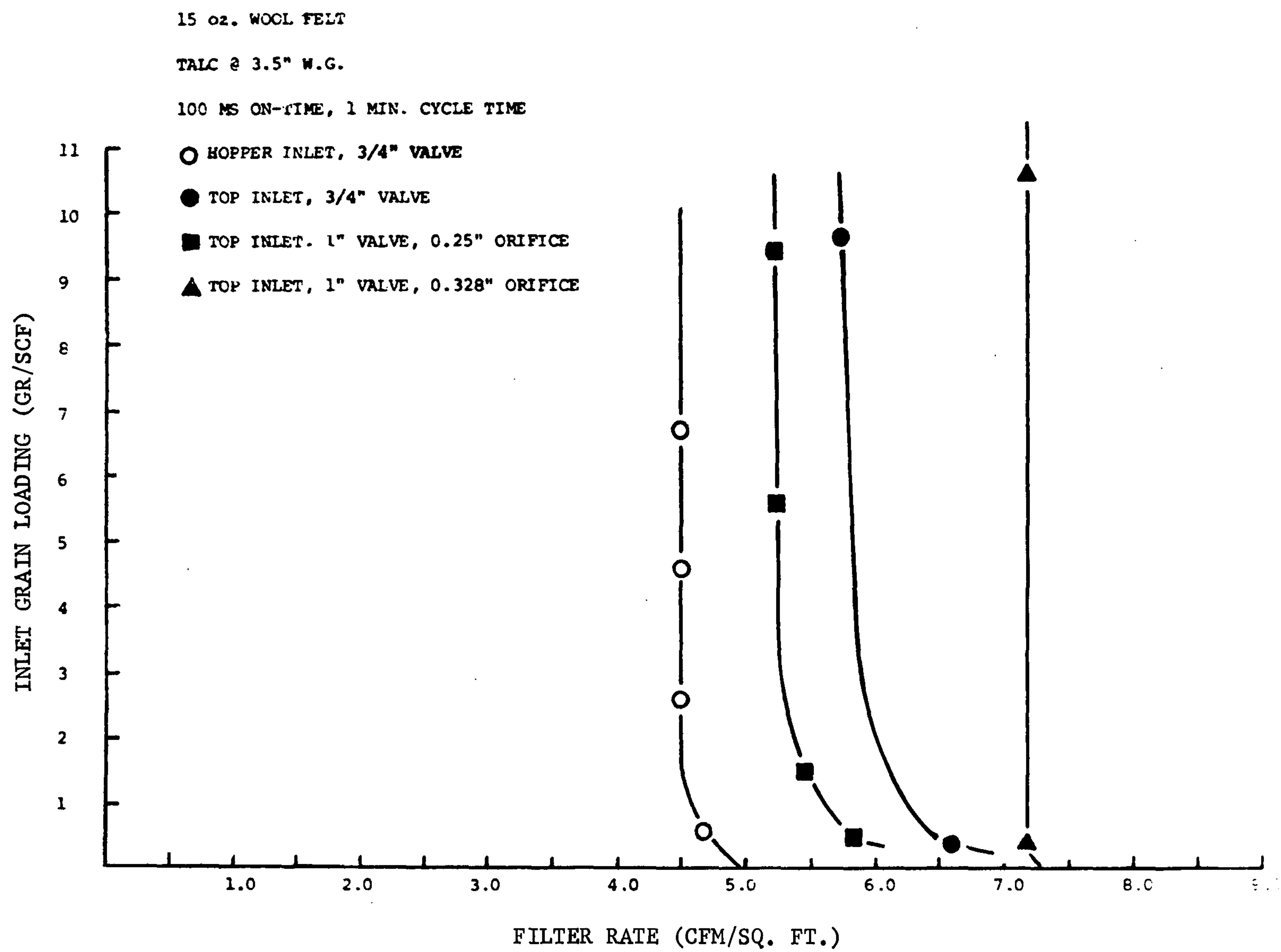

Figure 6. Inlet grain loading versus filter rate

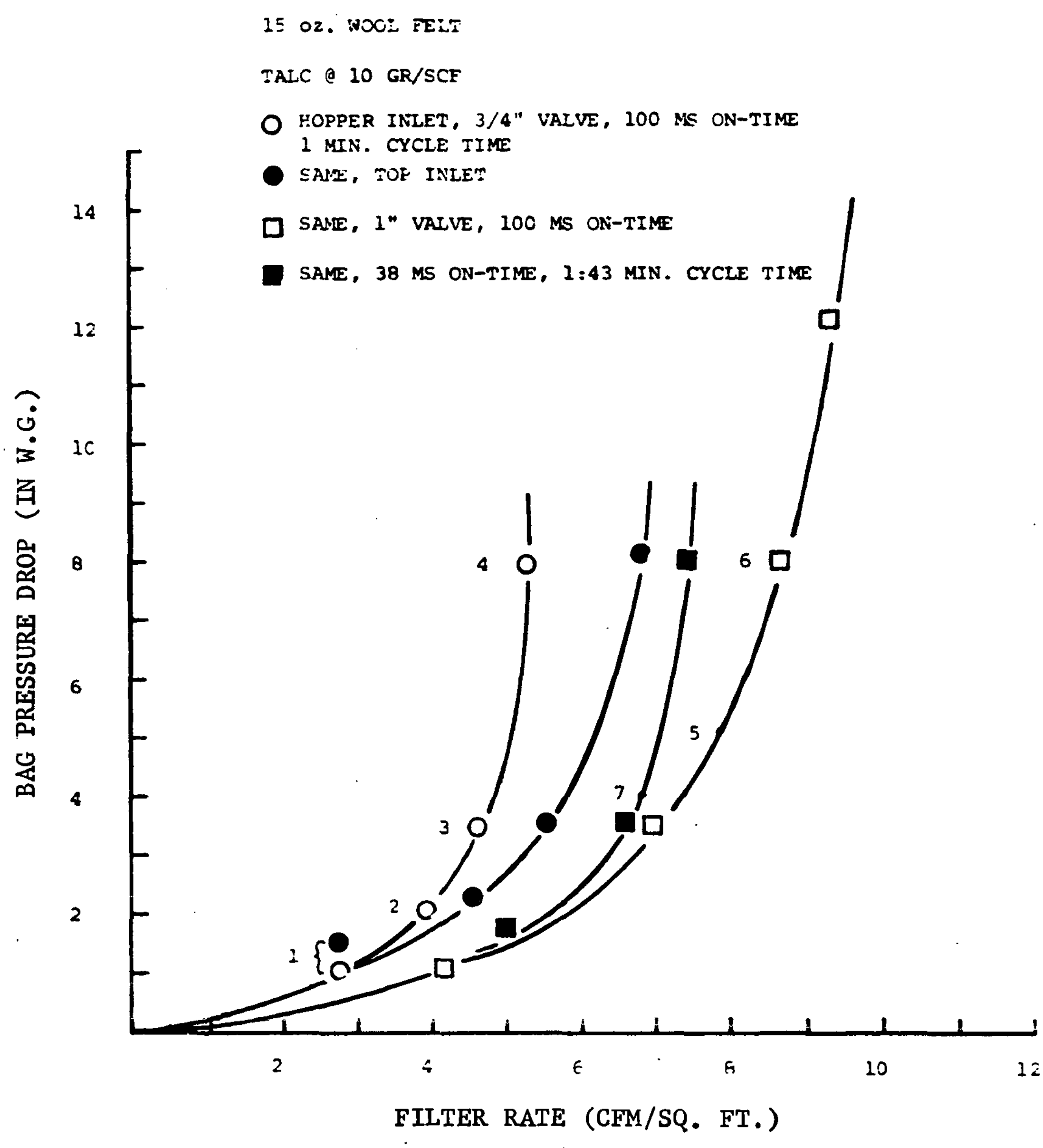

Figure 7. Bag pressure drop versus filter rate

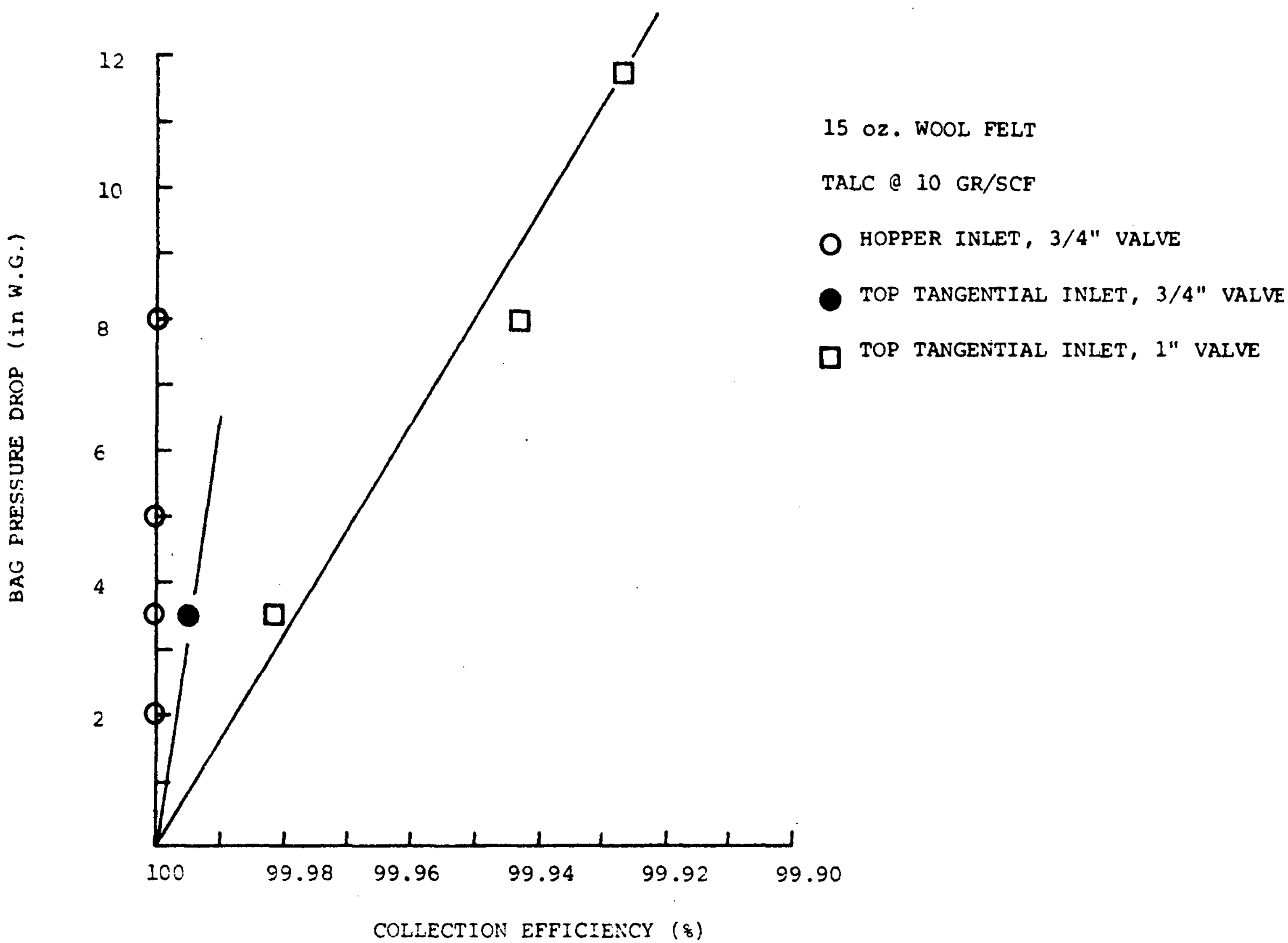

Figure 8. Bag pressure drop versus dust collection efficiency

efficient. However, as the inlet was moved to the top, the efficiency was found to decrease to 99.9945 percent at 3.5" w.g. pressure drop. Then as the valve size was increased to 1", giving higher air consumption, the efficiency decreased to 99.98 percent at 3.5" w.g. pressure drop and the relationship between efficiency and bag pressure drop was found to be linear.

Finally, the electrical on-time (the time period when the solenoid valve is open) was varied to study its effect on the filter rate. The results are shown in Figure 9, where the filter rate is plotted against the inlet grain loading. The latter was kept as constant as possible and the pressure drop was maintained at 3.5" w.g. This figure shows that the filter rate can be improved by increasing the valve on-time; however, this can only be done up to a certain point, or also overcleaning will occur. This means that the filter media is kept in an open state too long by the cleaning burst, the collected dust particles penetrate deep into the felt, eventually work their way through the felt, and are more difficult to clean out. As shown in Figure 9, the electrical on-time could be increased to 120 msec. with increases in flow, but after a short time operating at 120 msec., the flow would decrease. However, by reducing the on-time to 100 msec., the filter rate recovered to a maximum of 7.1 cfm/ft^2. The starting point was 6.4 cfm/ft^2 for 40 msec. on-time and an increase of 11 percent in filter rate was realized by adjusting the on-time.

If we relate the pressure drop vs. filter rate curves at a given inlet grain loading, as shown in Figure 7, to the jet pump curve (Figure 2), we can see how the dust collector is operating in relation to the maximum cleaning energy point on the jet pump curve. Assuming a constant permeability at any given point of the curves of Figure 7, the permeability lines can be plotted on Figure 2, and the bag operating point during cleaning is then the intersection of the permeability line and the jet pump curve. Using this method reveals the following.

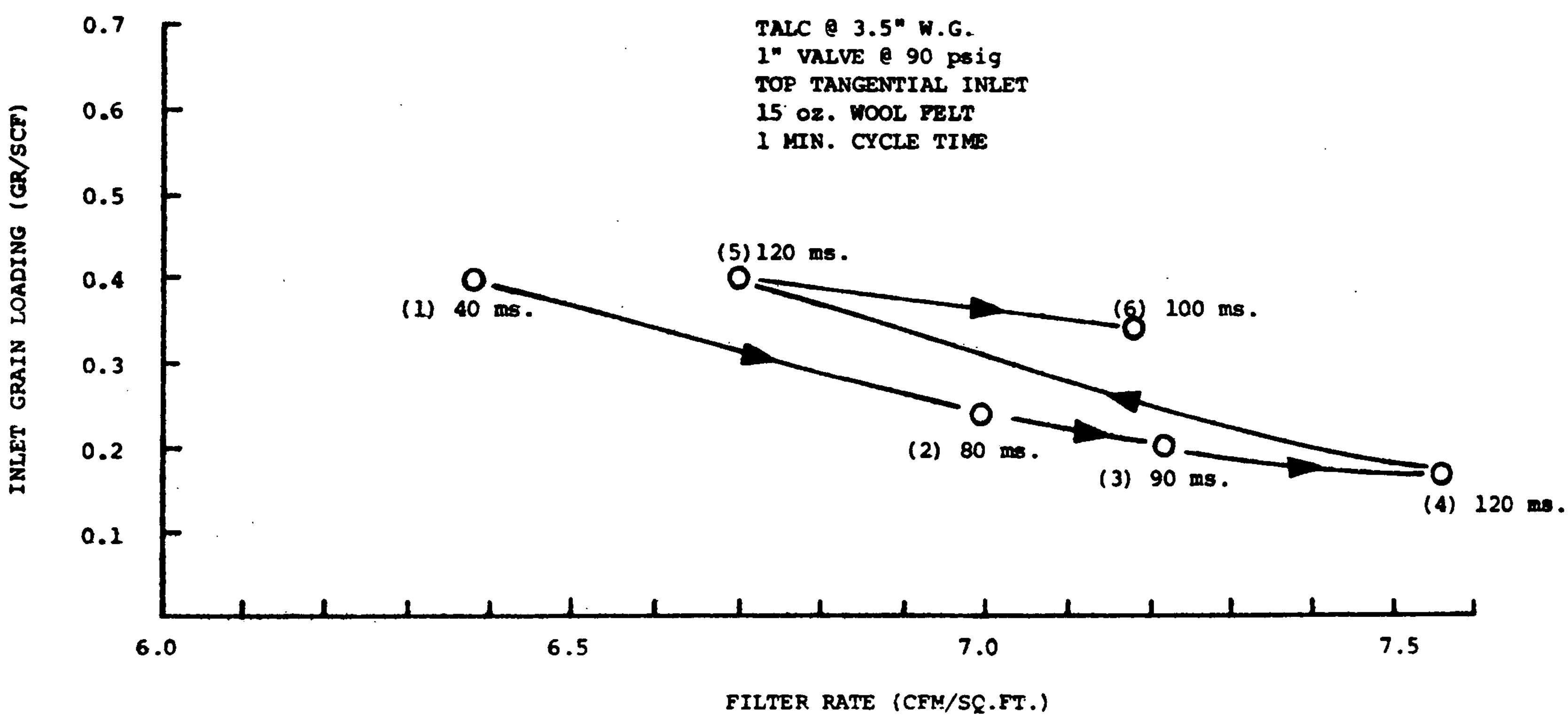

Figure 9. Inlet grain loading versus filter rate for different electrical on-times

As the slope of the filter rate curve gets steeper, the operating point slides upward along the jet pump curve. After passing the maximum cleaning point, the slope of the filter rate curve will become very steep, eventually to the point where the slope is vertical (e.g., point #4), and no gain in flow will take place by increasing the pressure drop. Also, if the cleaning operating point is close to the maximum cleaning energy point, the rate of change of the slope will be largest, or this will be the point where the filter rate curve rapidly starts to turn vertical. This can be illustrated by considering points 3, 5 and 7 on the jet pump and filter rate curves (Figures 2 and 7).

This analysis points to the fact that if the pulse-jet dust collector is operated close to the maximum cleaning power point (MCPP), performance will be at its best. The flow can still be increased without a serious increase in pressure drop. From a purely practical point of view, this finding has another important implication. If the operator of a dust collector wants to know whether he can increase the capacity of the dust collector, all he has to do is measure the total flow and divide it by the number of bags, measure the bag pressure drop, take the ratio of the pressure drop to the flow per bag, and plot it on the jet pump curve as described above. If the operating point during cleaning is below the MCPP, he knows the flow can be increased. If the point falls much beyond the MCPP, the collector is on the vertical part of the filter rate curve and any attempt to increase the flow will cause a very sharp increase in bag pressure drop.

The next phase of the program was to investigate the performance of the same pulse-jet collector on a very high filter rate application with different filter media. We wanted to operate the collector at filter rates between 20 and 30 cfm/ft^2, and a wood sander dust was selected as the material. However, in order to reach these high rates, larger Venturis had to be used. Their characteristics in terms of jet pump and pressure loss are shown in Figures 3 and 4 respectively.

Five different bag materials were selected: 10 oz/yd^2 polypropylene, 11 oz/yd^2 polyester, 12 oz/yd^2 rayon viscose, 16 oz/yd^2 polyester, and bags made of 15 oz/yd^2 wool. All felts had a permeability range from 30 to 40 cfm/ft^2 at 0.5" w.g. pressure drop.

The filter rate vs. inlet grain loading curves for the different bags are shown in Figure 10 for a top inlet. There is a significant spread in performance, with the 10 oz/yd^2 polypropylene giving the highest filter rate and the 16 oz/yd^2 polyester and 15 oz/yd^2 wool giving the lowest filter rates. Generally, the lighter weight material gave higher filter rates. Figure 11 shows the relationship between bag pressure drop and filter rate with an inlet loading of 10 gr/scf. Again, the slope of the curves can be related back to the operating points on the jet pump curve. The corresponding numbers in Figure 11 relate back to the numbers shown on the jet pump curve, Figure 3.

Figure 11 shows that the 12 oz/yd^2 rayon viscose performed very poorly at higher grain loading; the filter rate actually decreased when the pressure was increased beyond 3.5" w.g. This indicates that the felt is overloaded with dust and cleaning effectiveness deteriorates very rapidly. The bag cleaning point is beyond the MCPP, as can be seen by considering point #5 in Figures 11 and 3.

Finally, the top inlet was changed to a hopper inlet and inlet grain loading vs. filter rate curves for the different bag materials were developed. The results are shown in Figure 12. It is interesting to note that the spread in performance with the hopper inlet is much less. The reason for this is that very strong secondary motions exist in the bag area when the hopper inlet is used which increase the loading of the dust presented to the individual bags. Also, for the same reasons, the slope of the curves in Figure 12 is much steeper than for the top inlet (see Figure 10).

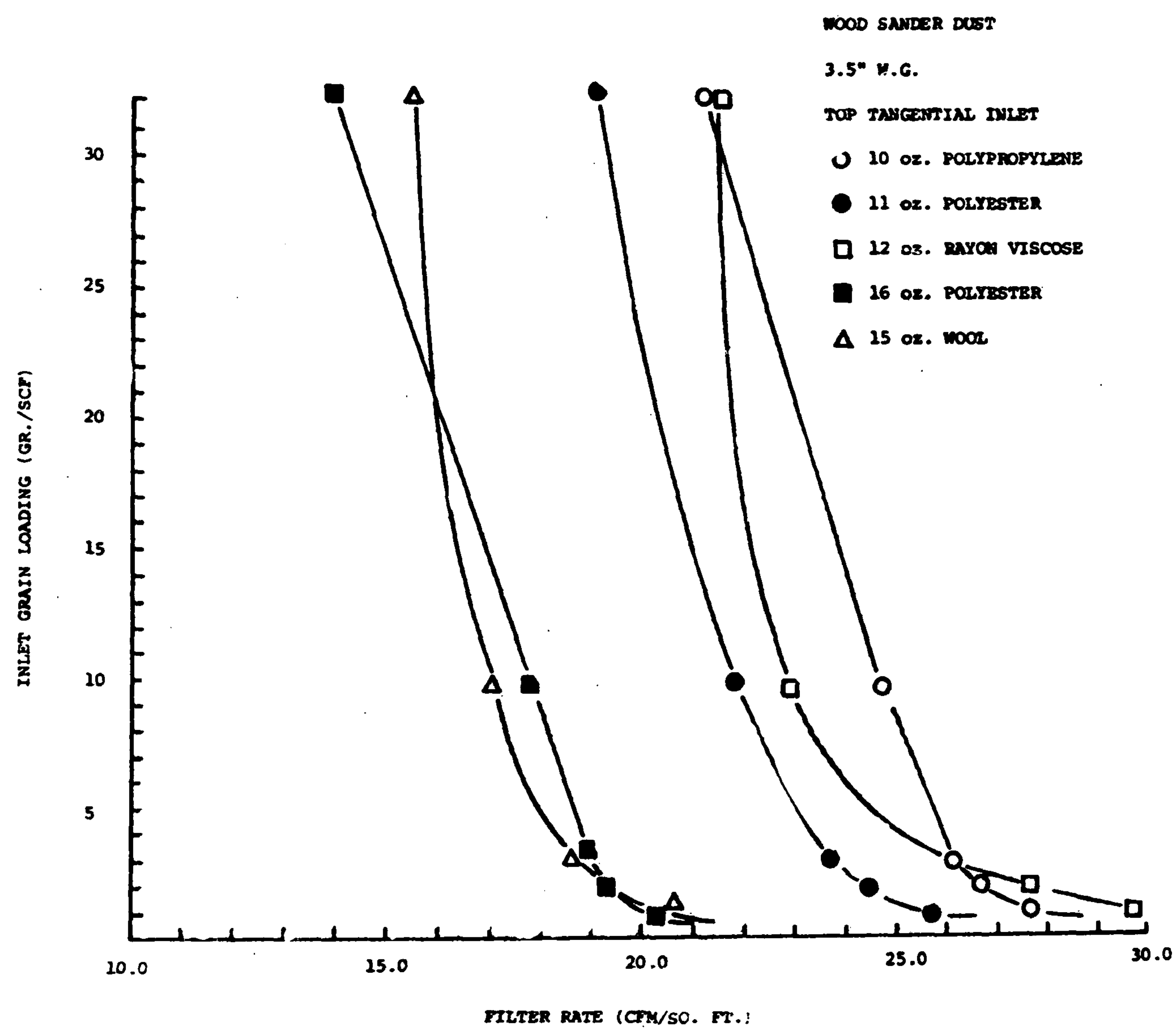

Figure 10. Inlet grain loading versus filter rate

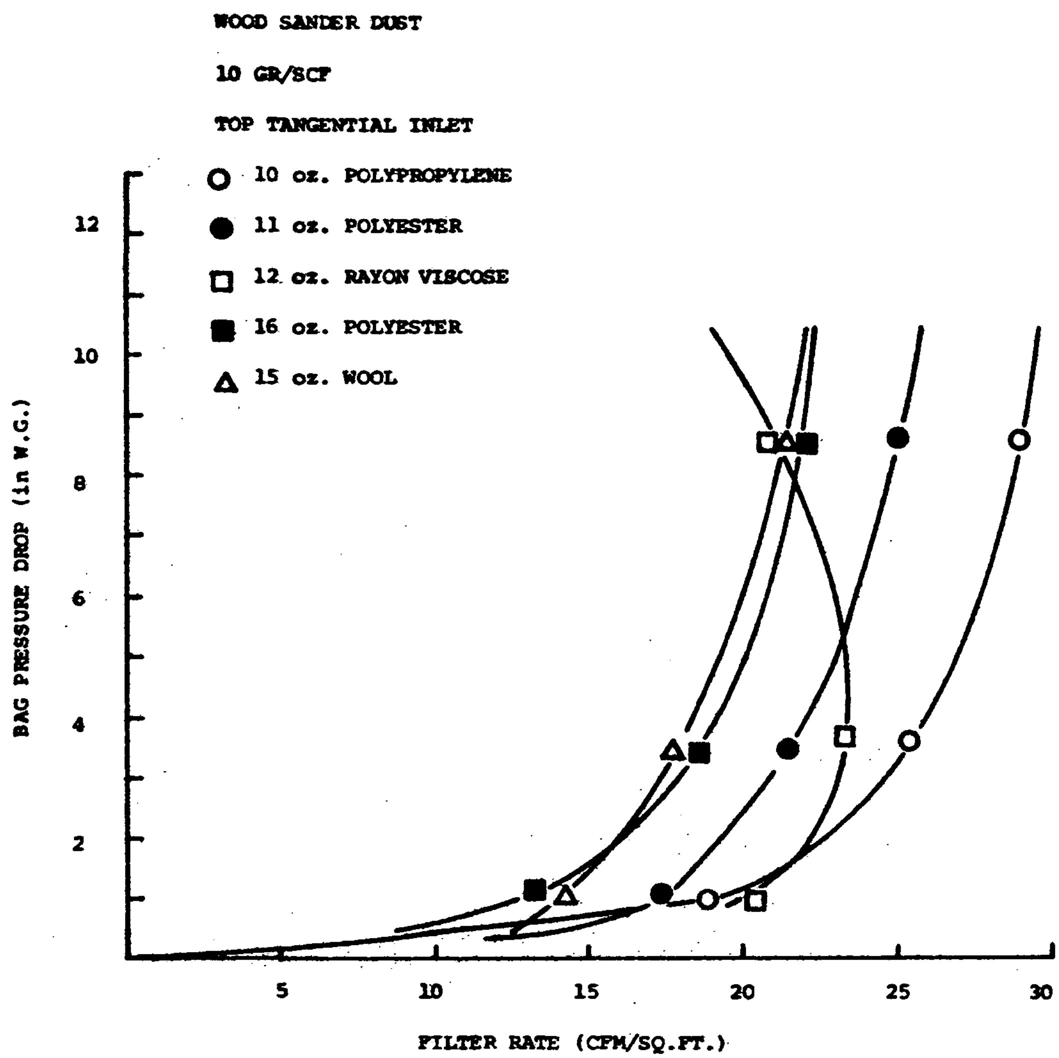

Figure 11. Bag pressure drop versus filter rate

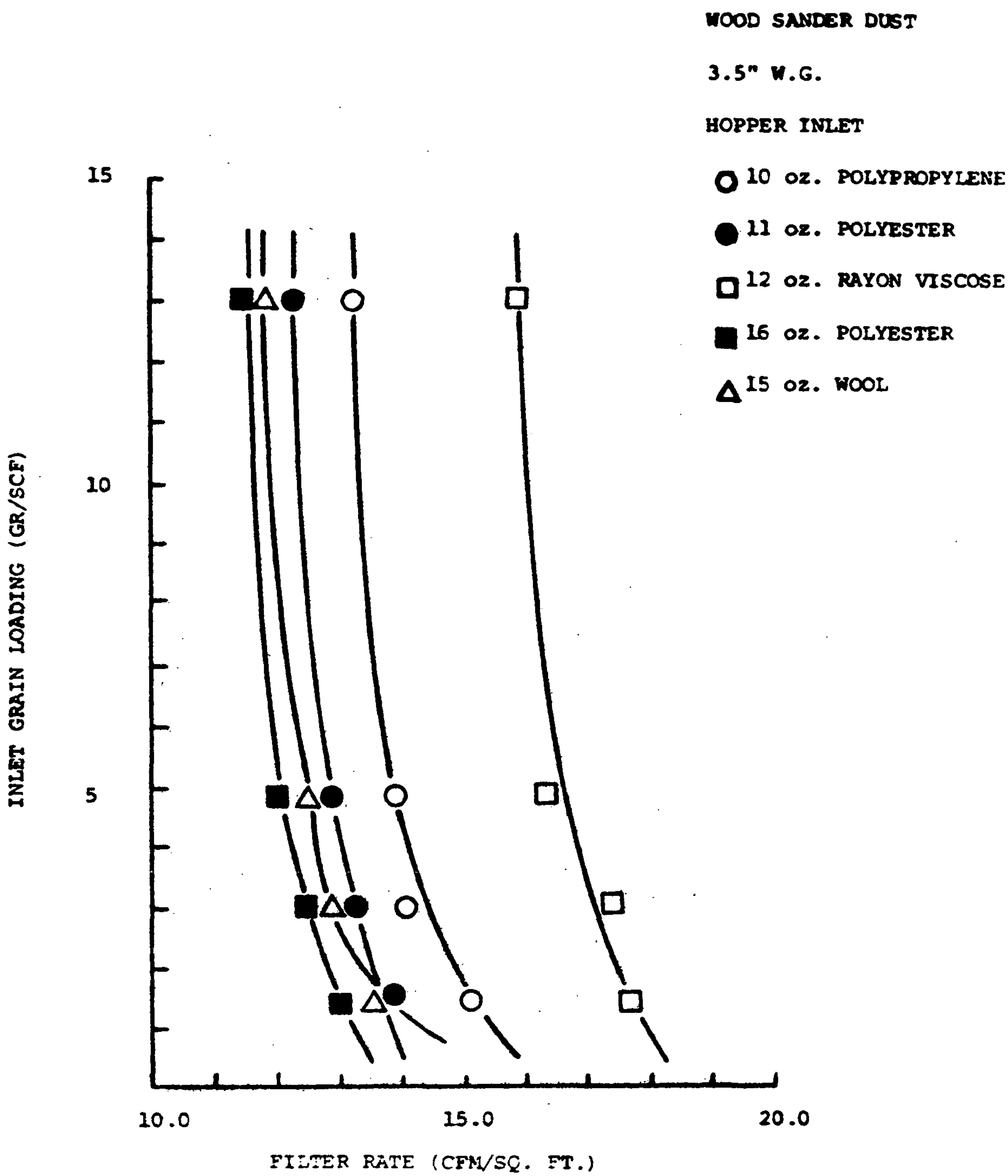

Figure 12. Inlet grain loading versus filter rate

The relative gain in filter rate when switching from hopper inlet to top tangential inlet ranges from about 40 percent for the 15 oz/yd^2 wool to 86 percent for the 10 oz/yd^2 polypropylene. The gain is inversely proportional to the weight of the material.

CONCLUSIONS

The following conclusions can be drawn from this study.

Using magnesium silicate with a mean particle size of 1.8 microns, the filter rate was increased by almost 62 percent after switching the inlet from a hopper type to a top tangential type and increasing the air consumption by a factor of 2.2. However, the outlet loading increased from virtually zero for the hopper inlet to a significant value for the top inlet with increased air consumption and bag pressure drop. Also, when the air consumption was increased, the dust collector could still be operated at a much higher pressure drop with significant increases in flow.

By adjusting the electrical on-time of the compressed air burst, an optimized on-time could be found. An increase of 11 percent in filter rate was realized by adjusting the on-time.

It was also shown that the performance of the dust collector, i.e. the relationship between filter rate and bag pressure drop, can be related directly to the jet pump characteristics of the cleaning pulse. The best performance is obtained when the bag permeability is such that the operating point during cleaning is at the maximum cleaning energy point on the jet pump curve. The same relationship was also found to be true for the coarse dust operating at a high filter rate.

When the different bags with varying weights and fibers were evaluated with the coarse dust, it was found that the lighter the felt, the higher the filter rate at a given pressure drop. It was also found that the spread in filter rates was much larger for the top inlet than for the hopper inlet.

Finally, it was found that the dust loading has more of an effect on the filter rate with top inlet; the higher the loading, the lower the filter rate. However, if the cleaning air consumption is increased, the change in filter rate will become much less.

ACKNOWLEDGEMENTS

The author expresses thanks to Mr. Peter G. Ford for conducting the tests in the laboratory, and to Dr. David Rimberg for many valuable suggestions concerning this paper.

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ENGINEERING AND ECONOMIC CONSIDERATIONS IN FABRIC FILTRATION

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INTRODUCTION

My presentation this afternoon will briefly review the basic engineering and economic factors relative to fabric filtration systems and then focus on several areas of current interest.

Industries, many for the first time, are considering the fabric filter or other pollution control device an integral part of the production process; a part that must be considered in the initial planning of a process, one that must be carefully selected and one that must be maintained.

As the design of fabric filter systems becomes more of a science than an art, the equipment manufacturer is faced with an increasing sophistication on the part of the customer. No longer are air pollution control systems given cursory, last second examination. They are now being evaluated by a more educated customer who is writing tighter and better specifications as his experience increases.

Certain of the economic considerations relative to fabric filter systems have been affected more than others by the spiral of inflation over the past four to five years. The most important of these considerations are the costs of labor, space, and utilities. Although the cost of material has risen significantly, particularly in the past six months, the steady increase in the cost of labor and overhead during the past several years has caused the most significant changes in the design of fabric filter systems. After briefly summarizing the basic engineering and economic factors, I would like to specifically discuss how the increase in labor costs have affected the design of the filter system.

ENGINEERING CONSIDERATIONS

The basic engineering considerations can be broken down into two major classifications. First, there are the properties of the process gas stream and, secondly, the variables involving system design to control the emissions from the process stream.

The properties of the gas stream which must be determined and evaluated in the design of the control system are as follows:

1. Average volume and temperature of the gas stream and fluctuations or peaks in the temperature or volume. Ideally, the customer should provide a graph of volume or temperature fluctuations during the process cycle. A fabric filter system can often be designed at less than the absolute peak volume and temperature conditions, particularly when these peaks are of short duration.

2. The constitutents of the gas stream which must be evaluated include, but are not necessarily limited, to the following:

a. Particulate matter

(1) Chemical composition

(2) Particle size distribution

(3) Presence of unburned carbon particles

(4) Concentration-maximum and average values

(5) Particle density, both packed and bulk

(6) Particle angle of repose

(7) Particle electrical properties

b. Gases

(1) Chemical composition

(2) Acid dew points

(3) Water vapor

c. Special Properties of Gas Stream

(1) Toxic properties

(2) Explosive properties

(3) Corrosive properties

(4) Abrasive properties of particulate

Once the properties of the process gas stream are available and analyzed, the following basic engineering factors are taken into consideration in the design of the control system:

1. Space restrictions relative to the size of collector.

2. Method of cleaning the dust from the fabric tubes, basically shaking, reverse air, or pulsing.

3. Suction or pressure system.

4. Collector construction, basically structural, panel or modular.

5. Type of fabric.

6. Gas to cloth ratio.

7. Gas cooling or pre-conditioning requirements.

8. Maintenance provisions and access:

   a. To fabric tubes

   b. To dampers

   c. To material handling equipment

   d. Other points of access such as sampling points

   e. Miscellaneous maintenance equipment such as vacuum cleaning provisions

9. Method of getting the particulate matter from the emission source to the fabric filter:

   a. Hoods

   b. Duct

   c. Fans and motors

   d. Associated equipment

10. Material handling equipment:

    a. Screw conveyors

    b. Air locks

    c. Pneumatic conveying, storage, pelletizing, etc.

11. Effluent discharges:

    a. Stacks

    b. Monovents

    c. Louvers

12. Electrical controls:

a. Cleaning cycle

b. Damper operation

c. Fan and motor controls

d. Other electrical equipment

ECONOMIC CONSIDERATIONS

The economic considerations in the design of fabric filtration systems can best be analyzed by referring to the "pie" diagram from the 1969 GCA Survey, as presented in Figure 1.[1] As shown in this figure, the cost of the fabric filter itself is approximately 5 percent of the annual cost of the total system. It is also interesting to note that the largest piece of the "pie" is the labor portion. Since the GCA Survey in 1969, the costs of all components of the total picture have increased but their relation to each other has probably remained relatively constant. If one area has increased in relation to the others, it is in the labor segment of the total cost picture. The cost of labor can be broken down into two major areas: fabrication and erection costs and maintenance costs.

I would now like to focus on these two cost areas and describe how the design of the fabric filter system has changed during the last five years as a result of the increase in labor costs.

FABRICATION AND ERECTION COSTS

During the last several years we have witnessed a growing trend toward shop rather than field fabrication. Shop fabrication has the following advantages over field fabrication:

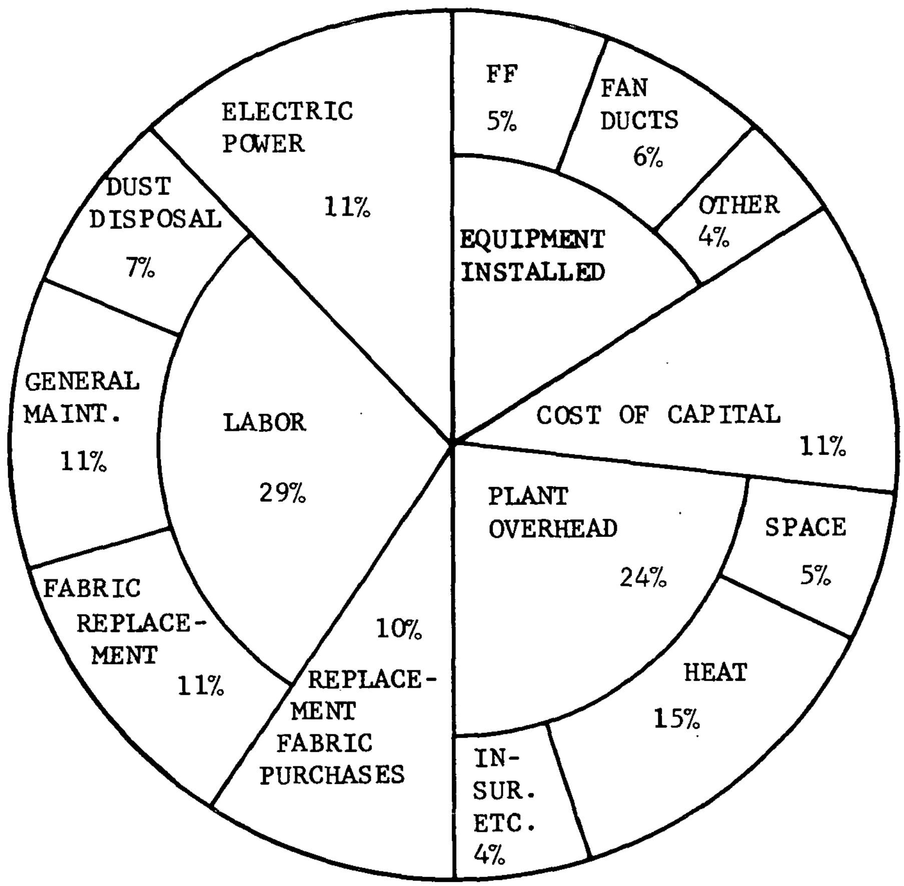

Figure 1. Fabric filter cost distribution (from GCA survey, 1969)

1. Non-union labor can often be used in the shop, whereas field work normally requires union workers.

2. Productivity of workers in the shop is approximately 20 percent higher than productivity in the field for similar work. This assumes good weather and work that can be done equally as well in the field as in the shop.

3. Weather conditions add to the cost of field labor as compared to shop labor.

4. Bad working conditions in the field may require premium pay.

5. Often a per diem rate must be paid to field personnel that travel over a certain distance from their homes. As the cost of transportation, lodging and food has increased significantly during the past year, the per diem rates have also increased.

6. Tools are more readily available in the shop than in the field.

For the above reasons, the basic fabric filter construction has changed from the panel or structural designs of the 1960's to the modular design of the 1970's. A module is a pre-fabricated section of a fabric filter system that is shop assembled to the maximum extent possible. Normally a single module consists of the largest practical box that can be economically shipped to the jobsite as a unit. Almost by definition a module must be difficult to ship --- if it is small enough so that shipping is not a problem it probably will not be competitive. Normally all internal components such as tube sheets or venturi sheets, cleaning mechanisms and even fabric tubes are shop installed in the module. Although the idea of modular construction is not new, the ever increasing gap between shop and field labor makes the modular concept more important every day.

MAINTENANCE COSTS

The cost of maintenance, more than any other factor in fabric filter design, is being more closely evaluated every day by the customer. As the GCA Survey indicates, approximately 29 percent of the annual cost is in maintenance labor.[1] As a result of the increasing evaluation of fabric filter maintenance, the equipment manufacturers have made more changes in collector design over the past five years to cut maintenance costs than for probably any other reason.

Perhaps the most important maintenance cost associated with fabric filters is the cost to locate and change a broken tube. With most filter designs in the past, (an exception is the pressure type structural baghouse), this was a dirty, time-consuming and difficult or in some cases impossible task.

As one of the more outspoken equipment manufacturers put it, in describing his tube access provisions, he tried to eliminate "sweaty trips through the bowels of the baghouse to search out broken bags." This is probably the best description of the task that I have seen. In some cases, workers must be paid a premium to enter the fabric collector to change tubes, particularly where a noxious or toxic dust is present.

Some of the design changes to provide better tube access are as follows:

1. Top access provisions are now standard on many types of pulse units. Access to the tubes is accomplished through doors in the roof and a broken tube can be quickly identified and replaced. In some cases, enclosed upper access areas rather than doors in the collector roof are providing the ability to remove tubes from pulse collectors during inclement weather.

2. Top access is also being provided in shaker and reverse air type units either in the form of a tilting walkway near the top of the unit or the more preferred upper access area with removable grating panels directly over the tube support members.

3. Snap band type cuffs are now standard on most small diameter bags for shaker and reverse air units. The snap band arrangement not only allows for substantially lower tube sheet costs but also for much easier maintenance. Tubes are merely snapped into the tubesheet without the need for tools to loosen the hose clamp as in earlier designs. Any dust that accumulates on the tube sheet floor can easily be swept into the hopper. With the older collar type design, the dust had to be vacuumed from between each collar.

In addition to design changes that make fabric tubes easier to inspect and replace, other areas were re-evaluated to minimize maintenance costs including the following:

1. Stair, rather than ladder access is becoming more prevalent, especially on the larger units. On one job now being engineered by American Air Filter where 34 foot tubes are being used to filter several million cfm, the customer originally specified that an elevator be provided to get from grade to tube sheet and tube suspension level.

2. Many specifications now call for training sessions for maintenance personnel.

3. Specifications are also calling for "maintenance compartments" in addition to cleaning compartments that can be off-line for extended periods of time without affecting overall system performance.

4. Five years ago, most shaker mechanisms were provided inside of the dust collector housing, especially on low temperature applications. The trend since that time has been toward outside mounted shaking mechanisms and today the "inside" shaker is almost obsolete. It did not take the customer long to realize that there is no such thing as the "clean" side of a fabric filter. One side of the tube is dirty and the other side is very dirty. Thus motors and bearings have been removed from the inside of the units and placed outside protected from the dust and heat.

CONCLUSION

In conclusion, I would like to say that the customer is becoming increasingly aware that the cost of the equipment is a small percentage of the total annual cost and has demanded and gotten changes in collector design to minimize maintenance. Although much work remains to be done, the philosophy of encouraging effective maintenance by design is, and will continue to be, one of the most important considerations in the planning of fabric filter systems.

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COLLECTION EFFICIENCY AS A FUNCTION OF PARTICLE SIZE, SHAPE, AND DENSITY: THEORY AND EXPERIENCE

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INTRODUCTION

Increasing concern about the potential physiological hazards and visibility problems associated with fine particle emissions from a multiplicity of stationary and mobile sources leads us to re-examine the particle collection capabilities of fabric filter systems. Electrostatic precipitators and high energy wet scrubbers can provide high efficiency collection for certain high temperature, wet and/or corrosive gas streams that are difficult to clean with filtration equipment. Fabric filters, however, afford the best means for the retention of fine particles. In the present discussion, fine particles are considered to range from about 2 μm diameter down to nuclei sizes ~ 0.001 to 0.1 μm. The particles of concern here are those emitted from stationary sources such as fossil fueled heating or power plants and numerous industrial operations wherein the uncontrolled emissions frequently exceed permissible discharge levels based on mass emission rates and/or plume opacity.

The present primary and secondary ambient air quality standards, 75 and 60 $\mu g/m^3$, respectively for the annual geometric means, are based solely on the mass concentrations in the atmosphere although it is the particle size properties of the suspended particulate that determine its environmental impact.[1] Except for being able to infer that the clean suburban aerosol of 25 $\mu g/m^3$ following a rainfall is principally submicron, or, conversely, that the 200 to 500 $\mu g/m^3$ concentrations occasionally encountered in heavily industrialized areas reflect a significant 5 to 10 μm size fraction,[2] one cannot predict from current ambient measurements the true extent of potential particulate problems. Similar limitations are encountered with respect to the size descriptions of particulate emissions from stationary sources. In the absence of size parameters, it is not possible to establish the meteorological dispersion patterns nor the available particle surface for gas adsorption and chemical reactions.

With the exception of such highly toxic substance as asbestos, beryllium or plutonium, the assessment of ambient concentrations or stack emissions on a mass basis has heretofor been considered sufficient to determine the potential hazards. For this reason, plus the fact that accurate size determination measurements are difficult and costly to make, the performance of most air and gas cleaning equipment is described in terms of mass (or weight) collection efficiency. Exceptions to the above approach include the use of stain efficiency tests for moderate efficiency filters or low-voltage electrostatic precipitators designed to reduce the soiling properties of ambient atmospheres and the use of special DOP aerosols, $\sim 0.25\ \mu m$, to rate high efficiency, HEPA or AEC type particulate filters.

In this paper, we have analyzed the performance features of both industrial and experimental fabric filter systems with respect to the concentration and particle size properties of the collector effluents. It is quite simple to cite from a qualititative viewpoint those factors that should influence significantly the collection characteristics of a fabric filter system. Key factors should include the following:

- Dust Properties - concentration, size distribution, shape factor, density, charge, chemical reactivity, surface features.

- Fabric Properties - woven, felted; yarn and fiber properties, i.e., density, twist, dimensions, staple, filament; fabric density, thickness, porosity, tensile properties; chemical composition, mineral, natural, synthetic, surface treatments.

- Operating Parameters - filter velocity, resistance to air flow, gas temperature and composition, cleaning frequency.

- Filter Cleaning Method - mechanical shaking, pulse jet, reverse flow, reverse jet.

- Critical Interdependencies - dust/fabric, dust/resistance, dust/cleaning method, resistance/cleaning method, cleaning method/service life.

When it becomes necessary, however, to predict quantitatively the performance of a filter system or to establish design parameters for a given field application the available guide posts are quite limited with respect to any generalized approach. Considerable data have been reported, however, based upon industrial experience and laboratory studies that provide excellent support for limited applications.

In the following sections, we have reviewed the results of past and present studies that aid in describing the basic relationships between various fabric filter and particulate systems. Emphasis is directed toward certain concepts that must be clearly understood before selecting or designing fabric filter equipment.

FABRIC FILTER EFFICIENCY CHARACTERISTICS

FILTER LOADING AND EFFLUENT CONCENTRATION

Fabric filters are classically rated as 99 to > 99.99% efficient for the average field application. At these levels, the incentive to examine rigorously the effluent size properties is low when mass emission criteria are the only concern. More important, in terms of materials recovery, one is seldom impressed with the difference between 99.9 and 99.99% collection. In the above case, however, there is a tenfold difference in the emission levels and were the efficiency to increase to 99.999% a 100 times decrease in effluent concentration would result.

The above comparisons are based on a constant inlet loading. Another way to evaluate efficiency ratings for filter systems is to apply a fixed efficiency rating to a variable inlet concentration for a specified dust. If the efficiency were actually constant, for example, at 99%, the effluent concentrations for inlet loadings of 0.1 and 10 grains/ft.^{3} would be 0.001 and 0.1 grains/ft.^{3}, respectively. In the latter case, the effluent concentration far exceeds permissible emission levels. Actually, field and laboratory studies have indicated that it is the filter effluent concentration rather than the efficiency that is more nearly constant for a given fabric filter design and a specified aerosol.

The dependency of filter efficiency on inlet concentration levels for otherwise similar systems has often been neglected for filters operating at < 1% penetration. According to Figure 1, however, field measurements indicate an inverse relationship between penetration and loading.[3] On the premise that equal gas volumes are filtered, these measurements suggest strongly that the mass emission rates are essentially constant for a given dust/fabric system irrespective of the inlet loading. It is interesting to note that recent tests with a coal fly ash[4] having size properties similar to the foundry dust, ~ 5 μm MMD, fall on the regression line for the foundry dust. As far as the field measurements are

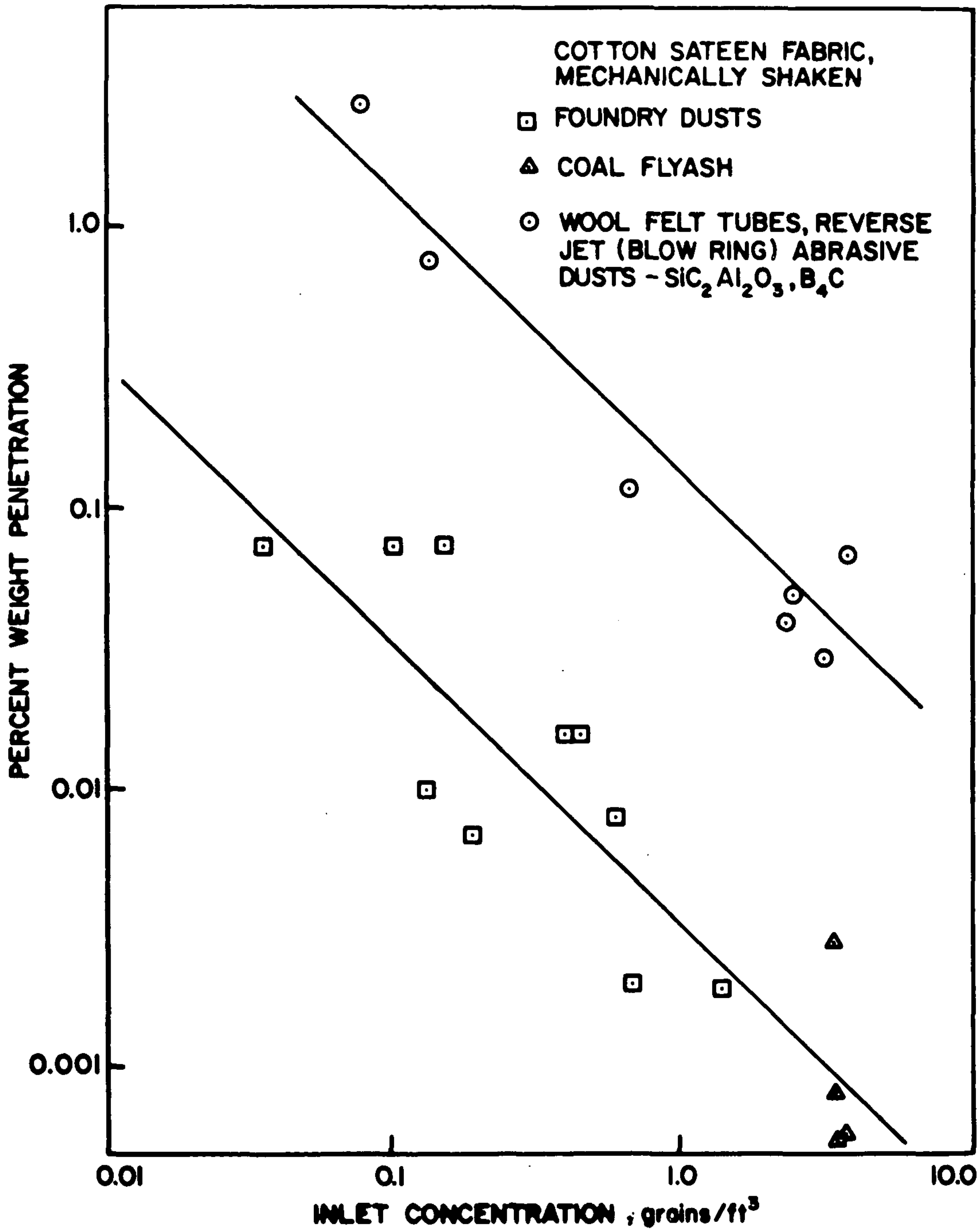

Figure 1. Inlet concentration versus percent weight penetration--ambient temperature

concerned, the general spread of experimental points reflects variations in filtration velocity, shaking intensity and quality of field maintenance.

The same test series also indicates that the effluent size properties as determined by light field microscopy are similar to those for low atmospheric dust concentrations and only slightly dependent on inlet dust size distributions. The above findings are qualitatively consistent with filtration theory; i.e., only those particle diameters of the order of 1 μm or less should exhibit any singificant penetration. Despite the strong correlation between penetration and inlet concentration, however, the best estimates of outlet concentrations from Figure 1 or related graphs are of "order of magnitude" quality until the pooled variables are examined separately.

FILTER EFFICIENCY VS. PARTICLE SIZE

It has been the policy of some manufacturers of air and gas cleaning equipment to provide fractional particle size efficiency ratings for devices such as inertial separators, wet scrubbers and occasionally electrostatic precipitators. On the premise that the size properties of the inlet aerosol components have been determined, it should be possible to estimate both the mass concentration and size distribution of the collector effluent. Unfortunately, graded efficiency data for the above devices are seldom usable for particle diameters below 2 μm. Thus, their primary application is constrained to coarse particulates in the 10 μm mass median diameter (MMD) range or larger.

The concept of fractional particle size efficiency is valid when the characteristics of the inlet aerosol and the capture forces within the collector do not change. For example, once steady-state conditions relative to wall deposition and re-entrainment rates have been reached in cyclones, scrubbers or electrostatic precipitators, the size properties of the effluent aerosol will be nearly constant. It has been observed, however, that very large variations in inlet concentrations, ~ 100 times, lead to increased cyclone efficiency, due mainly to agglomeration effects in the peripheral zone.[5] Under these circumstances, enhanced collection of small (1 to 5 μm) particles is attained by agglomerative attachment to larger particles.

Various high porosity filters (bulk fiber and deep bed units) and even conventional woven or felted fabrics tend to exhibit relatively constant collection efficiencies for given particle sizes when inlet particle concentrations are low; e.g., order of ambient levels or less. After several months, however, dust accumulation on the fibers and within the pore structure will lead to increased interstitial velocities and projecting deposited particles will provide additional and more effective collection targets.

Under typical field conditions at dust loadings of the order of 1 grain/ft.^{3}, a few minutes dust accumulation changes completely the internal and superficial structure of the filter. During the course of a normal filtration cycle (from the start of filtration following fabric cleaning to termination of filtration immediately before cleaning), very great differences occur in filter effluent concentrations and particle size distributions. Thus, there is no way that one can assign any specific fractional particle size description to a fabric system. In the case of highly repetitive processes in which the inlet dust concentrations and the filtration cycles are constant, one can calculate average parameters to describe adequately the effluent characteristics. For example, fractional size parameters described by Harris and Drehmel[6] are based upon relatively lengthy (~ 2 hours) sampling periods of fabric filter effluent streams.

Data published by Whitby et al[7] give fractional size efficiencies for very low (< atmospheric dust level) concentrations for organic dye particles when filtered through "loaded" and "just cleaned" sateen weave cotton fabrics, Figure 2. Although Whitby's original presentation defines very clearly the limitations of these data, out-of-context interpretations have given the impression that fractional particle size efficiencies are readily available or calculable parameters. The experienced individual will recognize that Whitby's values apply uniquely to the specified dye aerosols, the dust deposits (fly ash or A.C. dust) on the filters, and the filter structure itself. Furthermore, the tests are not realistic since the inlet dust differs from that deposited previously on the filter and the inlet concentrations are several orders of magnitude lower than found for most industrial applications. Perhaps the most important conclusions to be drawn from Whitby's study are that a) fractional particle efficiencies in the 0.05 to 0.5 μm range are not strongly size dependent, and b) fractional particle size efficiencies may vary from 85 to 99.5% depending upon the weight and size distribution of the dust deposited on the filters.

OUTLET CONCENTRATIONS VS. FABRIC PROPERTIES

A recent report of EPA research[8] examines in considerable detail the base performance characteristics of more than 130 synthetic woven filter fabrics, principally Dacron but also including some Dacron/Nylon weaves. A resuspended coal fly ash was the principal aerosol although limited tests were performed with limestone and amorphous silica. The fabrics were light weight, ~ 4 to 5 oz./yd.^{2}, with many variations in warp and fill counts, mixes of multi-filament and staple fibers, permeability, and free area. Inlet fly ash concentrations and filtration velocities were 3 grains/ft.^{3} and 3 ft./min., respectively, while the cleaning was performed every 20 minutes by mechanical shaking. (4 cps for 2 minutes at 1-7/8 inch amplitude.)

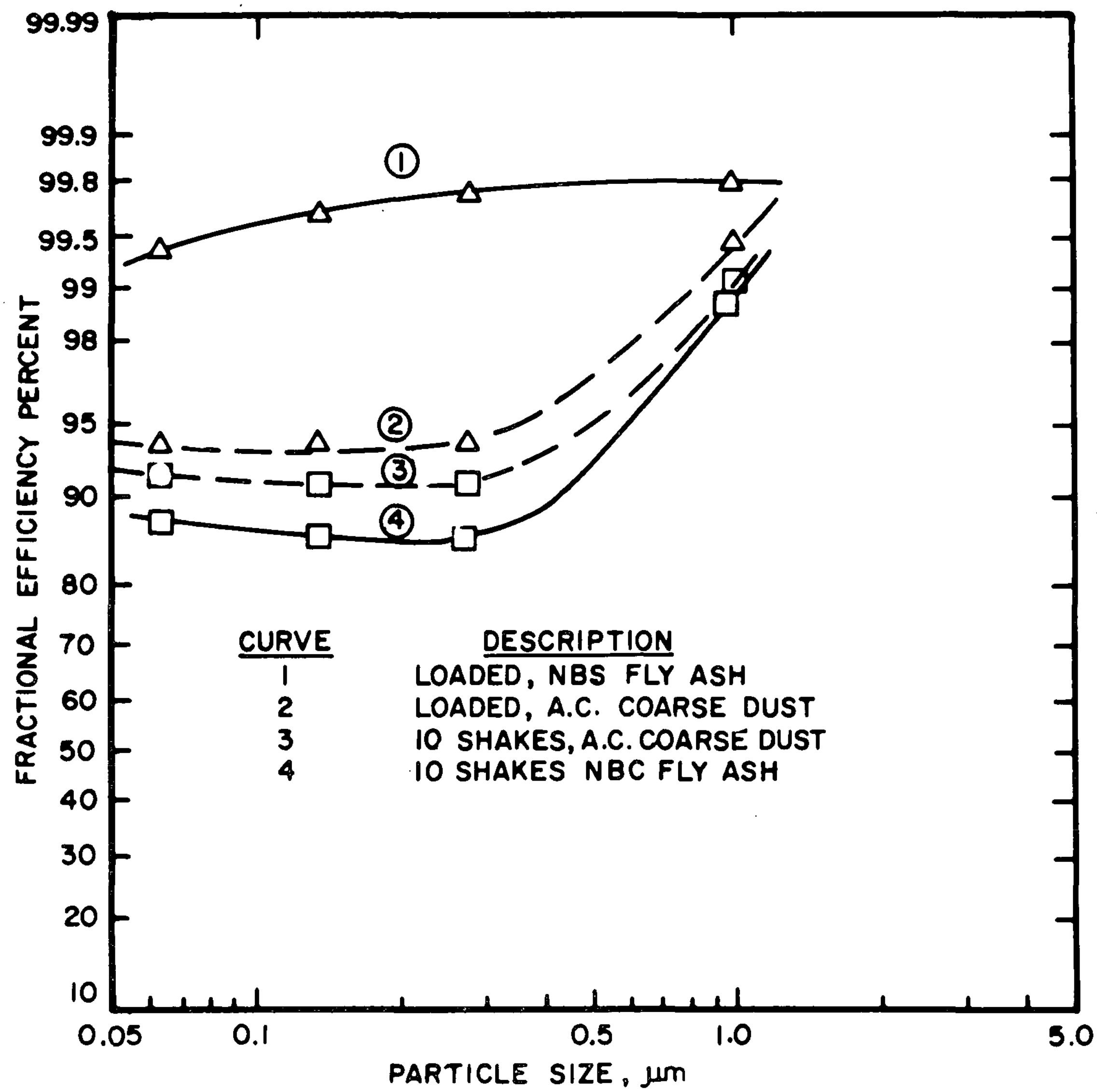

Figure 2. Fractional efficiencies, loaded and shaken sateen weave cotton filter media, a.c. coarse dust and NBS fly ash[7]

The outlet concentrations determined during the evaluation of several different fabric weaves have been plotted against the fabric free area in Figure 3. Free area is defined as the fraction of open or "see through" area with the line of sight normal to the fabric surface. In cases of high thread counts and flattened yarns, the calculated free area may sometimes have a negative sign, although zero was the lower limit used in EPA computations. Although many fabrics were described by the same free areas, there were often significant differences in thread count, yarn dimensions and construction, weave, and particularly in the effective residual drag, Se, observed during filtration tests. The latter variation in Se appeared to contribute significantly to the data point spread at low free areas.

Inspection of the regression line, Figure 3 , indicates that one should not expect to obtain high level particulate removal if the fabric possesses a high free area. Practically speaking, the broad lumping of filter structural parameters in Figure 3 does not permit a refined estimate of particulate emissions for the tighter fabric weaves. Furthermore, the dust being filtered also plays a major role in describing the concentration/ free area relationship shown in Figure 3 .

OUTLET CONCENTRATION VS. EFFECTIVE DRAG

Outlet concentrations shown in Figure 3 were also correlated with effective (residual) filter drag, the latter quantity based upon the filtration of fly ash as described in the previous section. As indicated in Figure 4, the data points associated with any drag level depict several fabric weaves, types of yarns, pore sizes and free areas. Generally, the spread in data points approximates that for the concentration/free area relationship with the free area differences accounting for the large dispersion of points at the higher drag levels.

Based upon the measurements presented in Figure 3 and 4 , one can deduce that the effective drag for specified dust and filter operating parameters

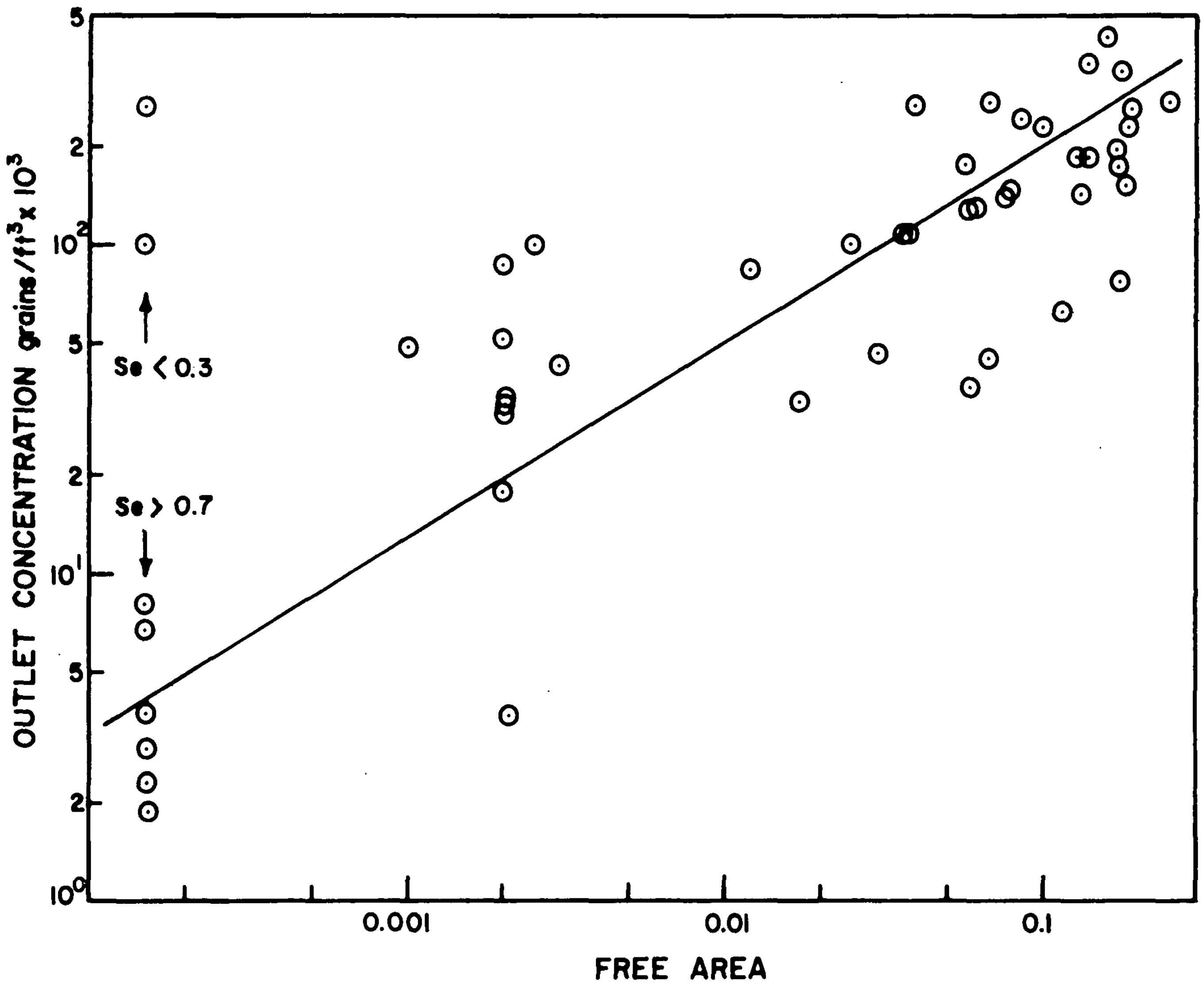

Figure 3. Outlet loading vs. free area. Woven Dacron nylon bags, fly ash filtration at 3 grains/ft^3 and 3 fpm [8]

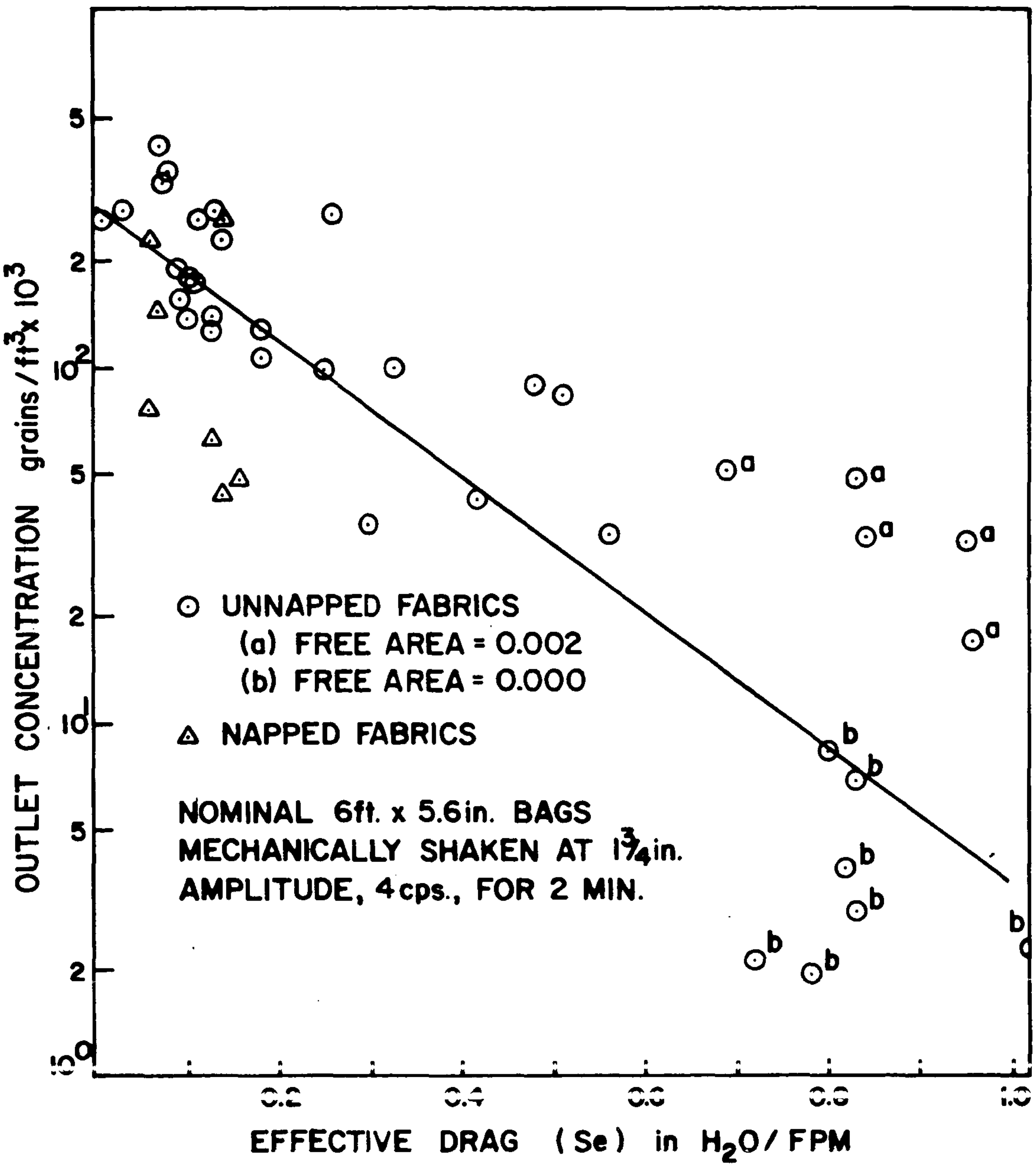

Figure 4. Outlet loadings vs. effective (residual) fabric drag woven dacron and nylon bags, fly ash filtration at 3 grains/ft^3 and 3 fpm [8]

must depend upon many factors in addition to free area. It can also be seen that the use of drag values alone for predicting outlet concentrations is no more precise than the free area approach.

Table 1 presents data excerpted from EPA studies[8] that indicate outlet concentrations, C_e, and specific resistance coefficients, K, for several

Table 1. FILTRATION PERFORMANCE FOR TWILL WEAVE DACRON FABRICS WITH VARIOUS TEST DUSTS

	Fly ash MMD = 3.7 μm		Limestone MMD = 18.5 μm		Amorphous silica MMD = 17 μm	
Fabric[a]	C_e[b]	K[c]	C_e[b]	K[c]	C_e[b]	K[c]
W 76 f F 82 f F.A. 0.001 P.D. 0-10	8.0	8.5	8.6	15.3	2.9	43.5
W 76 f F 73 s F.A. 0.0109 P.D. 17-35	84.0	11.0	4.5	14.0	2.9	33.2
W 76 s F 82 s F.A. 0.037 P.D. 50-60	106	3.2	11.4	11.5	1.5	27.2
W 59 s F 54 s F.A. 0.0198 P.D. ~ 100	261	1.1	142	4.9	272	18.4

[a] W76, F82 = warp and fill thread counts, f = continuous multifilament, s = staple, F.A. = free area, P.D. = pore diameter, μm.

[b] C_e = outlet conc., grains/10^3 ft.^{3}.

[c] K = spec. resist. coef. $\frac{\text{in. } H_2O \text{ (ft/min)}}{\text{lb./ft}^2}$.

dust/fabric combinations. Fly ash tests, which are also described in Figures 3 and 4 , show an increase in dust penetration as the filter free area and pore diameter increase. Outlet concentrations increase rapidly when the fabric pore diameter is of the order of 10 times the particle diameter. It is assumed that bridging is only partially completed when the ratio of pore to particle diameter is > 10 such that considerable dust penetrates the filter.[9] This concept appears quite reasonable when the outlet concentrations for limestone and silica are examined for pore diameters < 60 μm. Comparison of the latter measurements also points out that the characteristic size of the dust is not sufficient to estimate K values which are seen to be much higher for the amporphus silica.

The principal reason for presenting the Table 1 data is to emphasize the fact that the concept of a unique K value for a given dust or specified particle size is usually incorrect. Because emission characteristics and K values vary with respect to dust, fabric and dust/fabric combinations it is difficult to predict performance without prior field or laboratory tests. It is apparent, therefore, that more fundamental and applied measurements programs are required.

RECENT EXPERIMENTAL MEASUREMENTS

TEST PROCEDURES

As part of a fabric filter cleaning mechanisms study,[4] weight collection efficiencies and particle number concentrations were determined for several dust/fabric combinations and three common fabric cleaning procedures. The detailed results of this study will be presented in a forthcoming report. Although the background data given here are sufficient to describe the test systems, they do not reflect the complexity of the measurements nor the numerous instrument problems. Additionally, it is not recommended that the experimental findings be extrapolated to dust/fabric systems and operating conditions differing significantly from those reported here.

Test Fabrics

The filter bags evaluated in this study were readily available and commonly used commercial products. Bags used in mechanical shaking systems were sewn with a top loop for attachment to the shaker arm and a bottom cuff for connection with the thimble plate. Felted tubes used with the high pressure, pulse jet system were fabricated with a flat, closed bottom and a top cuff for clamping to the interior supporting cage. Basic bag specifications are given in Table 2.

Test Dusts

In this paper, test results are given for coal fly ash and commercial talc dust only. The size properties of the resuspended dusts as determined by Andersen impactor in the inlet air stream are given in Figure 5 . According to microscopic sizing of the dry powders when well dispersed in immersion oil, the MMD value of the fly ash was lower, roughly 3 μm. It was concluded, therefore, that the 90 psig compressed air used in the ejector-dispersor system was insufficient to break up all the agglomerates. Inlet dust concentrations, unless otherwise indicated, were usually in the range of 3.5 and 12 grains/ft.^{3}, respectively, for shaking and pulse jet systems.

Basic Testing Conditions

Air to cloth ratios for shaking and pulse jet tests as reported herein were maintained constant at 3.5 and 8.5 ft.^{3}/min. per ft.^{2} of fabric. Most measurements, except for woven fabric life tests, were performed with single bags and a total system gas flow ranging from 25 to 44 ft.^{3}/min. Gas temperature and relative humidity levels were held within the bounds

Table 2. DESCRIPTION OF FABRICS USED IN PARTICULATE EMISSION STUDIES

Filter fabric	Weight oz./yd.^{2}	Weave	Yarn count	Permeability	Application
Cotton	10	Sateen	95 x 58	13	Shaking
Cotton (napped)	10	Sateen	95 x 58	13	Shaking
Dacron^R	10	Plain	30 x 28 (staple)	55	Shaking
Dacron^R	10	1/3 Crowfoot	71 x 51 (filament)	33	Shaking or reverse flow
Dacron^R	18	Felt, needled		35	Pulse jet
Wool	16	Felted, no scrim (HCE treatment)		30 - 40	Pulse jet

Note: Woven fabrics - 10 ft. x 6 in., 10 ft. x 4 in. and 5 ft. x 6 in. bags

Felted fabrics - 6 ft. x 4.5 in. tubes

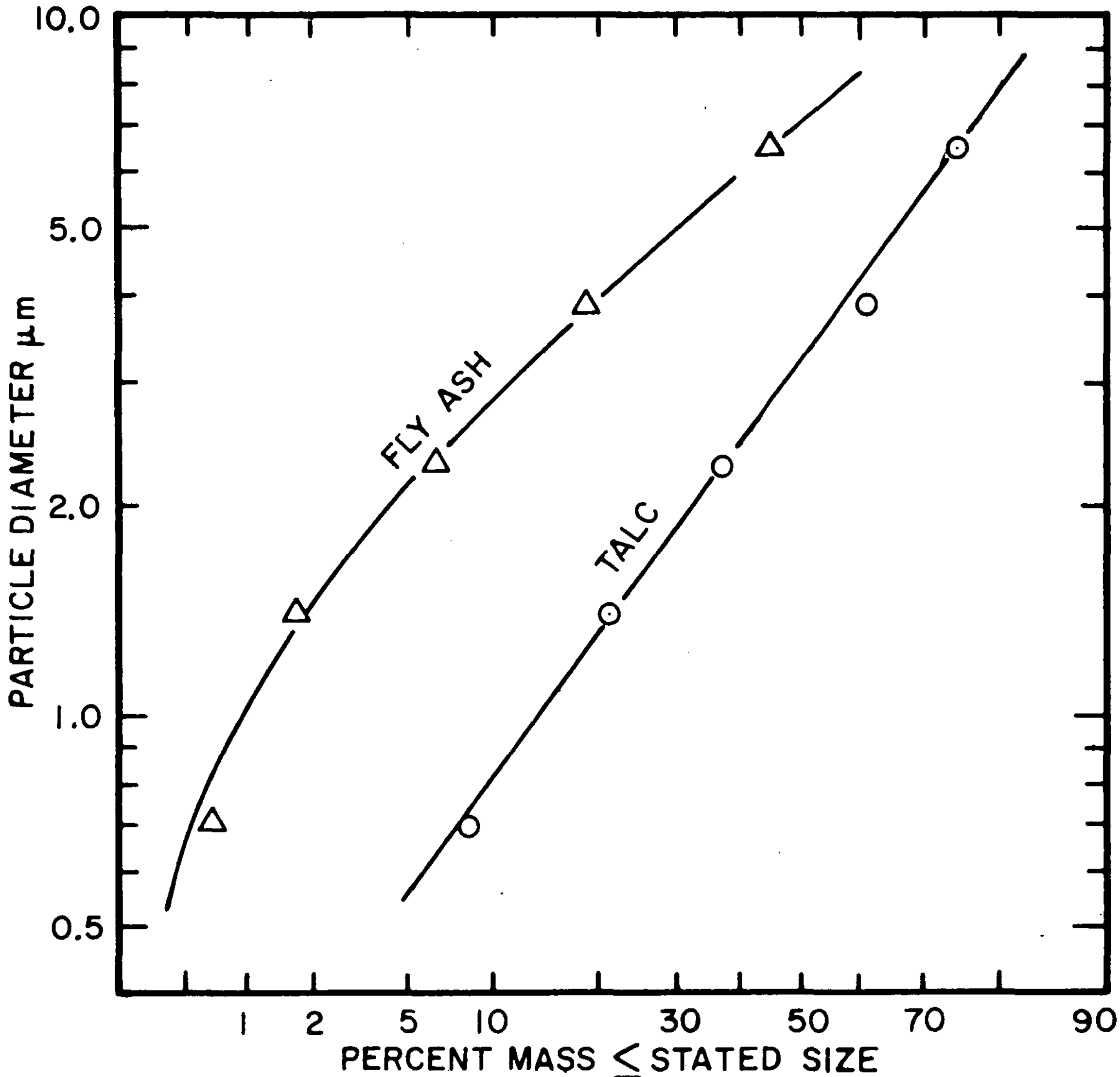

Figure 5. Comparative size properties for resuspended fly ash (coal) and talc by Andersen Impactor

of 70 ± 2°F and 40 to 50% R.H. Filter bags cleaned by mechanical shaking were operated for a 30 minute cycle with fly ash and a 20 minute cycle with talc to maintain similar resistance increases.

Cleaning Procedures

The mechanical shaking motion consisted of an essentially horizontal, harmonic displacement over a range of shaking amplitudes and frequencies of 1/2 to 2 in. and 4.3 to 11.4 cps. In a forthcoming report,[4] it will be shown that for a fly ash/sateen weave cotton system dust removal is a strong function of the acceleration, $\sim a^2$, imparted to the shaker bag for accelerations less than 4 g's. At greater g values, the dependency on acceleration is weaker, roughly $\sim a^{1/2}$, with an indication that there is a limiting acceleration beyond which no further useful cleaning is attained. The same study program[4] and prior tests reported by Walsh and Spaite[10] also point out that there are upper limits (~ 200) to the number of shakes needed to obtain effective dust removal. A 45 second shaking period was preceded and followed by a one minute settling interval while the filter flow was shut off. Pulse jet testing described here is limited to one basic cleaning system; i.e., 70 psig air pressure, a pulse frequency of one pulse per minute, and a pulse duration of about 0.06 second. By means of a supplementary damping tank, the wave form of the pressure pulse was altered in some tests to reduce the rate of pressure decrease when the pulse air was stopped.

Dust Concentration Measurements

Inlet dust concentrations were measured by one or a combination of dust feeder delivery rate, hopper dust recovery, filter samples or Andersen impactor measurements. Effluent concentrations from shaken bag systems were usually determined by Bausch and Lomb (B&L) single particle light scattering counter because of the very low concentrations. When filter performance was less effective (~ 99.9%) an RDM mass monitor* was used to determine the integrated mass concentration. The effluent gas stream from pulse jet systems was sampled with the RDM and/or the B & L sampler depending upon the purpose of the test. Even when effluent concentrations were in the 10^{-3} grains/ft.^{3} range, it was necessary to sample approximately 2 hours with the cascade impactors. Therefore, any calculated fractional efficiency values represent only average performance. Additionally, to have any predictive capability, it is also necessary that inlet loading conditions be constant or follow some fixed cyclical pattern.

There were both advantages and limitations to the sampling equipment cited above. The Andersen impactor could be used for both up and downstream size and concentration measurements (different sampling periods) when filter efficiencies were of the order of 99.9 to 99.99%. On the other hand, the B & L device was confined to downstream testing since extensive dilutions, ~ 10^4 times, would have been required to use it for upstream sampling. Because of its high degree of sensitivity and rapid response time, the B & L was a very useful device to track changes in particle size properties and number concentrations during a filtration cycle. Although the computation of downstream mass concentrations from B & L measurements required somewhat tenuous assumptions with respect to particle density and light scattering properties, comparisons with concurrent RDM measurements usually indicated agreement within a factor of 5. Although the B & L values were recongized to be low in many cases, their principal function was to indicate relative changes in concentration levels.

TEST RESULTS

A study of the factors that determine the overall effectiveness of various fabric cleaning methods has shown that filter effluent properties (concentration and size distribution) for a single dust/fabric system can

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*Single stage, cascade impactor with mass sensing by beta attenuation.

undergo extreme changes. As pointed out previously such variations are sometimes overlooked when filter systems operate at 99.5% or higher weight collection efficiency. In view of prospects for more stringent emission standards, however, it is essential that the filter effluent be characterized along with those parameters defining operational and power requirements.

The data presented in this paper involve only a small fraction of the tests performed to identify and investigate the physical mechanisms responsible for dust removal in shaken bag and pulse jet cleaning systems. The results are considered to furnish a good index of <u>single</u> bag field performance under the stated cleaning conditions and for similar fabrics and dusts having the same basic properties of coal fly ash or industrial talc. It should be remembered, however, that most large filter units operate as multi-chamber systems with sequential compartment cleaning. In the case of single compartment pulse jet systems, the tubes (or other filter medium configurations) may be sequentially cleaned as individual or groups of tubes. The net result is that the integrated effect on filter drag, total gas velocity distribution, and particulate emissions for multi-chamber units must be developed in accordance with procedures suggested by Robinson et al,[11] Walsh et al[12] and Spaite et al.[13] Analyses of the above approaches and many other concepts by Billings and Wilder[9] indicate that the success of such predictions depends upon the availability of specific performance information for the dust/fabric combination of interest. In the absence of such base line data, the particle concentration and size results described in this section may be used to predict relative but not <u>absolute changes for filter media and aerosols not</u> included in the study.

The experimental results described in this section suggest that the particulate emissions from a filter can be attributed to some combination of the following sources:

a. Inlet dust that because of its small size, passes directly through the filter, usually in progressively smaller amounts as the filter pore structure becomes plugged.

b. Dust that migrates through the filter by successive deposition and re-entrainment under the combined effects of aerodynamic and mechanical (vibrational) forces. Such dust penetration is often referred to as "seepage" in commercial parlance. It may be more pronounced in the case of multi-filament yarns, spherical or smooth surfaced regular particles, and in the absence of electrostatic or other forces enhancing adhesion or cohesion.

c. Dust dislodged from the shaken fabric during cleaning that has penetrated to the clean air region. Resumption of air flow flushes out the clean air side of the system, often producing a visible puff of dust.

d. Dust loosened during the cleaning process whose bonding to the fibers or interstitial dust structure is not sufficiently strong to resist the combined dislodging forces (aerodynamic and mechanical flexure) when system air flow is resumed.

Although it appears difficult to weigh the relative importance of the above sources, it is suspected that items c and d may account for a large fraction of the total mass emission, probably in the form of a few large particles, whereas items a and b are responsible for the discharge of most of the submicron material.

Based upon the relationship between adhesive and/or cohesive forces and particle size; it appears that particles collected singly on the filter surfaces will most likely be dislodged in the form of agglomerates. One could conceive of the extreme case where a freshly generated fume composed of particles less than 0.5 μm could very readily produce a filter effluent composed of much coarser particles despite a high overall mass collection efficiency.

Mechanical Shaken Systems

Several experiments were performed with unnapped, cotton sateen bags (10 ft. x 6 in.), Table 2 to determine filtration parameters for a fly ash aerosol. During these tests, filtration velocity and inlet dust concentractions were held constant at about 3.0 ft./min. and 3.5 grains/ft.^{3}, respectively. The bags have been described as new (N) since each had experienced less than 10^4 individual shakes. They were essentially at equilibrium, however, with respect to air flow/resistance data for repetitive filtration cycles. The main variables for the above tests were shaking amplitude and frequency as shown in Table 3. The filtration interval was 30 minutes and 360 shakes were used in all tests.

The effect of amplitude and frequency variations on outlet mass concentration (and % penetration) is shown in Figures 6 and 7. Emissions decreased by as much as 5 orders of magnitude over the first 5 minutes of filtration. The sensitivity limit of the B&L counter allowed for no estimates of number concentrations less than 150 particles/ft.^{3} nor derived mass concentrations less than 10^{-9} grains/ft.^{3}. Approximately 90% of the dust emission took place during the first minute of filtration and the average concentration for the 30 minute filtration period (10^{-6} to 10^{-5} grains/ft.^{3}) was about 30 times lower. Average dust emissions were shown to increase significantly (order of 30 times) for the amplitude range 1/2 to 2 in. but were essentially unchanged with respect to frequency variations.

The filtration of ambient air* showed a more pronounced increase in outlet concentration over the complete 30 minute cycle with 2 in. amplitude shaking, Figure 8. It is interesting to note that the average emission for 30 minutes, however, was about the same as that for fly ash, Figure 9.

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*Inlet loading defined as room air when dust feeder was turned off. In fact, some fly ash deposited in the inlet piping was probably resuspended when the air flow was resumed.

Table 3. COLLECTION EFFICIENCY AND EFFLUENT CONCENTRATIONS FOR VARIOUS SHAKING SYSTEMS[a]

Shaking system		Average effluent concentration - grains/ft^3				Shaking tension (lbs.)	Fabric[d] dust holding (grains/ft^2)
		Fly ash filtration[b]		Ambient air filtration[c]			
cps	Ampl. (in.)	First minute	30 Minutes	First minute	30 Minutes		
7.5	2	3×10^{-4}	1×10^{-5}	2×10^{-4}	2×10^{-5}	10.7	200
7.5	1	3×10^{-5}	1×10^{-6}	2×10^{-5}	1×10^{-6}		300
7.5	1/2	1×10^{-6}	3×10^{-7}	1×10^{-5}	3×10^{-7}	3.5	410
4.3	1	1×10^{-4}	3×10^{-6}	2×10^{-4}	1×10^{-6}	4.8	420
7.15	1	5×10^{-5}	2×10^{-6}	2×10^{-5}	1×10^{-6}		290
11.3	1	5×10^{-5}	2×10^{-6}	2×10^{-5}	1×10^{-6}	7.5	200

[a]360 shakes per cleaning cycle, sateen weave, unnapped cotton bags. New, $< 10^4$ shakes.

[b]Fly ash, 3.5 grain/ft^3.

[c]Ambient air $\sim 10^{-4}$ grains/ft^3.

[d]At resumption of filtration.

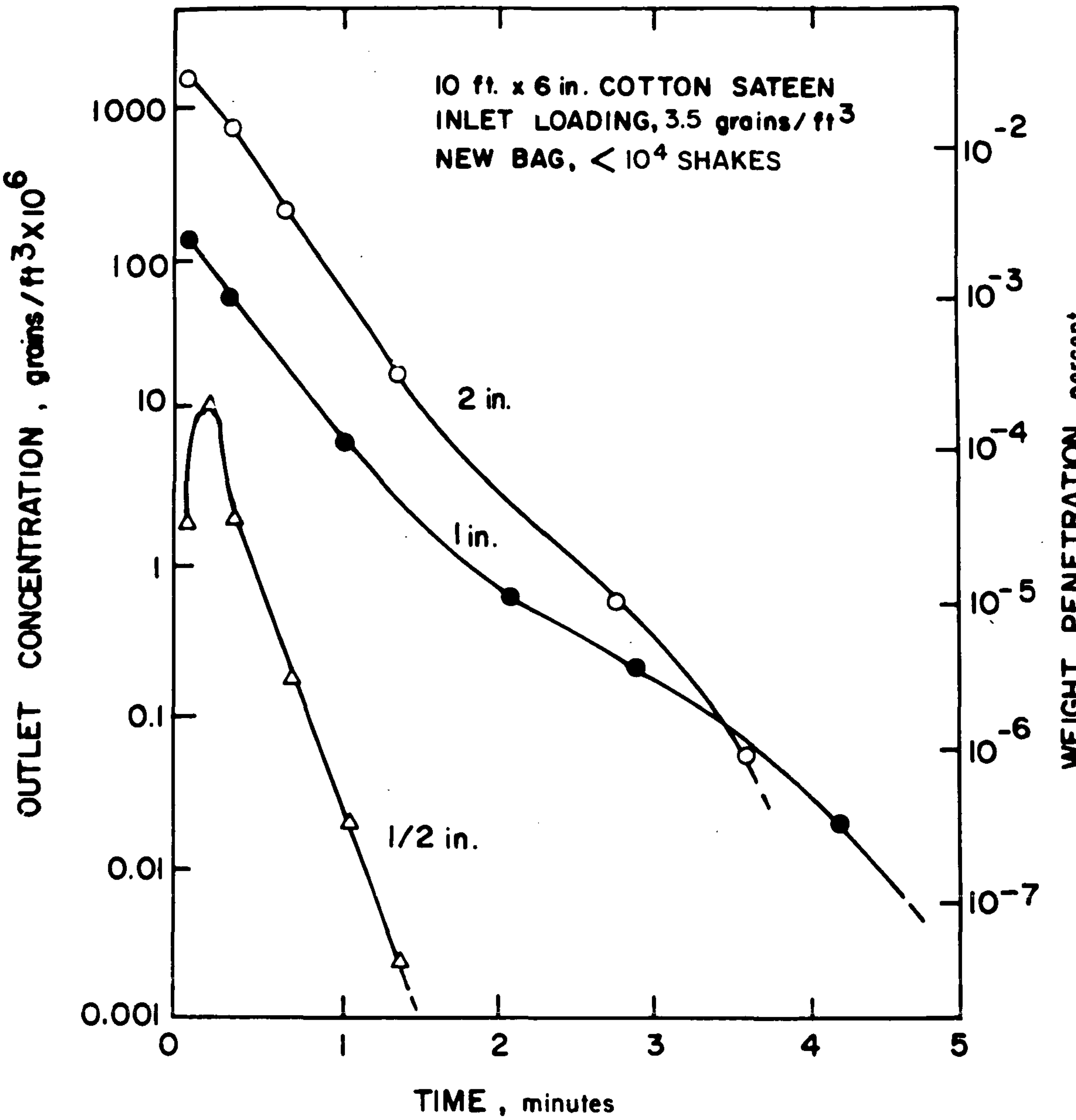

Figure 6. Penetration versus shaking amplitude at constant frequency (7 cps)

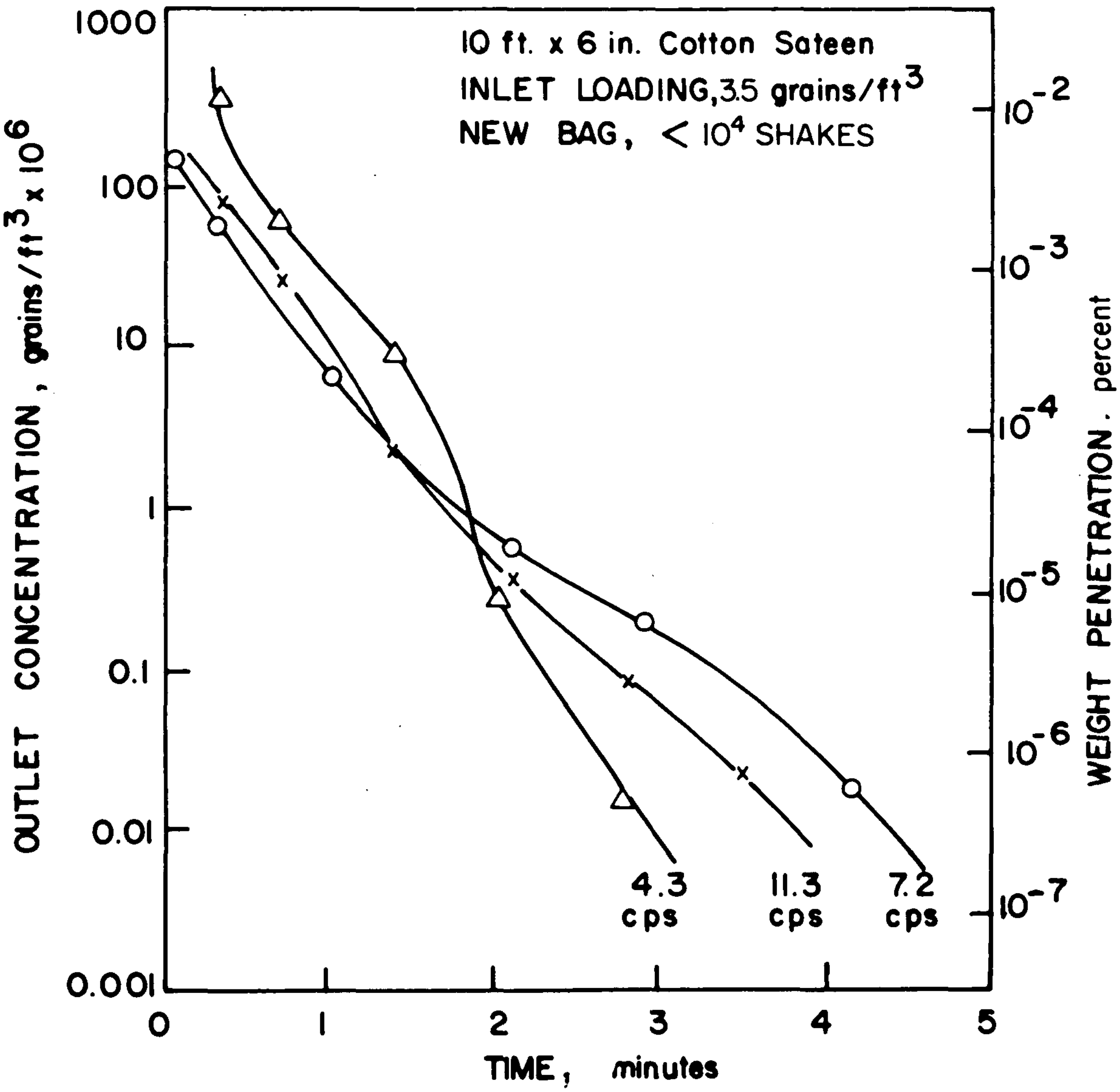

Figure 7. Penetration versus shaking frequency at constant amplitude (1 in.)

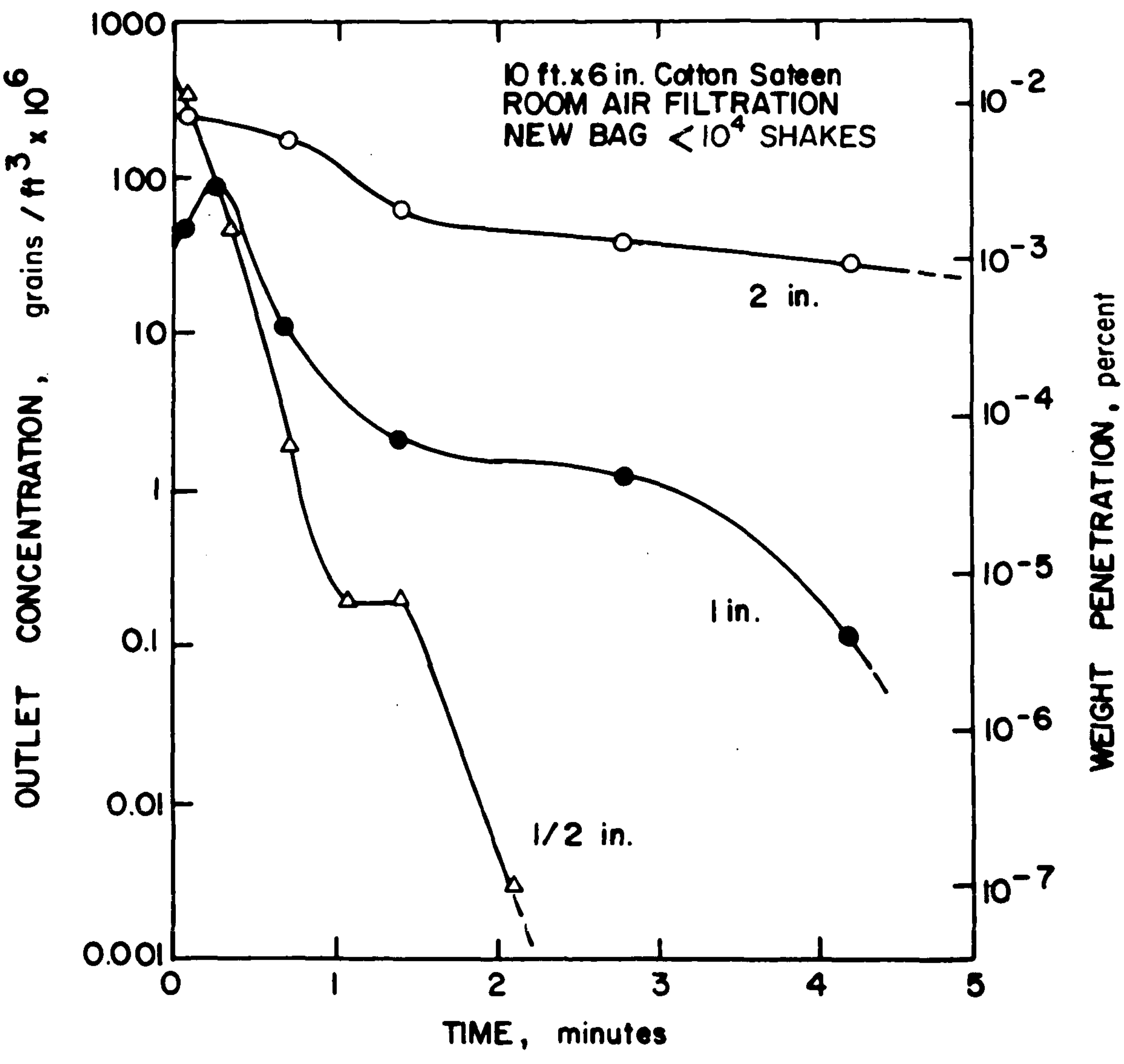

Figure 8. Atmospheric dust penetration versus shaking amplitude at constant frequency (7.5 cps)

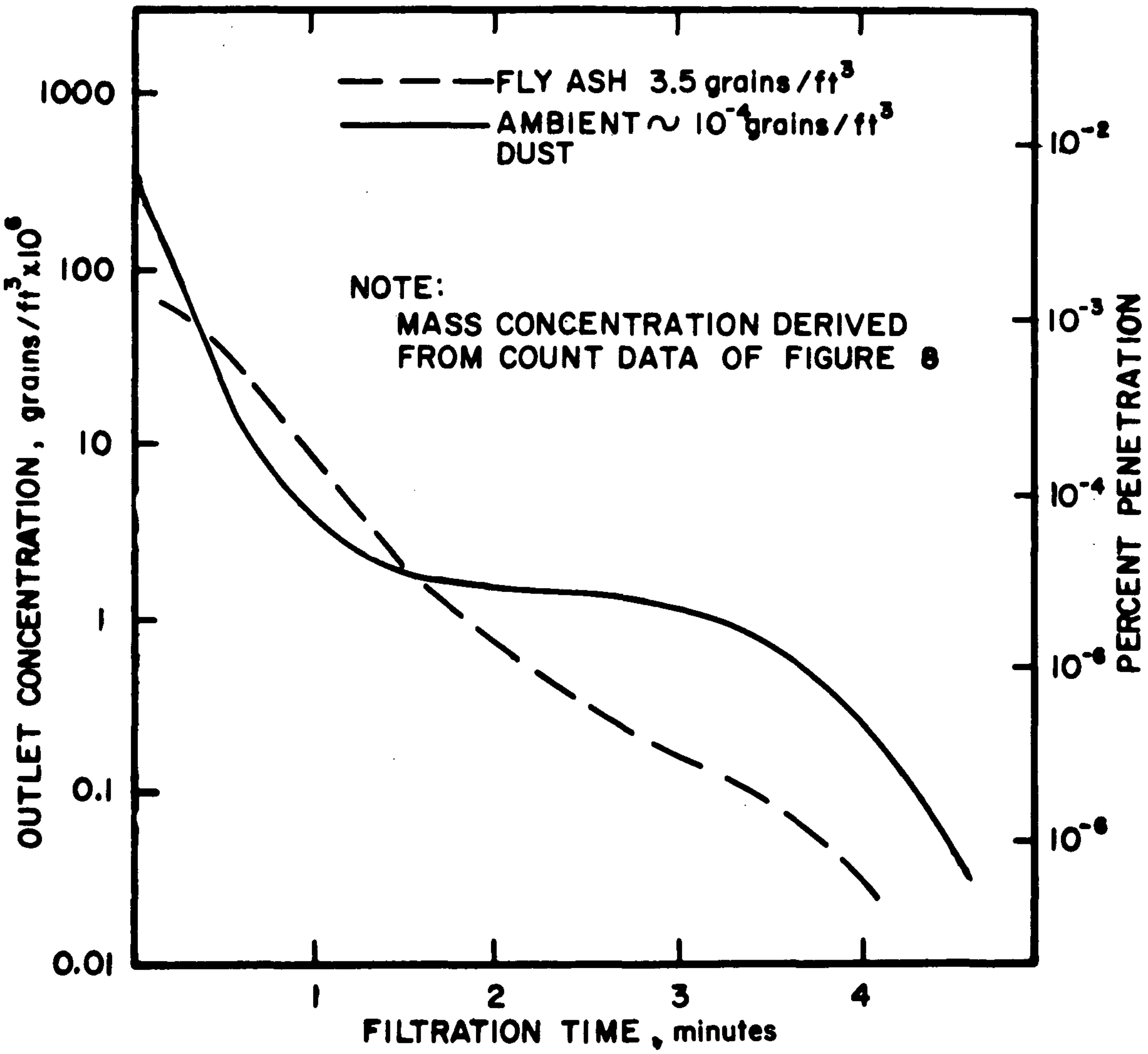

Figure 9. Decreased in outlet mass loadings with increased filtration time for low and high inlet concentrations

The above comparison applies to a shaking system using 360, 1 in. amplitude shakes at 7.2 cps. This finding appears to support field data presented in Figure 1 that show nearly constant outlet loadings for a fixed filter type (and dust) regardless of inlet load levels.

Figure 10 shows how particle number concentrations varied with respect to filtration time based upon B & L measurements. Mass concentrations at specified times were computed from these data by assuming a specific gravity of one and using the arithmetic average of diameters for each size range.* Although one does not expect this calculation process to be very accurate, the outlet concentration and penetration values for the pilot plant fly ash/sateen weave cotton system fall on the Figure 1 regression line for foundry dust/sateen weave cotton measurements.

Inspection of Figure 10 indicates that the discharge of particles > 1 μm is restricted to the first few minutes of filtration thus explaining the very rapid decrease in outlet mass concentrations.

Accelerated shaking of cotton bags in conjunction with periodic fly ash dust loading and 30 minute filtration tests was carried out with sateen weave cotton bags to simulate probable performance changes over extended periods of use. After 20×10^6 shakes, it was postulated that a bag had seen the field equivalent of 3 to 5 years service. Average 1 and 30 minute outlet concentrations are shown in Table 4 for bags shaken at two tension levels, one fairly taut at 3.1 lbs. and the other installed at near slack conditions, 1.3 lbs. Surprisingly, the increases in average emission levels were relatively small, roughly a one- to twofold increase after 20×10^6 shakes. At the same time, the bags shaken at the higher tension showed consistently higher (about 1 to 2 times) outlet concentrations for both abbreviated and extended shaking.

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*0.3 to 0.5 μm range, $\bar{d}$ = 0.4 μm
0.5 to 1.0 μm range, $\bar{d}$ = 0.75 μm.

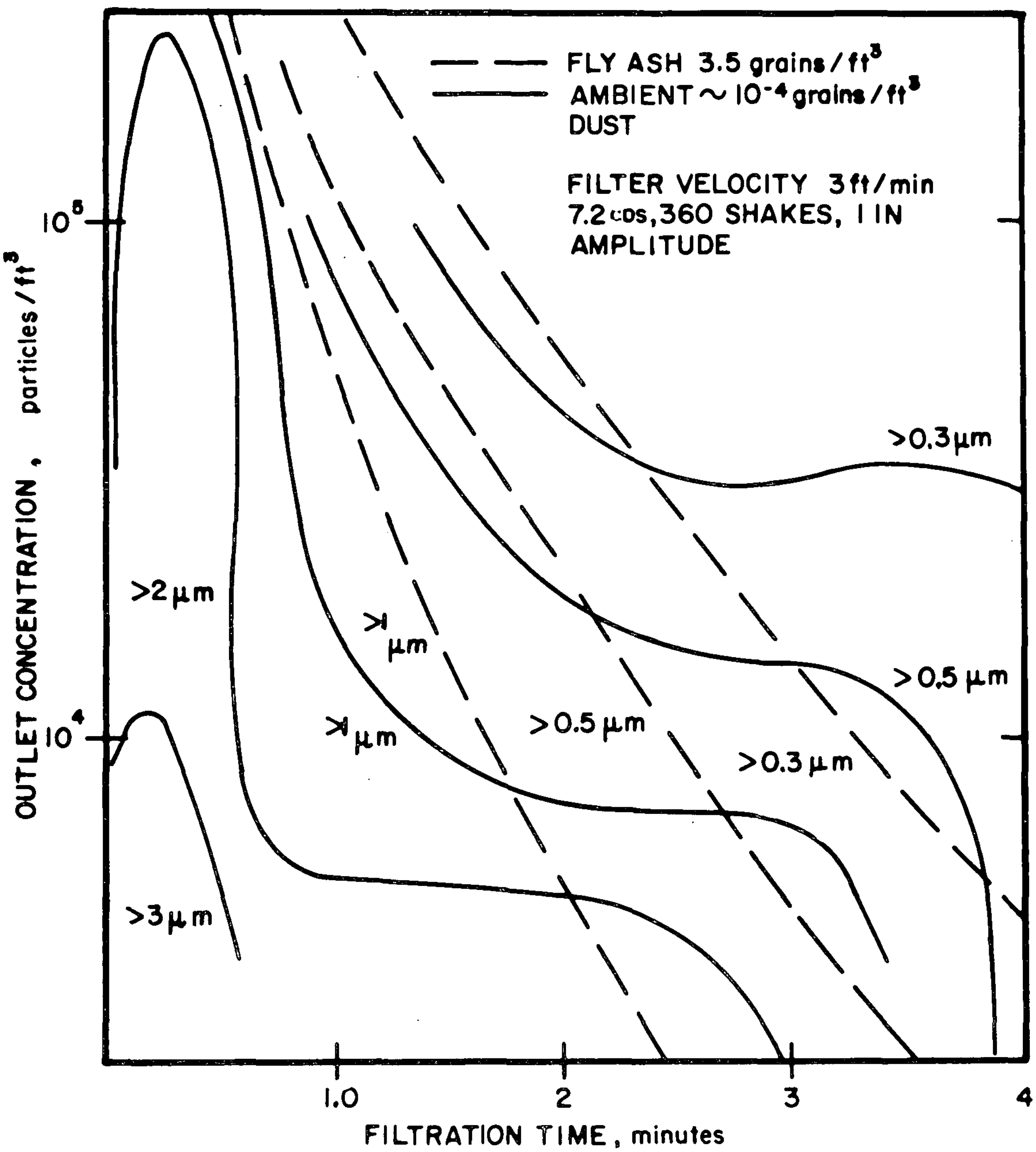

Figure 10. Variation in outlet loadings (number and size basis) for shaken cotton sateen bags (no nap - B and L size measurements)

Table 4. FLY ASH EFFLUENT CONCENTRATIONS VS. NUMBER OF SHAKING CYCLES FOR 1 AND 30 MINUTE AVERAGING PERIODS, UNNAPPED COTTON SATEEN 10 FT. X 6 IN. BAGS, 3.5 GRAINS/FT^3 INLET LOADING, 3 FPM FILTER VELOCITY

Number of[b] shaking cycles	Average effluent concentration - grains/ft^3 x 10^6 [a]			
	Taut bag[c]		Loose bag[d]	
	First minute	30 Minutes	First minute	30 Minutes
6×10^6	750	25	250	8.7
10×10^6	750	25		8.3
15×10^6	500	17	350	12
20×10^6	900	30	450	15

[a]Measurements made after loading filter to ~ 700 grains/ft^2, and then cleaning.

[b]Shaking cycle 8 cps, 1 in. ampl. 360 shakes.

[c]Static tension = 3.1 lbs., shaking tension 6.5 lbs.

[d]Static tension = 1.3 lbs., shaking tension = 4.5 lbs.

Size distribution curves were constructed from B&L data of the type shown in Figure 11. These data, Figure 11, show that the dust discharging from the filters was composed of relatively coarse material during the earlier phases of filtration. After 3 minutes, however, the outlet dust size properties were reduced to approximately those of atmospheric dust as determined by light field microscope.

The filtration characteristics of fly ash were also studied with napped sateen weave cotton, plain weave Dacron and crowfoot weave Dacron, Table 5. These comparisons were made at a 3.5 grains/ft.^{3} loading, 3 ft./min. filtration velocity, and a 30 minute filtering period. The cleaning cycle consisted of 360, 1 in. amplitude shakes at 8 cps. Changes in outlet concentration with time were again computed from B&L counter

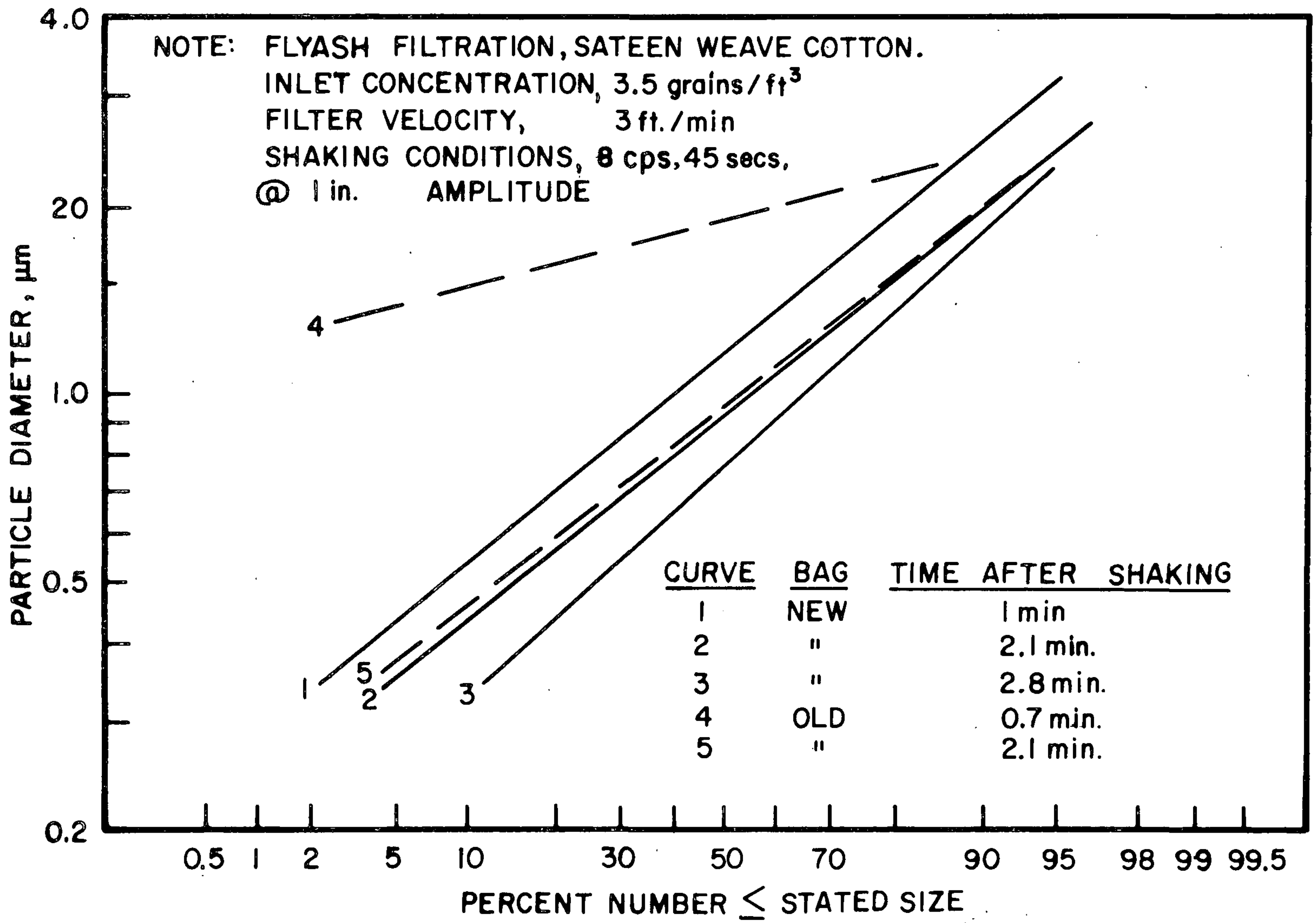

Figure 11. Changes in effluent size properties with filtering time for new (< 10^4 shakes) and old (2×10^7 shakes) bags (Sizing by B and L optical counter)

Table 5. FLY ASH FILTRATION CHARACTERISTICS FOR NEW (< 10^4 SHAKES) AND WELL-USED (2×10^7 SHAKES) BAGS

	Fabric type[a]							
	Plain weave Dacron		Crowfoot Dacron		Napped cotton sateen		Unnapped cotton sateen	
	N	U	N	U	N	U	N	U
Residual drag in H_2O/fpm	0.17	-	(0.37)[b]	(0.02)	(0.20)	(0.53)	0.47	(0.60)
Effective residual drag in H_2O/fpm	(0.35)	0.30	0.43	0.47	0.23	0.67	0.67	(0.73)
Terminal drag in H_2O/fpm	(0.81)	0.73	1.12	1.11	0.82	1.17	1.24	1.41
Dust collected[c] per cycle grains/ft^2	278	255	288	275	295	312	284	290
Residual dust grains/ft^2	207	113	92	73	449	336	413	375
% Dust removed[d] by shaking	57	69	76	79	40	48	41	41

[a] 10 ft. long x 6 in. diam. bags, N = new, U = well used.

[b] Parentheses indicates estimated values.

[c] Inlet loading - 3.5 grains/$ft.^3$, filter velocity - 3 fpm, 30 min. filter cycle.

[d] Cleaning cycle - 360 shakes, 1 in. amplitude, 8 cps.

measurements. Reference to Figure 12 shows that measurable effluent concentrations for both types of Dacron media persisted throughout the 30 minute filtration interval. In contrast to sateen weave cotton, the 1 minute and 30 minute concentrations were not appreciably different (2 to 5 times) and the average outlet concentrations over the full 30 minute filtering cycle were about <u>1000 times</u> higher. In terms of weight collection efficiency, the average values for the Dacron bags were about 99.8%.

Average outlet dust concentrations were compared with the filter residual holdings at the resumption of filtration. The differences in residual dust holdings (expressed as grains per $ft.^2$ of fabric) resulted from experimental variations in the shaking method, type of dust and type of fabric.

According to Figure 13, the amount of dust retained by the fabric matrix after cleaning plays a significant role in determining dust retention. It may be inferred that the pore sealing process is more nearly complete for cotton media than for the Dacron weaves. It should also be noted that whereas the differences in filter resistance indicated that fan power requirements would be about 25% higher for cotton fabrics when treating identical gas streams choice of the cotton would reduce particulate emissions by roughly 1000 times. When emission data for similar talc filtration studies were adjusted for deposit bulk density (roughly 4.5 times lower than fly ash) they too fell on the same regression line. Since the residual dust holdings for talc were about 4 to 5 times lower than the fly ash levels, it appears that talc is more readily dislodged from the fabrics and also that a more permeable filter media should result. However, on the premise that the higher specific volume of the talc requires 20 to 25 percent as much to fill a given pore, the dust retention properties shown in Figure 13 appear reasonable. In effect, it is assumed that it is the volume and not the mass of dust within the pores that controls the emission characteristics.

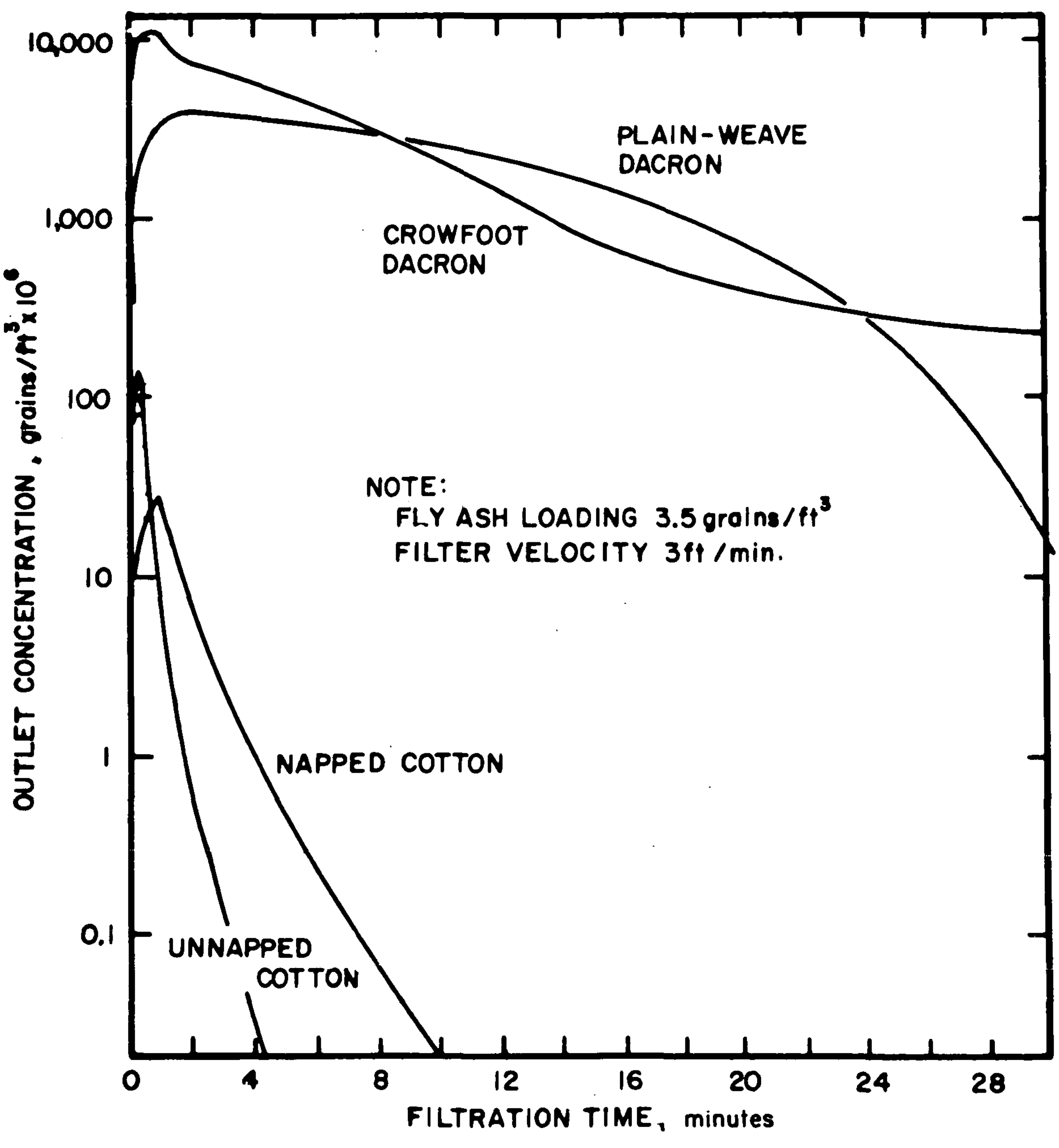

Figure 12. Fly ash emissions for various filter media cleaned by mechanical shaking; 30-minute filter cycle, new bags, less than 10^4 shakes (based on optical counter measurements)

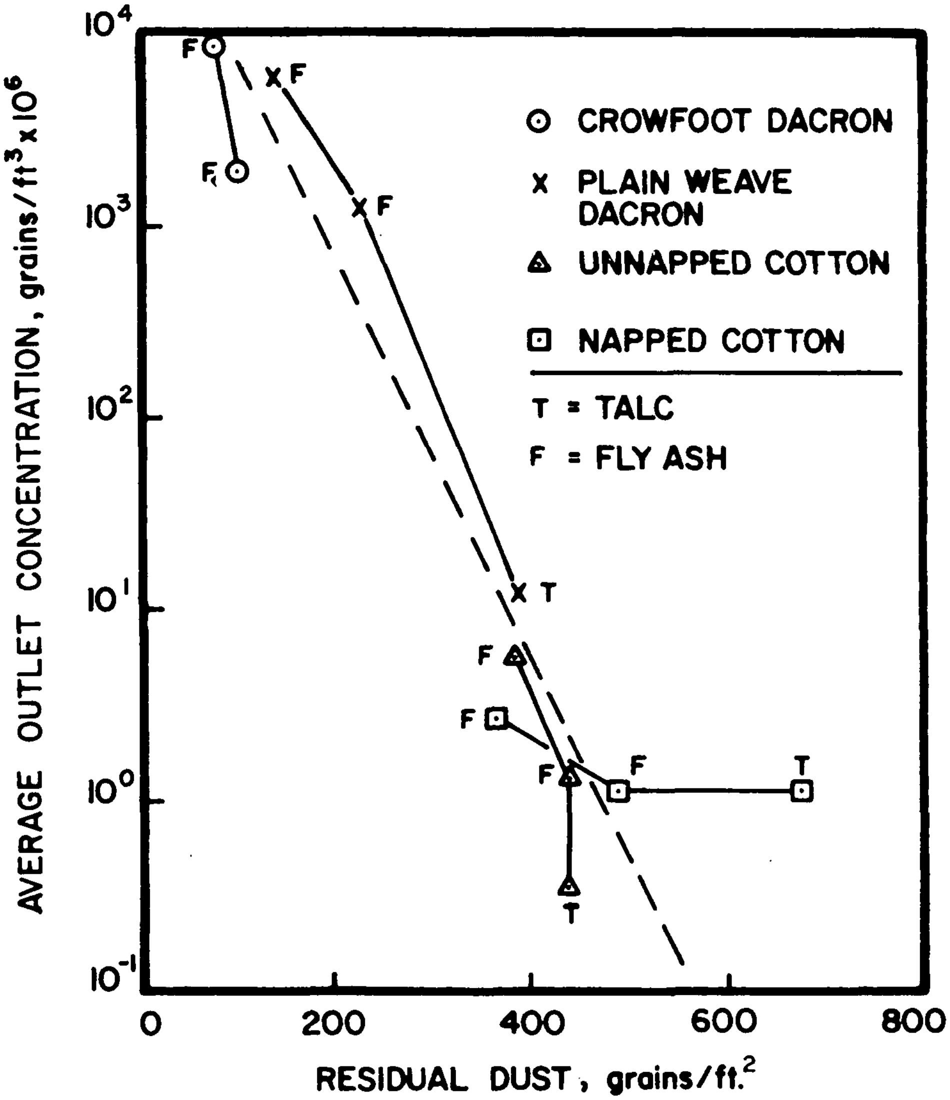

Figure 13. Average outlet concentration vs. residual dust holding

The result of EPA studies summarized in Figure 4 show a similar relationship between outlet concentration and effect drag. It should be noted, however, that the effluent concentrations from the 10 oz./yd.^{2} media (Dacron or cotton) are about 500 to 1,000 times less than those for the 4.5 to 5 oz./yd.^{2} fabric forming the basis for the Figure 4 data. One may conclude, therefore, that fabric aereal density as well as filter drag, free area, and residual dust holding must also be considered in forecasting filter behavior.

Pulse Jet Systems

The results of pulse jet cleaning studies cannot be extrapolated directly to field applications because measurements were made with a single tube system. As with any large compartmented units the resultant effluent from several tubes undergoing sequential cleaning should be cleaner than that from the most recently pulsed tube. A precise definition of the field effluent depends upon the fraction of tubes cleaned at any one time, the apportionment of gas flow among all the tubes in the system, and the effect of the pulse jet parameters on particulate emissions.

The pulse jet tests described in this section involved the following variations in cleaning parameters:

Pulse jet pressures - 40 to 100 psig (direct and damped)
Pulse duration - 0.06 second
Pulse interval - 1 minute

Direct pulses were the result of the direct venting of compressed air from the reservoir tank to the bag exit region. Damped pulses were produced by placing a dead end expansion tank in the line such that a more gradual decrease in pressure took place within the bag when the solenoid valve was closed. In both cases, the rate of pressure rise and the maximum reverse pressure were the same. All tests reported here were made with fly ash and wool or Dacron felt tubes at inlet dust loadings ~ 12 grains/ft.^{3} and an inlet velocity of 8.5 ft./min.

Average outlet concentrations for fly ash filtration are shown in Figure 14 for direct and damped pulses at varying reservoir pressures.

Outlet concentrations for direct pulse systems were significantly higher than those with damping. High speed photography showed that bag deflation in the absence of damping took place with a sharp, snapping motion in the direction of normal filter flow. Thus, both the return air flow and the bag acceleration acted in concert to increase the penetration of any agglomerates loosened by the initial pressure shock. Absolute outlet concentrations were about 1000 times greater than those determined for shaken cotton bags.

The minimum operating resistance after cleaning varied inversely with pulse jet reservoir pressure, Figure 15. The 20 percent higher resistance levels associated with damped pulses are presumed to result from a higher residual dust holding. The approximately fourfold reduction in outlet concentrations, however, may represent an advantage despite the higher minimum and average resistance values.

Changes in particle number and mass concentrations are shown in Figure 16 for typical fly ash filtration tests with the pulse jet system. It can be seen that the same trends noted previously for mechanically shaken bags; i.e., a rapid tailing off in the penetration of dust particles as the filtration continued, was also exhibited by the pulse cleaning process. Although the highest number concentrations were noted during the first 20% of the cycle, the initial mass concentration was seldom more than 2 to 5 times the average outlet concentration. These results suggest that a brief, ~ 1 minute, filtering period is insufficient to permit any extensive pore blockage.

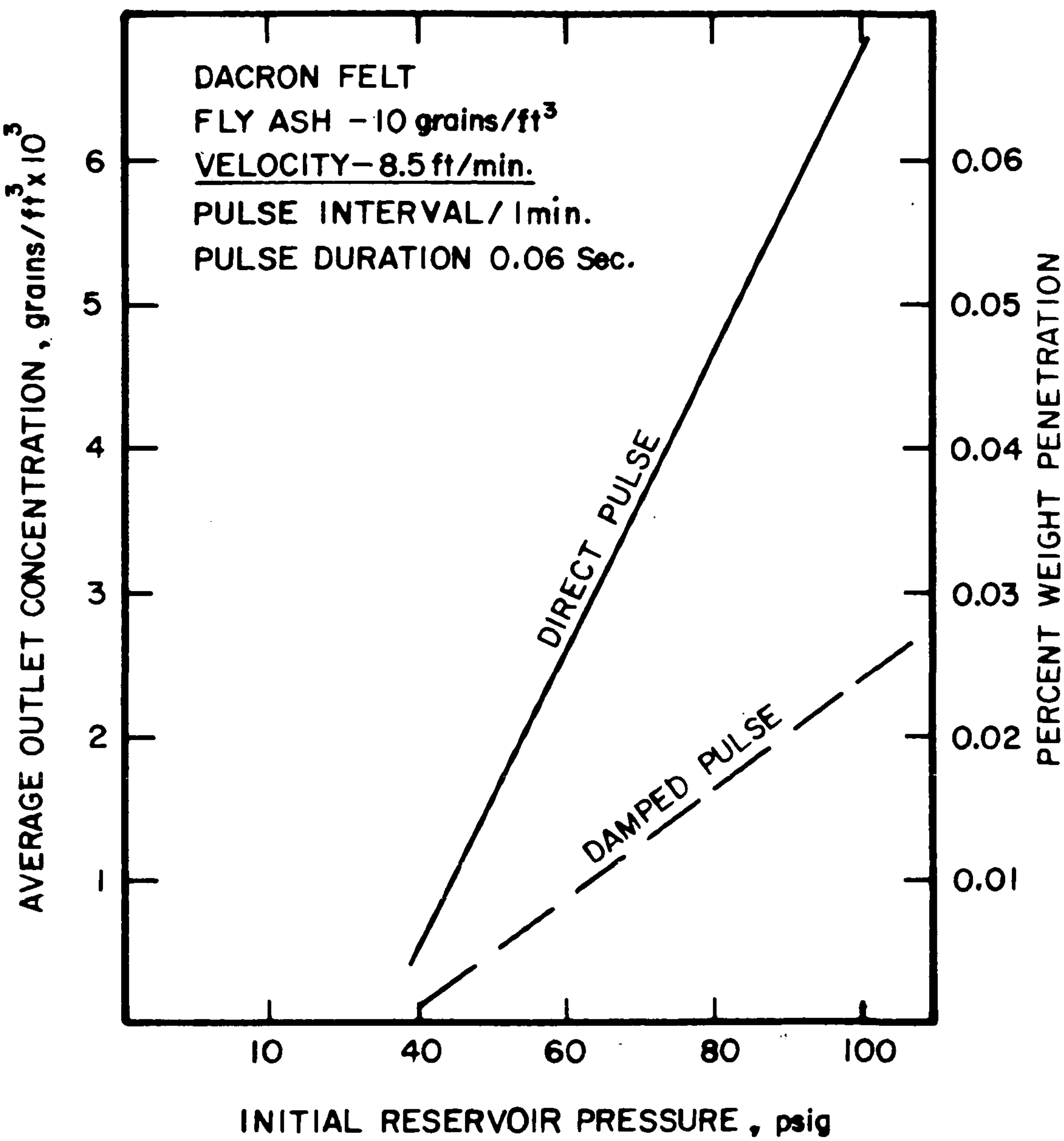

Figure 14. Dust emissions for fly ash versus pulse intensity and pulse wave form

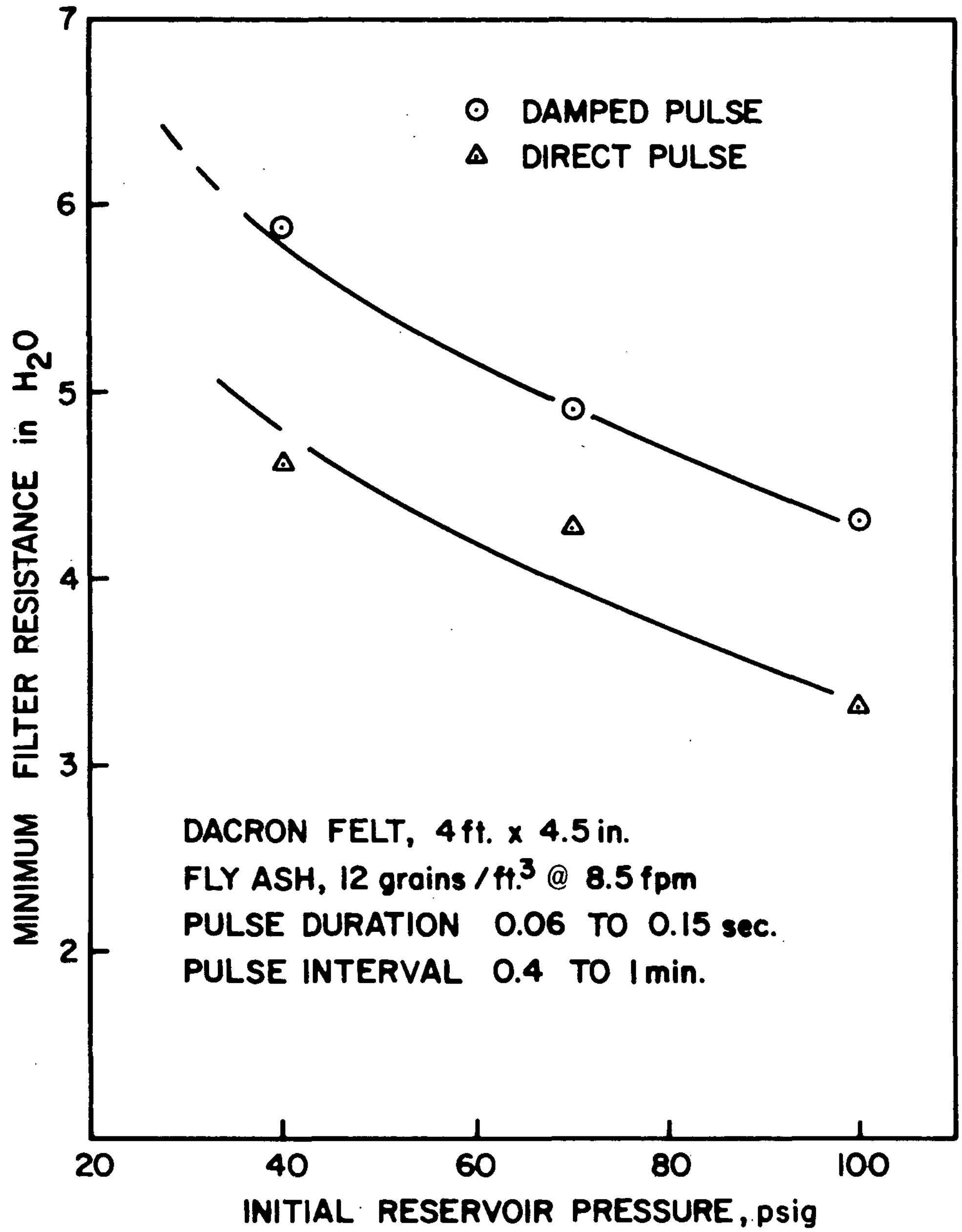

Figure 15. Pulse jet pressure vs. minimum bag resistance for direct and damped pulses

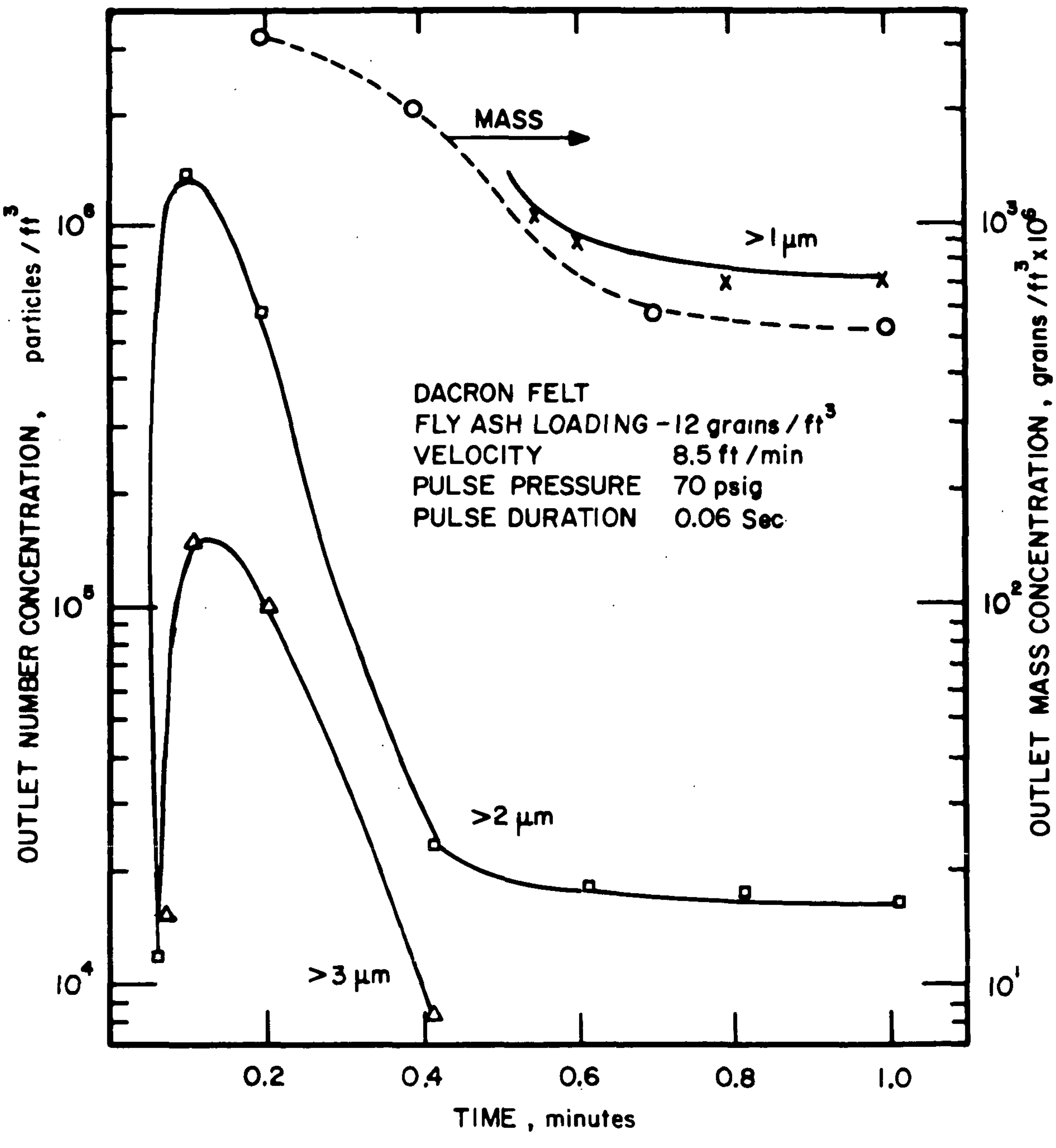

Figure 16. Variations in particle number and mass concentration versus diameter and time

Because of the much higher effluent concentrations, it was seldom possible to make B & L measurements for particle diameters less than 1 μm due to choking in the fine particle channels of the B & L. Under these conditions, erroneously low estimates of number concentration were expected. With a few exceptions, however, there appeared to be a constant ratio (~ 5/1) between B & L and RDM or Andersen impactor mass measurements. As pointed out previously, the relative and not the absolute values of the B & L measurements were the primary considerations in this study.

Comparative outlet concentrations (number basis) are shown in Figure 17 for direct and damped pulsed systems and wool and Dacron felts.

In accordance with the higher outlet concentrations (mass basis) observed for the direct pulse system, higher outlet concentrations were also indicated for particle sizes greater than 3 μm, Figure 17. Presumably, it is the large size fraction that accounts mainly for the increased penetration. The limited data presented here show no significant differences between Dacron and wool felt performance.

A comparison of up- and downstream Andersen impactor measurements in Figure 18 shows that the average effluent aerosol is actually slightly coarser than that entering the system. No rules of filtration are contradicted by these results. The downstream particulate is composed largely of agglomerated material loosened by the high energy pressure pulse and driven to the clean air side of the felt by a combination of fabric acceleration and normal air flow. It is emphasized that the effluent from a multi-tube system would probably show a finer downstream particulate in almost all instances since the majority of the coarse particles are associated only with the most recently pulsed element.

These data should not be interpreted to mean that effluent dust from pulse jet collectors is always larger or the same size as that entering the collector. Figure 18 information relates specifically to the dust/fabric combination studied and the indicated operating and cleaning parameters.

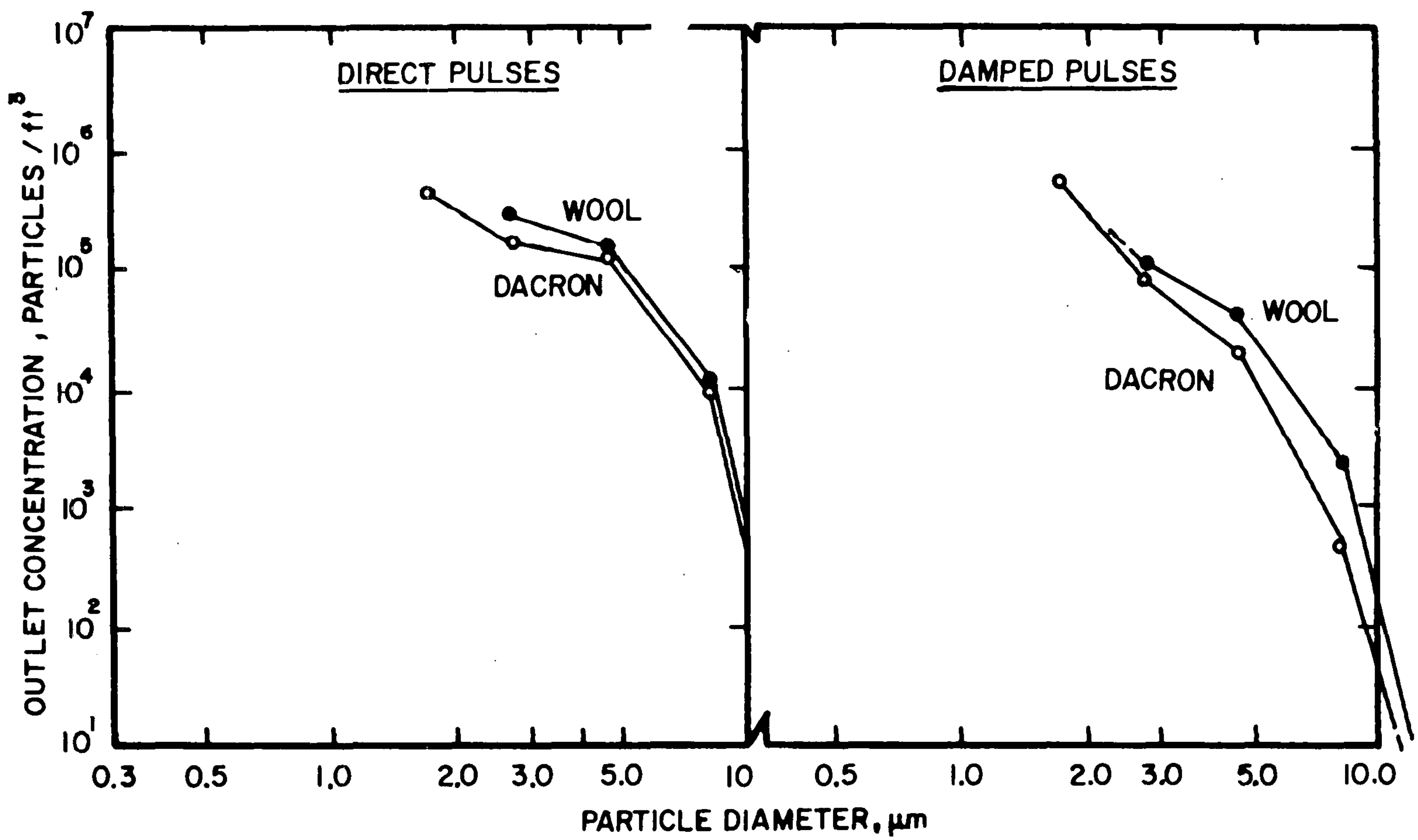

Figure 17. Average outlet number concentrations for 1-minute pulse intervals - pulse jetting at 70 psig for 0.06 sec

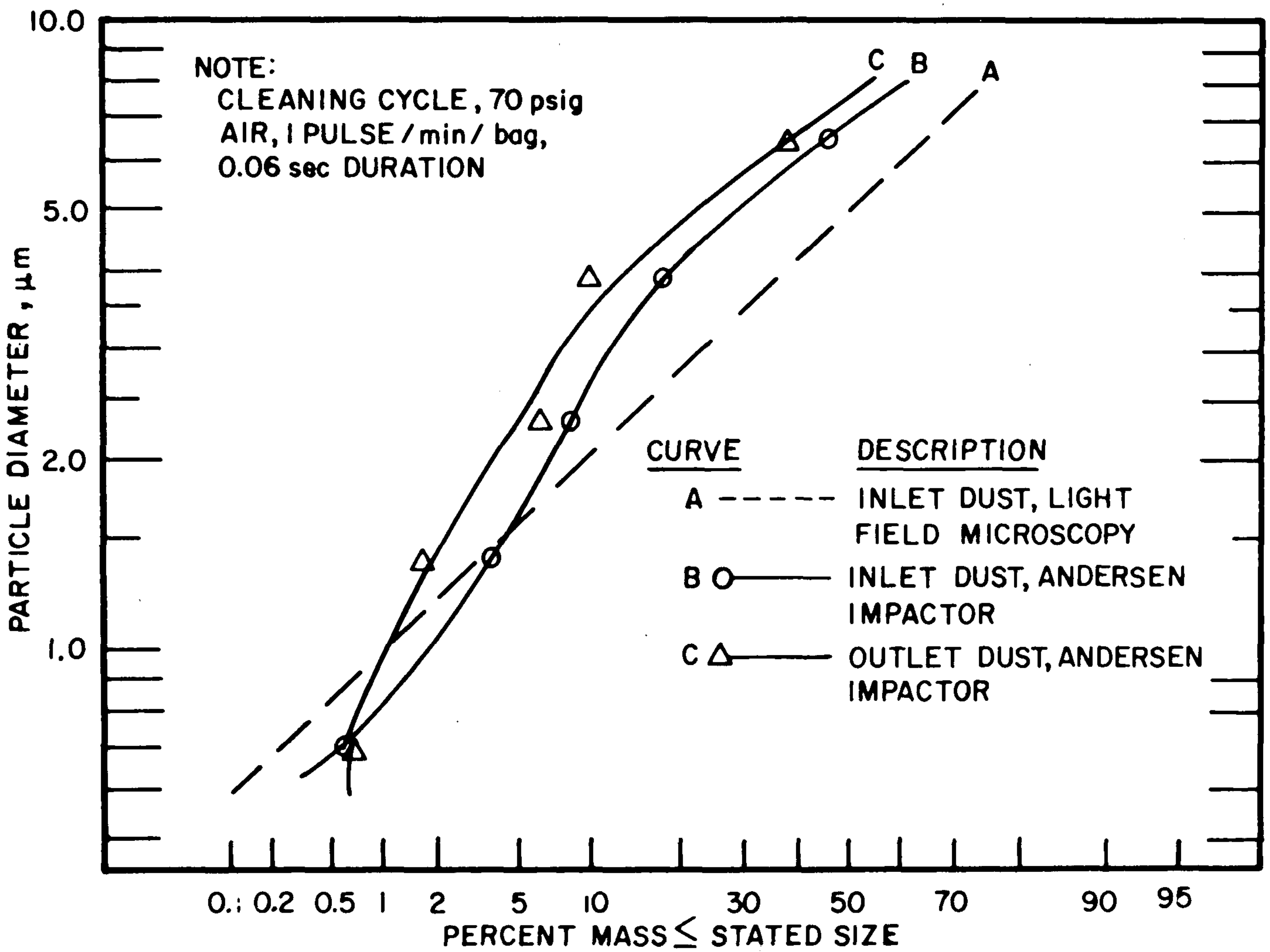

Figure 18. Fly ash filtration which Dacron felt and pulse jet cleaning. Size distribution for inlet and outlet dusts at weight collection efficiency of 99.83%

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SOME EFFECTS OF ELECTROSTATIC CHARGES IN FABRIC FILTRATION

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INTRODUCTION

In filtration operations, electrostatic charges may have both good and bad effects. The good features that result in outstanding collection efficiency are believed to be attributable to particle-to-fabric attractions and agglomeration. On the bad side, static charges and their forces of attraction don't necessarily, stop at the end of the collection cycle and, therefore, they often restrict cleanability. But, this too, is sometimes desirable.

The charges generated, induced or whatever, on fabrics and undoubtedly on particles too, have specific characteristics, the features of which are dictated primarily by surface properties. These characteristics are polarity, intensity and rate of dissipation. Our experience indicates that these characteristics of the charges on the fabric filter and on the particulates have a direct influence on one another and, most often, determine in large measure how the filter performs. Agglomeration, or a low density condition of the cake that resembles agglomeration, is promoted during the filtration process, according to our interpretations, by use of a fabric with suitable electrostatic properties. In general, then, we contend that effective balancing of static properties of fabric and particulate and also a suitable charge dissipation rate in the medium, when such is needed, represent conditions considered necessary for attaining optimal filtration parameters.

In this review, special consideration is given to the electrical properties of fibers, of fabrics, of particles and of the gas that carries the particulates. The three ways that moisture affects the filtration process are noted and artificial charging, as a potentially new technique, is also discussed briefly. Finally, a few case histories are offered to indicate how charge balancing leads to optimum filtration performance.

SOME EFFECTS OF ELECTROSTATIC CHARGES IN FABRIC FILTRATION

It is a pleasure indeed for me to consider with you some of our impressions concerning the effects of electrostatic charges in fabric filtration. Unlike other mechanisms of the classical filtration theory that contribute to the removal of particles by fabrics, electrostatics have received barely minimal consideration. But now that better control of submicron particles is demanded, the contribution and restrictive influence of electrostatic charges on both the collecting fabric media and on the collected solids must be understood and utilized fully. At the present time charge contributions to, and restrictions on, the filtration process are vaguely understood and rarely if ever applied knowingly in commercial practice.

Our experience from the evaluation of almost fifty different dusts by both shaker and reverse air-jet experimental filtration support a theory that emphasizes the importance of electrostatics for controlling operating parameters.[1] Accordingly, the electrostatic charge requirements of the preferred fabric filter seem to be dictated by the electrostatic, as well as the physical properties, of the collected particulate. Charge exchange, or neutralization between the medium and some dusts, leads to agglomeration that greatly enhances the efficiency of fabric filters. Inasmuch as charge retention on the filter tends to influence particle-to-fabric adhesion, the charge dissipation rate of the media and/or of the particulates influence, and sometimes may be modified to optimize, overall performance.

When conditions permit, the use of one kind of fabric filter in preference to others will most often lead to better control of fine particulates and to greatly improved performance.

In this report, I hope to consider the characteristic features and practical utilization of electrostatics in fabric filtration. No attempt shall be made to cover the theory of contact electrification. The basic static properties of polarity, intensity and dissipation rate, as they apply to fabrics, particulates and the carrier gases, however, will be reviewed and related to filter performance. Comments will also be directed to three ways that moisture influences the filtration process. Then, after considering the relatively recent development of an operation that I refer to as artificial electrification, a few case histories will be offered.

ELECTROSTATIC PROPERTIES OF FABRICS

Whenever two dissimilar materials (usually, at least one of which is an insulator) are rubbed together, one becomes electropositive, the other electronegative. This is the way particles and fabrics become charged.

This polarity difference that occurs between particulates and fibers is generally conceded to offer the means by which fabrics draw particles out of the gas stream to achieve very high collection efficiency; higher than predicted by the classical filtration theory. Polarity variations among fabrics reflect inherent fiber differences that may be demonstrated from rubbing tests. The testing unit that we used is shown in Figures 1 and 2. By the rubbing method, a triboelectric series may be obtained in which all fabrics may be listed from those that are very electropositive like wool, glass and nylon to those that are quite electronegative like the polyolefins, and especially, "Teflon". It will be apparent that by repeated rubbing trials, the series may be expanded to include any number of fabrics (refer to Table 1). A variety of materials, including particulates, may be located in the same series. Other factors being equal, the greater the spread between materials in the series, the greater the

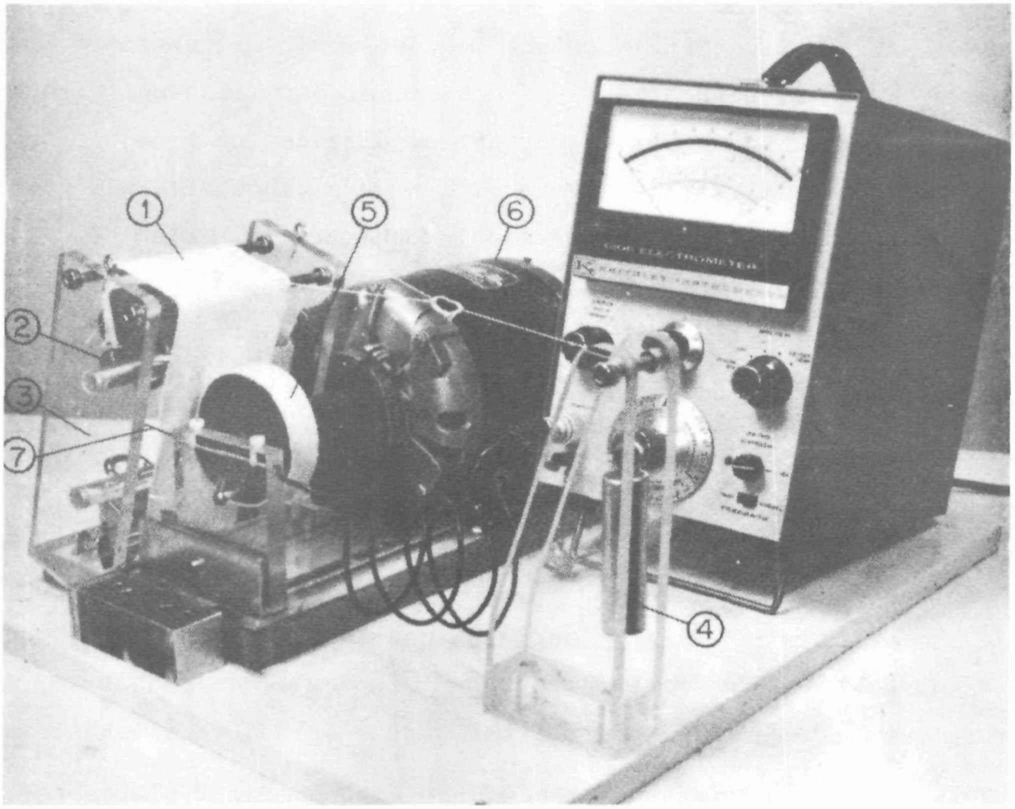


Figure 1. AFC static generation and evaluation equipment--static charge generation. 1. test fabric; 2. test fabric tensioning weight; 3. test fabric support frame; 4. test fabric frame tensioning weight; 5. reference fabric (contacting test fabric); 6. reference wheel drive motor; 7. voltage probe (retracted)

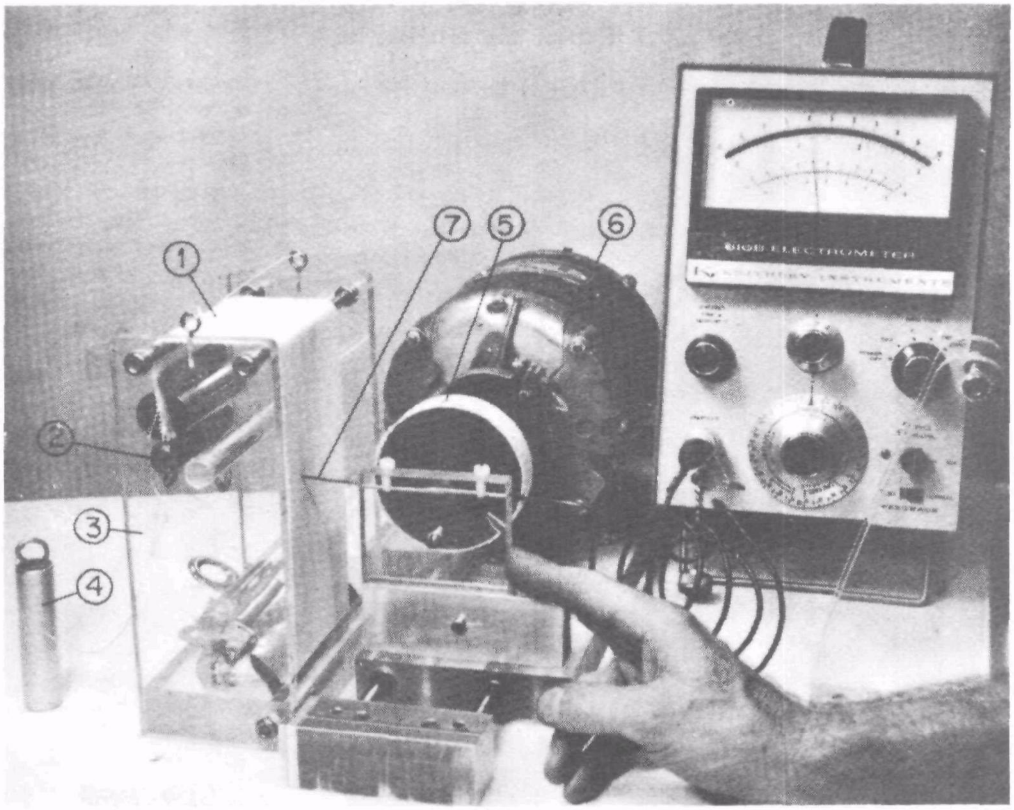


Figure 2. AFC static generation and evaluation equipment--static charge measurement. 1. test fabric; 2. test fabric tensioning weight; 3. test fabric support frame; 4. test fabric frame tensioning weight; 5. reference fabric (removed from test fabric); 6. reference wheel drive motor; 7. voltage probe in measuring position

Table 1. TRIBOELECTRIC SERIES FOR SOME PRODUCTION FABRICS

Positive	
+25	
	Wool felt
+20	
+15	Glass, filament, heat cleaned and silicone treated
	Glass, spun, heat cleaned and silicone treated
	Wool, woven felt, T-2
+10	Nylon 66, spun
	Nylon 66, spun, heat set
	Nylon 6, spun
	Cotton sateen
+5	Orlon 81, filament
	Orlon 42, needled fabrics
	Arnel, filament
	Dacron, filament
	Dacron, filament, silicone treated
0	Dacron, filament, M-31
	Dacron, combination filament and spun
	Creslan, spun; Azoton, spun
	Verel, regular, spun; Orlon 81, spun (55200)
	Dynel, spun
-5	Orlon 81, spun
	Orlon 42, spun
	Dacron, needled
-10	Dacron, spun; Orlon 81, spun (79475)
	Dacron, spun and heat set
	Polypropylene 01, filament
	Orlon 39B, spun
-15	Fibravyl, spun
	Darvan, needled
	Kodel
-20	Polyethylene B, filament and spun
Negative	

interaction between the two materials. Table 2, the triboelectric series arrangement for fabrics used in one (Co-A) of the test programs, further emphasizes the fact that not all fabrics made from the same type of fiber fall in the same location in the series.

The intensity of the electrostatic charge (together with any polarity difference) has a marked influence on collection efficiency and is a function of surface (fiber, yarn or fabric) roughness as well as of the inherent properties of the polymer. Other factors equal, the rougher the surface, the higher the generated charge. Rough fibers like wool, rough yarns like low twist spun yarns and high cover fabrics like those that are napped, tend to develop higher charges than smooth surfaced materials such as those made from smooth (melt extruded) continuous filaments fibers in low twist, pressed, calendered or otherwise smooth fabrics.

Naturally, chemical as well as mechanical treatments can impart roughness and influence the intensity of the generated static charge. The resin treated wool that serves as an extremely efficient filter in respirators is one example of how extreme polarity combined with roughness frictional properties that increases charge intensity produces super high particle-to-fiber attraction.

The rate of charge dissipation that so often affects cleanability critically, is a function primarily, but not exclusively, of fiber resistivity. It will be evident from Table 3 that as the fabric's volume resistivity[3] or surface resistivity decreases much below 10^{10} ohm cms or 10^{12} ohms, respectively, the rate of charge bleed-off increases significantly.[4,5]

Other differences among fibers, yarns and fabrics also contribute to differences in the rate of charge decay. As fibers become longer and smoother, as yarns become more compacted and smoother and as fabrics become tighter, more compact and smoother, charges tend to bleed-off faster. Charges are surface generated and here they remain until they flow-off either internally (as in an electrical conductor) or along the surface or directly to the surroundings. For effective dissipation, they must find a route like that offered by conductive elements in the surrounding atmosphere or, if these are absent, they may travel, usually relatively slowly, over

Table 2. TRIBOELECTRIC SERIES OF FABRICS USED IN THE CO-A TEST PROGRAM

Positive (+)

Nylon 800

Dacron 2362 NS (90360)

Dacron S 484 (89979)

Orlon 2339 (80889), Orlon 2420 (81332), Orlon S 481 (93423) Orlon S 481 (900780), Orlon S 481 NS (93423A), Orlon S 481 NS (90078B), Orlon S 428 (90251B), Dacron 2362 (82924), Dacron 2362 (82386)

Dacron S 485 (89953), Orlon 81 - 2459 (81660)

Dacron 2362, Dacron S 484 (93424), Dacron S 447 (90840) Dacron S 483 (89952B)

Orlon S 627, Orlon 2339 NS (84651)

Darvan [B-831], Darvan S 547, Darvan S 456 (81214)

Darvan S 456 (90784), Darvan S 626 (16321)

Darvan S 456 NS (90784A)

Negative (-)

Note: The two underlined fabrics served as electrostatic references.

Table 3. RESISTIVITY[a] VS. ANTI-STATIC RATING

Volume vertical resistivity[b] (ohm cm)	Surface horizontal resistivity[c] (ohm)	Anti-static rating
$> 10^{11}$	$> 10^{13}$	Nil
10^{10} - 10^{11}	10^{12} - 10^{13}	Poor
10^{9} - 10^{10}	10^{11} - 10^{12}	Moderate
10^{8} - 10^{9}	10^{10} - 10^{11}	Fairly good
$< 10^{8}$	$< 10^{10}$	Good

[a] ASTM D257-61 Method.

[b] Report of E. R. Frederick to Mellon Institute, December 1, 1964 - May 31, 1965.

[c] "The Electrical Resistance of Textile Materials as a Measure of Their Anti-Static Properties," Wilson, D., J. Text. Inst., 54, T104, 1963.

the fiber surface. For short (spun) fibers, the path is short and the charges tend to accumulate at the ends. They are likely to remain there until they either bleed-off slowly on the surrounding gases or they may build-up until they reach a point at which discharge occurs as they reach the breakdown voltage of the surrounding gases.

The atmosphere surrounding the fibers always has an influence on the rate of charge dissipation. But when the same low conductivity conditions exist for both spun and filament yarns (of the same polymer), the filament fabric displays a higher rate of charge loss. Similarly, a compacted calendered fabric will lose its electrostatic charge faster than the same fabric at the lower density without the smooth surface.

Treatments can have a profound influence on the performance of a filter fabric. If the finish applied to the fiber is fugitive, as most organic treatments tend to be in ordinary service, its influence can hardly be favorable. Initially, the finish exerts one kind of an effect but this will change in service use, and finally disappear completely upon heating. Among the potentially serious problems is that which may be introduced by the fiber producer's finish. These fiber lubricants applied to minimize fiber damage in processing, may not always be removed completely by the fabric manufacturer. As a result, that finish which remains, like the anti-static resin treatment that we studied, may be converted to the amine derivative of the original finish. In this new form, the treatment produces a very strong electropositive influence before it finally burns-off completely. A finish of this type, therefore, may cause the fiber to exert three different static effects--anti-static at first, then strongly electropositive and, finally, that which reflects the true properties of the fabric. This is further support for a practice that would provide electrical data for both the as-received and as-cleaned filter fabric.

ELECTROSTATIC PROPERTIES OF PARTICLES

The electrostatic properties of particles are more obscure than those of filter fabrics. Presumably, as noted, particles may be located together with fabrics in the same triboelectric series. Certainly, electrical resistivity must have a primary influence on static properties and it would also seem evident that particle-size--shape--roughness, etc., must influence charge intensity and, to a lesser extent, charge retention. That resistivity varies for different kinds of the same particulate and also changes with temperature, will be evident from Figure 3.

A relatively crude test that exposes a number of fabric swatches to dust tends to support the view that particles may be located with fabrics in the T.E. series. Differences in the weight of dust picked-up by similarly constructed fabrics made of different fibers serve to specify polarity differences. The extent of differences appear to indicate a location for the particulates in the triboelectric series with the test fabrics. Other factors being equal, the fabrics most distant from the dust in the series

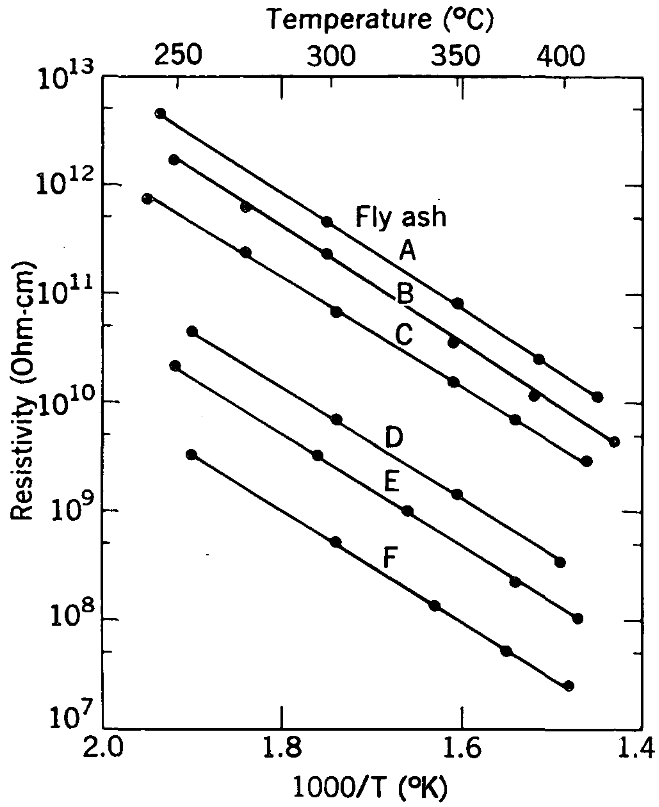


Figure 3. Typical log resistivity versus reciprocal absolute temperature plots for ashes A, B, C, D, E, and F

attract the greatest quantity of dust. The method, with refinement, may deserve further consideration.

Agglomeration is another feature of most dusts that appears to have a very significant, if not a controlling influence on many filtration operations. Our observations suggested that the many dusts that can agglomerate may be agglomerated or at least produce an effect like agglomeration by contact with a filter fabric of preferred polarity.[6] The evidence indicated that agglomeration or this effect that resembles agglomeration occurred with varying ease but the condition could usually be assured in the formation of the cake when a fabric was used that had high intensity of charge opposite in polarity to that of the particulate (refer to Figure 4).

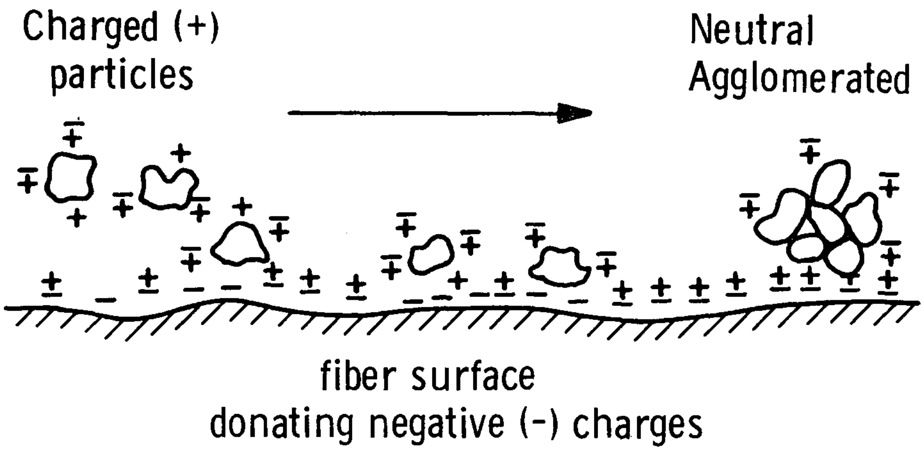


Figure 4. Particulate agglomeration through charge neutralization [5]

FABRIC PRESCRIPTION FOR CONTROL OF FINE PARTICLES

The following comments summarize the electrostatic needs of fabrics for filtering fine particulates efficiently, according to our interpretations of experimental and commercial data.

When both the necessary electrical and physical data of the particulate are known, fabric filter requirements may be specified for attaining optimal overall collection efficiency. Accordingly, for:

A. - Very Fine, Non-Agglomerating Particulates, the most effective filter medium is that which becomes highly charged to a polarity opposite to that of the particles so that the forces of attraction are maximized. In addition, to be sure that minimum leakage occurs during successive filtration cycles, some of the cake must be retained on the filter surface after cleaning. This may be achieved with a fabric of very low rate of charge decay.

B. - Very Fine, But Agglomerating Particulates, the most effective filter medium is that which becomes charged, sometimes to a very high intensity, to a polarity suitably opposite to that of the particles to cause the charges on the particles to be neutralized. Once neutralized, particle-to-particle contact is no longer restricted and agglomeration may proceed on the filter surface. Depending upon the ease in effecting agglomeration, the rate of charge dissipation from the fabric may be high or low. A low rate is preferred when a difficult-to-agglomerate dust is being collected, whereas a high rate may be desired for its value in improving cleanability when it does not interfere with the agglomeration process. For some dusts, agglomeration occurs so easily that mere neutralization by rapid charge bleed-off by contact with a grounding or anti-static surface, for example, is adequate to cause this desirable change.

CARRIER GAS

The composition of the gas carrying the particulates most certainly can have an influence on charge generation and on charge retention. A gas of high resistivity favors high charge build-up and slow charge bleed-off. The presence of conductive elements in the gas restricts charge retention because, of course, these paths offer a means for any charge to be carried away. It will be apparent that the conductive component of the gas may take many forms. At least twice, in the course of our triboelectrification studies, we related a failure to obtain even a small amount of charge in the testing of fabrics to the presence of radiation products in the laboratory atmosphere.

MOISTURE EFFECTS

Our experience indicated that triboelectric charging and charge retention is not restricted at room temperatures by values of relative humidity of up to at least 35 percent. No doubt, the relative humidity at which charge bleed-off becomes high falls off quite appreciably as the higher temperature of most industrial filtration processes is reached. At some relatively low moisture content dependent upon the temperature, then, charge bleed-off becomes very rapid.

Excess moisture in the particulate carrying gas stream may have other effects. Below the dewpoint, for example, moisture may cause the formation of a paste of the dust on the filter surface. The severity of the pasting effect may depend upon other factors including the water solubility of particulate or other components of the gas stream. The end effect of the paste formation with its subsequent surface blinding of the filter, however, is quite obvious.

When the components of the filter system are capable of reacting, moisture often serves to promote the reaction. The chemical reaction in itself may not pose a serious threat to the filter process, but the reaction products can be a real problem if they form around and become locked within the fibers to produce an unremovable type of plug. Repetition of this process, of course, leads to complete binding of the filter.

ARTIFICIAL CHARGING

Artificial charging or the combination of principles akin to electrostatic precipitation and fabric filtration has been receiving more and more consideration as a means for improving collection efficiency. Whether or not the technique has real merit for upgrading the filtration of very fine particles is not known, but a positive effect might be postulated. Certainly, according to our experience of a decade ago, the other parameters of fabric filtration were all upgraded by applying artificial charging. In these trials, we compared the filtration performance of certain preferred fabric media with and without the influence of an applied electrical field. Actually, a rather large number of variations with respect to voltage levels and current types (d.c. and a.c.) are possible but I shall confine my remarks concerning our studies to the program that applied 7500 volts a.c. between a wire passing down the center of a three inch diameter test bag and either the test bag itself or a metal screen cage surrounding the test bag. It will be apparent that when the bag itself served as one electrode either it was inherently electrically conductive (carbon fabric) or was made so by suitable (metallizing) treatment. Both colloidal graphite and the electro-less metallizing (copper or nickel coating) processes were used to impart electrical conductivity to certain conventional filter fabrics.

To determine the influence of the conductive coating and artificial charging, four separate filtration tests with the same type of particulate were conducted. Comparative data were obtained for the normal filter fabric, for the conductive finished fabric of exactly the same type, for this latter fabric with a voltage impressed between a center wire and the fabric and finally, for the normal fabric with voltage impressed between a center wire and a screen cage surrounding the fabric during the collection cycle. In order to permit variations in cleaning methods for the latter test, the wire cage was hinged for removal during this part of the process. Now, to avoid extending this portion of the review excessively, let me provide a summary of some of our conclusions.

First, not all particulate collection operations are benefited in even a minor way by artificial charging but there appears to be a tendency for the moderate-to-low resistivity dusts (carbon, certain cement and zinc oxides) to improve in their collection parameters by using a conductive filter medium or especially by applying artificial charging during the collection cycle. For example, by substituting a conductive fabric for the same normal filter fabric in the collection of cement dust the amount of dust collected increased by 100 percent as the process was continued to the same pressure drop. At the same time, the amount of plug accumulated in the fabric was reduced by 18 percent. With the electric field applied to the metallized fabric, collection was further increased by 37 percent with the plug continuing to show a reduction of at least 12 percent. Thus, compared to the normal fabric, the artificially charged fabric showed an increase in filtration capacity by 175 percent and a reduction in plugging by 13 percent. The improvement by artificial charging between a center wire and a cage surrounding the normal filter fabric was the same as that achieved by electrification of the metallized fabric. Similar studies, again with finished cement dust but with a carbon filter fabric with and without artificial charging, demonstrated that electrification doubled cement dust collection and reduced plugging by 24 percent (refer to Figure 5).

Within the last two years, apitron, a collection system offered by Precision Industries, is claimed to offer better filtration performance by reason of artificial charging.[7]

Professor Gaylord Penney, whom you will recognize as the inventor of the two stage electrostatic precipitator, demonstrated over a year ago the usefulness of artificial electrification in fabric filtration.[8] Using fly ash in filter tests without and with added electrification, he not only demonstrated that the collection cycle could be more than doubled but also that the nature of the deposited cake was responsible for this improvement by reason of its "pyramid-like" structure.

Professor T. Ariman of Notre Dame, has also shown from recent studies that significant advantages may be realized by electrifying a fabric filter.[9]

SOME FILTRATION CASE HISTORIES

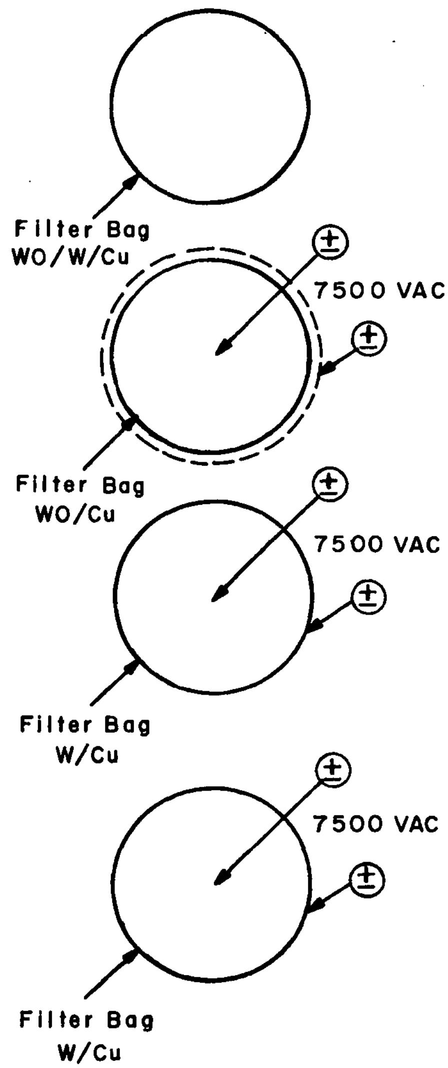
TACONITE--REVERSE AIR-JET COLLECTOR

After a comprehensive study of the fabric requirements for collecting taconite by the reverse air-jet or blow-ring method, a polyester (Dacron) needled felt of 72 cfm/ft^2 (at 0.5" wg) permeability was selected as the preferred filter medium. Since repeated trials verified the reliability of this choice, one of the test bags was washed clean of the collected dust and treated with colloidal graphite to a 2 percent add-on. When this fabric of the very same base fiber and same permeability was used or, rather, was tried under the same conditions as before, leakage was so very serious from start-up that the operation had to be terminated after just a few minutes.

Our explanation for this change in filter performance was the significant change in electrostatic properties. Originally, the charging properties

CONDUCTIVE AND NON CONDUCTIVE FABRICS, W/WO ARTIFICIAL CHARGING CEMENT (FINISHED) FILTRATION A/C = 3.6 CFM/FT^2, 90^oF, DUST LOADING = 27-28 g./MIN CLEANING - ONE VACUUM PULLBACK ONLY

Test Conditions



Wiring cross section	Fabric	Observations
1	Dacron (866 B) without & with Cu coating, permeability (cfm/ft^2 0.5 wg) 34.5 19	Compared to fabric without Cu collectability up ~ 100% Plug down 18% Very low leakage
2	Dacron (866 B) without Cu coating, permeability 34.5 cfm/ft^2 0.5wg	Compared to fabric without Cu & without electrification Collectability up ~ 175% Plug down 13% Low leakage
3	Dacron (866 B) with Cu coating, permeability 19 cfm/ft^2 0.5 wg	Compared to fabric without Cu & without electrification Collectability up ~ 175% Plug down 13% Very low leakage
4	Dacron (866 B) with Cu coating, permeability 19 cfm/ft^2 0.5 wg	Compared to fabric with Cu & without electrification Collectability up ~ 37% Plug up ~ 6% Very low leakage

Figure 5. Effect of artificial electrification

of the dacron fiber were suitable in polarity and intensity to cause the taconite to agglomerate into relatively large particles on the filter surface. When the same fabric was made conductive by means of the graphite finish, the charges were no longer adequate for agglomerating taconite because they were carried away rapidly to ground over the conductive fabric surface.

URANIUM OXIDE AND GRAPHITE--REVERSE AIR-JET COLLECTOR

Professor Caplan reported a similar problem but offered no explanation. In the reverse air-jet filtration that he mentioned, the collection of a uranium oxide-graphite mixture proceeded extremely well until the fabric became impregnated and/or coated with the graphite component of the particulate. When this condition was reached, dust leakage occurred to a very serious extent and the operation had to be discontinued.

DISPERSION GRADE PVC--SHAKER TYPE COLLECTOR

This extremely active (electrostatically) dust was to be collected by a new type air-shake collector but this innovation was insignificant by comparison with the exaggerated charge needed to cause agglomeration of this PVC dust. After proving the need for extreme polarity, high intensity and low dissipation rate, and then establishing the capability of a highly positive wool-nylon fabric, this new filter fabric was adopted. The fabric was a high grade, relatively lightweight woven fabric made on the woolen system with 75 percent wool and 25 percent nylon at a permeability of 50 cfm/ft^2 (at 0.5" wg). Repeated laboratory tests verified the effectiveness of this new fabric. First commercial trials in an entirely new collector using the air-shake cleaner system and supposedly the same type of wool-nylon filter fabric were not so favorable. In fact, the pressure drop was higher by far than we had predicted and leakage was quite serious. Examination of the fabric indicated that the fabric supplied for the commercial installation had a permeability of 80 cfm/ft^2. This high degree of openness explained the high leakage but what about the high pressure drop? Examination of the fabric and laboratory collection trials reaffirmed the high permeability, the high pressure drop and the excessive leakage. Further study of the fabric revealed that the unsatisfactory fabric had two less picks per inch and much less cover fiber than the preferred fabric. With this information, a new wool-nylon fabric of 55 cfm/ft^2 permeability was provided in the filter bags of the commercial baghouse. This new fabric, that met the original specifications, performed favorably in the field as well as in the laboratory.

CALCINED CALCIUM SILICATE "MCE"--REVERSE AIR-JET COLLECTOR

A number of different needled fabrics examined as the filter media both in the field and in the pilot plant for collecting this very fine dust failed completely, mostly because they leaked so seriously. The tests carried out on dacron bags, regardless of construction, had to be terminated early in the program because dust leakage was excessive and equilibrium could not be attained at reasonable air-to-cloth ratios. Orlon bags, on the other hand, at the same permeability (25 cfm/ft^2 at 0.5" wg) as the tested dacron fabrics, performed favorably without leaking even as the air-to-cloth ratio was raised to 20 to 1. When these same orlon bags were treated with a charge dissipating (anti-static) finish without changing its permeability, leakage again became very serious. A darvan needled fabric also functioned quite well but only below the 20 to 1 A to C level. At the higher flow rate, leakage became excessive even though the pressure drop did not rise significantly.

On the basis of the observations that both orlon and darvan fabrics were much more electronegative than the dacron bags but that the more favorable orlon material displayed a lower rate of charge loss than either dacron or darvan and, of course, much lower than the antistatic finished orlon, we believe:

> The reverse jet collection of this "MCE" dust is favored by an electronegative medium (or fabric of quite opposite polarity) with a low discharge rate so that a protective "filter-aid" layer of the particulate is held on the surface at all times.

AGGLOMERATION BY GROUNDING

Professor Caplan mentioned another filtration anomaly that I believe might be explained on a basis of electrostatic effects. He noted that a bag collector failed and had to be replaced by another kind of control device when an inactive screw-conveyer was removed from the duct carrying dust to the baghouse.

I suggest that in the original process, the electrically grounding screw with very considerable surface area caused the dust to dissipate its charge and become agglomerated before entering the collector. When the screw was removed and the large charge bleed-off contacting surface was no longer available, the bags in the collector received fine, mostly non-agglomerated particulate. Conceivably, if the "right" filter fabric had been used, agglomeration could also have been accomplished to make the baghouse feasible.

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DESIGNING A FILTER SYSTEM TO MEET SPECIFIED EFFICIENCY AND EMISSIONS LEVELS

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When I was requested to present this paper, my immediate reaction was "Why? We know so little about the control of submicron particulate by using fabric filters." Upon reflection, however, it seemed to me to be a good idea that those of us deeply involved in fabric filter technology sit down and discuss what we know and those things we need to learn. As a representative of the manufacturing part of the industry, I can state that we can supply very little practical field data at this point in time to substantiate some of our feelings with regard to control of submicron particulate.

It is a well-known fact that only in the past year have acceptable methods become available to use in sampling submicron particulate. Even today, the number of people qualified to conduct this type of testing is very limited. Thus it is to be expected that good field data is so limited at this point as to be practically meaningless. However, we do have available to us good field data that tells us generally that a fabric filter is highly efficient, in at least a part of the submicron range.

With these comments as a background, let's launch into a discussion as to what we believe the place of the fabric filter and associated systems may be in control of submicron particulate. First, I would like to state unequivocally that it is my opinion that both woven and felted fabric filters represent viable means for collection of submicron particulate. In the course of this paper, I will present the reasons for this belief. In any case, the fabric filter is only part of the collection device. The system represents the other part of the total collection equipment and it is impossible to divorce one from the other when examining performance. It is well-known that in certain metallurgical processes the effects of gas cooling on the particulate characteristics are pronounced. I believe we should, therefore, examine several of the industrial processes generally handled by fabric filters where we know that submicron particulate exists so as to determine the adequacy of present system designs in this rather new area.

One of the major sources of submicron particulate must be the metallurgical fume which is generally in the submicron size range. I would like to examine one specific metallurgical fume generating process with the thought that the principles discussed will be applicable pretty well across-the-board to other metallurgical processes. For purposes of discussion, I have selected the electric arc furnace as a device which generates relatively large amounts of submicron particulate. As most of you know, an arc furnace will generate between 20 and 50 pounds of fume per ton of steel melted. This fume ranges between 70 and 90 percent less than 2 microns in particle size. A detailed size analysis below two microns is not available but we feel that most of this will fit our discussion category of submicron particulate.

In the area of fume pickup, there are three generally employed systems. As you know, there are the direct shell evacuation system, the furnace mounted side draft hood system, and finally, the canopy hood system. I believe that the first two of these will be totally adequate to meet any requirements for collection of submicron particulate. In fact, if any particulate is missed by these two types of pickup it would probably be the larger particles which are less subject to directional change influences. If you will examine the principle of the side draft hood, you will see that it depends upon horizontal vectors caused by airflow to turn the fume emitted from the furnace electrodes into the collecting hood. Certainly, submicron particulate should be much more susceptible to this physical force than the larger particulate. The same will be true of the direct shell evacuation system.

I have some doubts, however, about the adequacy of a canopy hood system in this area. For the very reasons that the first two devices appear to be unaffected, I feel that a canopy hood system, which depends upon thermal drive to carry the fume into the collection hood located some 20 to 40 feet away, could be adversely affected in the submicron range by building cross-drafts. Once again, the heavier particulate given proper thermal drive in an upward direction will probably continue unless cross-drafts are excessive. However, the submicron particulate because of its extremely small size and relatively large surface area to weight ratio will probably be subject to the influences of cross-drafts to a much greater degree. I, therefore, have reservations about the adequacy of a canopy hood system in this area, and I believe that we must do field testing on existing installations which appear on the surface to be more than adequate in order to determine the performance in this new area. Unfortunately, this testing will be neither simple nor inexpensive.

I feel that the comments given on the process, as described above, can be carried pretty well across-the-board to most industrial processes. The thought would be that those processes that are subject to very local dust or fume pickup can be adequately ventilated even in the submicron particulate range without undue concern. On the other hand, those processes that depend upon remote pickup will probably have to be restudied in some industries in order to achieve greater control of submicron particulate.

In those industries generally using fabric filters for ventilation of various processes, I believe that the following processes currently have system designs that are adequate to insure pickup of the submicron particulate:

Carbon black furnaces

Cement and other kilns

Power and industrial boilers

Primary and secondary metals reverbatory furnaces

Secondary metal rotary furnaces

Secondary metal blast furnaces

Cement clinker coolers

Driers and rotary coolers

Some of the existing systems that I believe may be inadequate from a submicron particulate pickup standpoint would be:

Electric arc furnace canopy hoods

Basic oxygen furnace charging and tapping

Kish collection and hot metal transfer

Asbestos milling

Material handling systems if involving submicron particulate

Charging and tapping operations in the primary and secondary nonferrous industry

Each of these processes must be further studied to determine the adequacy of present systems. As you can see, we believe that the pickup systems, in the majority of cases where fabric filters are employed, will be adequate in the submicron particulate area. Now I believe we should study what happens after the material is picked up and prior to the time that it enters the filter.

The most important feature of the system between the pickup point and the fabric filter, as far as submicron particulate is concerned, will be in those processes utilizing gas cooling. The cooling method may have at least two effects in the behavior of the particulate once it reaches the fabric filter. Generally, these effects will not be found but they occur in a sufficient number of cases so that they warrant some discussion.

In a limited number of metallurgical processes, and in a few other applications, shock cooling of the gases is recommended. Shock cooling seems to provide a different crystalline formation of some of the particulate from that experienced when slow cooling by radiation or other means is employed. This different crystalline formation obviously affects the filtration characteristics of the particulate once it reaches the fabric filter.

Secondly, the use of waterspray cooling provides a high moisture content in the carrying gas stream to the fabric filter. While the electrostatic phenomena occurring in a fabric filter are not well-understood, it is obvious that the high moisture content and change in conductivity of the conducting gas stream will have a major effect in those processes where electrostatic phenomena do occur. I am sorry to say that we know very little about either of these two areas of fabric filtration but I believe that they may become increasingly important as we continue to investigate the ability of fabric filters to efficiently handle submicron particulate at reasonable pressure drops.

Finally, we come to the fabric filter itself, and the selection of the proper device to handle the process effluent picked up and prepared for filtration by the system designed. Once again, we must admit to inadequate knowledge in this new area of concern. Of primary importance will be the selection of either a woven fabric filter or a felted fabric filter. Our previous experience would indicate that both of these filters can operate efficiently on submicron particulate. We would have some concern in the area of felted fabric filters, however, because of the blinding tendencies experienced when handling certain types of metallurgical fume. Is the blinding characteristic a function of only particle size or is it a function of some other characteristics of metallurgical fume that would not exist on other submicron particulate? Frankly, I believe it is a function of other characteristics and I believe that the felted fabric filter is able to operate successfully in the submicron particle size range.

We know that the woven fabric filter has a history of successful operation in handling particulate in this size range. Woven type fabrics have been employed for years in handling particulate as fine as carbon black, which ranges down to 300 angstroms in particle size, and in ventilating many metallurgical processes where most of the fume generated is submicron. I am sure that we not know all of the associated phenomena but I believe agglomeration plays a great part in the ability of the fabric filter to operate in this range, particularly in handling materials such as carbon black. I believe that our limited knowledge would suggest the selection of a woven fabric filter in most metallurgical processes for technical reasons with the choice being left open between a woven fabric filter and a felted fabric filter with economics being the dictating factor on other processes even though they involve submicron particulate.

Once the type of filter is selected, I am sure that we all agree that cloth construction can be critical, particularly in the ability of the fabric filter to operate efficiently in the area under discussion. There are other papers on the program that will cover this subject in-depth and, therefore, I will not attempt any discussion in this area.

I do believe, however, that we should briefly discuss the relationship between the type of fabric and the method of cloth cleaning in a woven fabric collector. The two generally available types of cloth cleaning are, of course, reverse air and mechanical shaking. We feel that filament type fabrics generally lend themselves to reverse air cleaning while staple or combination type fabrics lend themselves to shaker type cleaning. While there appears to be little difference in the efficiency of either fabric construction as related to an individual process, we have found that in some cases the staple or combination type fabrics do allow operation at lower pressure drops particularly where fine particulate is involved.

We would not expect any significant variation in efficiency due to different fabric composition. Fabric selection will generally be dictated by temperature and chemical considerations. In a few isolated cases, we have found variations in pressure drop characteristics that are probably due to the little understood electrostatic effect. As indicated previously, I believe that these electrostatic effects need to have substantially more study as we enter into the problems of submicron filtration.

In summary, I believe it is fair to state that many of the existing system designs used in conjunction with fabric filters will be adequate to meet the requirements of submicron particulate capture. Further, I believe that fabric filters as we know them today can adequately handle submicron particulate in most cases, and finally, I feel that now that we have the tools of submicron particulate testing available to us, we will be able to rapidly progress our level of knowledge in this area.

LABORATORY GENERATION OF PARTICULATES WITH EMPHASIS ON SUB - MICRON AEROSOLS

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INTRODUCTION

Aerosol generation is an important part of any laboratory research program involving aerosols. The calibration of aerosol measuring or sampling instruments, the testing of particulate control devices and the fundamental study of aerosols all require aerosol particles with prescribed physical or chemical properties.

During the past few years considerable advances have been made in methods and techniques for the generation of monodisperse aerosols. In particular, methods have been developed for generating monodisperse aerosols of a known size and concentration, aerosols which can be used as primary standards in the field of aerosol physics and technology. Such monodisperse aerosol standards can now be generated from 0.01 μm to over 50 μm in particle diameter at concentration levels up to 10^6 particles/cc in certain size ranges. In addition, aerosols can be generated from a variety of solid and liquid materials, and the particle size can be calculated from the operating conditions of the aerosol generators directly to a high degree of accuracy (1 percent or better). Thus the need to measure the size of the generated particles by the tedious and often inaccurate optical or electron microscope methods has largely been eliminated.

In this paper we will briefly review these recent advances in aerosol generation techniques, focusing on work done in our Laboratory.

Two approaches have been used for generating monodisperse aerosol standards, one involving the controlled disintegration of a liquid jet by a vibrating orifice, and the other the pneumatic atomization of a liquid and the electrostatic classification of the polydisperse aerosol. The first method is applicable to larger particles over 0.5 μm in diameter while the latter method is more suited for generating smaller particles below 0.5 μm.

THE VIBRATING ORIFICE MONODISPERSE AEROSOL GENERATOR

Figure 1 is a schematic diagram of the vibrating orifice monodisperse aerosol generator described by Berglund and Liu (1973).[1] The generator consists of a droplet generation and dispersion system and an aerosol dilution and transport system. A Krypton-85 radioactive neutralizer of 10 millicurie activity is placed within the generator drying column to neutralize the particle electrostatic charge incurred during the droplet generation process.

In the vibrating orifice generator, uniform liquid droplets are generated by forcing a liquid through a small (5 to 20 μm diameter), vibrating orifice by a syringe pump at a predetermined rate of Q_1 cc/sec. The orifice is vibrated by a piezoelectric ceramic at a predetermined frequency of f Hz supplied by a signal generator. Within an appropriate frequency range, the liquid jet is broken up into uniform

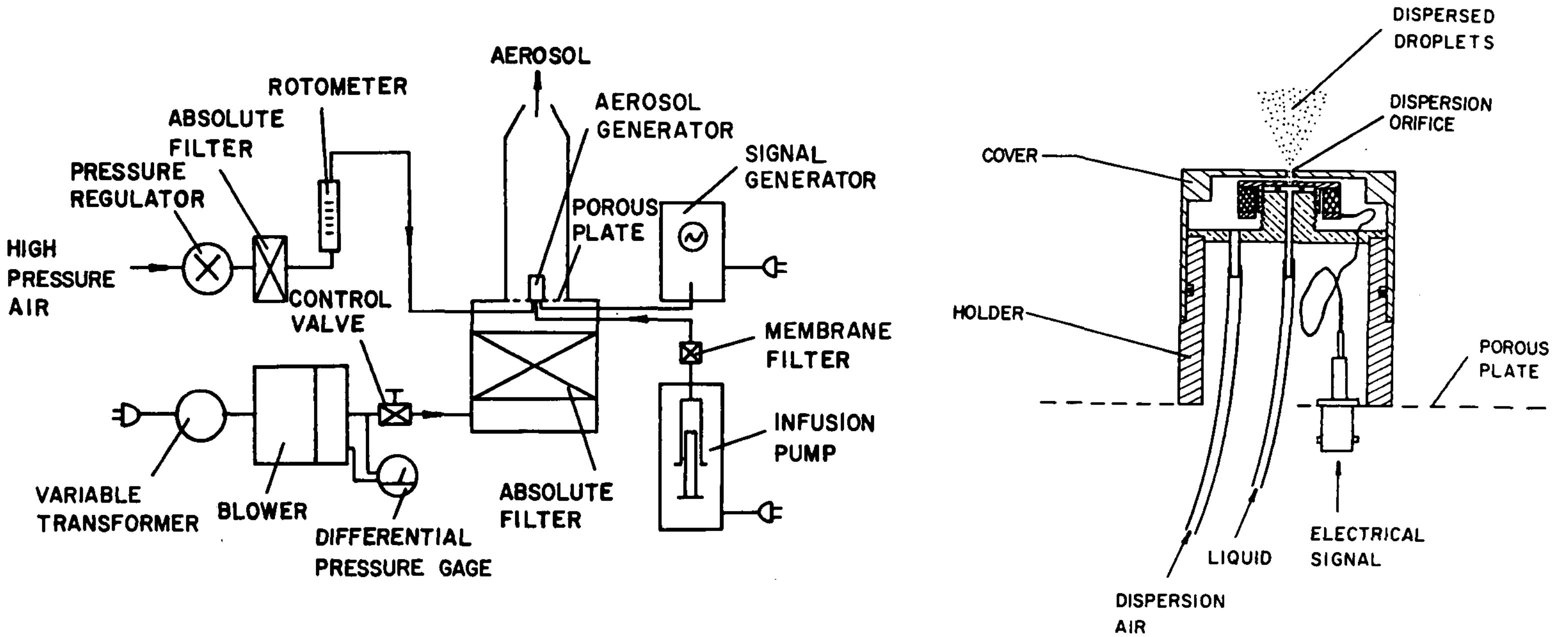


Figure 1. Vibrating orifice monodisperse aerosol generator[1]

Left: schematic of system
Right: generator head

droplets. Since each cycle of the disturbance produces precisely one droplet, the individual droplet volume is equal to

$$V_d = Q_1/f \tag{1}$$

The uniform droplet stream is then injected axially along the center of a turbulent air jet to randomize the particle motion and to prevent particle collision and coalescence. The dispersed droplets are then mixed with a much larger volume of filtered dry air to evaporate the solvent and to obtain a stable aerosol of a particle diameter

$$D_p = (6\ Q_1\ C/\pi\ f)^{1/3} \tag{2}$$

where C is the volumetric concentration of the non-volatile aerosol material in the liquid solution.

Equation (2) shows that the diameter of aerosol particles produced by the vibrating orifice principle can be calculated from the liquid flow rate, Q_1, the frequency, f, and the solution concentration, C. Since these quantities can be easily measured to a high degree of accuracy, the particle diameter can also be calculated to a high degree of accuracy by means of Equation (2). However, when dilute solutions (small C) are used, the non-volatile impurity in the solvent must be taken into account in the calculation of particle diameter. Experiments have shown that with proper precautions, the particle diameter, D_p, can be calculated by means of Equation (2) to a considerably higher degree of accuracy than can be measured by the conventional microscope techniques.

Table 1 is a summary of the operating conditions of the generator for three orifice sizes, and Figure 2 shows some typical particles produced by the generator.

Table 1. CHARACTERISTICS OF THE VIBRATING ORIFICE MONODISPERSE AEROSOL GENERATOR

Diameter of liquid orifice (μm)	Nominal frequency (kHz)	Droplet diameter (μm)[a]	Particle diameter range (μm)[b]	Nominal concentration (particles/cc)[c]
5	450	15	0.6 - 15	273
10	225	25	1.0 - 25	137
20	60	40	1.8 - 40	36

[a]Continuously adjustable over an approximate 25 percent range by varying the frequency

[b]Obtainable by the solvent evaporation technique

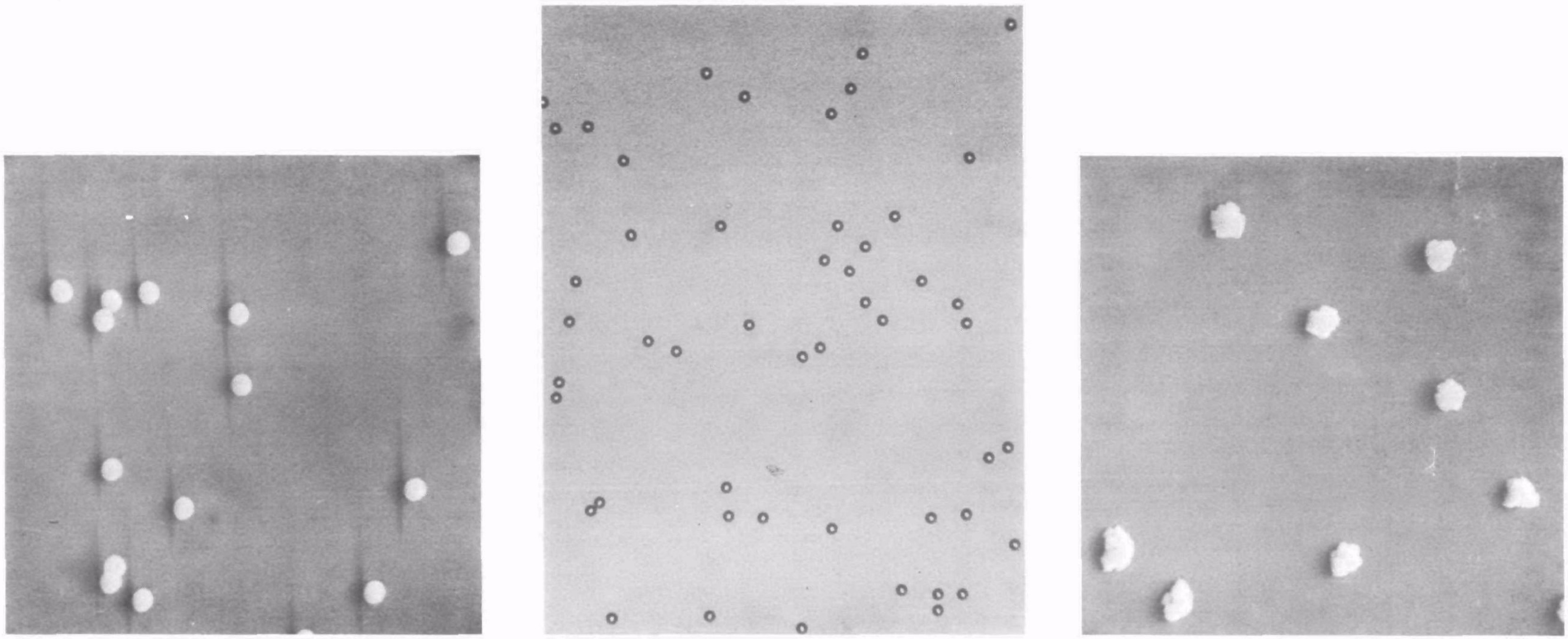
[c]Theoretical concentration based on the nominal aerosol output of 100 liters per minute

Theoretically the vibrating orifice generator can also produce aerosols of a known particle concentration. The theoretical aerosol concentration is given by

$$N_{th} = f/Q_a \qquad (3)$$

where Q_a is air flow rate.

The actual aerosol concentration at the generator output is less than the theoretical concentration due to particle loss in the drying and neutralization chambers and in the transport system. However, the operation of the generator is sufficiently stable so that after these losses are determined the aerosol concentration at the generator output is known. Figure 3 (Liu, Berglund and Agarwal, 1974)[2] shows the measured aerosol concentration at the generator output expressed as a percentage of the theoretical concentration and as a function of particle size. The actual concentration is seen to be about 81 percent (± 5 percent) of the theoretical concentration for particles



(a) (b) (c)

Figure 2. Monodisperse particles produced by the vibrating orifice generator[1]

(a) 3.7 μm diameter solid methylene blue particles
(b) 9.5 micron diameter liquid DOP (di-octyl phthalate) particles collected on an oil-phobic slide
(c) solid sodium chloride particles of 27.4 cubic micron volume

smaller than 6 μm diameter, and the actual concentration decreases steadily with increasing particle size. This particular feature of the generator is very convenient for determining the sampling efficiencies of aerosol measuring and sampling devices. For instance, to determine the absolute sampling efficiency of an optical particle counter, it is necessary only to apply the aerosol to the counter and to compare the counts registered by the counter with counts calculated from the known aerosol concentration and the sampling flow rate of the counter.

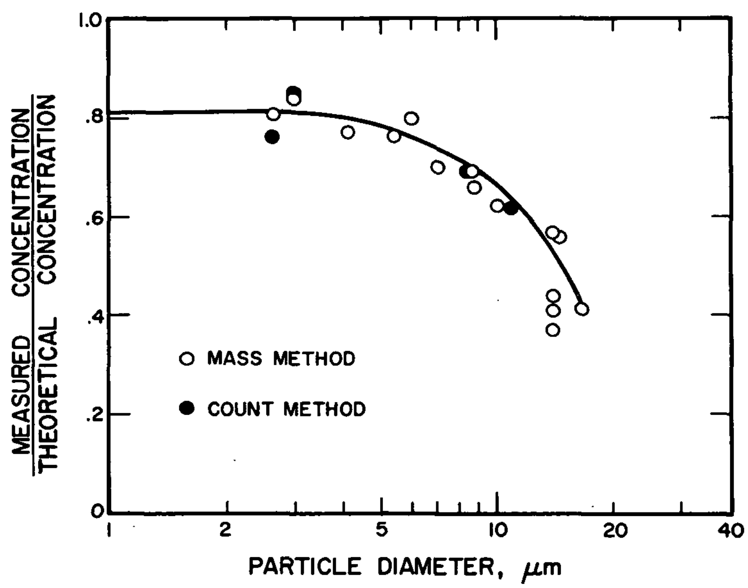


Figure 3. Output aerosol condensation of the vibrating-orifice aerosol generator as a function of particle diameter (Liu, Berglund and Agarwal, 1974)

GENERATION OF SUB-MICRON AEROSOL STANDARD BY ELECTROSTATIC CLASSIFICATION

For generating sub-micron aerosol standards below 0.5 μm, the system shown in Figure 4 has been developed (Liu and Pui, 1974).[3] The device produces uniform (relative standard deviation 0.04 - 0.08) particles at concentration levels up to 10^6 particles/cc by pneumatic atomization and electrostatic classification. The system consists of a Collision atomizer, a Krypton-85 radioactive neutralizer, a diffusion dryer, a differential mobility analyzer, and an electrometer current sensor.

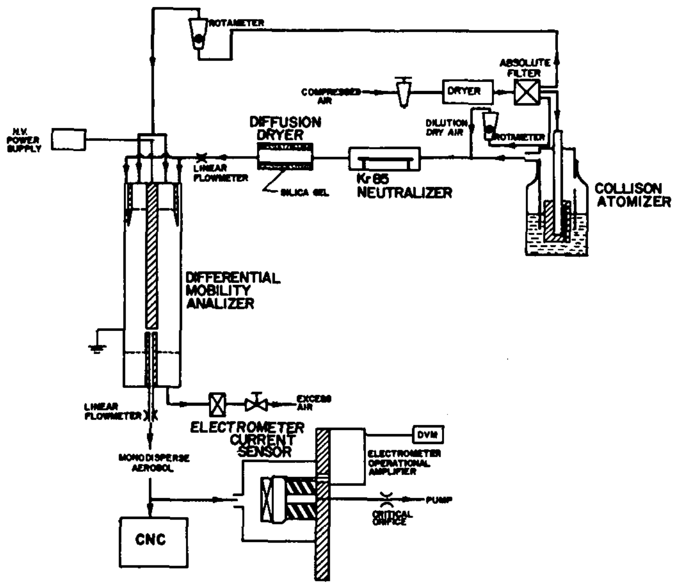


Figure 4. Apparatus for generating sub-micron aerosol standards (Liu and Pui, 1974)

In the apparatus a polydisperse aerosol is produced by the Collision atomizer. The aerosol particles are then brought to a state of charge equilibrium with bipolar ions produced by the ionizing beta radiation from the Kr-85 source. Below a size of about 0.075 μm diameter, most of the particles are either electrically neutral or carry one elementary unit of charge with an electrical mobility of

$$Z_p = 300 \ eC/3\pi \ \mu \ D_p \quad cm^2/volt\text{-}sec. \qquad (4)$$

where $e = 4.8 \times 10^{-10}$ esu is the elementary unit of charge, C is the dimensionless slip correction, μ is the gaseous viscosity, and D_p (cm) is the particle diameter. These singly charged particles can then be separated into monodisperse fractions by means of the differential mobility analyzer.

The differential mobility analyzer shown in Figure 4 is in the form of a cylindrical condenser with concentric electrodes. The inner electrode is held at a high voltage and the outer tube is grounded. Under a given set of operating conditions, charged particles in the aerosol stream flowing along the outer tube are deflected through the inner clean air core. If these particles have the appropriate electrical mobility, they would arrive at the exit slit near the lower end of the center electrode and be swept out by the air stream flowing through the slit. The electrical mobility of the particles is given by

$$Z_p = \left[Q_o - (1/2)(Q_s + Q_a)\right] \ln (r_2/r_1) \; / \; 2 \pi V L \tag{5}$$

where Q_o (cc/sec) is the total flow in the mobility analyzer, Q_a (cc/sec) is the aerosol flow at the inlet, Q_s (cc/sec) is the sample aerosol flow through the slit and at the generator output, r_2 and r_1 (cm) are the outer and inner electrode radii, V (volts) is the applied voltage on the center rod, and L (cm) is the distance between the aerosol inlet and the exit slit.

The monodispersity of the aerosol at the generator output is determined by the ratio of flow $(Q_s + Q_a)/Q_o$. In the experiments reported by Liu and Pui (1974)[3], the relative standard deviation of the aerosol ranges from 0.04 to 0.08.

Since nearly all the particles classified by the differential mobility analyzer were singly charged and the percentage of multiply charged particles in the aerosol stream is small, particularly for small particle sizes, the absolute concentration of the aerosol can be measured by measuring the total current associated with the aerosol particles,

$$I = q_e e N \tag{6}$$

where q_e (cc/sec) is the aerosol flow rate and N (particle/cc) is the aerosol concentration. The electrometer current sensor shown in Figure 4 is used to measure this current from which the aerosol concentration, N, can be calculated by means of Equation (6).

This generator has been used to provide an absolute concentration standard for calibrating condensation nuclei counters. The particle diameter accuracy is about ± 2 percent and concentration accuracy, ± 5 percent. These accuracies can be further improved if necessary. By the use of a fluidized coal dust feeder, in place of the atomizer shown in Figure 4, monodisperse coal particles having the same degree of monodispersity have been generated (Liu, Marple, Whitby, and Barsic, 1974).[4]

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METHODS FOR DETERMINING PARTICULATE MASS AND SIZE PROPERTIES: LABORATORY AND FIELD MEASUREMENTS

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INTRODUCTION

In order to determine the fractional efficiency of particulate control devices, measurements must be made of the size and concentration of particles suspended in the flue gas at both the inlet and outlet of the devices. In making these measurements, one encounters a wide variety of testing conditions. Flue gas temperature, pressure, moisture content, and the physical properties of the particulate vary widely from device to device. Concentrations vary by orders of magnitude from inlet to outlet, and from one control device to another. Because of this complexity and the limited range of testing devices, more than one instrument is required to give complete information on the particle size distribution, even at a single site.

Currently, practical particle sizing techniques for making fractional efficiency measurements fall into three categories: inertial, diffusional, and optical. Of these, only the optical and, to a certain extent, the diffusional methods offer the capability of real time, continuous monitoring. An electrical particle counter being developed at the

University of Minnesota is a promising candidate device for real time data acquisition for particles in the 0.01 to 0.5 μm range. Also, an instack "Beta-Tape" impactor being developed for the Environmental Protection Agency by GCA/Technology Division may provide very nearly real time data for particles in the 0.3 μm size range.

INERTIAL METHODS

Impactors, impingers, cyclones, and centrifuges have been used for many years for determinations of particle size distributions. Because of its compact arrangement, the cascade impactor has generally been found to be the most suitable inertial device for mass distribution measurements of pollution emission sources.[1-5, 8-10] In most cases, the impactors can be inserted directly into the duct or flue, thus eliminating many condensation and sample loss problems which occur when probes are used.

DIFFUSIONAL METHODS

A diffusion battery consists of a number of long, narrow, parallel channels, or a cluster of small bore parallel tubes. Systematic variations in length and number of channels (or tubes) and in the aerosol flow rate are used as a means of measuring the number of particles in a selected size range. It is assumed that once a particle diffuses to the wall of a diffusion battery, it will adhere and thus be removed from the sample gas stream. Because particle diffusivities increase with decreasing particle size, the fraction of an influent aerosol that penetrates a battery will depend on the particle size distribution of the aerosol. The penetration of the battery can be measured with a condensation-nuclei (CN) counter. Figure 1a shows a typical diffusion battery geometry used in the work described in this paper, and Figure 1b shows the penetration characteristics of this battery under typical operating conditions.

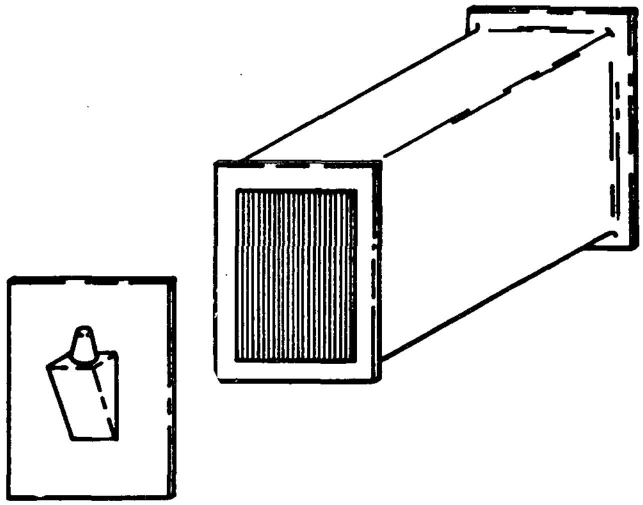


Figure 1a. Parallel plate diffusion battery - the batteries have 12 or 100 channels, 0.1 x 10 x 48 cm

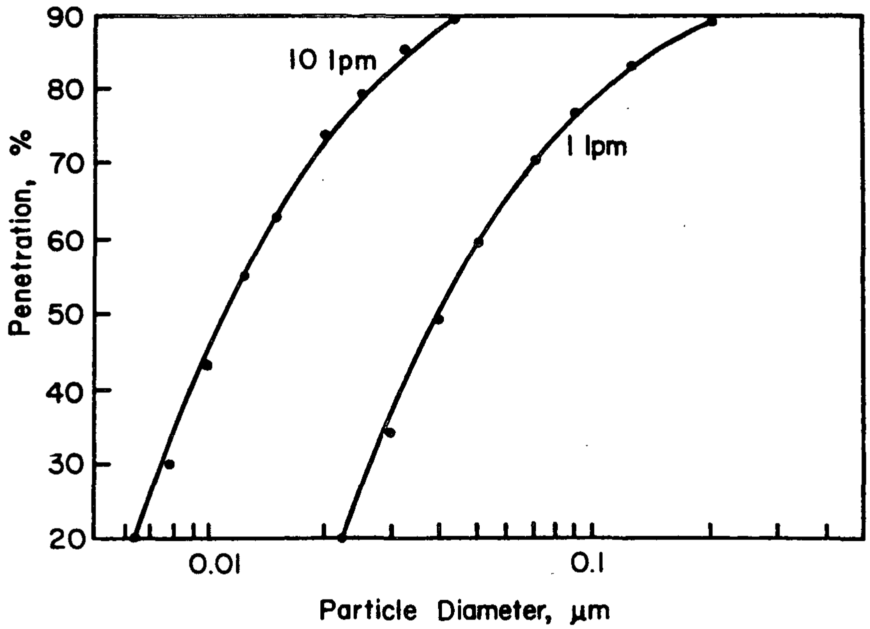


Figure 1b. Penetration curves for monodisperse aerosols (100 channels, 0.1 x 10 x 48 cm)

OPTICAL METHODS

Optical/Electron Microscopy

One method for determining the concentration and size distribution of particles in a process gas stream is to collect the particles on a suitable medium (i.e., a membrane filter, electron microscope carbon film substrate, etc.) by filtration, electrostatic deposition or some other suitable technique. This sample can subsequently be examined at the microscope and by manual or automated counting techniques arrive at a size distribution based on some characteristic dimension of the particles. In practice, this method tends to be slow. Furthermore, the surface density of the particles on the collection medium must be low in order to avoid overlapping particles, thus, the total gas volume sampled may be small and may not be representative of the total process gas stream.

Photoelectric Particle Counters

Photoelectric or optical particle counters function on the principle of light scattering. Each particle in a continuous flowing sample stream is passed through a small illuminated volume. Light scattered by the particle is imaged on the surface of a photodetector during the time of the particle is illuminated. The intensity of the scattered light is a function of particle size, shape, and index of refraction. Photoelectric particle counters will give reliable information if the concentration of particles is such that the probability of illuminating more than one particle at a time is low. Typically, this restriction places an upper limit of about 300 particles/cm^3 for instruments providing size information down to diameters of 0.3 μm, the practical lowest sensitivity for optical sizing. Thus, optical particle counters are effective in the same size regime as inertial sizing devices. Disadvantages are the necessity to dilute the sample to number concentrations less than 300/cm^3 and the dependence of the calibration upon the index of refraction and shape.

MEASUREMENT TECHNIQUES AS USED IN CURRENT PRACTICE

IMPACTORS

Table 1 shows some characteristics of several commercially available cascade impactors. It is usually impractical to use the same impactor at the inlet and outlet of a pollution control device for efficiency measurements because of the difference in particle concentration. For example, if a sampling time of thirty minutes is adequate at the inlet of a control device with a collection efficiency of 99 percent, approximately 3000 minutes (two days), of sampling would be required at the outlet for the same amount of sample to be collected if the same sampling flow rate is used. Although the flow rates of impactors can be varied somewhat, they cannot be adjusted enough to compensate for this difference without causing undesirably large shifts in instrumental calibration and other problems. For example, extremely high flow rates result in particle bounce and in scouring of impacted particles from the lower stages of the impactor where the jet velocities become extremely high. On the other hand, using a high flow rate for inlet sampling may necessitate short sampling times which can result in atypical samples being obtained as a result of momentary fluctuations in the particle concentration or size distribution within the duct.

The actual extraction of a size fractionated sample from a gas stream using cascade impactors is a well established procedure at this time.[1,2,3,5,8] The following paragraphs deal mainly with unexpected or non-ideal behavior that has been encountered in field applications.

Wall Losses

Particles are lost within an impactor by diffusion and impaction of the walls and jets. Lundgren[9] and Gussman *et al*[10] have shown that the losses per stage can amount to as much material as is collected by the stage. Measurements of mass concentrations taken with impactors in the course of

Table 1. SIZE FRACTIONATING POINTS OF SOME COMMERCIAL CASCADE IMPACTORS FOR UNIT DENSITY SPHERES

Stage	Modified Brink	Andersen Mark III	U. of W. (Pilat)	E.R.C. Tag
	(0.85 LPM)	(14 LPM)	(14 LPM)	(14 LPM)
Cyc	18.0 μm			
0	11.0			11.1 μm
1	6.29	14.0 μm	39.0 μm	7.7
2	3.74	8.71	15.0	5.5
3	2.59	5.92	6.5	4.0
4	1.41	4.00	3.1	2.8
5	0.93	2.58	1.65	2.0
6	0.56	1.29	0.80	1.3
7		0.80	0.49	0.9
8		0.51		0.6

field work performed by Southern Research Institute have consistently produced results about 70 percent as large as those obtained by the non-sizing, standard techniques. Laboratory work is now underway at SRI to determine the magnitude of interstage losses in the various cascade impactors commonly used for stack sampling.

Reentrainment

All the particles that strike a collection stage do not stick. A technique used to enhance the retention of particles on the original impaction site is to coat the impaction substrates with a suitable viscous grease. One approach that was found to be satisfactory was to make a 10 to 15 percent suspension or solution in benzene of high vacuum silicone grease or certain ethylene glycol compounds used in chromatographic columns. After placing an appropriate quantity of this suspension on the collection surface and allowing the benzene to evaporate, the coated substrates are baked for about an hour at 400°F and desiccated until actually used. As yet, no coating suitable for use at temperatures over 400°F has been found; however, some high temperature lubricants appear to offer promise for this application.

Even with greased substrates, significant scouring and loss of material occurs on the last stages if the jet velocities are too high. Experimentally, we have found a value of about 65 m/sec to be the maximum velocity usable without reentrainment or grease erosion using greased substrates, and about 35 m/sec using ungreased substrates. In effect, these phenomena place an upper limit on the flow rates at which an impactor may be operated to obtain a valid particle size distribution.

One model of the Andersen Stack Sampler uses glass fiber filters as impaction substrates. These filters seem to be a satisfactory alternative to a greased substrates in minimizing particle bounce and reentrainment. Glass fiber substrates have also been used with the Brink impactor at high temperatures.

Weighing Accuracy

The maximum stage loadings for any of the currently available impactors are about 10 mg or less, depending on the impactor stage, the material being collected, and the operating conditions of the impactor. If the sample collected at the most heavily loaded stage can be, at most, only 10 mg, some stages will collect samples of only a few tens or hundreds of micrograms. In order to maintain reasonable accuracy in the results, a weighing accuracy and sensitivity of about 10 to 30 micrograms is necessary.

Techniques which have been used to minimize problems in weighing to the required accuracy are: to reduce the tare weight of the collection stages by using lightweight inserts made of aluminum foil, stainless steel shim stock, or glass fiber filter material. In instances in which the concentration of large particles is high, as compared to the concentration of fine particles, two techniques are commonly used to prevent overloading of the first stages of the impactor before obtaining adequate samples on the last stages. These techniques are to purposely bias the sample against large particles by pointing the nozzle downstream or to use cyclone precollectors to remove large particles before the sample enters the impactor. The use of lightweight substrates and cyclone precollectors is becoming more common. This combination gives the maximum weighing accuracy and still permits near isokinetic sampling to be used, allowing one to obtain some information on the concentrations of large particles. The capture efficiency of the precollector cyclone must be taken into account when doing data analysis; however, or the results will not be representative of the true aerosol for large particle sizes.

Isokinetic Sampling

A selection of nozzles having different bores is available for each impactor so that at a single volumetic flow rate, several velocities may be achieved at the inlet of the impactor. Once a sampling velocity is chosen, however, it cannot be changed during a test because the fractionation points of each collection stage would change. Since the impactor flow rate is fixed during a test, any velocity fluctuations in the process gas stream will introduce errors in the sampling of the larger particles. Traverses of a duct are best obtained by suitably averaging several single point samples.

Particle Size Calculations

The Stokes diameter may be used to describe a particle size. This is the diameter of a sphere having the same density and terminal velocity as the particle, and frequently provides a reasonable approximation of the true physical dimensions of the particles. In the presentation of much cascade impactor data, an aerodynamic diameter is used. This is the diameter of a sphere of unit density which has the same aerodynamic behavior as the particle; that is, the particle behaves in the impactor in the same way as would a water droplet of the indicated size.

Stage collection efficiencies for cascade impactors are calculated using equations developed by Rantz and Wong.[4] The effective stage fractionation points (D_{50}) may be determined for unit density spheres (as was done in Table 1) and corrected for density as required, or approximate physical diameters calculated for spheres having the estimated density of the aerosol particles, depending upon the intended use of the data. An "average" density can be calculated from true particle volume-weight data taken with a helium pycnometer for a representative sample. If the chemical composition of the particles is known, the bulk density may be used. In some cases, the aerodynamic diameter may be the only information needed and density is not a factor.

The validity of size information based on an average density depends upon the uniformity of the density from particle to particle. A mixture of particles having very different densities could cause large errors in attempts at estimating true diameters of the particles collected on the various stages.

The results of a typical set of measurements based on 20 samples is shown in Figure 2. This figure presents mean mass concentration in equal logarithmic size intervals centered on the indicated sizes and probable error bands.

OPTICAL AND DIFFUSIONAL METHODS

Dilution

Because of the concentration limits for operating optical counters (300 particles/cm^3) and condensation nuclei (CN) counters (10^5 particles/cm^3), problems with condensation in the sampling lines, and losses due

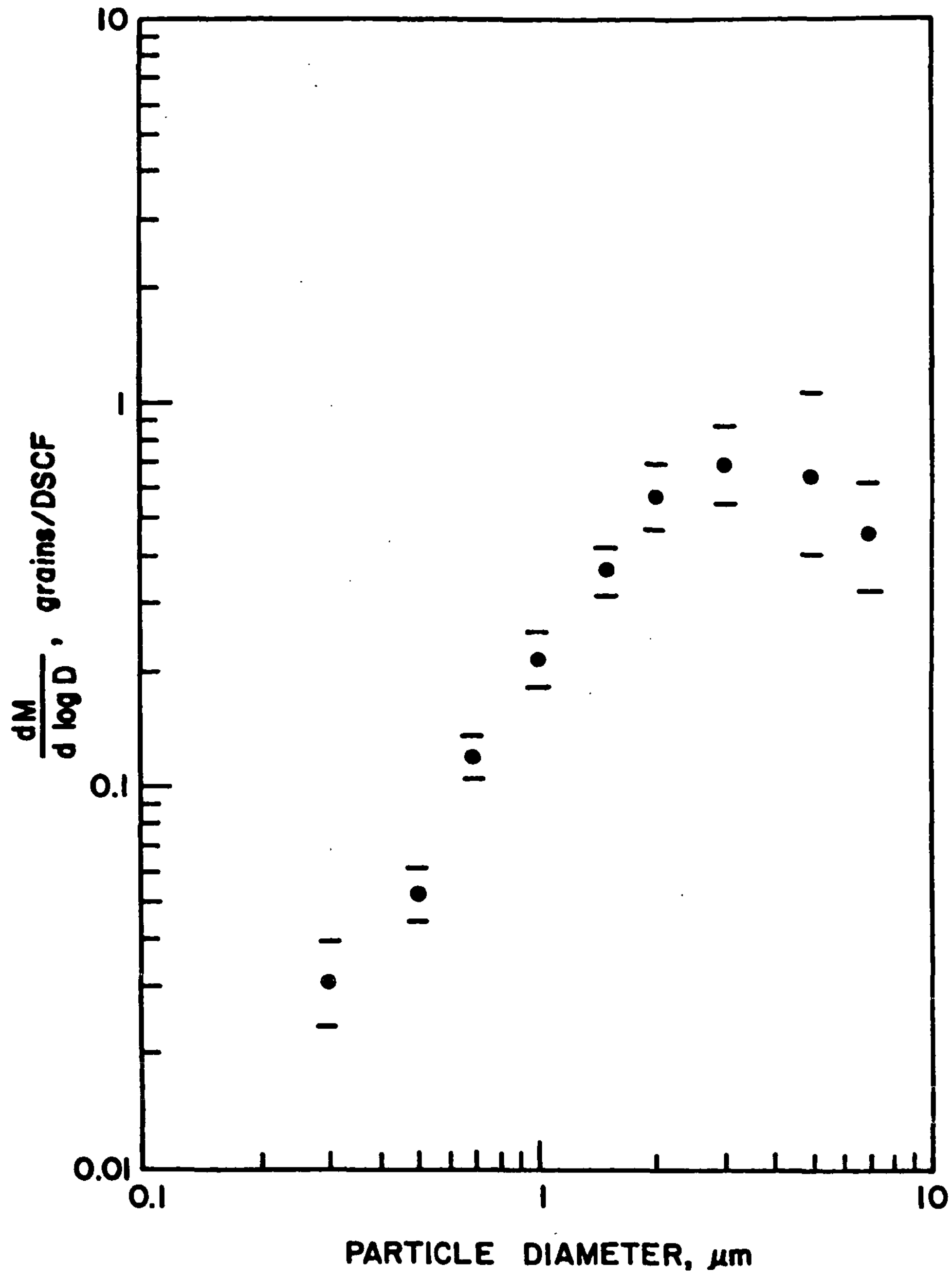


Figure 2. Mass size distribution for a coal fired power plant burning western coal as measured with cascade impactors

to agglomeration during the measurement process, it is necessary to dry and dilute the sample aerosol before it reaches these devices.

Figure 3 shows schematically the testing configuration for optical and diffusional sizing. The sample is introduced at the apex of a perforated cone and clean dry dilution air is pumped through the perforations, creating a highly turbulent mixing zone. In verifying the performance of the diluter in the laboratory using test aerosols, it was found that calculated and measured dilution factors agreed to within the uncertainty in measuring the sample and dilution air flow rates. The concentration was found to be uniform for sampling points from wall to wall across the body of the diluter.

Plugging of the sample metering orifice can be a problem, even when condensation does not occur. To prevent this, a cyclone precollector with a D_{50} of about 2 μm is used to eliminate large particles. Typical sample flow rates are from 0.1 lpm to 5 lpm with the cyclone flow rate maintained at about 14 lpm.

Diffusional losses in the probes and sample lines used in our work are estimated to be about 98 percent at 0.001 μm diameter, 25 percent at 0.005 μm diameter, and 12 percent of the 0.01 μm diameter particles. Ström has shown that particles having diameters less than about 2 μm are not lost by impaction or settling for a wide range of conditions.[11] Thus, losses in the sampling lines used in this work are probably not significant for particles having diameters between 0.005 μm and 2 μm.

Optical Sizing

A Climet Particle Analyzer, Model No. CI-201, is the primary instrument used in our field work. Other manufacturers of similar instruments are Royco and Bausch and Lomb. These instruments use light scattering by single particles to obtain particle size information. A view volume is

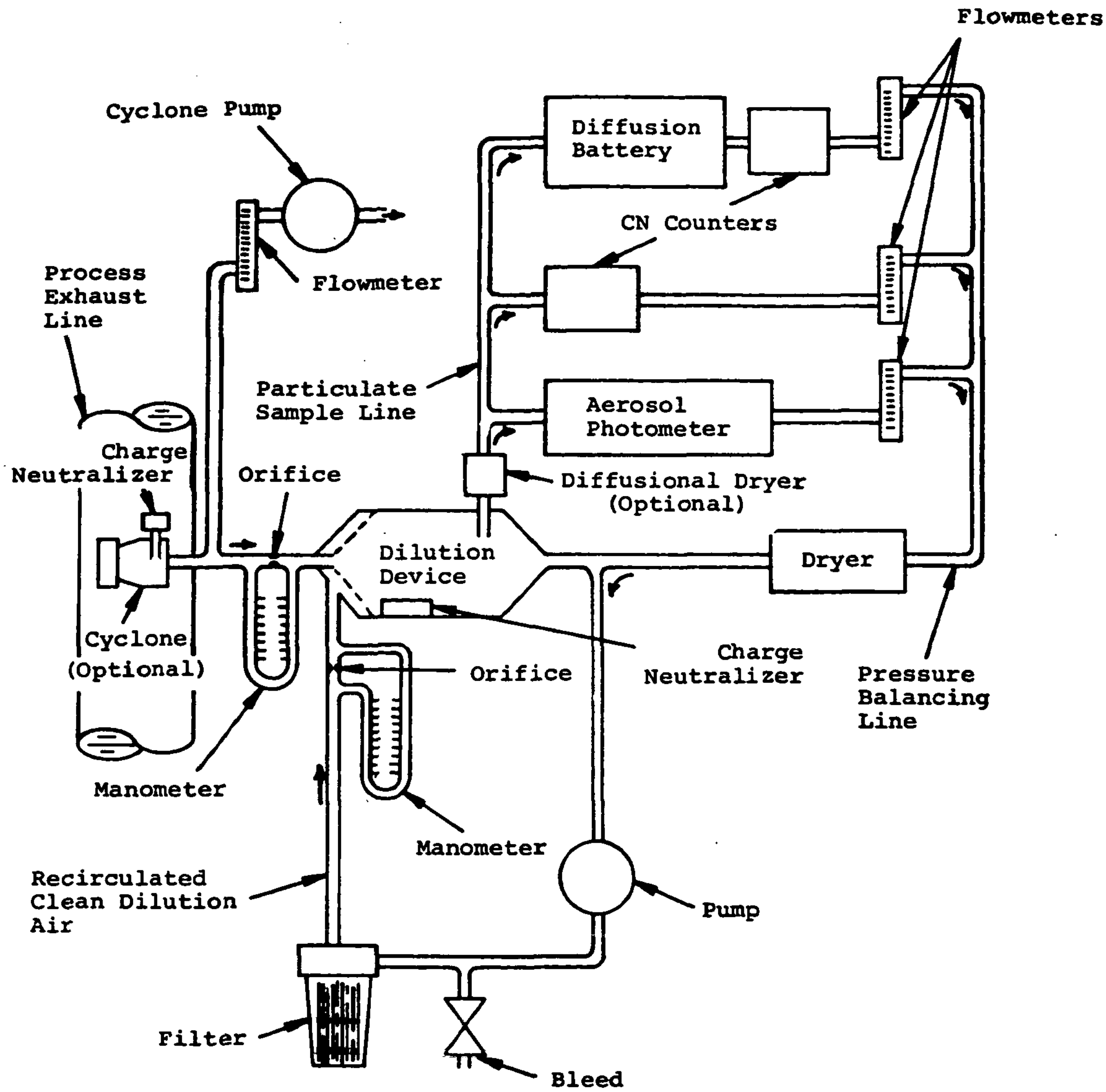


Figure 3. Optical and diffusional sizing system

located at the focus of an illuminator optical system, and the photomultiplier is used to detect scattered light from particles as they pass through the view volume. The amplitude of the scattered light pulses is related to the particle size and the rate at which the pulses occur is related to the particle concentration. Operated in the configuration shown in Figure 3, with a cyclone precollector, such a counter has an effective upper limit of about 2 μm for sizing. Also, the counters have inherent lower limits of about 0.3 μm. Thus, the counters respond to a limited size range, but give information in an important regime, that where data from the diffusional and impactor measurements converge.

Optical particle counter responses are affected by the index of refraction, and shape of the particulate. Some generalization may be made from Hodkinson's review.[13]

When using white light as a source of illumination, the response to an assembly of randomly oriented, identical, nonspherical particles will be the same as that for the spherical particles of equal mean volume whose polydispersity resembles the "orientation polydispersity" of these particles. The major effect would be more apparent polydispersity than actually exists.

If the scattered light is collected in some small angle about the forward direction, and white light is used, the dependence of the amplitude upon index of refraction can be minimized. For particles greater than 2 μm diameter, the amplitude of the forward scattered light pulse is almost independent of the index of refraction and is proportional to the cross-sectional area of the particles. For particles less than 2 μm diameter, however, there is no simple relationship between particle size and amplitude, and the index of refraction is more important. Berglund found that measurements deviated from theory by as much as a factor of two in the size range of 0.4 μm to 1 μm and in some cases the same response was obtained for several particle sizes.[14]

Figure 4a shows our laboratory calibration for polystyrene latex spheres having an index of refraction of 1.6. Calibration shifts caused by refractive index changes can be made from a theoretical basis; however, because of the uncertainty in making a theoretical correction for index of refraction (n), we generally correlate the optical data with sedimentation data, a method which is independent of refractive index.

Referring again to Figure 1, if the diffusion batteries are laid on their sides, so that the long dimension of the slots is horizontal, the most important mechanism for the removal of large particles will be sedimentation, with rather high efficiencies being obtained for micron-sized particles. Concentrations of particles producing particular optical responses entering and exiting the sedimentation chambers can be measured with the optical particle counter and Stokes diameters based on sedimentation losses can be calculated for the particles producing the particular scattered light intensity. A typical set of correlations obtained in this manner at a coal fired power plant is shown in Figure 4b.

Diffusional Sizing

Fuchs[15] has reviewed diffusion battery sizing work up to 1956, while Sinclair,[16] Breslin et al,[17] Twomey,[18] and Sansone and Weyel[19] have reported more recent work, both experimental and theoretical.

Diffusion measurements are less dependent upon the aerosol parameters than the other techniques discussed and perhaps are on a firmer basis theoretically.

Disadvantages are the bulk of the diffusion batteries and peculiar problems introduced by particular testing situations. For example, on one occasion, when testing emissions with a high gaseous SO_2 content, particles were actually "created" within the diffusion batteries by oxidation of SO_2 to SO_3 and subsequent formation of macro-molecular

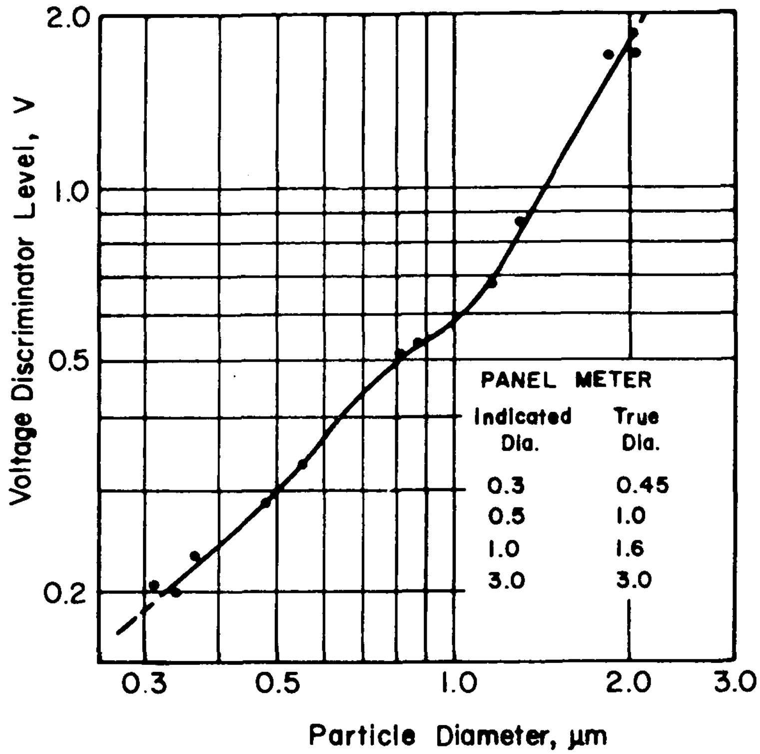


Figure 4a. Calibration curve for climet optical particle counter. Polystyrene latex (PSL) spheres were used as standards

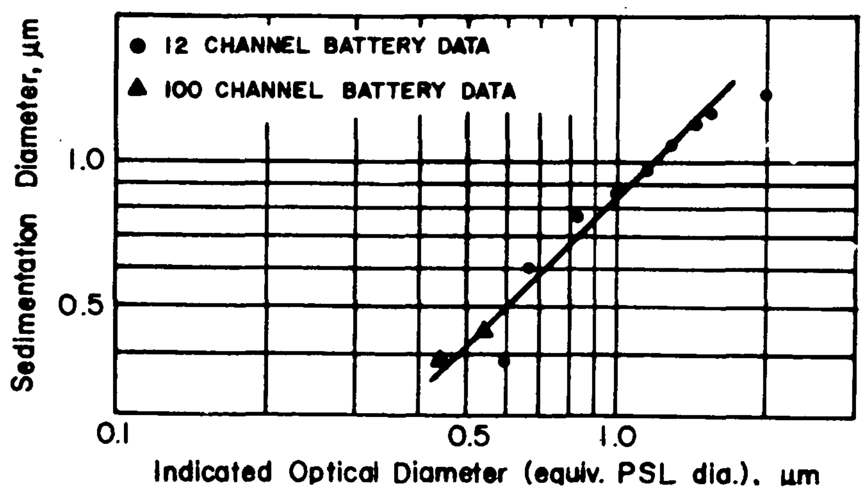


Figure 4b. Correlation of optical and sedimentation diameters

clusters of sulfuric acid molecules. As in the case of optical sizing, dilution and drying of the sample air is necessary to prevent coagulation, growth of hygroscopic particles, and water condensation.

The geometry chosen for our experimental work was that of parallel plates (see Figure 1), partly because of ease of fabrication and availability of suitable materials, but also because sedimentation can be ignored if the slots are vertical, while additional information can be gained through settling if the slots are horizontal. The mathematical expression for penetration (n/n_0) of a rectangular slot or parallel plate diffusion battery by a monodisperse aerosol was given in series form by Gormley.[20] The coefficients were calculated and tabulated by Twomey.[18]

The data reduction technique used in our work was suggested by Sinclair.[16] A nomograph is prepared using the penetration for each diffusion battery geometry and flow rate and a large number of monodisperse particle sizes. Comparing this nomograph with experimental penetrations, one calculates the particle size distribution using a "graphical stripping" process.

By using several diffusion batteries, each at several flow rates, a large number of data points can be obtained. The inlet and outlet concentrations may be measured with a single CN counter, or in cases where the concentrations fluctuate rapidly, the inlet and outlet concentrations can be monitored continuously using two CN counters. Flow pulsations caused by the cyclic processes in the CN counters were minimized by using anti-pulsation devices as described by Sinclair.[16]

Diffusional sizing is independent of density, index of refraction, and to a large extent, shape. Further, if the response of the CN counter is linear, diffusional sizing and control device efficiencies derived therefrom are independent of errors in calibration of the CN counter.

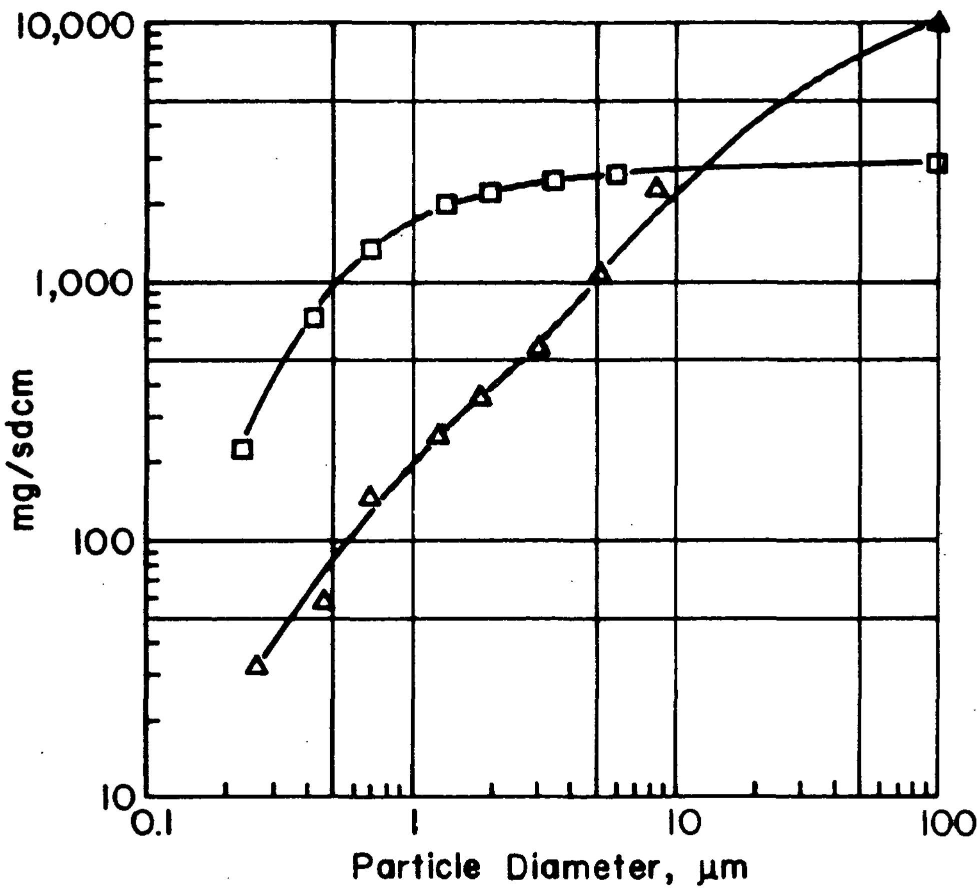
RESULTS

To date, the methods described in the previous sections have been used to determine fractional efficiencies of four full scale and six pilot scale control devices. The particulate sources included coal fired boilers burning both eastern (moderate to high sulfur) and western (low sulfur) coals, an open hearth furnace, and SO_2 absorbers installed on a sulfite pulp mill and a coal fired power boiler.

Typical size distributions of the influent to some control devices are shown on a mass basis in Figure 5 which includes data from a coal fired boiler and the open hearth furnace. Figure 6 shows size distributions for these same sources over the range from 0.01 μm to 1.0 μm as determined by optical and diffusional methods together with control device outlet data for a scrubber installed on the open hearth furnace, and an electrostatic precipitator installed on the coal fired boiler. Transformation from number distribution to mass distributions up to a limiting size of 1 μm was done for data from one of the coal fired boilers. Comparison of the mass distribution thus obtained with the mass distribution obtained with impactors showed a reasonable agreement ($\pm$ 50 percent) on a cumulative mass basis.

CONCLUSIONS

Although no single particle size measuring device was found suitable in both the fine and ultrafine particle size regimes, the combination of impactors, optical counters, and diffusion batteries with condensation nuclei counters has been successfully used to measure particle size distributions and fractional efficiencies from 0.005 μm to 10 μm diameter. It is believed that this combination represents a viable package which will continue to be useful in making measurements of this type.



△ Coal fired boiler (Precipitator A)
□ Open hearth process (steam-hydro scrubber)

Figure 5. Typical inlet mass distribution data from pollution sources

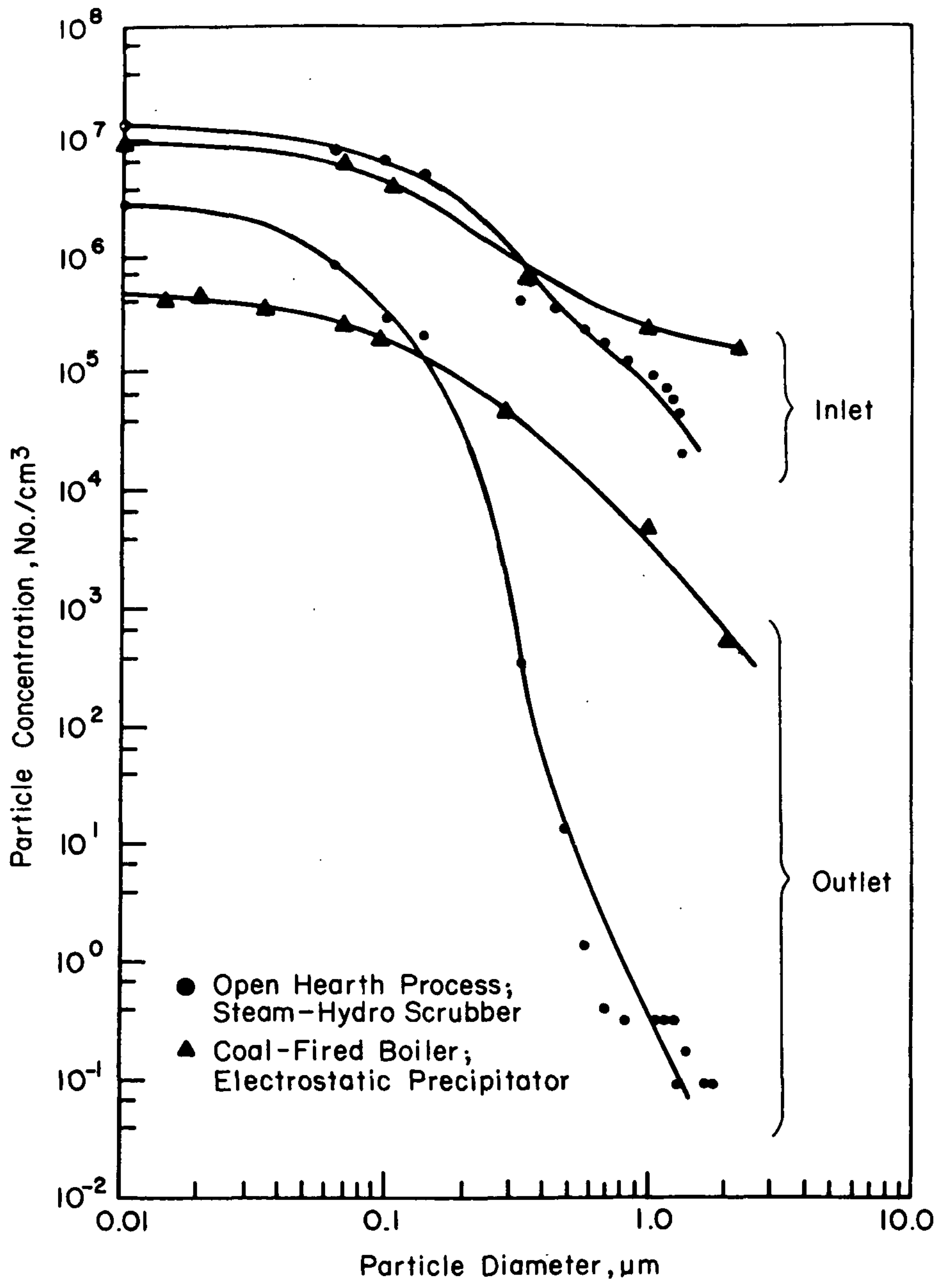


Figure 6. Typical inlet and outlet cumulative number distribution data from pollution sources

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MOBILE FABRIC FILTER SYSTEM: DESIGN AND PRELIMINARY RESULTS

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INTRODUCTION

The high efficiency capabilities of fabric filters and the increasing need to control fine particulate emissions has resulted in an intensive effort to learn more about the parameters determining the performance of filter systems. While considerable data are available on the overall mass efficiency of fabric filters, only limited data are available on their collection capabilities for fine particulates. Fabric filters are therefore the subject of many laboratory and field studies, some with special emphasis on fractional size efficiencies.

One advantage of laboratory experiments is that the experimenter can custom design the total system so that the parameters under study may be conveniently and systematically varied while those not being studied can be held constant. Draemel[1] was able to evaluate 123 fabrics with various dusts while studying the relationship between clean cloth fabric structural parameters, dust parameters and filter performance. Laboratory situations are well suited to wide ranging studies of the fundamental effects and interrelationships of fabric filter parameters. However, a major disadvantage of laboratory studies is that the test aerosol seldom, if ever, duplicates the real industrial aerosol. The basic techniques for dust dispersion are compressed air dispersion and venturi mixing. These methods may fail to generate a fine particle distribution comparable to representative industrial sources because of incomplete dust redispersion. Many fine particulates encountered in the field result from condensation processes such as the zinc oxide fume from a secondary brass foundry. Although this operation could be simulated by boiling zinc in a chamber with sufficient oxygen to form zinc oxide, this technique would be difficult and not entirely satisfactory. In addition to duplicating the particle size and concentration properties of an actual field emission, one would also desire to duplicate the other aerosol properties such as chemical composition, density, shape and surface characteristics, and electric charge properties, as well as the temperature, humidity, and contaminants present in the gaseous stream. Problems in extrapolating laboratory performance to field performance are often encountered, since differences in aerosol properties such as those mentioned above are very common.

Field studies of operating industrial fabric filters do not, of course, present the problem of dust generation. The Environmental Protection Agency has and is now sponsoring field tests that will provide important data on fabric filter performance during normal operations. However, it is generally not possible, or at least not practical, to vary the cleaning parameters, change the fabric, vary the filtration velocity or make other changes in the operation of an industrial fabric filter. In order to study the effects of fabric filter parameters when filtering an actual industrial effluent stream, it is necessary to vary these parameters in the field. In an attempt to provide this needed information, the Environmental Protection Agency has contracted with GCA/Technology Division to design, fabricate and operate a mobile fabric filter system.* The design characteristics of this apparatus and some preliminary field data collected with this system are summarized in this paper.

*Contract Number EPA 68-02-1075.

MOBILE FABRIC FILTER SYSTEM DESIGN

GENERAL DESCRIPTION

The mobile fabric filter system is designed for the purpose of determining the effects of dust properties, fabric media, cleaning parameters and other operating parameters on fabric filter performance. Specifically, the mobile fabric filter system has the following capabilities. Filtration can be conducted at cloth velocities as high as 20 fpm with a pressure differential up to 20 in. of water, and at gas temperatures up to 550°F. The mobile system can be adapted to cleaning by mechanical shaking, pulse jet or low pressure reverse flow. Cleaning parameters can be varied easily over broad ranges. One to seven filter bags of any fabric media, 4 to 10 feet long and up to 12 in. in diameter may be used. Automatic instruments and controls permit 24-hour operation of the mobile filter system.

The system is transported to field sites on a 1-1/2 ton stake truck having a body platform 12 feet long and 7 feet wide. Although the equipment will be operated on the truck in most cases, it can be removed from the truck with a small truck-mounted crane and operated at locations not accessible to the truck. The heavier components of the system are the primary fan (about 400 pounds), the compressor (also about 400 pounds), the five sections of the filter housing (total weight about 600 pounds), and the control console that weighs approximately 200 pounds. Figures 1, 2, and 3 are schematic diagrams of the mobile fabric filter system.

SPECIFIC DESIGN FEATURES

In order to minimize any possible short- or long-term corrosion problems caused by test aerosols or climate factors, the five section filter housing was constructed of stainless steel. Section 1 consists of a

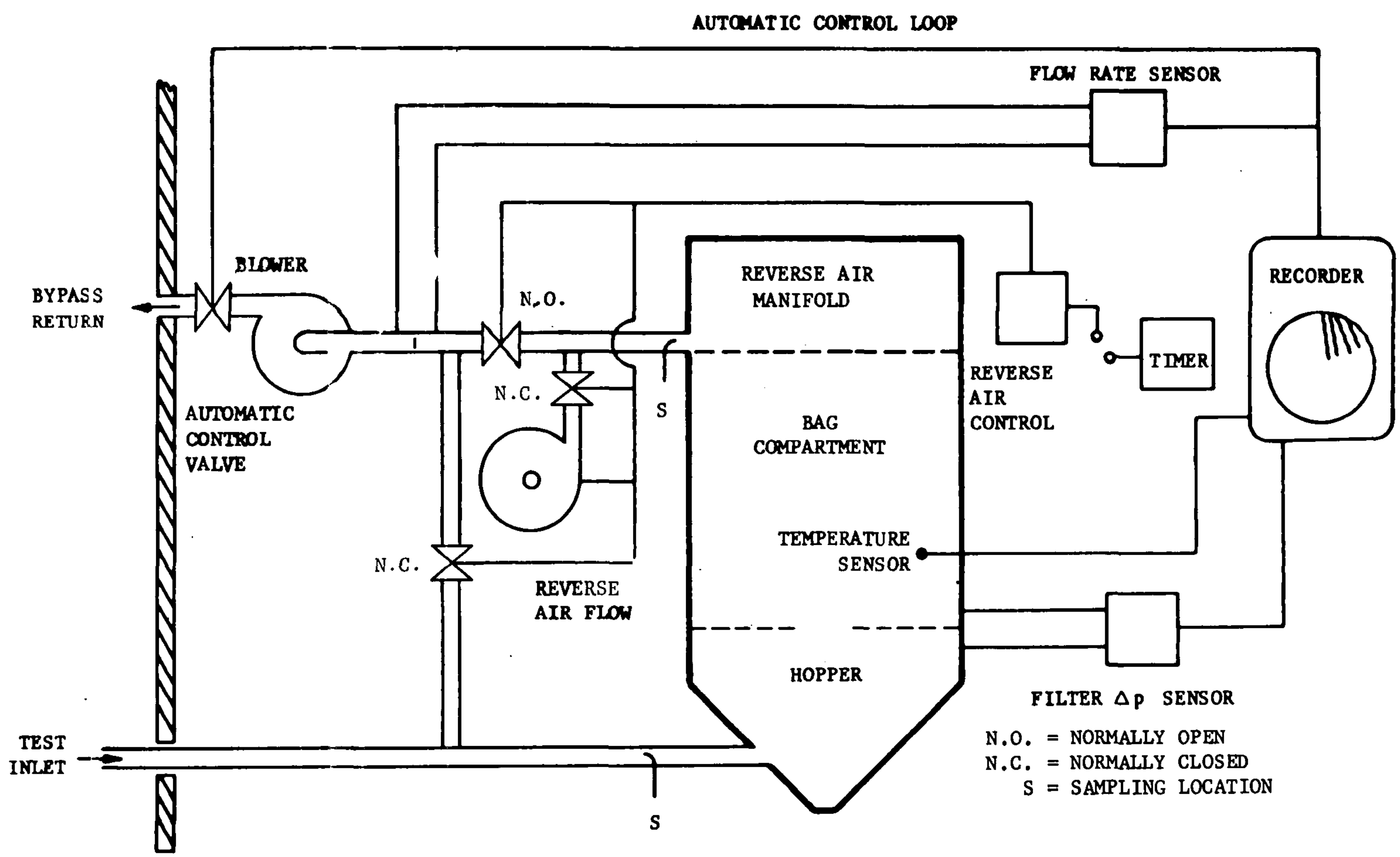

Figure 1. Reverse flow system control arrangement

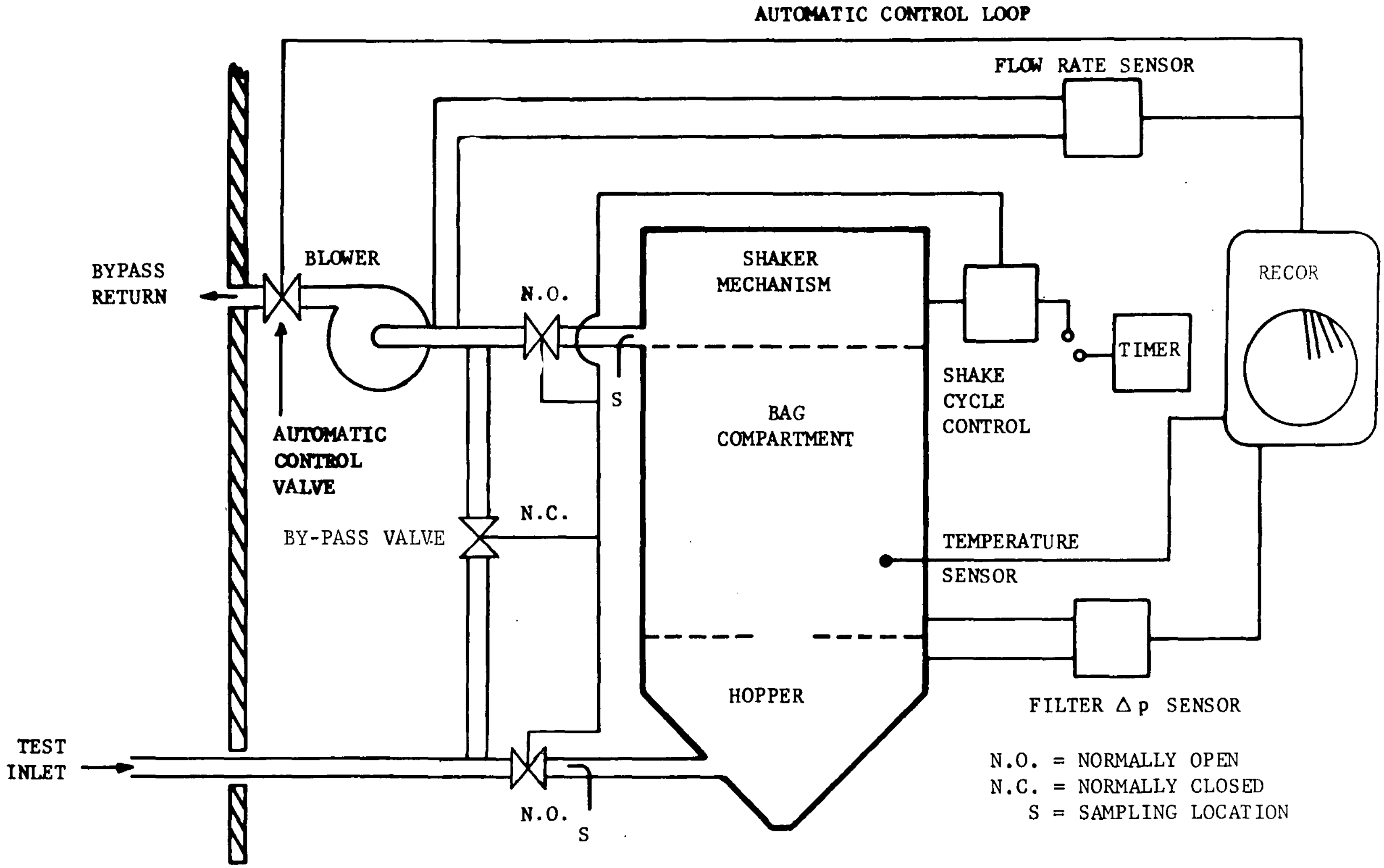

Figure 2. Mechanical shaking system control arrangement

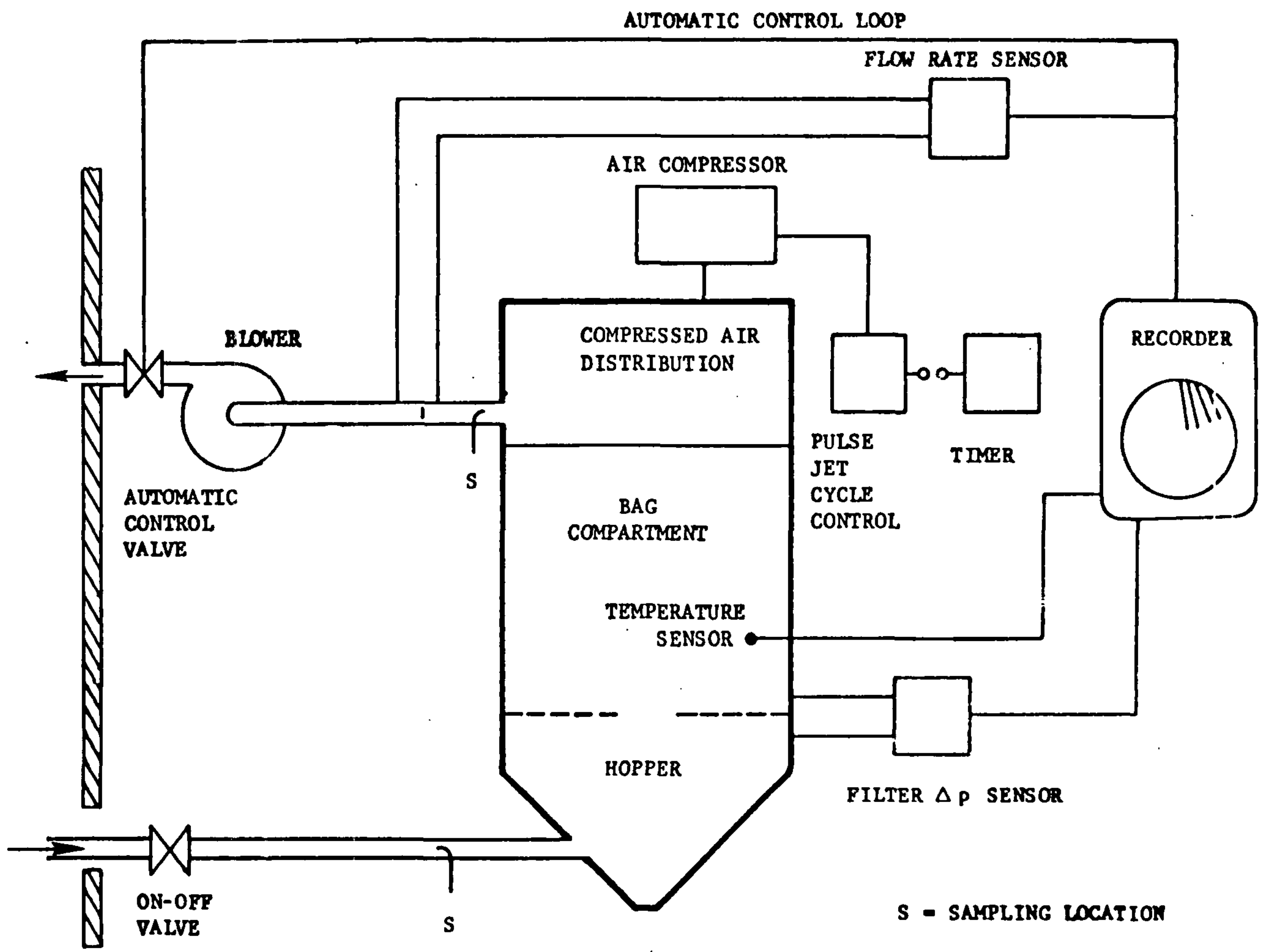

Figure 3. Pulse jet cleaning system control arrangement

hopper with a rotary dust discharge valve, designed to operate at 550°F. Section 2 is a 4-foot section that is presently used for pulse jet cleaning. The third section is a 6-foot section that is now used for shake cleaning. Both the 6- and 4-foot sections can be assembled in series so that bags up to 10 feet long may be used. Separate top sections have been built for shake cleaning and pulse jet cleaning. Reverse flow cleaning can be employed with either of the two top sections cited above.

Gas flows ranging from 26 to 280 cfm, as determined by cloth velocity, bag size, and bag number, must be carried by the mobile system ducting. Duct velocities are maintained between 2000 and 4000 fpm to minimize dust settlement and to prevent excessive pressure drop. Thin-walled, stainless steel pipe joined by Morris* couplings is used.

The primary fan for the mobile fabric filter is a Chicago Turbo-Pressure Blower+ capable of supplying 21 in. of water suction at 550°F. At ambient conditions it can supply 42 in. of water at a flow of 420 cfm at 5 horsepower. Although the fan is designed primarily for clean air use it can be and has been used briefly on dusty air.

Automatic valves for diverting the gas flow when cleaning by shaking or reverse flow were fabricated by GCA (see Figures 1 and 2). These modified gate valves, which provide tight sealing during shutoff and relatively fast response, are corrosion resistant and are able to operate at high and varying temperatures. These valves have a tested leak rate of less than 0.01 cfm at 20 in. of water pressure differential. A schematic diagram of the modified gate valve is shown in Figure 4.

The system pressure, flow, temperature, time controlling and recording instruments are located in a single control console. Flow through the fabric filter is indicated by the differential pressure across a Stairmand

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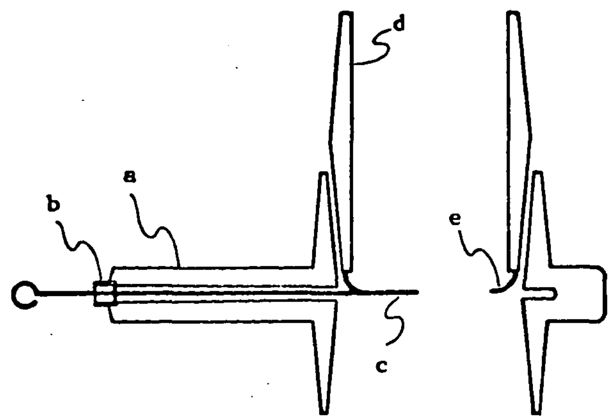
*Morris Coupling and Clamp Company, 2240 West 15th Street, Erie, Pa. 16512.
+Chicago Blower Corporation, 1675 Glen Ellyn Road, Glendale Heights, Illinois 60137.



The valve seats are cut from stainless mixing bowls, of suitably shallow curvature and springiness.

The seat is welded to the nipple. Adjustment of the nipple affects the degree of sealing.

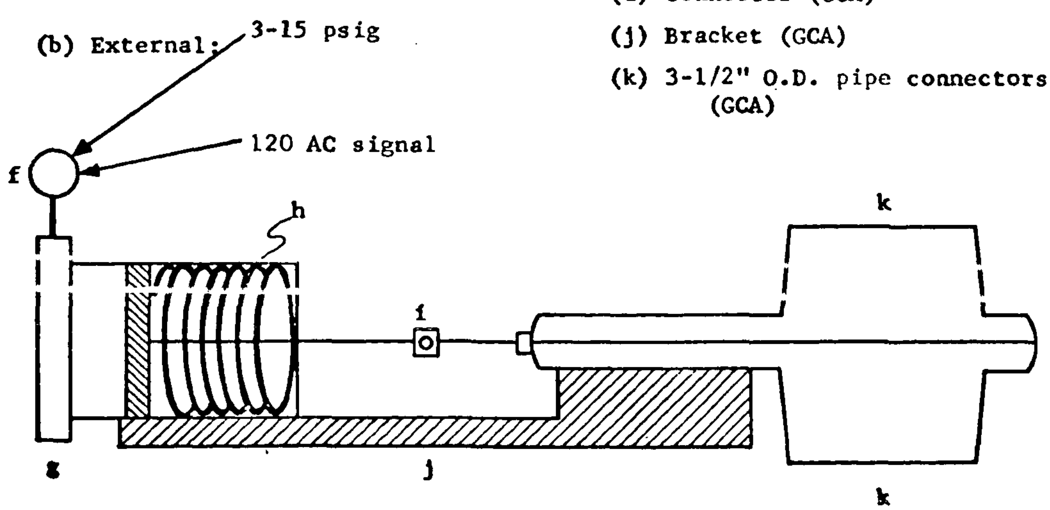


Figure 4. Gate valve

disk. The above pressure differential and that across the fabric filter are displayed on Magnehelic gauges, Bailey indicating gauges* and also recorded on a dual channel recorder. A pneumatic controller permits automatic operation at either constant flow or constant filter pressure drop. Filtration temperature is maintained above the gas stream dewpoint but is not allowed to exceed the temperature limit of the fabric. Fiber glass insulation and three heating tapes are used to maintain appropriate gas temperatures. A thermocouple temperature recorder with an on-off controller and adjustable high and low setpoints is used to activate the heating tapes. The temperature controller and one of the previously mentioned automatic valves can be used for dilution cooling, if necessary.

Automatic timing of the system operating and cleaning cycles is provided. Five timers and two stepping switches control the system when using the mechanical shaker. The first timer (T_1) with a range of 3 to 60 minutes controls the filtration time. At the end of the filtering interval, timer T_1 causes the bypass valve to open, the valves isolating the filter housing to close, and timer T_2 to start. The second timer, T_2, provides a delay time for the isolation valves to close, engages through a stepping switch the bag or bags to be shake cleaned and initiates the shaking. Timer T_3 or T_4 then controls the length of the shaking cycle. T_3 has a range of 1 to 10 seconds for short shaking cycles and T_4 has a range of 11 to 150 seconds for longer cycles. After the shaking has ceased, timer T_5 allows a delay of 0.25 to 5 minutes for the dust to settle and then repeats the filtering cycle as controlled by timer T_1. Although reverse flow operation uses the same timers, timers T_3 and T_4 operate the reverse flow fan in lieu of the shaker motor. A different control system consisting of two timers and a stepping switch is used to operate the pulse jet cleaning system. The first of these timers sets the interval between pulses, 0.25 to 5 minutes while the second timer sets the length of the pulse 0.01 to 99 seconds. The stepping switch selects the bag to be cleaned.

*Bailey Meter Company, A Subsidiary of Babcock and Wilcox, U.S.A., Wickliffe, Ohio 44092.

Electric power is distributed to all components of the mobile fabric filter system through circuit breakers and receptacles located at the rear of the control console.

An apparatus designed to shake the upper end of a row of up to three bags was constructed. Shaking motion is adjustable with regard to amplitude which may be varied between 3/8 and 3 inches. A 1/2-horsepower permanent magnet DC motor and a solid state speed controller is used to select and regulate shaking frequency over a working range of 2 to 15 cps. Frequency is measured through a microswitch on the motor which controls a counter mounted on the control console. Pneumatic clutches permit shaking of one bag at a time. This option was included to simulate operation of a 3-compartment system, as well as special series filtration tests. The bag suspension points can be adjusted vertically in order to adjust the bag tension. Bags may be attached at the top either by a loop or a cap arrangement. Removable windows at the top and bottom of the filter housing permit easy access to the bags and quick changing of filter media. The amplitude and frequency range for the shaking apparatus was chosen to encompass that usually encountered in the field and also to provide the necessary energy transmission to clean the fabric. With minor changes, the present frequency and amplitude range can be increased if test conditions require it.

An apparatus designed to clean up to seven bags by high pressure reverse pulse jet was constructed using standard commercial valves, venturi bag cages and bags purchased from Mikropul.* A 5-gallon pressure tank is mounted immediately on top of the pulse jet unit in order to maintain supply air pressure during pulsing. Compressed air is provided by a compressor which can furnish 8.3 cfm (free air delivery) at 90 to 125 psig. A digital solid-state timer is used to set the exact length of the signal that activates the solenoid valve that controls the pulse. The amount of air that is delivered per pulse for various pulse durations and reservoir

*Mikropul Division, U.S. Filter Company, Chatham Road, Summit, N.J. 07901.

pressure was determined so that the economics of a particular cleaning method could be evaluated.

The low pressure reverse flow cleaning fan is designed to supply air at a minimum back pressure of at least 2 inches of water to a filter system having a cloth area of about 30 square feet. Based on an estimated minimum residual drag of 0.5 in. water per fpm, this pressure will be accomplished by a flow of up to 120 cfm. For high temperature operation, especially when the aerosol contains appreciable amounts of water vapor, the filter bags should not be cooled during reverse flow. Therefore, a heat exchanger will be used to heat the reverse flow air when necessary. An orifice meter, a damper valve, and the previously mentioned automatic valves are the other components used during reverse flow operation.

A variety of sampling and measurement techniques are needed to evaluate filter efficiency on a mass and/or number basis. Inlet mass concentration can be determined by conventional sampling with glass fiber papers or by weighing the dust collected in the hopper dust valve over some selected averaging period. Downstream mass concentrations, usually over longer averaging periods, can be determined with glass fiber filter papers provided that the concentration is not too low. At very low effluent concentrations, a B and L* light scattering particle counter can be used to obtain a rough estimates of both mass and number concentrations. Particle size concentrations before and after the fabric filter are currently determined by impactor measurements. A Brink+ impactor operated at 0.03 to 0.1 cfm is generally used before the fabric filter while the higher flowrate, 0.5 to 0.8 cfm, Andersen‡ impactor is used on the downstream side. Particle size distribution by number can be determined for the effluent with a B and L light scattering particle counter. In addition,

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*Bausch and Lomb Incorporated, 820 Linden Avenue, Rochester, N.Y. 14625.
+Brink Impactor--Monsanto Enviro-Chem Systems Inc., 800 North Lindbergh Blvd., St. Louis, Missouri 63166.
‡Andersen 2000 Inc., P.O. Box 20769, Atlanta, Georgia 30320.

preparations are underway to measure fine particulate size distributions with a diffusion battery and condensation nuclei counter.

PRELIMINARY RESULTS OF FIELD TESTS

PROCESS DESCRIPTION

The mobile fabric filter system was operated recently at a secondary brass foundry in Massachusetts. Emissions from these plants are principally zinc oxide and lead oxide fumes with a particle size range of 0.03 to 0.3 microns.[2] Since the typical brass foundry melts 50 tons/day[3] and the emission factor for an uncontrolled reverberatory furnace is 70 lb/ton,[4] such an operation would be expected to emit 1.8 tons/day. Some secondary brass operations have emission control equipment consisting of wet scrubbers and electrostatic precipitators whose performance has not always been satisfactory.[5] Because of the small particle size, fabric filters are the most frequently employed collectors for solids emissions from secondary brass processes. Regulations[6] for new secondary brass refineries will require control efficiencies of approximately 99 percent. Therefore, it is most important that the capabilities for controlling fine particulates by fabric filter be investigated at these installations. The plant at which the mobile fabric filter tests were performed now employs a shaker-type fabric filter.

The brass ingot manufacturer uses an oil-fired, cylindrical reverberatory furnace to melt 45,000 pounds of scrap metal per 7-hour melting cycle. Each cycle consists of the following steps:

Step 1. About 30 percent of the total scrap metal is charged to the furnace and heated for 140 minutes.

Step 2. The oil burner is shut down and 23 percent of the total scrap metal is charged. Charging takes about 15 to 20 minutes.

Step 3. After charging, oil firing is resumed and the furnace is heated for 70 to 85 minutes.

Steps 2 and 3 are repeated three times before the melting process is terminated. Since most of the emissions occur during the melting cycle, the fabric filter system operation was altered during the charging cycle so that no cleaning took place. The step was taken to prevent overcleaning, and hence excessive dust penetration, during the charging period when dust emissions were relatively low.

During these field tests, the mobile fabric filter system was operated on the truck. The plant test effluent was extracted approximately isokinetically at 70 to 110 cfm through a 3.3-inch nozzle from the main duct about 45 feet upstream of the plant fabric filter. Lightweight 2.5-inch OD stainless steel tubing was used for the remainder of the necessary piping leading to the mobile unit. Fiber glass insulation and 50 feet of 460-volt heating tape were used to maintain the gas temperature between 250 and 390^{o}F at the mobile fabric filter inlet.

PULSE JET CLEANING

Pulse jet cleaning was used during the first series of tests when the refinery was producing a brass alloy of the following composition:

Material	Weight %
Copper	77-79
Zinc	9.75-14.5
Lead	6.0-8.0
Nickel	0.0-1.0
Iron	0.0-0.4

Particulate Sampling Procedures

Particulate concentrations entering the mobile fabric filter were determined by glass fiber filters and by the weight of dust collected in the fabric filter hopper. During charging, the inlet mass concentration was less than 0.05 grain/scf, while during each heating cycle the concentration varied between 1 grain/scf at the start and 2 to 2.5 grains/scf at the end of the cycle. Average inlet dust concentration, exclusive of the charging period, was 1.7 grain/scf. Three Brink impactor measurements were made, each on a different day, to determine the inlet particle size distribution. The results, assuming spherical particles and a density of 1 gm/cm^3, show a mass median diameter of 0.5 μm. Results of the Brink impactor measurements were in good agreement. Figure 5 shows the inlet particle size distribution.

System Operating and Cleaning Parameters

Nomex, 16 oz. per square yard, felt bags were used for the pulse cleaning tests. The test conditions and filter characteristics are shown in Table 1. Three bags, each 4-1/2 inches in diameter and 4 feet long were used. The gas flow direction was in the conventional "outside to inside" direction used commercially with wire cage supported felt tubes. The filter velocity was maintained at an average of 8 fpm so that the total flow was 110 cfm for a cloth area of 13.9 ft^2. Average filtration temperature was 320^oF. The fabric filter was run for a complete 7-hour cycle before the collection of performance data was undertaken.

The pulse jet cleaning parameters are listed in Table 2. The interval between pulses was 40 seconds for the first two tests and 20 seconds for the third test. Since the cleaning was continuous and three bags were being used, the total time to cycle through all the bags was 120 seconds for the first two tests and 60 seconds for the last test. Pulse duration was a nominal 0.1 seconds, as set on an electronic timer for all tests. The above time duration actually designates the electrical "open time"

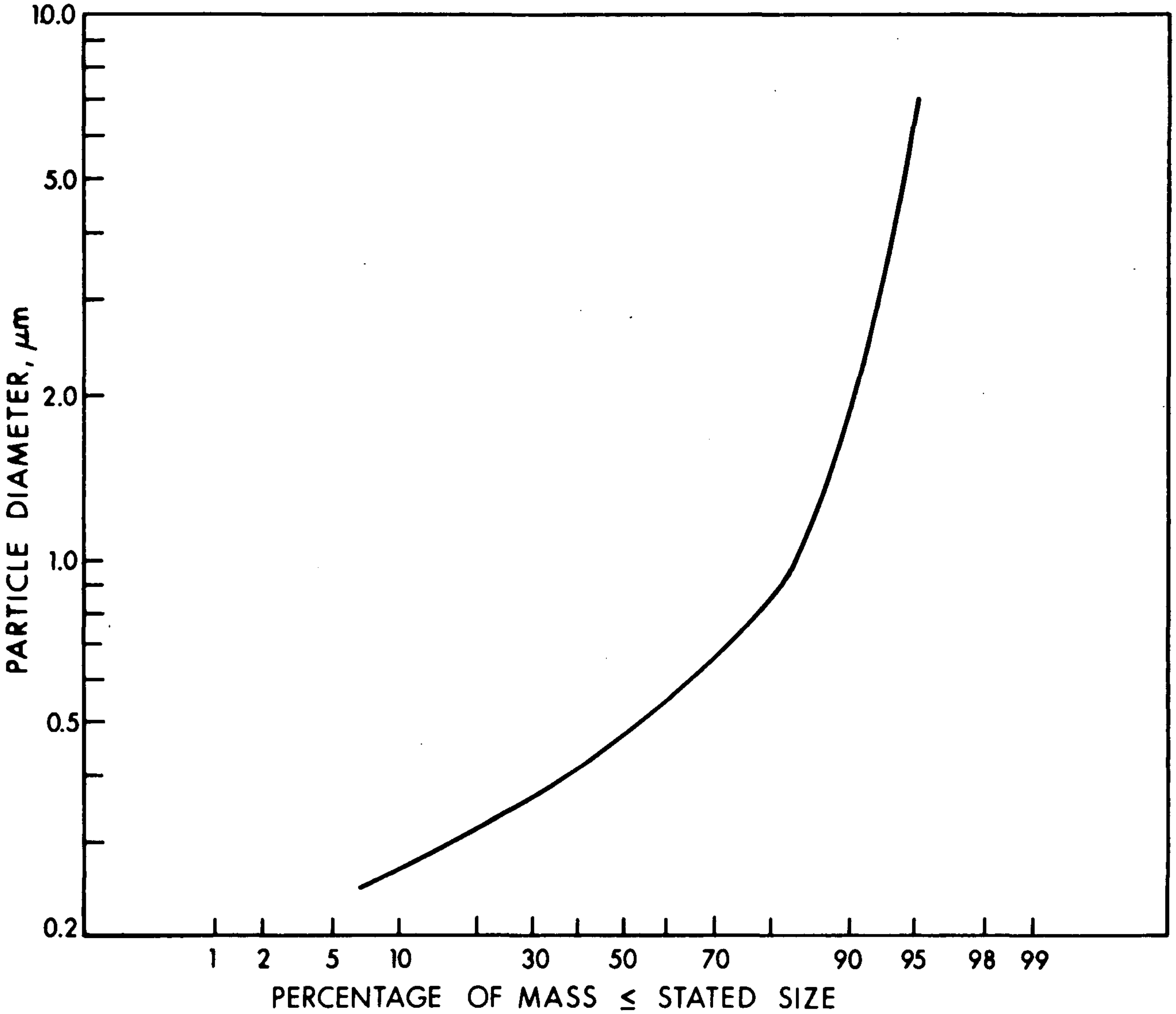

Figure 5. Inlet particle size distribution for zinc oxide fumes, from brass refining furnace by Brink cascade impactor

Table 1. SYSTEM COMPONENTS AND MAJOR OPERATING PARAMETERS FOR ZINC OXIDE FILTRATION BY MOBILE PULSE JET FILTER

Filter material	Nomex felt, 16 oz/yd^2
Bag dimensions	4-1/2 in. diameter, 4 ft long
Number of bags	3
Support	Wire cages
Filtration velocity	6 ft/min
Total filter area	13.9 ft^2
Total gas flow	110 ft^3/min, STP
Inlet dust concentration, average	1.7 grain/ft^3, STP
Inlet particle size	0.5 μm, mass median diameter
Test duration	7 hours

Table 2. PULSE JET CLEANING PARAMETERS, FOR ZINC OXIDE FILTRATION

	Test 1	Test 2	Test 3
Interval between pulses, sec	40	40	20
Cycle time, sec	120	120	60
Pulse duration, sec	0.1	0.1	0.1
Pulse supply pressure, psig	60-80[a]	80	80
Compressed air requirement, ft^3/min (STP)/1000 ft^2 filter area	40[b]	40	80[b]

[a]Supply pressure increased to 80 psig for last half of test.
[b]Equivalent to 0.37 ft^3/pulse.

and not the effective open time of the valve whose motion lags significantly electrical start-stop signals. Pulse supply pressure was 80 psig except for the first half of Test no. 1 when the pressure was 60 psig. The amount of compressed air used by a pulse jet cleaning fabric filter, which is an important economic consideration, was estimated to be 40 scfm per 1000 square feet of filtration area for the first two tests and 80 scfm/1000 square feet during the last test.

Experiment Results

Fabric filter performance for each of the three pulse cleaning tests (7 hours long) is summarized in Table 3. The filter pressure drop shown in Table 3 is the average for each test with the peak pressure drop in parenthesis. During Test 3, in which the filter bags were cleaned twice as often, the average pressure drop across the filter was only 5 inches of water as compared to 9 and 10 inches of water for the first two. tests. However, another result of the increased cleaning frequency was doubling of the percent penetration. Percent penetration was 0.081 and 0.078 percent for

Table 3. SUMMARY OF PERFORMANCE PARAMETERS FOR ZINC OXIDE FILTRATION

	Test 1	Test 2	Test 3
Inlet dust concentration, grains/ft^3, STP	1.7	1.7	1.6
Inlet particle size, μm	0.5	0.5	0.5
Average filter pressure drop, in. water	10 (14)[a]	9 (13)[a]	5 (6)[a]
Outlet dust concentration, grains/ft^3, STP STP	0.0014	0.0013	0.0028
Penetration, %	0.081	0.078	0.15
Efficiency, %	99.919	99.926	99.85

[a]Values in parens indicate peak pressure drop.

the first two tests but increased to 0.15 percent during the last test. Corresponding efficiencies were 99.919 and 99.926 percent and for the third test 99.85 percent. Tests 1 and 2 are approximate replicates despite the lower pulse supply pressure at the start of Test 1. Effluent concentration (and source strength) were approximately doubled as a result of the increased cleaning frequency.

Two Andersen impactor samples were taken at the fabric filter outlet in an effort to determine effluent size properties. Insufficient material was collected on any of the impactor stages, however, to determine an accurate fractional efficiency even though the impactors were run 1 to 2 hours. Most of the exiting fume was collected on the Andersen back-up filter indicating that the outlet aerosol was smaller than the inlet aerosol. The failure to collect a significant amount of material on the Andersen impactor was the result of high filter efficiency (~ 99.9 percent) and the small inlet particle size, mass median diameter 0.5 μm and 85 percent by weight less than 1 μm, see Figure 5.

Because fabric filter pressure drop is a very important design consideration, graphs of filter pressure drop versus time are presented in Figures 6 through 8 for Tests 1 through 3. Figure 6 shows the instantaneous pressure drop across the filter versus time during Test 1. After 2-1/2 hours the furnace oil burner was shut down for charging during which interval the fume loading to the fabric filter was very low. A few pulses lowered the pressure drop to about 4 inches of water. At this time, the pulse cleaning unit was shut off until the furnace was re-ignited as evidenced by a rise in the filter pressure drop. The pulse cleaning system was shut down during charging operations so that the bags would not be excessively overcleaned. The perturbations in pressure drop reflect variations in the inlet dust concentration.

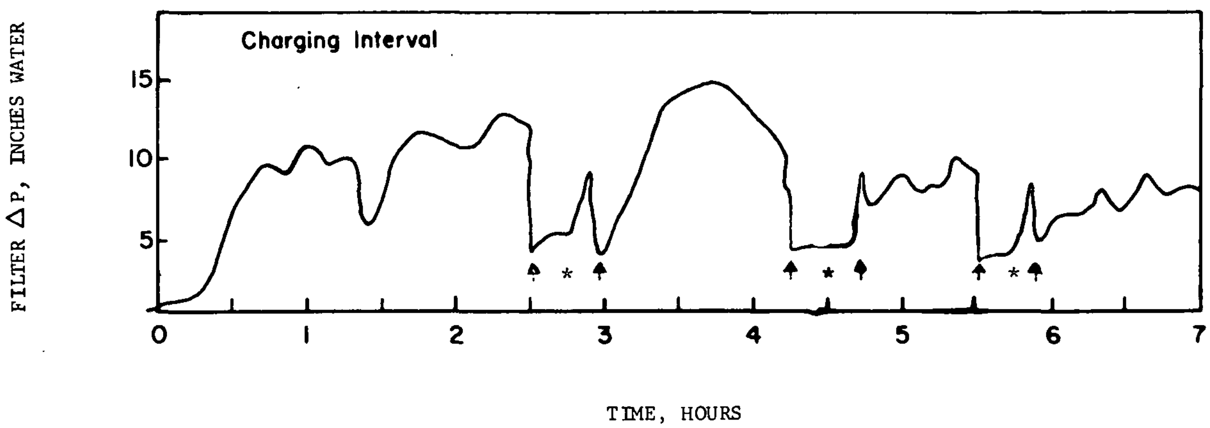

Figure 6. Pressure-time relationship for brass fume filtration with pulse jet cleaning, Test 1

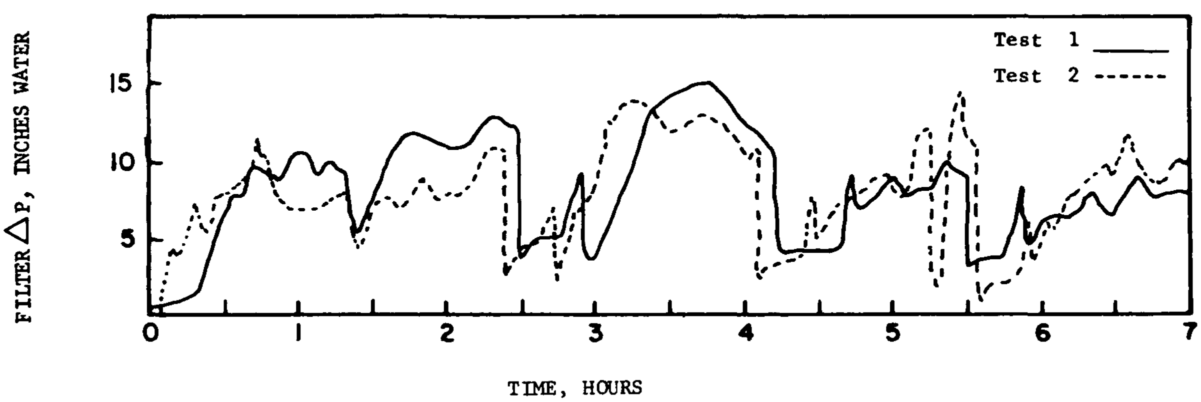

Figure 7. Pressure-time relationship for brass fume filtration with pulse jet cleaning, comparison of Tests 1 and 2

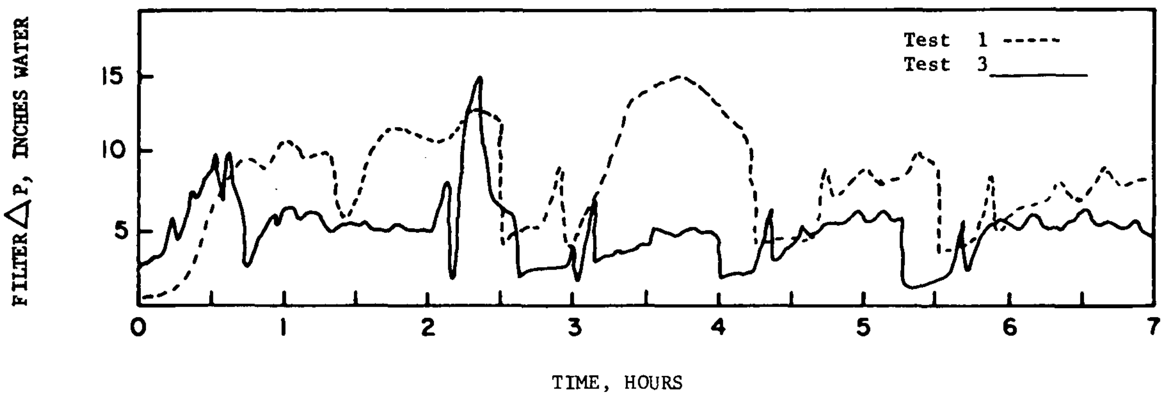

Figure 8. Pressure-time relationship for brass fume filtration with pulse jet cleaning, comparison of Tests 1 and 3

Figure 7 compares the pressure drop versus time relationships for Test 1 (solid line) and Test 2 (the dotted line). The filter pressure was lower during the first half of Test 2 because the pulse supply pressure was 80 psig compared to 60 psig during the first half of Test 1. After 5-1/2 hours of Test 2 there was a sudden rise in the pressure drop because the pulse jet cleaning system had been prematurely shut down. Generally, the variations in filter pressure drop throughout Tests 1 and 2 are similar.

In Figure 8, the pressure drop versus time results for Tests 1 (solid line) and 3 (dotted line) are compared. The lower pressure drop during Test 3 reflects the doubled pulse rate. The transient high pressure drop at the start of Test 3 was caused by a stepping switch malfunction.

The pulse jet cleaning tests suggest that the fine metal oxide fume from a secondary brass smelter can be efficiently filtered (~ 99.8 percent) with Nomex felt bags at a cloth velocity of 8 ft/min. By using 80 scfm of compressed air per 1000 square feet of filter area, the average filter pressure drop was maintained near 5 inches of water. It should be noted that the reported compressed air consumption for many industrial processes is often lower, ranging from 5 to 30 ft^3/min, STP.[7,8,9] In the present situation, however, time did not allow investigation of the feasibility of changing pulse jet parameters so as to reduce compressed air volumes (or delivery costs). The filter bags showed no signs of plugging or binding after 28 hours in use. The life span of Nomex bags in this type of operation, of course, cannot be determined from short period tests.

MECHANICAL SHAKE CLEANING

Several field measurements were also performed using a conventional mechanical shaking approach with woven Nomex bags, the latter conforming in fabric properties to those used in the present refinery fume control system. The objective of these tests was to simulate the operation of the plant fabric filter system so that by varying cleaning parameters on the mobile system the performance of the plant system might be improved. Refinery personnel have had problems with excessive pressure drops across the plant fabric filter that have reduced the system ventilation capability. Shake cleaning parameters cannot be varied conveniently on the plant fabric filter without major mechanical modifications.

Nomex filament fabric is used in the plant system with a design filtration velocity of 3 ft/min. A horizontal shaking motion with the bags spring tensioned at about 10 pounds, a shaking amplitude of 1/4 to 1/2 inch and a shaking frequency of 3 cps constituted the main cleaning parameters. The filter house consists of 4-compartments with each chamber on-line for 20 minutes, cleaned for 1 minute, and then shut down for 1 minute to allow the dust to settle. Rough Pitotstatic tube measurements indicated that the actual filtration velocity at 10 inches of water pressure drop across the filter was only 1.5 to 2 ft/min.

System Operating and Cleaning Parameters

The Nomex multifilament fabric used in the mobile system was 3 x 1 twill with a thread count of 98 x 79 and a weight of 4.5 ounces/square yard. Clean cloth permeability was 18 $ft^3/min/ft^2$ at 1/2 inches of water pressure drop. The mobile system bags were 6 feet long and 5-9/16 inches in diameter while the plant system used bags 8-1/2 feet long and 5-1/2 inches in diameter. Because the bag motion in the mobile system follows a slightly arcing path in contrast to an essentially horizontal path for the plant system, the bag tension on the mobile system was set lower than the plant filter. For the initial simulation of the plant system, the amplitude was 3/8 inch, the shaking frequency was 3 cps, and the filtration velocity was 3 fpm. The filtering and cleaning cycle per compartment was the same as that for the plant system except that a 15-second pause immediately before cleaning, allowed the automatic valves to move. At an amplitude of 3/8 inch and a frequency of 3 cps the maximum acceleration of the shaker arm was estimated to be 0.35 g. Based upon prior GCA tests,[10] which indicated poor cleaning for g levels* below 4 to 5, effective cleaning was not expected for either the plant or mobile filter system.

Filtration conditions for Tests 4 and 6 differed from those of the pulse jet cleaning tests because the brass melts contained less zinc, 4.5 to 6.0 percent versus 9.75 and 14.5 for the earlier pulse cleaning studies. Detailed data on brass compositions are presented in Table 4.

Experimental Results

The average inlet dust concentration during Tests 4 and 6 was 0.65 and 0.54 grains/ft^3, STP compared to 1.6 grains/ft^3, STP during the pulse jet cleaning tests, mainly because of the reduced zinc content. During mechanical shake cleaning Tests 5 and 7, the same type of brass was produced as that during the pulse jet cleaning tests. However, the average inlet dust concentration was only 0.90 to 0.92 grains/ft^3, STP as compared to 1.6 grains/ft^3, STP for the pulse jet cleaning tests. Table 5 summarizes key aerosol data for Tests 4 through 7.

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*1 g = 32.2 ft/sec^6.

Table 4. BRASS COMPOSITIONS DURING MECHANICAL SHAKING TESTS

Test number	4 and 6	5 and 7
Brass type	1	2
Composition		
Copper		
Tin	4.4 - 6.0	2.0 - 3.25
Lead	4.0 - 5.7	6.0 - 8.0
Zinc	4.5 - 6.0	9.75 - 14.5
Nickel	0.5 - 1.0	0.0 - 1.0
Iron	0.0 - 0.25	0.0 - 0.4

Table 5. AEROSOL PARAMETERS FOR MECHANICAL SHAKING TESTS

Test number	4	5	6	7
Brass type	1	2	1	2
Inlet dust concentration, grains/scf	0.65	0.92	0.54	0.90
Inlet particles size,[a] microns	0.5	0.5	0.5	0.5
Inlet gas temperature, ^{o}F	240	270	270	270
Gas dew point, ^{o}F	50-60	50-60	50-60	50-60

The first test, Test 4, was designed to simulate the operation of the plant fabric filter. Therefore, the initial cleaning conditions consisted of a 3/8 in. shaking amplitude, 3 cps shaking frequency, and a bag tensioning of 5 lbs with a 3 ft/min filtration velocity. As expected, very little cleaning was accomplished during the first two hours of this test. According to the pressure drop-time curve of Figure 9, the resistance rose to 14 in. water and even after shaking was only slightly reduced to 13 in. water. After 3 hours, the shaking frequency was increased to 5 cps which increased the shaker arm acceleration to 0.93 g. However, cleaning was still not significantly improved. After 4 hours, the shaking frequency was increased to 6 cps (a shaker arm acceleration of 1.33 g) but the cleaning remained unsatisfactory. At the end of the test, the filtration velocity had fallen to 2.3 ft/min but the pressure drop was near 16 in. of water. It is emphasized here that the mobile system flow would probably have decreased to much lower levels than the 2.3 ft/min cited above had a conventional exhauster been used, $\sim$ 10 in. water static pressure. Because of the need for flexibility in the mobile system, a special high static, thin scroll centrifugal fan was selected that minimized flow variations. Further evidence of poor cleaning was the small amount of dust, 50 to 100 grams, collected in the hopper during the entire 7-hour test. At the end of the test, the bags were shaken by hand and about 640 grams of dust were collected. After being shaken by hand, the pressure drop across the bags was reduced to only 1 in. of water at 3 ft/min velocity.

In an attempt to improve collector performance, shaking amplitude was increased to 7/8 in. during Test 6 and the bag tension adjusted to about 1 lb. The shaking frequency was maintained at 6 cps for the first hour of filtration followed by an increase to 8 cps for the remainder of the test. The alloy composition and fume inlet concentration were about the same as those noted for Test 4. The energy imparted to the shaking bags as defined by shaker arm acceleration was 3.2 and 5.7 g's, respectively, for the two frequency levels.

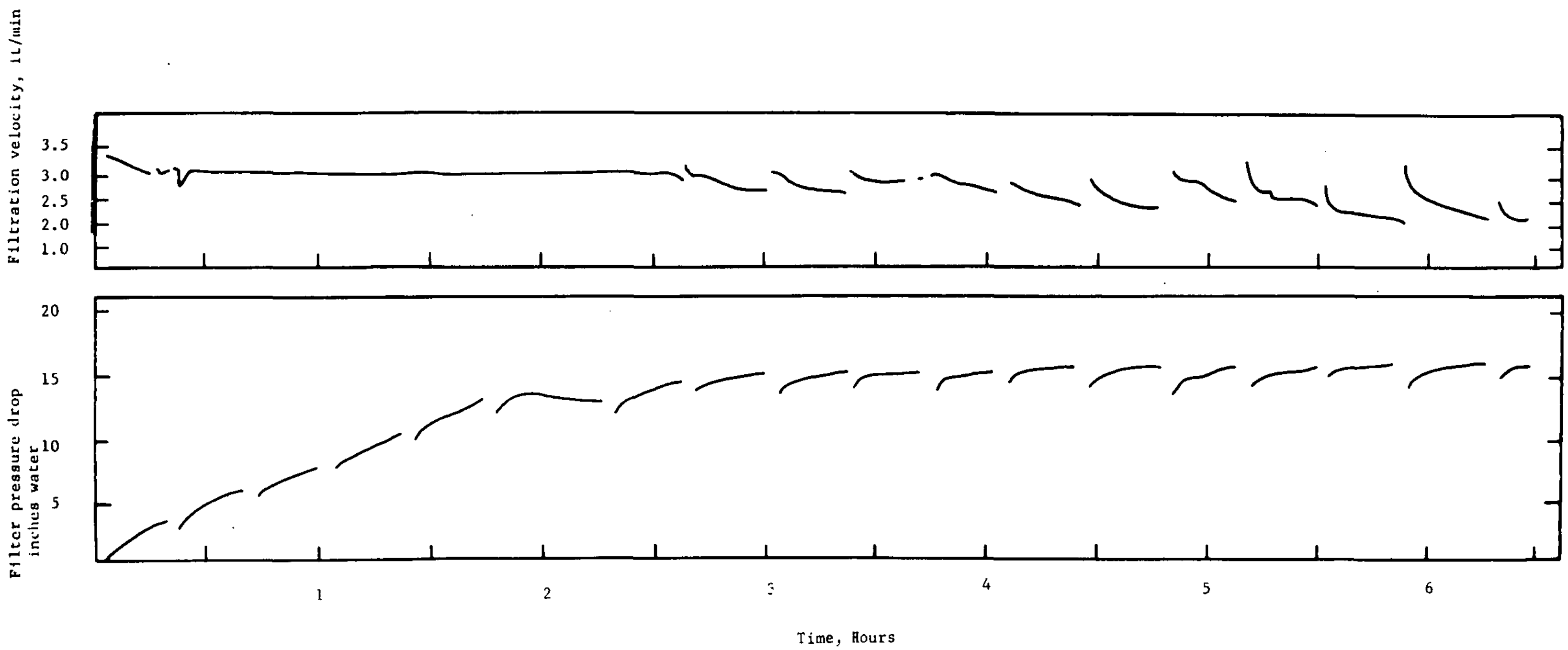

Figure 9. Pressure-time relationship for brass fume filtration with mechanical shaking, Test 4

In Figure 10, the graphs of filter resistance and filtration velocity versus time show a marked improvement for the higher shaking amplitude (dashed line) relative to the system performance obtained under Test 4 conditions (solid line). After 2 hours of filtration, the pressure drop across the bags was 9 in. of water instead of 14 in. as in the previous test. Filter pressure drop after cleaning was reduced by 3 in. of water compared to less than 1 in. for Test 4. Through most of Test 6, filter pressure drop was maintained between 8.6 and 10.6 in. of water while, at its termination, the pressure drop was 11 in. of water at a velocity of 3 ft/min compared to 16 in. of water at 2.3 ft/min in the previous test.

A net twenty to fifty grams of dust were dislodged after each cleaning cycle instead of a total of 50 to 100 grams for the entire test. Additionally, only 100 grams of dust were collected by hand shaking at the end of Test 6 compared to 640 grams in Test 4. It was concluded that increasing the shaking frequency and amplitude (both contributing to higher bag acceleration) reduced the filter pressure drop and increased the filtration capacity.

Average fume penetration was 0.08 percent during Test 4 and 0.16 percent during Test 6. The results are consistent with theory which indicates an inverse relation between dust penetration and filter dust holding. One can also infer that the more intense acceleration and particularly the increase in shaking amplitude would enlarge the filter pores thus allowing more dust to penetrate the fabric structure.

Tests 5 and 7, Figure 11, reflect mobile filter system operation at the higher fume loadings (see Table 5) obtained with the high zinc alloys. Test 5 was run at a filtration velocity of 3 ft/min, a shaking amplitude of 7/8 in. and a shaking frequency of 6 cps. The pressure drop characteristics were only slightly higher than those for Test 6 despite the lower shaker arm acceleration of 3.2 g's and the higher inlet dust concentration of 0.9 grains/ft^3, STP. Tests 5 and 7 were the same except for the lower

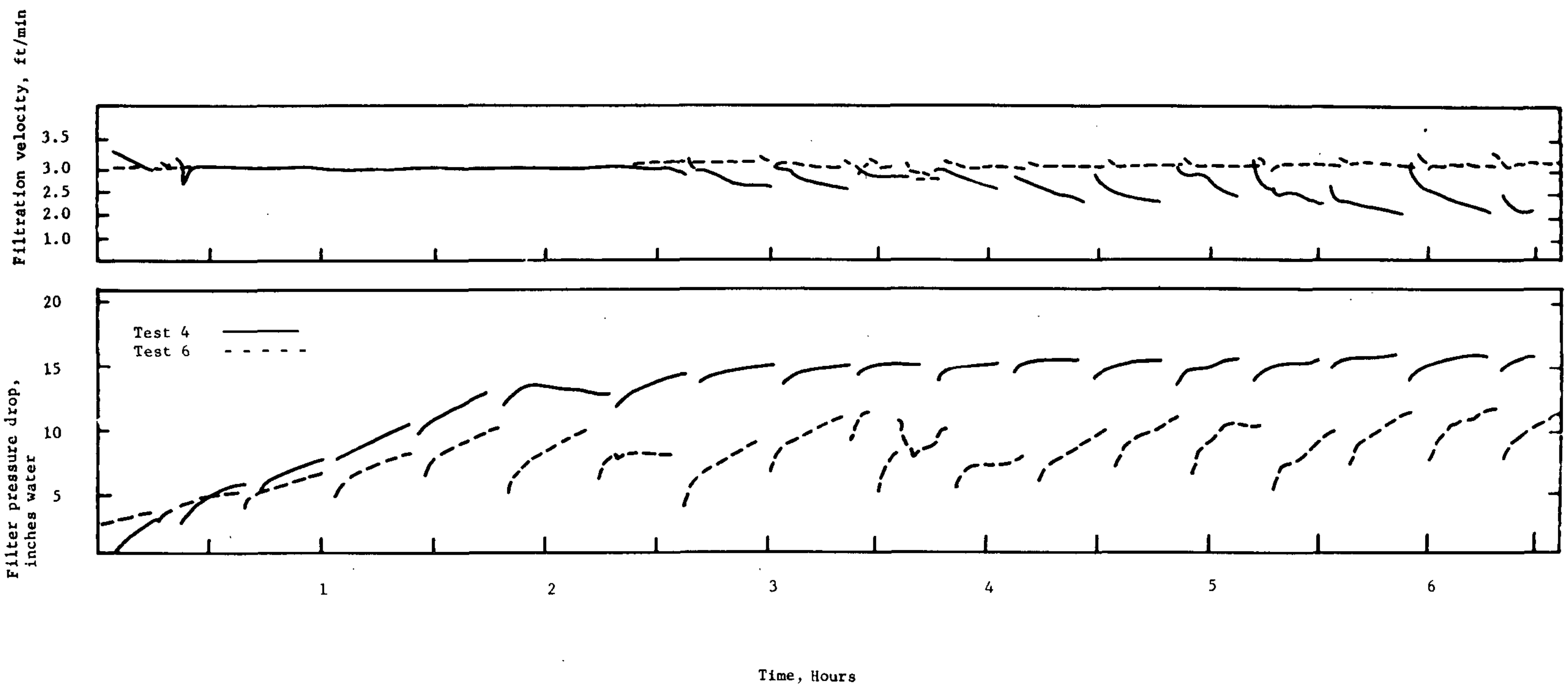

Figure 10. Pressure-time relationship for brass fume filtration with mechanical shaking, comparison of tests 4 and 6

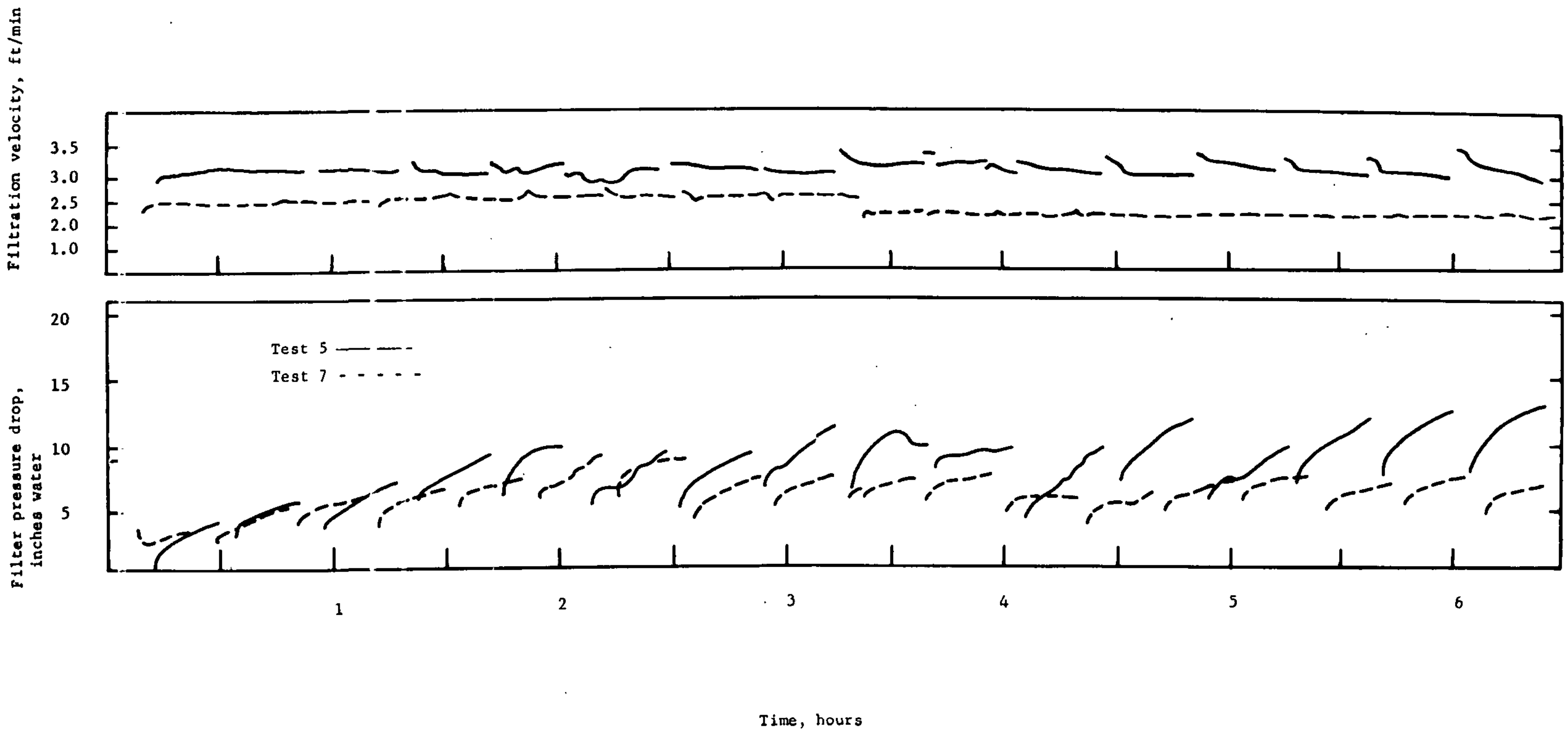

Figure 11. Pressure-time relationship for brass fume filtration with mechanical shaking, comparison of tests 5 and 7

filtration velocity during Test 7. During Test 7 the filtration velocity was 2.5 ft/min for the first half and 2.0 ft/min for the remaining time. The resultant lower pressure drop is clearly shown in Figure 11. The lower penetration measured during Test 7 is attributed to the fact that residual dust holding should be greater with less vigorous shaking, 3.2 vs. 5.7 g's, and the lower filtration velocity should permit enhanced diffusional capture of fine particles. The specific dust fabric resistance coefficient K_2 $\left(\frac{\text{in. } H_2O/\text{ft/min}}{\text{lb ft}^2}\right)$ as calculated for various periods throughout the mechanical shake cleaning tests ranged from 150 to 300. Results of the mechanical shake cleaning tests are summarized in Table 6.

Low pressure reverse flow cleaning was also briefly tested. However, the test constituted a shake-down trial and the data collected did not warrant analysis.

ASSESSMENT OF TESTS AND FUTURE PLANS

It is premature at this time to make comparisons of the cost effectiveness of the fabric filtration techniques investigated in the field with the mobile filter system. With respect to regulations citing an upper limit of 0.022 grains/ft^3 STP for emissions from secondary brass smelting operations, both the pulse jet and mechanical shaking systems produced acceptable effluents (0.0014 to 0.0029 and 0.0003 to 0.0012 grains/ft^3 STP, respectively). On the average, the above performance for pulse jet and mechanical shaking system indicates that these levels are only 13 and 1.3 percent of the allowable values. Because it was not possible to explore several alternative combinations of cleaning parameters within the time frame of these tests, no cost estimates have been presented.

Table 6. SUMMARY OF MECHANICAL SHAKE CLEANING TESTS WITH ZINC OXIDE FUME

Test number	4	5	6	7
Cleaning parameters[a]				
Amplitude, in.	3/8	7/8	7/8	7/8
Frequency, cps	3-6	6	8	6
Tension, pounds	5	2	1	1
Filtration velocity, fpm	3-2.3	3	3	2.5,2.0
Filter pressure drop, in. water		(See Figures 9, 10, 11)		
Average penetration, percent	0.08	0.14	0.16	0.05
Average outlet dust concentration, grains/ft^3 (STP)	0.0005	0.0012	0.0087	0.0003

[a]The same cleaning cycle was used for all tests. Filtration for 20 minutes, a 15-second pause, a 1-minute shake followed by a 1-minute pause before filtration was resumed.

As a matter of practical concern, the apparent feasibility of using mechanical shaking based upon mobile system tests may be countermanded by the structural features of some full-scale commercial equipment. For example, separate evaluations of the smelter filter system indicated that shaking amplitudes in excess of 1/2 in. caused massive vibration and swaying of the bag house structure at low frequencies, ~ 2 to 4 cps.

These field tests have demonstrated that a mobile filter system having the flexibility to apply several methods of cleaning and to vary operating parameters, as needed, can provide useful design data.

It is planned to use the mobile unit to test fabric filter performance on a number of other industrial particulate emission sources. The next test series will study hot mix asphalt plants which may be very significant sources of fine particulates.[11] Most asphalt plants use a cyclone to collect coarse dust emitted from the rotary drier although some use wet scrubbers or fabric filters to collect particulates passing through the cyclone. Because the particulate concentration is high, pulse jet cleaners are the usual choice for asphalt plant fabric filters.

Other proposed field evaluations involve operating the mobile system at a coal-fired electric power plant and possibly at a municipal incinerator or iron foundry. Following these tests, the Environmental Protection Agency will take delivery of the system and use it in a large scale testing program incorporating other mobile particulate removal systems such as wet scrubbers and electrostatic precipitators.

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EXTENDING FABRIC FILTER CAPABILITIES

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INTRODUCTION

At present we can readily filter particles at temperatures up to about 550°F.* We can filter them in harsh atmospheres and we can filter them through the same bag for up to 10 years, although the average is more nearly 1 or 2. Fabric filters have often been touted as 99.9^{+} percent efficient as particle collectors, but there haven't been very many measurements made of the particle size efficiency on operating baghouses. EPA has some data, presented in Figures 1, 2 and 3, that imply good efficiency down to about a tenth of a micrometer, but which should be hedged about with all kinds of restrictions and reservations. The

*Although it is EPA's policy to use the metric system for quantitative descriptions, English units are used in this report in order to avoid confusion. Readers who are more accustomed to metric units may use the following conversions: multiply °F by 5/9 (°F-32) to obtain °C.; multiply ft/min by 0.508 to obtain cm/sec; multiply $lb/10^6$ BTU by 0.00180 to obtain $kg/10^6$ cal.

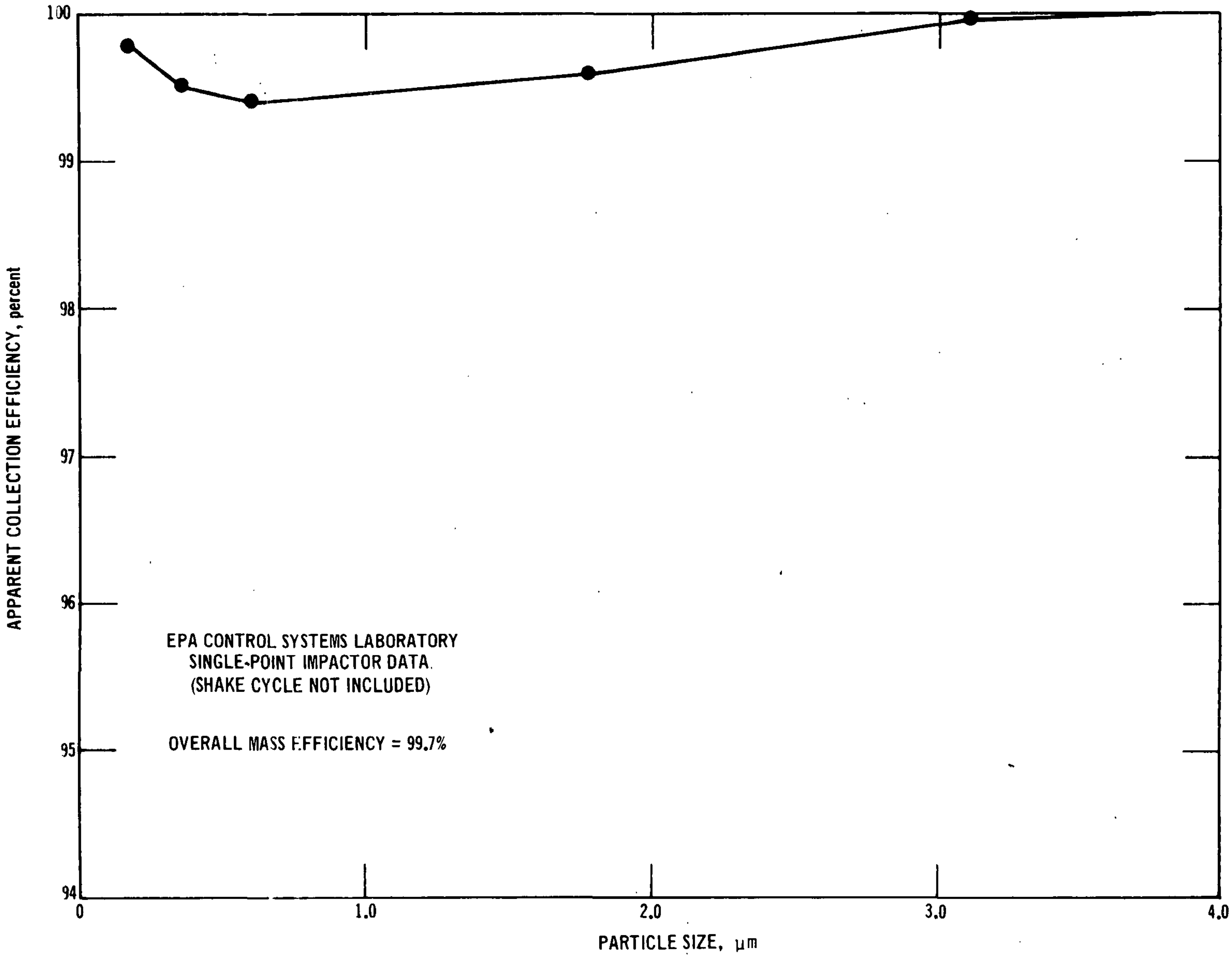

Figure 1. Baghouse performance

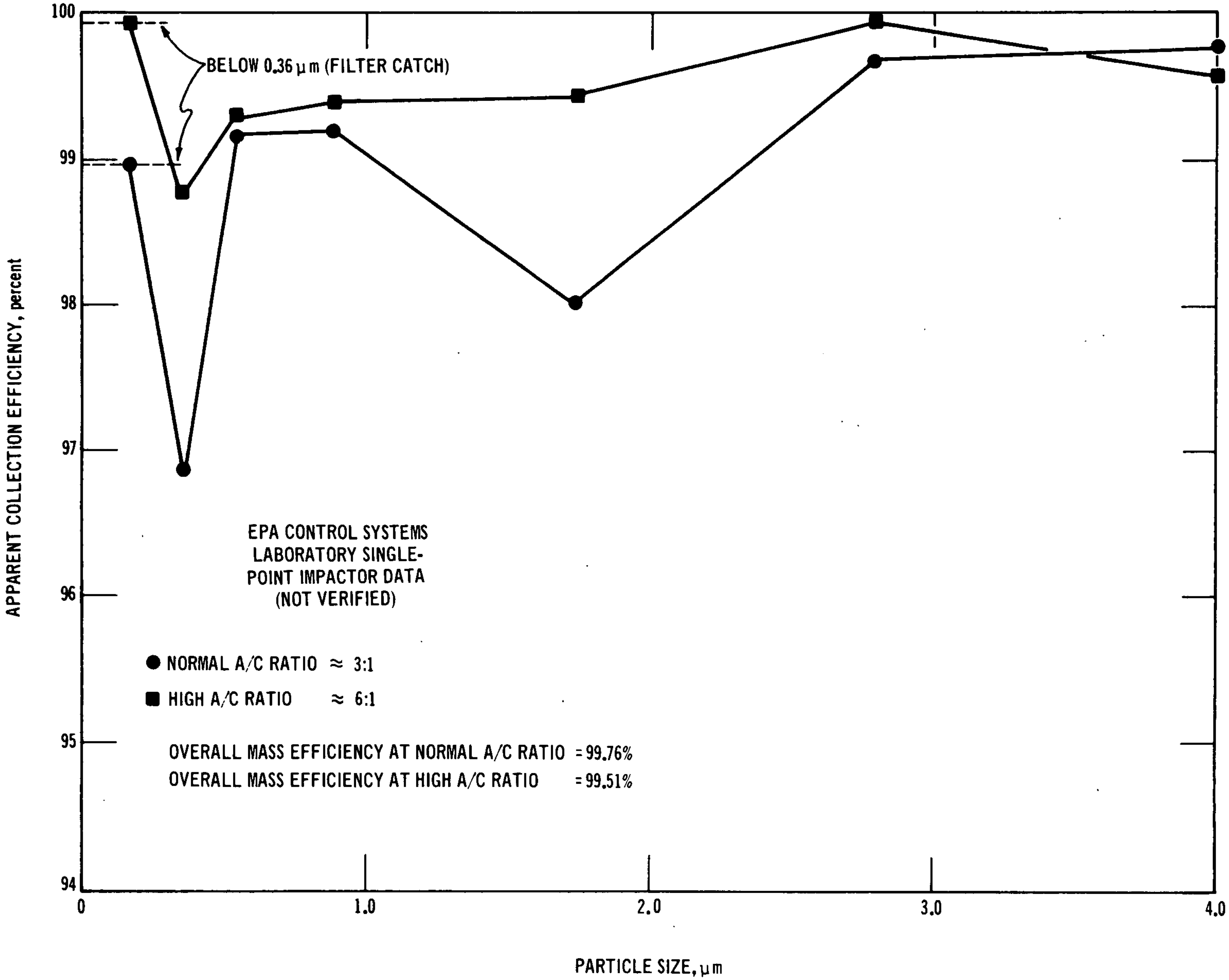

Figure 2. Baghouse performance, industrial boiler

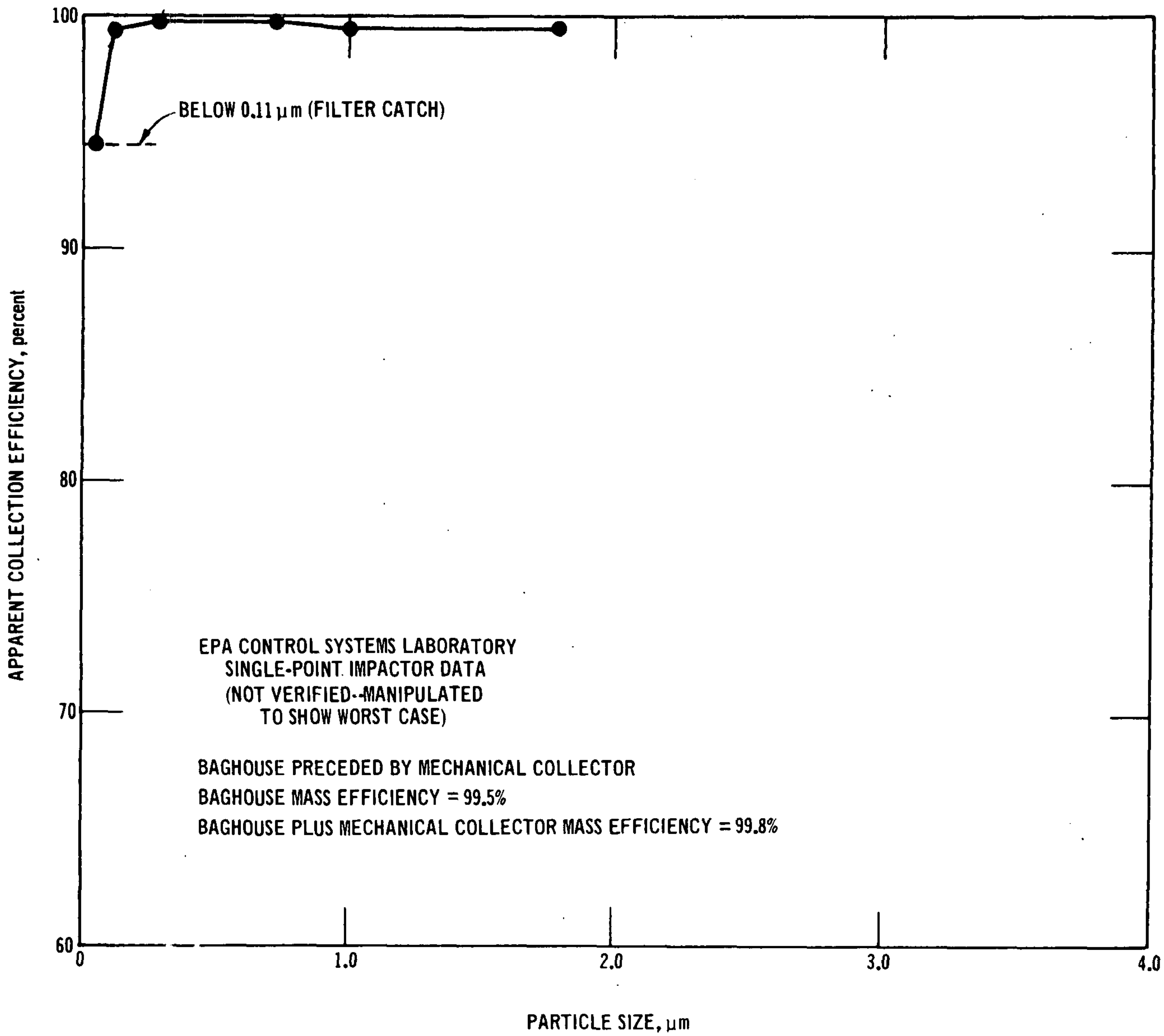

Figure 3. Baghouse performance, utility boiler

streams may not be representative; there may have been particle bounce through the impactors; sampling conditions may have affected results; but the graphs do imply good efficiency in the test range.

REASONS FOR EXTENDING CAPABILITIES

What are the reasons for wanting to extend fabric filter capabilities? The National Academy of Engineering[1] has cited fine particulates as being potentially harmful to health, as contributing to visibility problems and as contributing to weather modification, and EPA continues to do work which supports such a contention. It's not just fabric filter capabilities that need extending; it's also electrostatic precipitators (ESP's), scrubbers and any other good collection devices, and the extension isn't necessarily in general performance capabilities. Improvements need to be made in those areas in which collection efficiency is poor, and also in those applications in which control is not now exercised, or is exercised poorly. Referring back to the National Academy of Engineering report of 2 years ago: about 75 percent of crushed stone operations and about 38 percent of stoker fired industrial boilers were not controlled. Those two sources were assumed responsible for almost 40 percent of total mass emissions from major industry. In light of state and federal regulations on particulates, that looks like a lot of business for dust collector manufacturers, assuming the manufacturers are ready with working equipment for such sources.

If one talks specifically about fine particulates, the sources of primary importance get changed around. Crushed stone operations drop down on the list while industrial boilers stay near the top along with other combustion sources (utilities and municipal incinerators), iron and steel plants, ferroalloy plants and primary nonferrous metallurgy.

What has to be done to a fabric filter to make it capable of controlling any given one of these important sources, if it doesn't already control sufficiently well?

SPECIFIC AREAS FOR IMPROVEMENT

In some cases, perhaps not too many, the filter (not the baghouse) needs to be more efficient. The entire baghouse may require attention in regard to leaks, flimsy construction, lack of insulation and poor maintainability. If one must install control equipment at government behest, then the cost of buying and running such equipment should have no undue impact on the purchasers's wallet or on his process. For fabric filters this last requirement may lead to such areas as high temperature filtration and high velocity filtration.

HIGH TEMPERATURE PROCESSES

Since all of the leading fine particle producers involve high temperature processes one can start with extending high temperature capabilities. In a filtration paper written a number of years ago,[2] the range of 550 to 750°F was given as a practical maximum for filtration based on power requirements, gas viscosity and type of cooling. Filtration at temperatures above 750°F would be dictated by special process requirements. The paper did not, however, talk about changes in air-to-cloth ratio with temperature. Nor, with one exception,[3] does the writer remember seeing that subject explicitly dealth with. It would seem that baghouse vendors have taken that paper very much to heart, since the upper limit of commercial filtration has hovered around 550°F for about 25 years (albeit with increasing bag life and performance over that period).

Apparently the paper did not have as much impact on any electrostatic precipitator manufacturers who may have read it, since they have sold precipitators in the 700°F range and have worked on pilot units that go up to 1700°F.[4] Perhaps this statement is unfair to fabric filter manufacturers, since ESP design and operating problems appear less severe than those for filtration, and there is also a very high cost associated with development of new fibers and fabrics. There is one pilot baghouse that operated at temperatures up to 900°F,[5] and the Germans have introduced a filter fabric, Pyrotex T,[6] touted as good for continuous operation at about 660°F or at short bursts to 750°F. In this country Globe-Albany claims fabrics good to 600°F.

In order to go to higher temperatures, we are probably talking about inorganic fibers. There are already glass fiber filter fabrics, but some people have said that 600°F is the upper limit for glass because its strength drops off above that temperature. Other people are saying that, provided a suitable finish could be found for the glass, it should be useable at up to 1200 or 1300°F[5] which is still a few hundred degrees below the softening point. Protective finishes used up to the present have been siloxanes, siloxanes plus graphite, siloxanes plus Teflon^{R} and in some cases siloxanes plus graphite plus Teflon. Figures 4, 5, 6 and 7 are photomicrographs of glass fabrics coated with graphite/silicones and with Teflon, and in used and unused condition.

In order to protect glass to higher temperatures, one might use compounds such as polycarboranesiloxanes. Olin Corporation[7] makes such a compound which is supposed to be stable to 800 or 900°F, is resistant to most chemicals except strong bases and some organic solvents, and bonds to glass. A disadvantage to the material is its price: as a gas chromatography stationary phase it sells for $3000-4000 per pound, which is even more expensive than some fluorinated compounds. Given the market, Olin could probably produce specially tailored compounds at much lower prices.[8]

Ceramic or metal fibers have been looked at in the past and may come up again. The Pyrotex T fiber mentioned previously was stated to be a mineral fiber (presumably asbestos). Another pair of fabrics has been introduced by 3M Company.[9] These have alumina-boria-silica or zirconia-silica fibers as their basis. Maximum extended use temperatures are given as about 2200 and 1800°F, respectively, and one can even choose

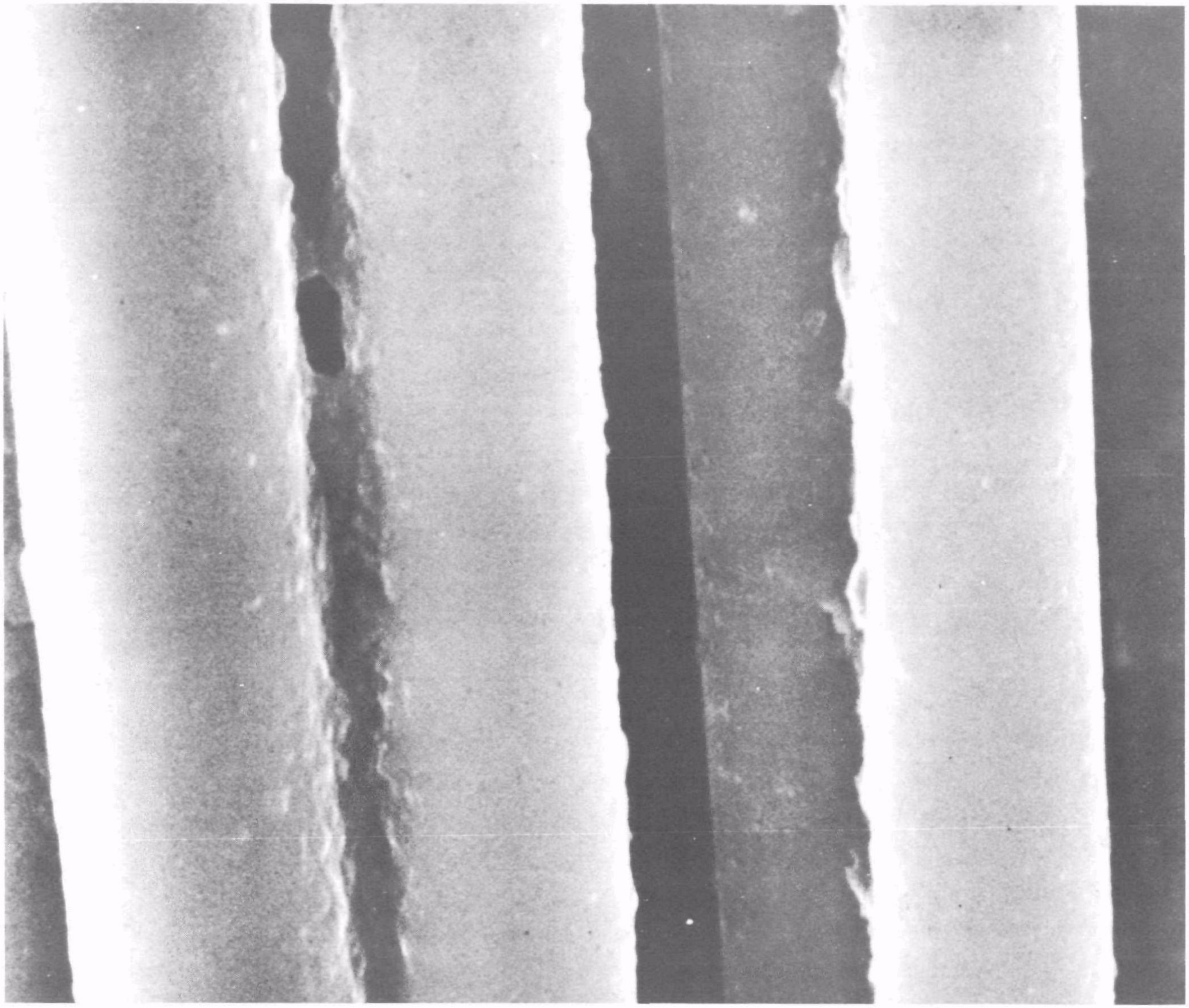

Figure 4. Clean glass fiber fabric, graphite-silicone treated. Treated fiber diameter approximately 7 μm

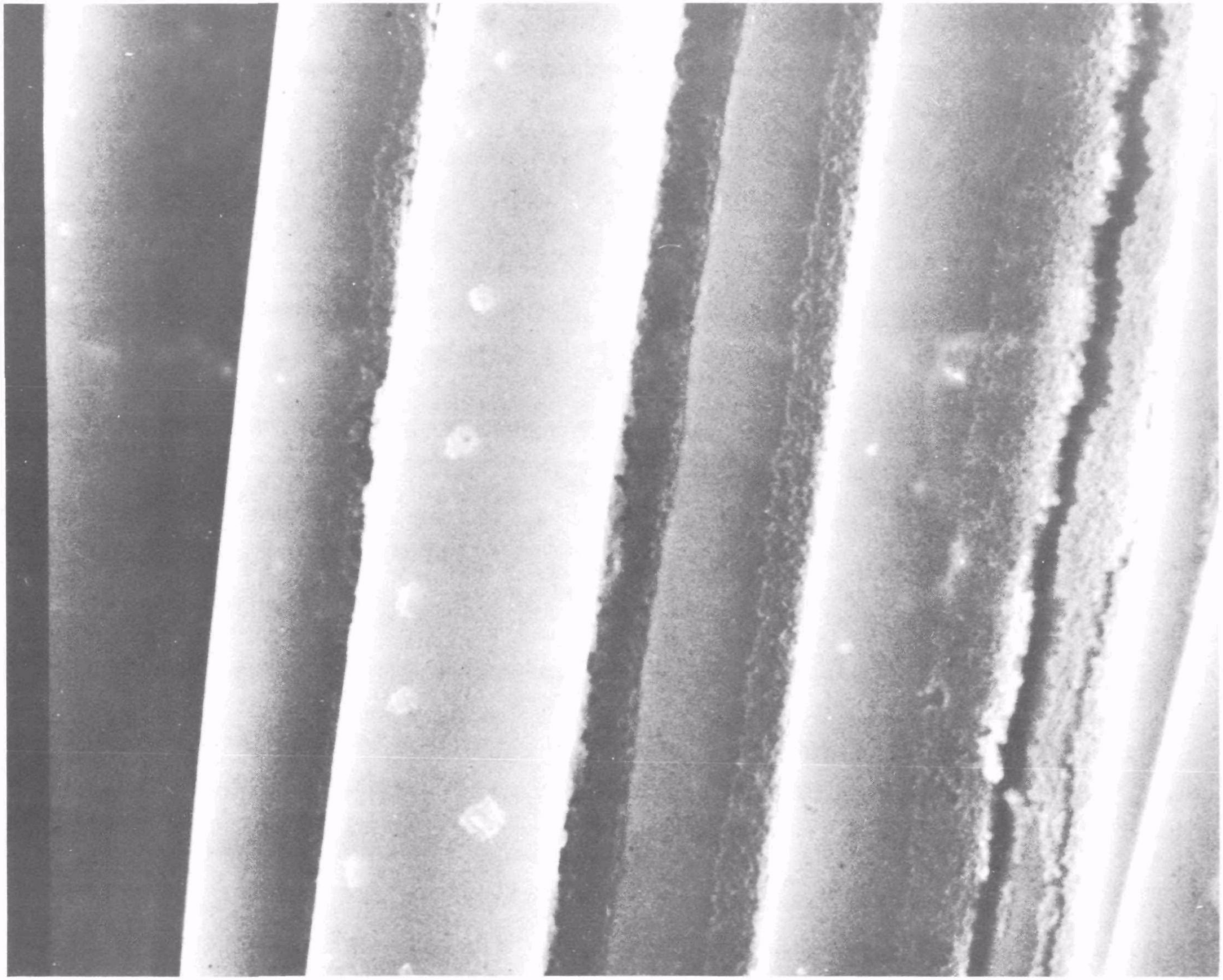

Figure 5. Clean glass fiber fabric, Teflon(R) treated. Treated fiber diameter approximately 7 μm

Figure 6. Dirty glass fiber fabric (cement dust), graphite-silicone treated. Treated fiber diameter approximately 7 μm

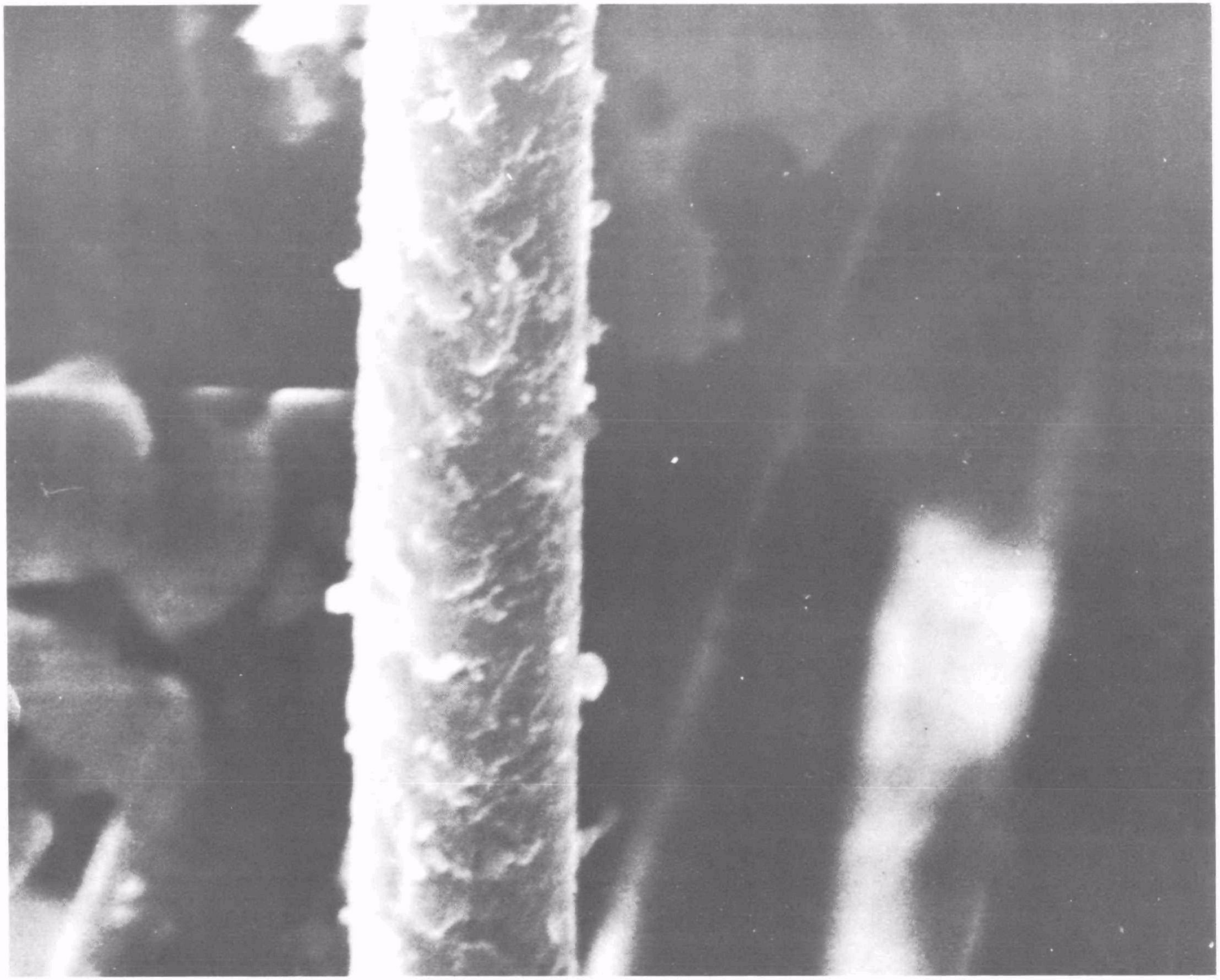

Figure 7. Dirty glass fiber fabric (cement dust), Teflon(R) treated. Treated fiber diameter approximately 7 μm

whatever color he desires. The cost of the fibers is on the order of \$25 per pound with projections of fabric prices at about \$10 per pound. Carbon and graphite fabrics have been mentioned, but they start oxidizing significantly near 600°F, and their price is high. Boron nitride would seem to be a good candidate material, but is expensive and may have other drawbacks as a filter fabric.

There are metal fiber felts such as stainless steel good up to about 850°F and sintered chrome-nickel mats for use to about 1100°F.[6] Electrical conductivity of these materials is high, so that they can provide good protection against static discharge and might well affect filtration or cleaning. The Brunswick Corporation[10] also makes a static control yarn containing 8 μm stainless steel fiber blended into nylon or other yarns.

If one doesn't wish to pay the price for high temperature fabrics, there is the option of paying for cooling the gas stream by radiation, water injection, dilution with air or conventional heat exchange. One way or another it's going to cost money to process a high temperature stream, and it appears that if a good high temperature fabric is available, there will be a market for it.

CHEMICAL RESISTANCE

Combustion effluents always present the hazard of acid attack, but there are ways to get around the problem. For applications above about 275°F one can use fabrics based on glass, Teflon® or Nomex®, and if there's very much SO_2/SO_3 present, and enough water vapor and a high enough temperature, Nomex in its present form will have short life. DuPont is purported to have an acid resistant Nomex in the works, which will be an improvement for organic fabrics. For inorganic materials, Pyrotex T is supposed to have good acid resistance and excellent alkali resistance and the 3M ceramic fibers are advertised as being "essentially chemical resistant".

Glass fabrics seem to be popular for combustion effluents, but become suspect for effluents containing fluorides. Since glass fabrics cannot survive without a lubricant on the individual fibers, it would seem that not the glass but the finish is what must really be resistant to fluoride attack, or that the fabric must be protected from contact with the fluorides. One interesting way of doing so is to put a sorbent or reactant material on the bag periodically while in service. Wheelabrator[11] used this method over a dozen years ago, and has recently used such a system for a primary aluminum pot line.[12] They don't say whether or not they're using glass bags, but Teller does in a similar system on a secondary aluminum smelter.[13] In a like manner Nomex can be protected from acid attack, to some extent, by pre-coating with lime/limestone.[14]

At lower temperatures there are several fabrics that display good resistance to a variety of chemical environments. Increases in resistance for these traditional fabrics would probably have to come from the fiber manufacturers.

FILTRATION EFFICIENCY

Until recently people have been saying that for most applications baghouses are 99^+ percent efficient and we don't even have to worry about efficiency. First of all that 99 percent is on an overall mass basis and the remaining 1 percent by mass can, for very small particles, make up a very large part of the total <u>number</u> of particles. Remember we said it was the little ones that we have become especially interested in removing. Although there is at present no federal standard for fine particulates (0.01 to 3 μm) there may well be one in the future. New Mexico has written such a standard into its laws for coal burning equipment: no more than 0.02 $lbs/10^6$ BTU of particulates less than 2 μm. In talking about removal efficiency for fine particulates, one needs either to talk about number efficiency, or else an equivalent, mass efficiency over small ranges of particle sizes. Many stack measurements have been made with cascade impactors, which makes it easier to use mass efficiency by size. While there have been quite a number of laboratory filtration investigations concerned with size efficiency,[15] there hasn't been much published on size efficiency of operating baghouses, or on actual size distributions and grain loadings by size into and out of baghouses. Six months ago many people thought that full scale collectors, precipitators and scrubbers as well as baghouses, tailed off in efficiency in the low or submicron range. EPA and contractor testing has shown, however, that for the small number of units tested, the efficiency can increase for sizes below about 0.5 μm for good collectors.[16] Tables 1 and 2 show the results of some of these tests. Theory predicts this behavior for collection targets: good collection by inertial impaction for large particles, possible good collection by diffusion for small particles and a no-man's land between about 0.1 and 1 μm.[17] For ESP's there are changes in charging mechanisms that help cause the dip in efficiency.

There are several implications from this testing. One is that no more work needs to be done on improving baghouse efficiency, which is an oversimplification, since the test data apply to limited measurements made under difficult conditions for specific dust/fabric combinations, and high, uniform efficiencies are desired. Another is that if a baghouse isn't efficient on a particular application there is either poor maintenance (leaks), an awful lot of particles in the no-man's land region, improper air-to-cloth ratio or else other phenomena which contribute to poor efficiency, such as electrostatic hindrance. Maintenance and maintainability are responsibilities of both the user and the designer. There have been baghouses that didn't even have a simple U-tube manometer for the operator to tell pressure drop, and maintenance programs that consisted of looking for broken bags when the plant manager thought the stack looked too dirty when he drove into the plant in the morning. That sort of system and program won't remain acceptable; the product of the tin bender's art must evolve into a better designed

Table 1. HIGH EFFICIENCY SCRUBBERS[a]

Source	Scrubber type	Particulate present, %		Mass efficiency, %	Fractional efficiency, %			
		< 3 μm	< 1 μm		1 μm	0.5 μm	0.1 μm	0.05 μm
Utility boiler (Bituminous coal)	3-stage turbulent contactor	60	20	99+	98	96	94	
Ferro-Alloy furnace	2-phase Venturi	60	15	93	95	90	80	
Open hearth steel furnace	Steam ejector Venturi	95	70	99.9	99+	99+	75[a,b]	70[a,b]

[a]Revised from Reference 16.

[b]The data indicate a minimum at about 0.05 μm and increasing efficiency for smaller sizes at least to about 0.01 μm.

Table 2. HIGH EFFICIENCY ELECTROSTATIC PRECIPITATORS[a]

Source	Particulate present, %		Mass efficiency, %	Fractional efficiency, %			
	< 3 μm	< 1 μm		1 μm	0.5 μm	0.1 μm	0.05 μm
Utility boiler (Bituminous coal)	25	10	99.6	99+	98	98	99+
Utility boiler (Bituminous coal)	5	2	99.6	95	92	98	94[a]
Utility boiler (Western coal)	15	3	98	96	91	98	99+
Kraft recovery boiler	90	60	99+	99	99	96[a]	

[a]Revised from Reference 16.

piece of equipment, and routine, adequate maintenance must be performed by the user. For the companies and designers who have not already performed this evolution there are helpful hints in the Handbook of Fabric Filter Technology[15] and the proceedings from the APCA specialty meetings in St. Louis and Buffalo last year.[18,19]

For the case of large amounts of particles in the 0.1 to 1 μm region it would seem that efficiency could be increased by agglomeration, or by changing filtration conditions to enhance either impactive or diffusional collection. Agglomeration might be promoted by adding moisture to the system;[20] by increasing residence time prior to entering the baghouse,[15] perhaps as part of a cooling system; by adding chemicals or other dusts to the gas stream; or by using sonics or by increasing turbulence,[21] although these last two methods may use too much energy to be effective.[17,p.217] Impaction may be aided by increasing velocity through the filter, decreasing the gas temperature, or making the path through the filter more tortuous. Diffusion should be helped by decreasing velocity, increasing temperature, making a more tortuous path through the filter and according to equations in Strauss,[17] also by using thicker filters with smaller diameter fibers and lower void volume.

ELECTROSTATICS

It seems that in most of the papers one reads about filtration efficiency or what makes filters tick, there is a reference to E. R. Frederick's paper[22] on electrostatics. Then there is a comment on how important electrostatic effects are in fabric filtration, followed by comments about how little we really know about electrostatic effects, and how we really should pay more attention to the subject. At that point the subject is usually terminated.

There are several ways that electrostatic augmentation might be looked at. Midwest Research Institute[21] has been investigating use of electrical fields as aids for conventional control devices. They recommend doing experimental work with both internal and external applied fields and with naturally occurring fields such as are found with electrets. Frederick has also given recent information on the subject.[23]

FABRIC STRUCTURE

In information available to the public, EPA has reported on effects of fabric structure on filtration performance.[24] Undoubtedly, there is a wealth of proprietary information on the same subject, and the writer would be interested in hearing from anyone in the audience who could confirm or deny EPA's experience. The major finding was probably confirmation of Tomaides' communication that particles can form a rather sturdy "bridge" about 10 particle diameters long.[15] In other words if the average fabric pore is more than 10 times the average particle diameter, filtration efficiency will be relatively poor. Another example would be work done by Textile Research Institute which shows that trilobal fibers give higher filtration efficiency at lower pressure drop than do round fibers.[25] In any case it appears that there is still much to be learned about the effects of fabric surface and construction on filtration performance.

CLEANING

One other aspect of efficiency is cleaning. More than half of the baghouses now being sold are supposed to be pulse jet units, which can bleed fine dusts on cleaning.[19] The popularity of this type of baghouse has been based on high air-to-cloth ratios and lack of moving parts in the baghouse; but it may be that for control of fine particulates the air-to-cloth ratios will have to be reduced, or else new fabrics or different cleaning conditions will have to be found. Penetration immediately after cleaning isn't limited to pulse jet baghouses so that revision of cleaning methods may be required for shake, and reverse air baghouses too. GCA Corporation has done work on filter cleaning mechanisms and kinetics which should provide a basis for modifying cleaning to reduce penetration of fine particulates.[26] It is apparent that, at least for single bags, control of the cake on the bag at the beginning of a filtration period could yield large dividends in stopping fines. An alternate to cake control might be momentary recycling of the effluent from a freshly cleaned compartment to the rest of the baghouse until cake repair has been completed in the cleaned compartment. EPA will evaluate such series filtration in a mobile filter used on field sources. It may even be possible, in some cases, to eliminate cleaning as a separate step. The writer knows of one instance in which the reverse cleaning air to a baghouse was stopped, but the filtration continued. Pressure drop increased a relatively small amount and then leveled out and didn't change. Apparently there was enough vibration in the baghouse and the cake was fluffy enough, so that the outer surface of the cake continued to slough off without destroying the cake next to the bag, and the filtration continued without the need for a separate cleaning step.

COSTS

The last topic before making some general comments and summarizing is costs. Ignoring Barnum's dictum about lack of birth control among suckers, let's assume that fabric filter systems aren't going to be sold for a given application unless they can do the job properly and cost less than competing control methods. In many areas it's going to have to be cost that sells a baghouse, because ESP's and scrubbers have turned out to be very efficient on fine particulates in given applications.

Starting with capital costs, what can be done to reduce the installed price of a baghouse and still maintain quality? Perhaps the largest single item is air-to-cloth ratio. If one could use ratios of 100:1 or 1000:1 baghouses would be in a much more competitive position. There are problems with bleeding of fines and/or rapid blinding of the fabric when relatively small increases are used; however, some work has been done on high velocity filters, which shows the expected efficiency decrease as ratios increase to about 100 fpm, but then there is a turnaround, and efficiency at 1000 fpm is better than at 5 fpm.[27] Additional work has been done at Harvard under Dr. Melvin First, and there is at least one company which is trying to commercialize a cleanable, high velocity filter, and has test data at up to 2500 fpm.[28]

Decreased operating costs are going to come from reduced maintenance requirements, but since lack of maintenance has long been a problem it would seem that smaller units and increased bag life are needed. Smaller units means we are again talking about higher air-to-cloth ratios, and longer bag life means either less strenuous cleaning or longer wearing fabrics. An example of the latter might be spunbondeds, which are potentially more efficient, longer lasting and cheaper than an equivalent woven bag.[29] One spunbonded nylon bag tested at EPA (2.4 oz/yd^2) survived 40 million shakes with an efficiency change from 99.5 percent at the start of testing to 98.8 percent at the end. Part way through the testing a repair of the bag was made with room temperature vulcanizing silicone rubber.

GENERAL COMMENTS

Fabric filtration has been around for a long time; it's practically an ancient art. If one wants to build a baghouse he often depends on company files rather than design equations to come up with a set of specifications. Referring to the proceedings from last October's APCA Buffalo meeting,[19] (in which there are many excellent papers), there is one striking lack. There are very few numbers. There are some cost figures and some temperature capabilities, but not many numbers one could use in design equations. On reflection this lack shouldn't be surprising, since there's also not much in the way of design equations for fabric filters, and that's the point. If one wants to design an ESP he can at least dust off the Deutsch equation, or its variants, and play around with it; calculations can be made of drift velocities and corona gradients and degrees of charging. Scrubbers aren't as far along, perhaps, but with baghouses the choices are especially limited. Since control of particulates in general, and fine particulates in particular, will call for extending control devices into unfamiliar regions and applications, it seems difficult for the fabric filtration industry to remain competitive if it can't analyze and design for potential applications mathematically as well as verbally. Regardless of the varied and understandable reasons for lack of analysis and design equations, it seems that the industry needs to enlist someone who can formulate and publish such equations. There is the caution that those who do the work must have an extensive background in fabric filtration. The subject is too complicated for rapid analysis by the neophyte.

There are similarities among the three major particulate collectors that might be taken advantage of for design and analysis. Each has a collecting chamber, each has an array of collecting surfaces, each is concerned with placing the collecting surface in the path of particulates (or influencing the path of the particulates toward the collecting surface), each has a means for regenerating the collecting surface, and each is vitally concerned with the interaction between collector surface and particles either as individuals or as aggregates. The change in magnitude of collecting forces with time between particle and collection surface is probably greatest for fabric filters and of lesser or secondary importance for ESP's and scrubbers. Fabric filters have one aspect with both good and bad connotations: the variety of collecting surface materials and shapes. Scrubbers generally use one material, water, in several shapes, drops, sheets or bubbles; ESP's are limited to a few metallic compositions for straight wires and for several shapes of flat plates; but fabric filters have a bewildering variety of collector materials, each of which can be formed in an equally bewildering variety of shapes. Bringing mathematical sense and order to the interactions between particulates and fabrics is certainly an awesome task, but it is one that needs doing.

SUMMARY

Reasons for needing better collection of fine particulates (health, weather, visibility) have been given, and areas of R&D which may prove fruitful in extending fabric filter capabilities have been suggested. These areas include extension to sources which are the major producers of fine particulates, mostly high temperature sources; more chemically resistant and more durable fabrics; more efficient collection of fine particulates through better maintenance, better cleaning or better fabrics; and major reductions in filter system capital and operating costs. Fabric filtration is at a disadvantage because of lack of analytical and design expressions, and work certainly needs to be done here. The question remains as to who will do all this R&D work. The National Academy of Engineers recommended a tenfold increase in government spending in the general area of R&D in particulate control,[1] but that was 2 years ago and the government, at least as represented by EPA, has not increased spending to that level. Universities rarely generate much of their own R&D money, and they've been falling on even harder times lately. That seems to leave one segment to get the work done: industry.

Many of the topics discussed in this paper may sound either contradictory, too costly or perhaps just pain ridiculous, but the idea has been to point out areas which are in some fashion documented and which may eventually lead to extended capacities.

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NEW FABRICS AND THEIR POTENTIAL APPLICATION

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Excitement in fabric filtration? Entirely new fabrics for future requirements? Although there are radical new innovations there is no "rotary engine" concept in fabric filtration, but there are some developments with quite encouraging prospects. Two areas of major concern to equipment manufacturers as well as to end users are: improved efficiency and cleanability of filter fabrics. However, this paper will deal basically with high temperature filtration 250°F. and higher.

Approximately 1/3 of the particulate emissions from industrial sources evolve from processes 900°F. or higher. The utilization of fabric filtration systems in these environments typically requires gas stream cooling by either radiative/convective means, air dilution or water systems cooling. Even in cases where cooling systems are employed, temperature surges sometimes occur and may cause damage to the operating elements of the filtration system, particularly to the fabric. Therefore, the demand for significant high-temperature resistance fibers in fabric filtration is certain.

The growth and development of the fabric filter has paralleled the expanding technology of synthetic fibers. The traditional barriers to baghouse developments as related to fabrics have been temperature limitations and chemical resistance of fibers, dimensional stability and flex strength. These limitations have often dictated the design limitation of the system. Significant improvements, according to Culhane,[1] have been made possible with cotton and wool being replaced with man-made fibers and glass.

The characteristics of most sub-micron particles to agglomerate have resulted in the ability of filter fabrics to remove 99.9 percent/wgt. of the sub-micron solid particles. This order of fine particulate efficiency is being achieved in separating:

1. Carbon Black from process reactors.
2. Silicone Dioxide in .02 - .05 micron range from submerged arc furnaces.
3. 100 percent of particles below 5 micron and 95 percent below 2 micron in ferrous fume emissions.
4. Fume dust from leaded glass melting furnaces either 80 percent of the particulate are below 2 micron and have poor agglomeration tendencies.[1]

Therefore, in designing an efficient economical fabric filter, one must weigh carefully the strengths and weaknesses inherent in each of the available fabrics to arrive at a system which has filter bags which do the job. To discuss all of these requirements at this time would be impractical. The development of new high-temperature fibers is being accelerated e.g. NOW 100 from DuPont would be such a candidate.

It is generally accepted that pollution control equipment, specifically fabric filters and electrostatic precipitators, are least efficient in removing particles in the critical 0.1 - 1 micron size range. Table 1 summarizes the separating mechanisms to particles of various sizes. In each case, there are circumstances in which a minimum exists in the curve of efficiency vs. particle size for constant flow velocity. In the case of the fabric filter, very small particles (smaller than 0.1 micron) are efficiently removed by Brownian motion and the finer the

Table 1. PARTICLE SIZE RANGE FOR SEPARATING MECHANISMS

Force	Particle size range, μ
1. Gravitational settling (for large size particles)	> 1
2. Physical or direct interception (For intermediate size particles)	> 1
3. Inertial impaction (for smaller size particles)	> 1
4. Diffusion of Brownian motion (for very fine particles)	< 0.01 - 0.2
5. Electrostatic forces present on either particle or fiber or both	> 0.01

easier their removal in the diffusion range. Figure 1 depicts the major particulate removal mechanisms operative in the case of a single fiber. Larger particles (larger than 1 micron) are collected by impaction and interception and their removal efficiency increases with particle size. The particle size most difficult to collect is in the range between removal by Brownian motion and by impaction.[2] These fine dust particles actually don't obey filtration laws.

This theoretical result has been experimentally verified for deep bed fiber filters and for clean cloth filters in laboratory studies. However, in an EPA sponsored review, Billings and Wilder, 1970, noted that field performance data for the efficiency of fabric filters as a fraction of particle size are lacking.[9] A somewhat similar situation exists for electrostatic precipitators commonly used for fly ash removal from power plant emissions. Particles larger than about 1 micron have high mobility because they are highly charged. Particles smaller than a few tenths of a micron can achieve moderate mobility even with a small charge because of aerodynamic slip (least charge ability). (A minimum in efficiency usually occurs in the transition range between 0.1 and 1.0 micron, more specifically 0.4 - 0.6 micron).

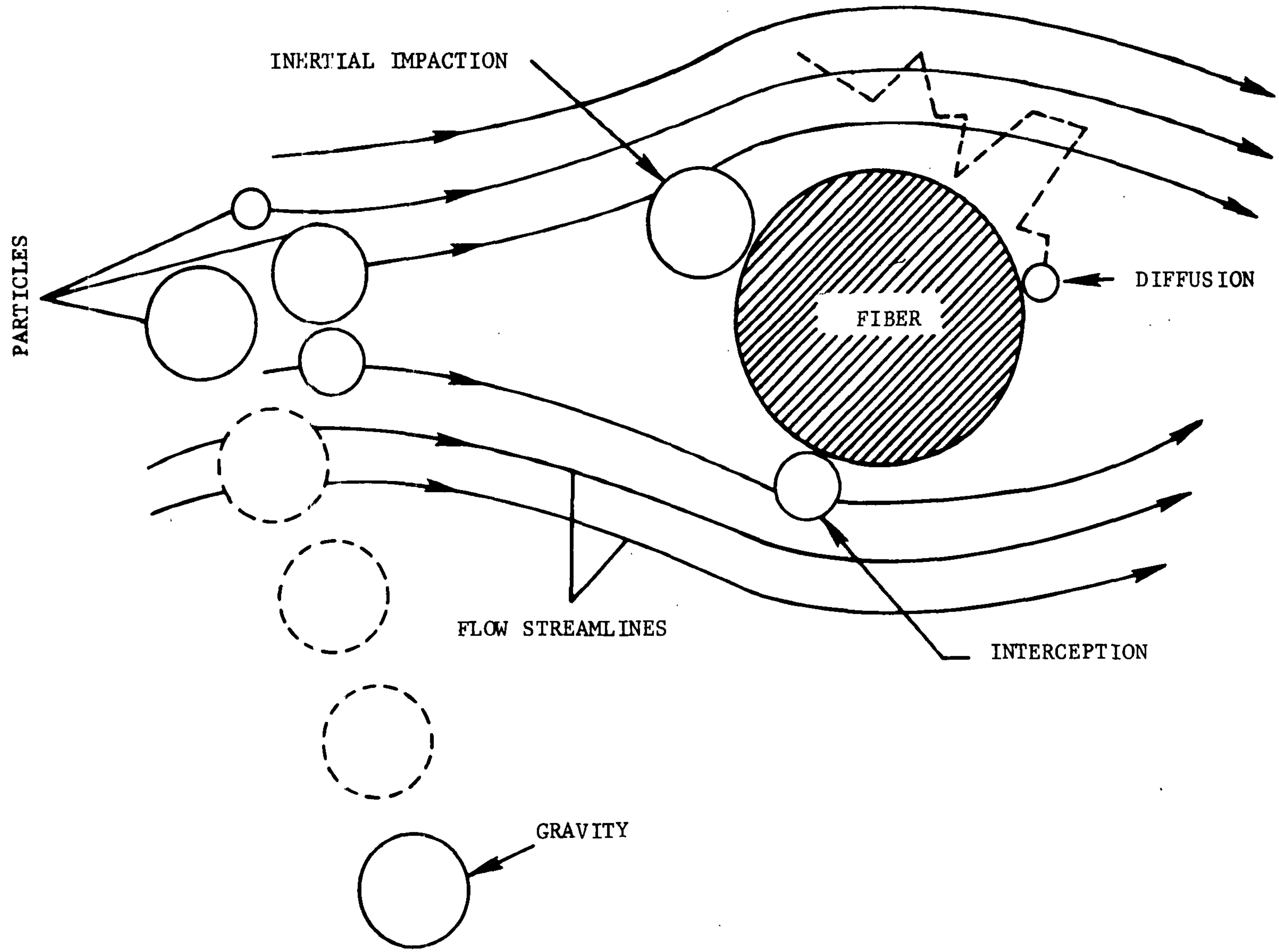


Figure 1. Mechanisms for particle removal by a fiber

Table 2 summarizes the factors affecting filtration efficiency in needled felts. As can be determined by review of this table we see that the decrease in efficiency due to an increase in fiber diameter is due to the reduction and flow tortuosity per unit weight or mass of filter. Needled felt efficiency, due to the diffusion phenomena, is reduced by increases in face velocity, particle density and fiber diameter. The one consistent fact, as far as the stated filter variables are concerned, is that one should use the finest filter diameters available to achieve maximum filtration efficiency.

Air permeability as discussed herein represents an approximation of the starting condition of an air filtration fabric. Generally, rapid changes in flow take place, the rate probably dependent upon fabric structure and the filtrate characteristics, until a new approximately steady state is reached (permeability equilibrium). Thus, while initial fabric structure and air permeability constitute only part of the spectrum of fabric performance characteristics, they undoubtedly are fundamental to the entire filtration operation, including the type and rate of cake build-up. Air permeability under working conditions - with dust layer- will remain basically between 20 percent and 50 percent of the initial throughput at differential pressures basically between 3" and 6" W. G. The air permeability at this stage is referred to the permeability equilibrium. It is the target in fabric design to keep this permeability equilibrium as high as possible.

SURFACE MODIFICATION OF FILTER MEDIA

The capacity, cleanability and efficiency of fabric filters are greatly influenced by surface properties. Surface modifications have been shown to have an especially marked influence on the performance of needled fabrics.[3] Fine particles readily penetrate ordinary felted fabrics and this often leads to serious plugging condition with

Table 2. FACTORS AFFECTING FILTRATION EFFICIENCY IN NEEDLED FELTS

	Efficiency due to:				
Increase in:	Gravity	Sieving	Inertial impaction	Direct interception	Diffusion
Face velocity	Increased	No effect	Increased	No effect	Decreased
Particle size	Increased	Increased	Increased	Increased	Decreased
Particle density	Increased	No effect	Increased	No effect	Decreased
Fiber diameter	No effect	Decreased	Decreased	Decreased	Decreased
Decrease in fiber diameter	No effect	Increased	Increased	Increased	Increased significantly

substantial reduction in air permeability. New developments in surface alteration through controlled heat treatment tend to inhibit serious penetration of particles by encouraging the formation of a primary protective dust layer on the surface with only minimal penetration into the fabric. As a result, permeability at equilibrium remains high and, therefore, better overall filter capacity is realized. In many applications, in fact, the improved surface promotes formation of a more porous dust layer.

Surface modifications of this type have been applied successfully to polyester, acrylic, polyolefin and high temperature (Nomex) aramide felts, but with each fabric system the modifying method differs. Needled felts, altered in this way, have already demonstrated their special effectiveness in collecting the emissions from asphalt, cement and certain chemical plants. The fabric is also being evaluated in a number of other applications.

Aggregates on the fibers collect some particulates by impingement and continue to grow in size, eventually bridging the spaces between fibers, as depicted in Figure 2. This formation of the dust cake within the fabric takes place over some little depth and having once formed, collection of particles either takes place on the outer surface of this dust cake, due to the self-filtering action of the cake, or on some of the fibers between the fabric surface and the cake surface. The dust cake rapidly builds back to the surface of the fabric and beyond it.

It will be noted that, in general, as the particle size decreases, the acceptable filtering velocity decreases. This is a reflection of the conditions within the media itself. In operation, the outermost fibers of the felt act as the base for the retention of the first particles to be filtered, until sufficient bridges have been established to support the filter cake which then serves to "sieve" further particles from the air flow.[6]

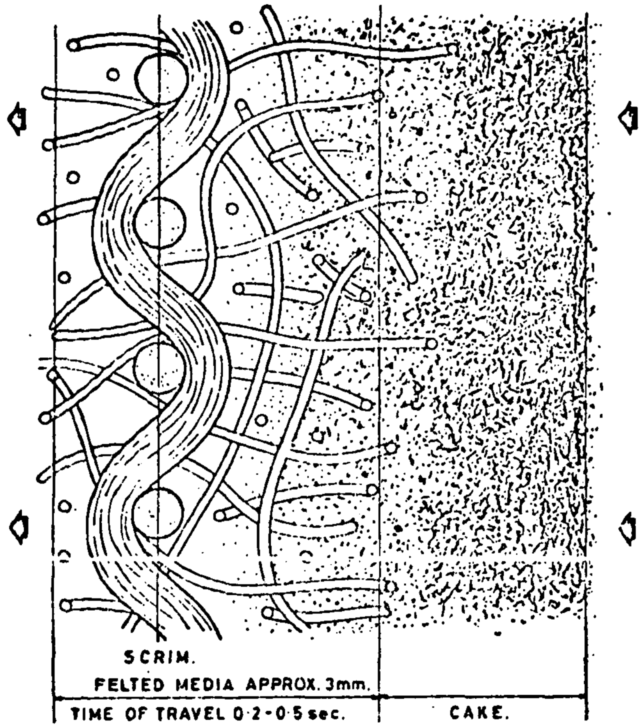


Figure 2. Section through felted filter media showing distribution of dust

When one considers the extension of such theories to needled felted fabrics, the limitation of these theoretical developments to practical situations are obvious, due to the three dimensionality of the system and the fact that the dust particles are almost entirely irregularly shaped. In the absence of an adequate theoretical treatment, or detailed understanding of the mechanism of separation principle of fabric filters, manufacturers have gradually built up a "know how" of satisfactory use of these filters.[6]

MATERIAL TO BE HANDLED

The shape and structure of a particle will influence its collection, its interaction with the fabric, and its behavior as an element in a granular deposited layer or cake. Figure 3 presents an artists conception of the major shapes of airborne particulates and summarizes the major sources of each particle shape. Characterization of the size, shape and structure for most particles of concern requires costly and sophisticated analysis and little has been done to relate properties of the particulate system to behavior in a fabric filter deposit or to effects on filter performance.

Most dry dust from manufacturing operations involving product handling, venting, and the related processes, consist of highly aggregated systems of single particles. Since they are often compacted so that their envelope shapes are approximately spherical, their aerodynamic behavior can be predicted adequately from spherical models. Most analytical treatments are based on resistance forces arising from spherical shape. Irregular shapes will experience greater resistance forces which counter the gravitational force and lead to reduced settling velocity.

Sub-micron fume is molecular in size and the ability of the baghouse to remove it is due to the filter cake formed by proportional number of light agglomerated particles. The finer particles form a tighter filter cake with higher density, resulting in a more compressive formation in comparison with a cake formed from coarser dust particles.

With trends towards more highly rated chemical plants and the increasing likelihood of handling thermally liable materials with unusual properties, filter manufacturers must be continually vigilant for the "problem material".

Typical organic solids fall mainly into the category of materials which have been subjected to a drying process and that the intermediate or final product is separated as a filter cake from usually an aqueous suspension. There are current trends to use fluidized bed or spray dryers. These have the advantage of considerably reduced settle times

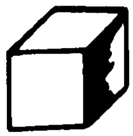
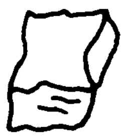
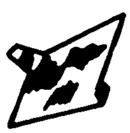
	SPHERICAL	SMOKES, POLLEN, FLY ASH
	CUBICAL	SALT CRYSTALS
	IRREGULAR CUBICAL	MINERAL DUSTS
	FLAKES	MINERALS, GRAPHITE, EPIDERMIS
	ACICULAR, SPINY	ZINC OXIDE, AMMONIUM SULPHATE
	FIBROUS	LINT, PLANT FIBERS, ASBESTOS, MAN-MADE FIBERS
	CONDENSATION FLOCS AGGLOMERATES	CARBON SMOKE, COAGULATED METAL OXIDE FUME (E.G. IRON OXIDE)

Figure 3. Major shapes of airborne particles

although a high velocity circulating or moving stream of air is essential for operation if much larger volumes of dust loaded air must be handled in classical counter current dryers.

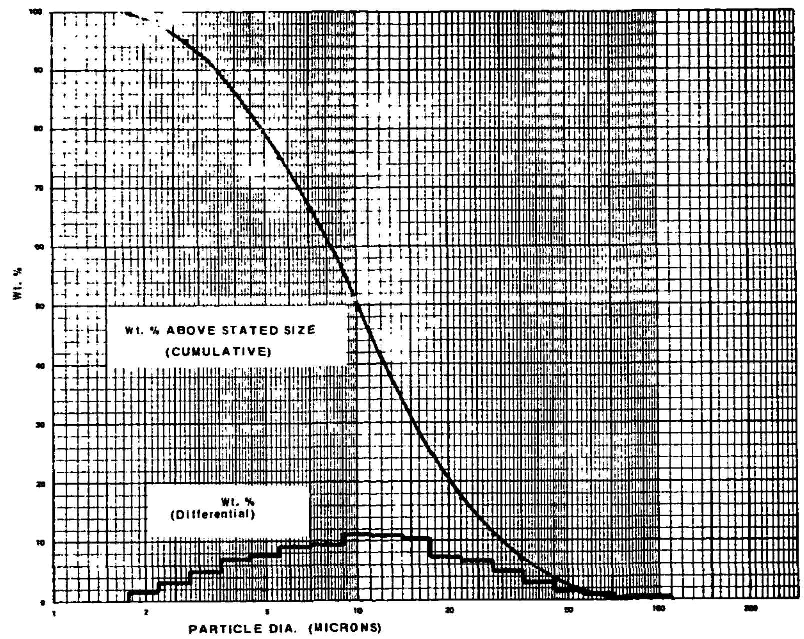
In the asphalt industry, for example, one of the most important considerations for any plant is the raw material to be handled and filtered. Recent studies show that particle size distribution down to the sub-micron size exhibit great variations, particularly with regard to the percentage by weight of particles in that low micron range, as demonstrated in Figure 4. It is not the coarse aggregates which cause major problems, but mineral dust. The "filler" usually consists of fine ground particles, crushed rock, limestone, hydrated lime, Portland cement, clay, Basalt, slag, sandstone, or other non-plastic mineral matter.

In some aggregate dust, 5 percent of the minus 74 micron material is below 5 microns, in the others, considerably higher amount of this micron range is common. Further complications arise in that each hot mixed asphalt plant produces a number of different asphalt mixes in which coarse aggregate containing very low amounts of dust are combined with fine aggregates in an infinite range of combinations at a moisture content ranging from 1 to 12 percent.

The selected filtering velocity varies from application to application depending upon the filtration characteristics of the dust and fume particulate. The filterability of any given quantity of particulate depends upon the particle size distribution, shape, surface properties, and electrostatic forces.

FILTER EQUIPMENT

The most rapidly growing type of fabric filter in recent years is the high ratio, pulse-jet or cage-type filter. The percentage of the total



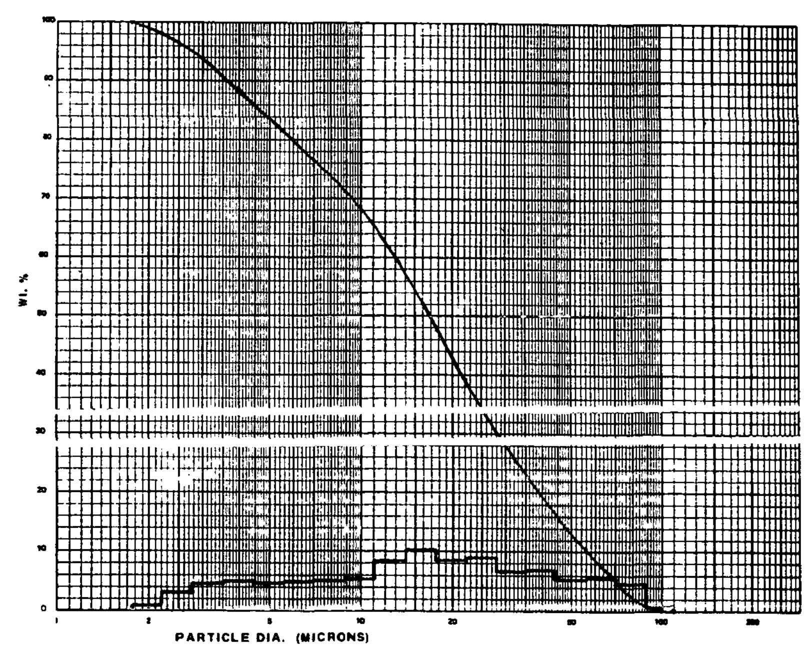
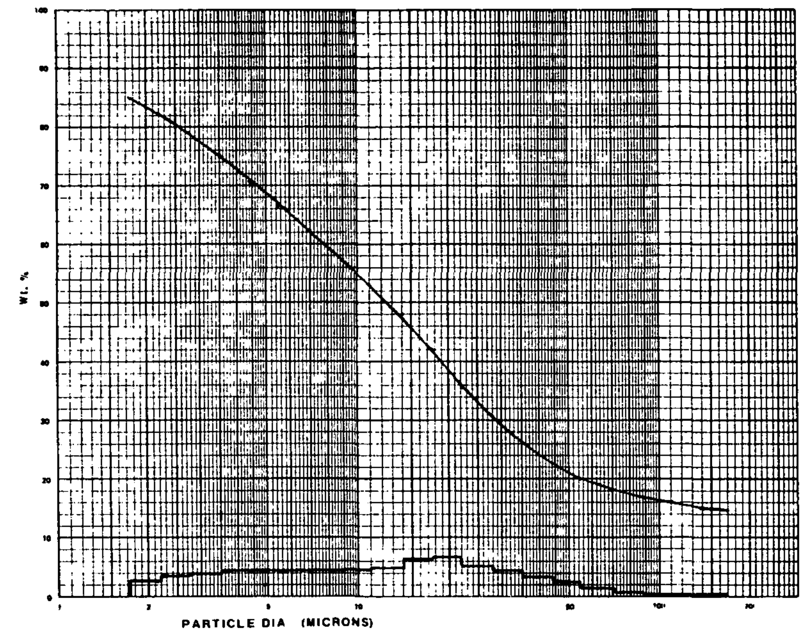


Figure 4. Particle size distribution of emissions for an asphalt plant



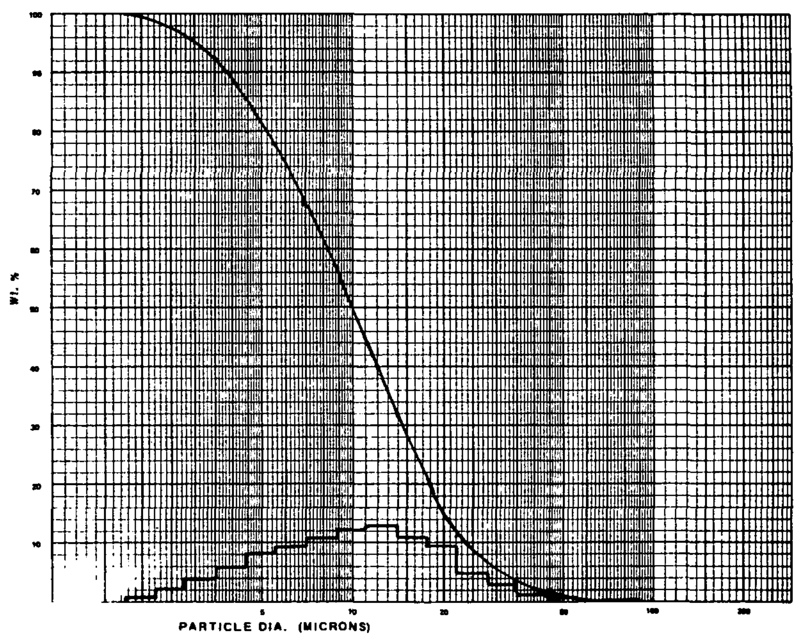


Figure 4 (continued). Particle size distribution of emissions for an asphalt plant filter market represented by this type of system is estimated to be as follows:

1969	-	5 percent
1970	-	10 percent
1971	-	40 percent
1972	-	50 percent
1973	-	55 percent

There are today approximately 40 manufacturers in the United States which offer this type filter with probably 50 different filter designs, but all utilizing needled fabrics and working at A/C ratios basically between 5:1 and 10:1. The cleaning device applied might have the most significant influence on performance.

"OVER-CLEANING" OR "PUFFING" EFFECT

The "over-cleaning" or "puffing" effect is observed with high energy/low air volume cleaning even if this method of bag regeneration has certainly many advantages as compared to reverse air and mechanical shaking type cleaning. The very abrupt full air shock destroys to some extent the primary dust layer. If the dust contains very many sub-micron particles, this layer has to be re-built each time after cleaning resulting in insufficient collection until this is accomplished. This phenomenon can be improved by lowering the cleaning pressure, but only at the expense of high differential pressure. Therefore, flexibility in solving an efficiency problem with lowering the cleaning pressure is limited.

In this connection, it should be mentioned that there are certainly several unknown factors in fabric filtration which should be the subject of more research and development work, particularly related to this type of filter. Some of these areas are: venturi design, length to diameter ratio, diameter influence on cleaning efficiency, venturi placed inside or outside of bags, double wall bag configuration, cake density effect on cleanability, air permeability of fabric during operation, pressure drop and particle size, particle shape, gas velocity and distribution, and relationship of cleaning cycle to inlet loading, to name a few.

FIBERGLASS

Glass fibers are unique compared with the wide range of fibrous materials used commercially for filtration purposes. They differ from naturally-occurring cellulose fibers and other man-made fibers in that they are circular in section, straight and of uniform diameter, and can be made far finer. They have a considerably higher density than cellulose and most man-made fibers and a far wider, useful temperature range. In addition, glass fibers do not suffer a change of form when prepared for processing, retaining their original cylindrical shape with none of the swelling or fibrillation associated with natural fibers.[5]

The all important factor controlling filtration characteristics of the flass fiber medium is the diameter of the fiber.[4]

Loeffler[5] reported that the collection efficiency of fiber filters is evidently vitally effected by a bouncing effect which occurs when the particles strike the fibers at speeds much below 1 meter per second and which reduces the collection efficiency.

The higher the filtration rate at which the particles had been filtered onto the fibers, the higher was the blow-off speed (compressivity) cake density.

EFFICIENCY OF NEW MEDIA

The collection efficiency of needled fabrics is no longer determined simply on a basis of weight and permeability. In addition to surface variations, fiber blends and inclusion of superfine fibers offers a new dimension to needled felts. As a direct result, collection efficiency has been improved. The inclusion of very fine glass fibers with Nomex in the needled felts increases the fiber surface area significantly. This allows more particles to be retained and causes more fine particles to be held at or near the surface.

GLAMEX

For pulse-jet filters particularly, fabric requirements are becoming more and more critical. Accordingly, new developments in felt-like fabrics have been and are being made with a degree of production sophistication not attained before. The fine glass - Nomex (Glamex) - fabric, for example, has effectively replaced some 14 oz./sq. yd. Nomex felt in several asphalt plants due to its ability to effectively control sub-micron particles. Other very successful applications of this combination fiber type of felt have been shown for controlling lightweight aggregate, silica dust, carbon black and cement clinker all at high efficiency and at elevated temperature.[4,8]

Man-made fibers in Nomex, polyester, polypropylene and others for filtration purposes are commercially available down to 2 denier or 1.5 denier. Denier is related to the fineness of the single fiber and its manufacturing is limited therein. (The lower the denier number the finer the fiber.)

Glass, a mineral fiber, is available in much finer deniers so that more fiber surface faces the dust and a larger portion of fine dust particles settles down rather than penetrating through a fabric.

In fabric filtration the fiber diameter is the denominator, hence, a decrease in fiber diameter will cause the parameter to increase yielding higher efficiency by diffusion. It is known that the face velocity in fabric filtration systems - the velocity at which the gas passes through the filter fabric - determines if fine dust is collected by impaction or interception rather than by diffusion. Tests have indicated and proved that the increase of fiber surface utilizing fine fibers influences fabric efficiency dramatically.

Efficiency of filter fabrics is influenced mainly by the ability of the filter media to attract the very fine particles. The specific gravity of these fine particles is very nearly equal to the molecular weight of the carrier gas or air. These very fine particles settle down due to the assistance of reflection on the fiber surface and become arrested by capilliary adhesion forces. Such movement is characteristic of small particles carried at low velocity.

Diffusional contact, therefore, is favored when small particles move at low velocity against large filter surface. A very simplified analysis: the human nose acting as a duct has at its entrance a network of hairs acting as a filter to remove any foreign material from the air stream before it reaches our lungs at a very low velocity.

Glamex has proven its ability in applications besides the asphalt industry; on Clinker Coolers in cement industries and spray dry applications in chemical processing. Difficulties occur because dust with a low tendency to agglomerate causes efficiency problems, particularly on high ratio filters.

It has been determined that the pressure, duration and cycle of cleaning have some influence on efficiency. Glamex has proved to be less sensitive to cleaning pressure.

Glamex has been in the field for four years and will go into other areas where the high ratio filter unit has proven its suitability. Glamex, as a new filtration concept, is certainly the answer in many areas where efficiency is a major problem.

The first generation Glamex fabrics use a woven glass scrim with a combination glass/Nomex blend or web. Needless to say, in terms of strength and, more specifically, flex characteristic, any glass scrim is inferior to 100 percent woven Nomex scrim. It is too early to make any prediction as to what time factor is involved with regard to bag life. Our results to date are quite encouraging. We have also developed a second generation Glamex fabrics which use the old spun Nomex scrim and the fine glass fibers only in the web. With reference to a special test of the Bureau of Mines, applied to respirator felts, silica dust is used in the 0.4 to 0.6 micron range. Efficiency tests have indicated that this second generation Glamex fabric is twice as efficient as a 100 percent needled Nomex fabric.

NEEDLED FABRICS IN SHAKER AND REVERSE AIR BAGHOUSES

Shaking will remove a dust cake which has built up on the fabric surface but it has little effect on the dust cake within the fabric. Reverse cleaning will remove some of this material. Thus, when the reverse flow dislodges, particles within the depth of the media are subject to impingement on fibers near the surface. The nearer the dust is to the surface the greater the likelihood of being removed by reverse flow.

Needled fabrics traditionally used on cage-type collectors are also being considered in shaker and reverse air baghouses in the United States today. Since the mid 60's experience in Europe with needled fabrics in these collectors has been quite encouraging. The basic baghouse design differs compared with this collector type in the U. S.

Bag sizes are 7 1/2 inches or 8 1/2 inches diameter and 8 feet or 11 feet long providing a length to diameter ratio of roughly 16, resulting in a relatively low entrance velocity in filter bags. In addition, most of these bags contain four to six spreader rings and operate at A/C ratios ranging between 4 - 6:1 versus 2.5 - 3:1 in most comparable U. S. shaker and reverse air filters.

Needled fabrics perform far better in large diameter bags than in smaller 4-inch or 5-inch diameter tubes. The stiffness of the felt, compared with woven fabrics, may cause mechanical wear problems in the bottom cuff area. In order to evaluate the problems, several companies designed their bags with woven boots. However, a flexible surface modified needled fabric has been our main objective for this application.

Is the needled fabric a better substitute for woven fabrics in these collectors? The answer has to be proven in the field. Results so far are very encouraging. The obvious advantages are:

- Improved efficiency
- Increased capacity
- Better cleanability
- Improved economics
- Suitable at elevated temperatures up to 400°F.

Due to the in depth filtration properties of needled fabrics one may consider higher A/C ratios when designing shaker or reverse air systems that used the needled bag instead of the woven fabric. Economically, therefore, such units consist of fewer compartments and, therefore, less hardware. Due to the needled felt structure, the efficiency is considerably better than an equivalent permeability. The air permeability of needled fabrics is generally higher, compared with most woven fabrics used in these collectors. A special surface modification provides a better cake release. Fine particles readily penetrate ordinary felts, resulting in serious blinding and high differential pressure. The needled fabric with a heat-treated surface inhibits serious penetration of particles by forming a primary dust layer rather on the surface. All of these advantages should lead to increased acceptance of needled fabrics in shaker and reverse air baghouses.

A large cement company in Canada, with a total of 24,000 filter bags operating a reverse air baghouse, converted more than 12,000 bags to needled fabrics. Better efficiency and lower differential pressures have been the main advantages. Several other trials are being conducted, particularly in industries where capacity is a main problem with existing fabric filters. Instead of adding additional compartments, the unit can be converted to needled fabrics, with the same number of bags but capable of handling a considerably greater amount of air. In some cases, duct work and fans have been enlarged to handle the additional air flow.

STATUS SUMMARY OF DIFFERENT INDUSTRIES

ASPHALT PLANTS

This industry employs approximately 800 to 900 fabric filters today, and it is anticipated that in 1974 another 500 to 600 units will be installed. While there are a number of needled felts which can be used for asphalt plant applications, as enumerated in Table 3, the industry is utilizing basically needled 14 oz. Nomex felt. The filter unit is a cage-type high ratio unit with an average of 5.5 - 6:1 A/C ratio. Temperature generally measures between 240°F and 270°F with temperature surges up to 375°F. Inlet loadings amount to 20 to 30 gr./cu.ft. One most important consideration from an efficiency standpoint is the amount of sub-micron particles. This industry has to meet the federal code of 0.04 gr./cu.ft. This becomes difficult to obtain on a consistent basis due to very fine raw materials, at least in some geographical areas. Special fabrics, i.e. GLAMEX and style S-2283NR (Glass/Nomex in the web-Nomex scrim) are doing a superior job in filtering these fines from the stream.

CEMENT INDUSTRY

For more than 15 years reverse air glass baghouses were very well known in kiln operations. Within the last 2 years, Clinker Coolers have been furnished with high ratio units. The average Clinker Cooler operation handles 120,000 cfm with an air to cloth ratio of 5:1 using a 16 oz. needled Nomex filter bag, and has expected bag life from 2 to 3 years. To date, 50 fabric filter units are in operation or under construction in Clinker Cooler filtration.

CARBON BLACK

This industry represents the largest user of glass fabrics used in reverse air filters. Several new treatments for flass fabrics, with

Table 3. COMPARISON OF DIFFERENT NEEDLED NOMEX FABRICS FOR ASPHALT PLANTS

	A	A	B	B	B	C	D	E	F
Fiber	Nomex	83% Nomex 17% Glass	Nomex	Nomex	Nomex	Nomex	Nomex	Nomex	Nomex
Weight (oz /sq. yd.)	14.1	14	14.1	14	13.2	14	13.7	13.6	15
Air Permeability	25 - 35	25 - 35	35 - 42	38 - 44	38 - 45	32 - 41	35 - 42	31 - 34	31 - 44
Air Permeability after dry heat exposure (3 hrs. at 400°F)	30 - 40	30 - 40	50 - 60	50 - 60	50 - 60	50 - 60	50 - 60	50 - 60	50 - 60
Scrim Type	Woolen	Woolen	Cotton	Cotton	Cotton	Cotton	Cotton	Cotton	Cotton
Scrim Count (W & F)	23 x 23	23 x 23	19 x 20	18 x 18	19 x 17	20 x 20	19 x 33	12 x 14	20 x 20
Scrim Weight (oz./sq. yd.)	4.0	4.0	3	3.4	3	3.1	9.7	1.8	3.1
MIT Flex (Warp)	300,000	300,000	200,000	259,160	60,446	53,977	50,000	17,669	56,427
Mullen Burst (lbs./inch)	300	425	620	560	590	400	590	470	600
Strength (lbs./inch - W & F)	150 x 225	196 x 270	250 x 480	175 x 230	300 x 394	272 x 390	159 x 356	220 x 330	260 x 360

an improved acid and flex abrasion resistance, are under trial. In many plants the third generation treatment (silicone graphite, teflon) has been replaced with superior treatments such as Q70 (Globe Albany Corporation) or Teflon B (Du Pont) or a new treatment GAT-13 which has been developed by Albany International Corporation.

The importance of fabrics to this industry is related to process filters which are part of the manufacturing equipment. Recently, also 100 percent woven Teflon is under test in this industry with the major objective of obtaining longer life. Efficiency remains questionable.

CUPOLA IN FOUNDRY

The Harsell cupola emission control system is well established and more than 70 installations are working very successfully. This unit is designed for an A/C ratio of 1.9:1, with inlet loadings between 1 and 2 gr./cu.ft., operating at about 550°F. Bag life is between 3 and 5 years. Bag sizes of 22 feet 6 inches by 11 1/2 inches diameter, provide a length to diameter ratio of only 23.5, avoiding extremely high entrance velocities which would abrade the bottom of the bag.

MUNICIPAL INCINERATION

This is a relatively new field for fabric filters. However, a few installations are under test. One filter manufactured by Combustion Equipment Associates came on stream last fall. This unit cleans by reverse air principle and handles 180,000 acfm at 500°F. A/C ratio is 2:1, inlet loading is less than 0.5 gr./cu.ft. with an acid dewpoint 240°F to 280°F and a designed differential pressure of 2 inches to 3 inches W.G. Bag size is 14 feet by 5-1/2 inches. Some minor problems have been experienced with condensation but, generally, this installation performed satisfactorily. Another approach is to utilize the high ratio cage-type unit. One installation will come on stream during 1974 furnished with needled teflon bags.

GLASS FURNACES

Due to government regulations, specifically covering leaded glass furnaces, glass manufacturers are being required to install pollution control equipment. The baghouse, specifically the reverse air baghouse with glass bags, has been under trial for several years. A modular-type baghouse is under consideration to assure that parts of this equipment can be maintained while the rest of the unit is operating at temperatures ranging from 400°F to 500°F. Inlet loading is very low and the dust is extremely fine, consisting of 2/3 particulate matter and 1/3 fume. SO_2 and SO_3 as well as fluorides and chlorides are of major concern to bag life. Today we know of approximately five to ten units operating in the United States and in Europe.

POWER GENERATING

Two major areas for fabric filters, representing significant potential, are: electric utilities and industrial boilers today use electrostatic precipitators as an interesting field for fabric filtration. Several reverse air baghouses are in operation. The largest unit contains 5,056 bags at Pennsylvania Power and Light Company in Sunbury, Pennsylvania. This unit has been in operation for approximately 1 year and is operating very satisfactorily.

Another installation in Colorado has been on stream since last fall and uses glass bags at a relatively high A/C ratio (3:1) and the reverse air method of cleaning. According to the consulting company this unit is doing well. Several other baghouses are under consideration or construction. However, the fabric for fabric filters is limited due to acceptability, maintenance, and liability of the currently available fibers. A huge baghouse handling 600,000 to 700,000 acfm will be considered for 1976 in Nebraska.

The most promising area for fabric filtration certainly is industrial boilers. The industrial process industry has to install pollution control equipment on their steam generating boilers. Roughly 12 to 15 installations are operating today. Several of them are pilot units.

In this area, reverse air filters with glass bags as well as high ratio units are under consideration. One plant started with roughly 1600 needled Nomex bags and lime injection early this year. There is only limited experience available so far, however, it looks very promising. A new acid resistant fiber from Du Pont will probably be available on a production basis during 1975 or 1976. This fiber will allegedly withstand acid environment in industrial boiler applications (SO_2 and SO_3). Due to discontinuous operation conditions, the acid dewpoint is of major concern to the fabric. The most promising progress will depend on the fiber availability. With this new fiber, cage-type filter units are the most likely candidates for this interesting and large filtration field.

SUMMARY

Looking at fabric filtration and specifically at fabrics and their ability to handle fine dusts, including sub-micron particulate and fumes, any new development will be measured in relationship to efficiency. The types of fiber available will determine if this fiber can be manufactured into a woven or needled fabric. This will be a determining factor as to the type of equipment used.

Glass fiber is not available today in a 100 percent needled fabric; this certainly would have merits in pulse-jet units if the life would be sufficient. This fabric is under development.

Viewing several market studies, it is safe to say that fabric filters, like small cars, are coming. They are, most likely, becoming the number 1 type of pollution control device used by industry. If the trend to more stringent outlet regulations continues, it is safe to say fabric filters in new equipment will surpass electrostatic precipitators. It is anticipated that this will happen in the next 2 to 3 years.

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NEW KINDS OF FABRIC FILTRATION DEVICES

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INTRODUCTION

Industrial fabric filters have been around for an extraordinarily long time in this era of rapid technological innovation and equally rapid obsolescence of mechanical devices. Has this occurred because the fabric filter, like the wheel, is a basic process and has been such a successful invention from the very beginning that all that has remained to be done can be classified as mere improvement through mechanization, optimization, and reduction in costs? It would be easy for me to conclude that this is, indeed, the case because I consider the fabric filter to be the preeminent air cleaning device for aerosol particles of all sizes and for the entire gamut of industrial dust loadings. I do recognize, nonetheless that the horsedrawn carriage had already reached a high state of technological development by the time it was suddenly and totally displaced by the automobile, except for certain ceremonial purposes in London. If we are now teetering on the receding edge of the age of the fabric dust collector and, tomorrow, we can expect a revolution in the methods we will use for the future to remove particles from aerosols, this revelation is hidden from me and I am only able to report to you new developments that promise to make the fabric filter we are thoroughly familiar with more versatile and more reliable.

Significant improvements to the industrial fabric filter began in earnest about 1950 with the invention and commercial introduction of the reverse-jet filter by Harry Hersey. His primary objective was to eliminate the visible puff of dust that was emitted from shaken bags each time they were returned to filtration service after cleaning and thereby to reduce gross dust emissions from filter houses. Even though he failed in his primary purpose (reverse-jet filters did not prove to be more efficient than shaken bags), he did produce a radically new method of fabric cleaning and came up with a filter design that was capable of operating indefinitely at almost constant air flow resistance. In addition, by continuous fabric cleaning, he was able to increase air-to-cloth ratios of fabric filters many-fold, and thereby, to reduce significantly the size and weight of filter houses.

During the 1950's, many new synthetic fibers and fabrics became available that increased the ability of filter houses to withstand the destructive effects of corrosive chemicals and elevated temperatures. Woven glass fabrics lubricated with Teflon, silicone oils, and graphite permit routine filter operations at temperatures up to 500°F. Orlon and polypropylene fabrics are capable of resisting many types of severe chemical attack for years on end.

A third major development occurred at the conclusion of the 1950's that has had a major influence on industrial filter design up to the present time. I refer, of course, to the introduction of the pulse-jet filter concept that, like the Hersey reverse-jet, permits continuous cleaning, filter operation at uniform air flow resistance, and high air-to-cloth ratios (though not as high as reverse-jet cleaning) and does all of these things with almost a total absence of mechanical devices. This simplicity of design has been an outstanding characteristic of pulse-jet fabric collectors and has been an important factor in maintaining the attractive price of this design.

It is relevant to point out that the development of the pulse-jet concept could not have taken place without the introduction of synthetic fiber needled felts during the 1950's. That is to say, a single important innovation is likely to trigger others of even greater value. This idea is by no means unique to fabric filtration.

This very brief historical review brings us up to the present day and to the topic of my talk, new kinds of fabric filtration devices. Many innovations that may hold some promise of improving the performance of fabric filters have been described at conferences such as this and have been the subject of innumerable patents over the past several years. Indeed, by reading patents one gets the impression that every American is entitled at birth to at least one patent to hang on the living room wall beside the college diploma. Fortunately or unfortunately, depending on whether you hold a patent or merely wish to subvert one, almost all patents covering air cleaning equipment are easy to get around by using slightly different mechanical devices to apply the same principles by other means. As a consequence, I suspect that one of the important factors that has greatly impeded innovation and the development of new devices for fabric filtration has been the near impossibility of obtaining patents that can be enforced; as distinct from the ease of obtaining patent papers on almost anything.

A further difficulty in trying to describe to you new kinds of fabric filtration devices is the concept of "new"; obviously, innovation diffuses through different societies at different rates depending on their degree of technological advancement and the urgency from improvement. As an example, at a September, 1973, Filtration Society Conference in London having the theme "What's New in Dust Control and Air Cleaning," the reverse jet filter was characterized as "the newer generation of fabric filters."[1] This suggests that "new" is a highly relative term and I shall take full advantage of this ambiguity during the remainder of my presentation.

But first, I would like to remind you why the fabric filter is important enough to be the subject of specialty conferences at frequent intervals here and abroad. The 1972 report of the Ad Hoc Panel on Abatement of Particulate Emissions from Stationary Sources[2] pointed out that "it may not be sufficient to evaluate the performance of pollution-control equipment on the basis of mass-emissions alone....Special emphasis needs to be placed on the amount of material in the fine-particle size range and on its chemical nature." Fabric filter efficiency is insensitive to particle size below about two or three micrometers (unlike many other high efficiency collectors, such as the high energy Venturi scrubber) and, therefore, has special application to the many processes, such as metal refining, that generate large quantities of submicrometer particles. This important characteristic of fabric filters has been reported by Dennis,[3] Beach,[4] and by other investigators, and was referred to by Turner in this Symposium. Additional developments that favor increased applications of fabric filters are new federal opacity regulations for many widely dispersed industries[5] and the passage of state regulations, as in Maryland, that prohibit visible emissions from all stacks. It will be obvious from this that if "order of magnitude" improvements in retention of small particles from stationary sources is required, the industrial fabric filter must be looked upon as the most important control device for many large and important industries. Satisfactory application of fabric filters to a larger variety of industries depends upon innovative modifications that are responsive to special industry problems such as high heat, condensing moisture, corrosive gases, and sticky or liquid particles.

FILTER PRECOATS AND FILTER AIDS

The use of filter aids for high efficiency hydrosol filtration by fabrics has a long and well documented history in chemical engineering publications. The use of filter aids for aerosol filtration is not new, having been investigated and documented since 1952[6] at the HACL, but it has been applied only sparingly since then. The original application of a filter aid to an industrial fabric filter was for the purpose of greatly increasing small particle retention from aerosols containing loadings of especially toxic dusts, such as beryllium, equivalent to those found in the atmosphere (i.e., 100 $\mu g/m^3$). About 10 years later, a filter precoat of calcined dolamite on glass fabrics was used at a Southern California Edison Company plant to trap condensed SO_3 droplets (H_2SO_4) formed during the burning of high sulfur-containing residual oils.[7] This flue gas treatment was successful in correcting stack opacity violations that had occurred because of the emission of 30 ppm SO_3. This is the first recorded use of successful fabric filtration for collecting aerosol droplets. The filter aid not only provided for high efficiency collection of the submicrometer condensed sulfuric acid droplets, but was effective in neutralizing the viscous liquid to avoid plugging the filter cloth and corroding the filter housings and shaking mechanisms.

This is contrary to usual practices in the power industry where every effort is made to avoid lowering the flue gas temperature below the acid dew point to protect air preheaters, induced draft fans, ducts, and stack from destructive corrosion. With the sudden rekindling of interest in fabric filtration by the electric power industry to achieve clean stacks when burning pulverized coal, the emphasis has been on high temperature, corrosion resistant fabrics that can operate successfully above the acid dew point, usually in the vicinity of 300^oF.

Glass and Teflon fabrics have been considered for this service. But is this the correct concept considering the current concern about sulfate in the atmosphere?

A more recent application of fabric filters for liquid droplets has been reported by Guilloud in the aluminum industry[8] where precoated fabrics are used for the collection of oil mists. The nature of the filter aid used for this purpose was not mentioned. The general applicability of this technique for collecting submicrometer aerosol droplets at very high efficiency is obvious and only requires the discovery of a suitable filter aid in each case, as well as a simple method of dispersing it in the airstream to be filtered.

Fabric precoats may be used for purposes other than particulate filtration. Adsorbent and reactant coatings can extend the application of fabric filters to gas treatment as well as to particle removal. This use of fabric filters gas treatment was documented in the Filter Handbook in the following passage:

> "The fact that good control of high specific surface powder and contact time are attainable with fabric filter systems suggests advantages over other collector types. Most recently, the removal of up to 98.4 percent of SO_2 by sodium bicarbonate powder on a fabric filter has been demonstrated at a coal-fired power plant in a joint APCO-Air Preheater Co. study. Fly ash and some NO_2 are removed at the same time."[9]

Although there appears to have been very little use of this concept up to now for treatment of gas mixtures, as distinct from aerosols, the potential is obvious. It seems possible to use finely divided activated charcoal for gas adsorption on a fabric support, discharging the precoat to a desorption stage when it becomes saturated, and recoating the fabric surfaces with a fresh charge of activated charcoal. Such a dynamic system is especially attractive for control of malodors as the concentrations are likely to be in the part-per-billion range and renewal of the carbon coating need not be made at frequent intervals. In this case, it would be convenient to ship the spent charcoal to the manufacturer for renewal rather than attempting to do it at the place of use. Shaking the spent charcoal into a collection hopper is certainly simpler, more convenient, and less costly than changing large numbers of canisters and trays. It has also been recorded that mineral dust filter precoatings, such as pulverized limestone, are effective in suppressing the incendiary tendencies of pyrophoric metal dusts, such as lead-copper alloys.[1]

NEW FABRICS

The importance of needled felts of synthetic fibers for the development of the pulse-jet fabric filter has already been noted. Recently experiments have been conducted to alter the surface characteristics of needled felts to improve cleaning characteristics. These fabrics have often been described as "frosted" and the treatment consists of heating the dust collecting side until the surface fibers melt together to form a smooth, hard finish that is supposed to prevent dust penetration and assist cake removal.[10] Insufficient experience has been accumulated with these surface-modified felts to arrive at any sound conclusions regarding their usefulness. On theoretical grounds, it is hard to see how a less porous fabric surface can assist filtration or dust removal; and on the basis of limited field experience, experiment seems to confirm theory in this instance.

Multiple fabrics were utilized for filtering electric arc furnace fumes as far back as 20 years ago.[11] The intent was to construct a fabric that permitted filtration in depth, i.e., to collect the bulk of coarse particles on the surface but provide for high efficiency collection of a small percentage of fine particles in deeper layers. This arrangement permits high efficiency dust collection with minimum pressure drop and imparts important physical properties, such as strength and porosity, to the composite fabric. In this case, also, little use has been made of this innovative development until recently. Bergmann[10,12] has described a number of multi-media fabrics compounded for strength, heat, corrosion resistance, and for good filtration characteristics. For example, needled felts prepared from blends of Nomex and glass fibers have been used in the asphalt concrete industry where intermittent operation, high temperature (with brief peaks to 500^{o}F), high moisture content, small particle size, and heavy dust loadings represent a severe exposure for filter bags.

Other industries have special fabric requirements and many of these have been described by Bergmann. Of special interest is a high temperature (660-750^{o}F) needled fabric prepared from mineral fibers on a metal scrim core. Fabrics woven from yarns prepared by twisting Fiberfrax fibers around fine stainless steel monofilaments were prepared by Carborundum Corp. 20 years ago. These fabrics are capable of withstanding temperatures of 1500^{o}F for prolonged periods. Fabrics woven from silica fibers are capable of withstanding still higher temperatures. Many other heat resistant fibers are available for fabric manufacture. The difficulty in raising filtration temperature does not lie with the fabrics but rather with the filter housings and cleaning mechanisms. There is little hope that conventional fabric filter designs can withstand temperatures in excess of those currently used for glass fabrics (550^{o}F) without radical redesign of the fabric holding structures. At present there does not appear to be a demand for what would prove to be an especially costly modification of a standard design, except for cleaning high temperature gases in preparation for additional high temperature processing such as catalysis.

AEROSOLS CONTAINING LIQUID PARTICLES

The principal deficiency of conventional fabric filters is their susceptibility to failure when the aerosol contains liquids. The presence of water vapor and sulfuric acid can be handled satisfactorily by heat-insulating the housing and maintaining the gas temperature substantially above the dew point. Modern heat-resisting and acid-resisting fabrics make this procedure routine.

Tar-like materials and other substances cannot be filtered satisfactorily by this technique. In addition, it is often highly desirable to remove offensive liquid substances such as sulfuric acid and oil mists by filtration after cooling and condensation.

A response to this requirement has been the appearance of fabric filters especially designed to collect solid and liquid particles and to be cleaned by washing. One design, not yet generally available commercially, utilizes a spinning cylindrical filter in such a fashion that centrifugal force tends to strip the dust cake from the outside surface of the cloth-covered cylinder. In addition, water or any suitable solvent can be sprayed inside the cylinder and allowed to flow radically outward through the fabric by centrifugal force, washing the cloth clean in the process.

It seems likely then that limitation of bag filters to dry dusts may no longer be necessary when equipment is available that will permit continuous filtration through wet fabrics.

OPERATIONS

A final series of developments of considerable importance for good performance of fabric filters is in the area of instrumentation and mathematical modeling. Good instrumentation of filter houses has always been considered a desirable practice that was largely ignored by purchasing and operating personnel. This is changing, and well-instrumented new units are beginning to be seen with reasonable frequency. This is, of course, a prudent policy to protect the considerable investment that is inherent in the installed cost of a unit of industrial size. But beyond this, it reflects the need to demonstrate by records adherence to new, rigorous emission standards, including low stack opacity regulations.

Predictive models for fabric filtration have a long way to go before they describe perfectly the interrelated behavior of the several static and dynamic systems that comprise a functioning fabric filter. They are, nevertheless, proving to be immensely useful for studies that have more limited objectives. You have already heard about several of these from previous speakers. In the Harvard Air Cleaning Laboratory we are, with EPA financial support, modeling filter cake parameters and basic factors of high velocity fabric filtration with the objective of developing the theoretical factors and experimental confirmation that will permit the design of industrial fabric filters having an order of magnitude greater air volume capacity without degrading capture efficiency. This desirable objective can be accomplished only with the infusion of an order of magnitude greater energy input to the fabric filter, but with Venturi scrubbers operating at 80 inches w.g. in the steel industry, this no longer seems to be a formidable barrier. Of greater concern, is the construction of fabrics and fabric supports capable of withstanding these forces. It is too early in these studies to report to you any results or to make any predictions.

SUMMARY

Industrial fabric filtration, the sleeping giant, is stirring. Devices and concepts only 20 years old are being rediscovered and, more important, being committed to commercial practice. It appears that we are about to experience a new period of innovation and development similar to the one that occurred during the 1950's. With the use of predictive modeling techniques and a greatly improved ability, through the liberal

use of modern instruments, to measure with accuracy transitory phenomena, we should have improved concepts of how fabric filters function and therby acquire the tools for improving their performance.

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NEEDED RESEARCH IN FABRIC FILTRATION

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The description of needed research in this field will consist of two new problems or areas of endeavor, only briefly described and not intended to be a research protocol; and a summary of the needs that have been implied by the reports of previous speakers.

RECIRCULATION

One of the new needs derives from a development in a related field which does affect fabric filter utilization. That has to do with the recirculation of cleaned air from industrial exhaust systems back into the workroom. The Ventilation Committee of the American Conference of Government Industrial Hygienists publishes a Manual of Recommended Practice, which is revised every two years; and which is cited by reference in the standards of the Occupational Safety and Health Administration, U. S. Department of Labor. In the latest revision, the subject of "recirculation" is covered in quite some detail. The Ventilation Committee had been pondering what action to take in this area for two years before the energy crisis hit the newspapers last fall.

Air exhausted from the industrial work place for reasons of health hazard control, of course, draws replacement air into the building. If that replacement air is heated, cooled, tempered, or otherwise conditioned, then that becomes what we call a make-up air system. Exhaust air systems are energy-expensive. Historically, we have been deliberately wasting the heat content energy of the air exhausted from the building. The recirculation of that air, of course, would result in almost 100 percent recovery of the thermal energy involved. Traditionally industrial hygienists have not permitted the recirculation of cleaned workroom air if the contaminants involved were other than nuisance; that is, if they had any real toxicity or other potentially harmful effect. Even though the air-cleaning system involved may have been basically adequate to clean up the air so that it could be recirculated, problems of misoperation or poor maintenance are very common with such equipment and no one wanted to undertake the risk of deliberately dosing the workroom air with excessive concentrations of toxic materials. With an abundant and cheap supply of energy, the easy way out was to forbid the recirculation of exhaust system air regardless of the cleaning system used if the contaminant was toxic. With the increasing cost of energy and the scarcity of fuel, it becomes economic to consider greater capital investment and greater expenditure of engineering and technical effort to design such recirculation systems so that they will be safe and can be operated without risking the health of the people involved. This has led the committee to propose a formula as follows:

$$C_R = \frac{1}{2}(TLV - C_o) \times \frac{Q_T}{Q_R} \times \frac{1}{K}$$

where C_R = concentration of contaminant in exit air from the collector before cleaning, any consistent units

TLV = threshold limit value of contaminant

C_o = concentration of contaminant in worker's breathing zone with local exhaust discharged outside

Q_T = total ventilation flow through affected space, cfm

Q_R = recirculated air flow, cfm

K = an "effectiveness of mixing" factor, usually varying from 3 to 10

In the typical circumstances to which this equation would apply, the probable range of C_r will be from 0.1 to 10 milligrams per cubic meter, depending on the properties of the substance and the ratio of recirculated air to total ventilation.

Two ways are proposed in which such recirculation would be permitted. One would be to have a second air-cleaning device in series with the the primary device, a back-up system, if you will, which is adequate to protect the workers in case the primary device is not properly operated and maintained. An example would be a dust-producing operation controlled by a local exhaust system with a good, properly-applied fabric filter cleaning the air for recirculation. The air discharged from the fabric filter would be clean enough "as is" to be recirculated to the workroom. However, a back-up filter would be required. This would be perhaps a stationary filter, or a renewable filter, not one that was self-cleaning. If there was excessive leakage through the primary filter for whatever reason, the back-up filter would provide the safety factor and would prevent excessive air contamination. Such filters of adequate efficiency are available. The problem is that such filters are not rated in terms that are usable in this application. They are rated on the National Bureau of Standards dust spot efficient test--which is an "optical dirtying power" kind of a test--or on the DOP test for ultrafilters. The loading characteristics or the proper kind of efficiency data is not available to design the back-up filter system in usable and practical terms related to the expected life and the practicality of the whole situation.

Another alternative system, somewhat less desirable as a safety provision, would be to install some kind of a monitoring device in the cleaned air stream. If excessive concentrations occurred, the system would be shut down or the discharge would be bypassed to the outdoors. The highly-sophisticated, expensive systems currently available for monitoring stack emissions from new sources are not justified or even practical for this application.

In the first place, the concentration ranges needed are lower. Secondly, the cost is much too high to be justified for many such systems where the total system cost is in the range of $10,000 to $50,000. Last but not least is a practical operating problem; in a factory where the relatively simple machinery represented by the fabric filter is not adequately operated and maintained, who is going to operate and maintain the delicate, sophisticated monitoring apparatus currently proposed for stack monitoring? The need is for a monitor that is relatively simple, relatively rugged, does not need a high degree of precision but needs a high degree of dependability. A cumulative device operating over a time span of several hours would be suitable for some applications.

It is my opinion that our society and our economy is going to find it more advantageous in the future to devote the capital expense and the technology necessary to enable conservation of energy by recirculation. In order to accomplish this, we need:

(a) efficiency and loading data for high-efficiency filters on different aerosols and in different terms than currently available; and/or

(b) relatively simple, relatively rugged monitoring devices for lower concentrations (but longer time spans) than currently contemplated for stack emission monitoring.

MECHANISM OF SEEPAGE

Several research needs have been implied during the course of this conference. One is the need for an in-depth investigation of the mechanism of bleeding, or seepage (as it is termed), through the fabric filter. We've heard from Mr. Frye, Dr. Bakke and myself, stories describing observations about this phenomenon. Mr. Dennis has reported that about the same size distribution was found on both the inlet and outlet sides of the fabric filter and that, for a given aerosol, there is a relatively constant emission rate regardless of the loading to the fabric filter. None of this is what one would expect as a result of the application of classical filtration theory to the behavior of fabric filters. I disagree with the approach that the classical theory is applicable. It may be theoretically valid, but the range of parameters that it evolved from is so different from the application of fabric filters; it is so far removed from the single-fiber/single-particle theory; that the quantitative difference is so great as to amount to a qualitative difference. The phenomenon of bleeding and seeping is not explainable from the classical filtration theory, and obviously we need to understand it in order to be able to prevent it or reduce it in a predictable way.

STACK SAMPLING: INLET VS. OUTLET CONDITIONS

Another direction needing more effort is that concerning instack sampling in order to dispense with the perennial problem of probe losses. Mr. Lilienfeld yesterday, in his announcement of the work GCA is doing in this area, indicated some progress. There remains, however, a major problem not being attacked by that research; the solution of the conflicting needs for variable flow rate capability for isokinetic sampling, and constant flow rate for aerodynamic sizing by impaction techniques. Aerodynamic particle size is generally more useful than other size descriptions; and since it is obtained directly by impaction methods, that aspect of the technique should be retained. This then leaves the problem of obtaining isokinetic conditions.

There is a temptation to derogate the need for isokinetic sampling on the clean side of high-efficieny equipment on the assumption that the particles are so fine that anisokinetic conditions create negligible error. But is this assumption really valid? There are several indications (see "Seepage" above) that it may not be.

Another solution sometimes preferred is to change intake nozzles for every point in the sampling traverse. In my opinion this alternative is to be summarily rejected as a long-term solution. It is viable only for cost-is-no-object research investigations, and then only because no better solution to the problem currently exists.

This leaves, then, a continuing need for providing both the variable flow rate for isokinetic sampling and the constant flow rate for impaction sizing. One step that may ease the problem is to abandon the approach which strives to achieve one "universal" technique and/or apparatus for both inlet and outlet sampling. (Although outlet sampling may be all that is needed for emission standards or emission monitoring, there are many and important needs for data on both inlet and outlet in terms of control technology.) Perhaps we should recognize that the thousand-fold range in concentrations and perhaps in particle size, inlet to outlet, is too great a span to expect of a single technique or a single apparatus. Perhaps a different technique and apparatus could be designed for inlet sampling, hopefully using the same basic separating and sizing mechanisms; and on the basis of theory, research, and practical experience, the inlet sample could be kept relatable to the outlet sample.

ELECTROSTATICS

Mr. Frederick gave very interesting descriptions of phenomena related to electrostatics. There is no doubt that more knowledge is needed, badly needed, in this area. I would like to add to the thoughts that he expressed, the request that we extend this type of investigation into electrostatics as a cause of dust explosions in filter systems. Such explosions typically are attributed to electrostatics. A dust fire or explosion from electrostatics presumably would occur only if the breakdown voltage of the air or gas had been reached; such voltages are greater than those described relative to electrostatic filtration properties of the materials and fabrics by several orders of magnitude. The lay approach to this question seems to me to border on the ridiculous. For example, in some industries the collector manufacturers are required to sew a ground wire in the vertical seam of the bag, and this is enough to satisfy the insurance company. For typical fabric filter dimensions, there is a linear distance of from one to several feet from the far side of the bag to the seam and the ground wire; and with a high dielectric filter fabric and a high dielectric dust, the concept of that ground wire effectively leaking off the electrostatic charges seems remote. I sometimes doubt that dust explosions in fabric filters--which are real enough--are truly caused by the electrostatic charges so frequently blamed. I don't believe this has been proven one way or the other. It needs more and better investigation, on a higher technical plane, than it has received in the past.

AN "UNDERWRITERS LABORATORY"

I wish to propose a new approach in the field of air pollution control for all types of control devices, not just fabric filters but including fabric filters. It is based on the presumption that the field of control equipment has reached the point where it is about time it "grew up." The expenditures of time and effort wasted in unsuccessful attempts to secure applicability and operability of air pollution control devices is getting to be significant. We heard a plea from Mr. Walsh that the basic generalizations were not sufficiently quantitative, that we lack predictability; (and predictability is one definition of engineering). Walsh reports that we cannot transfer or translate the data that we get from one process application to another; that we need some way to get adequate predictive capability. I couldn't agree more with what he had to say along these lines.

The idea that I am about to suggest is not fundamentally new. It has been used in other fields, and I suggest its adaptation and application to the field of air pollution control equipment. What is this idea? It is the idea of an "underwriter's laboratory" if you will, for air pollution control equipment.

One can set up a laboratory in which a number of different artificially-generated and dispersed contaminants could be tested against a manufacturer's model of a given line of his equipment. One could choose a series of aerosols, inexpensive so that new material is used under quality control for particle size and other properties. A series of materials could be chosen which, although not truly representative of any individual field application situation, would nevertheless present the filter or other control device with a spectrum of challenges. For example, the series could include ground limestone, obtainable in a number of grades of fineness; fly ash, which has been widely used for research; redispersed carbon black, freshly-generated iron oxide fume from an arc or from the destruction of iron carbonyl; etc. A whole spectrum of materials could be generated. The tested device would be a manufacturer's model, the smallest in a line of actual or proposed devices. It would be subjected to a battery of tests having to do mostly with performance parameters--pressure drop, power consumption, water consumption, efficiency, fractional efficiency; whatever is applicable, so that each individual commercial model could be given some kind of a laboratory classification. Presumably the laboratory would not be able to operate a test long enough to really develop any long-range maintenance information. The laboratory would produce a class rating which could be correlated with the extensive field testing that is going on and that is what would result in a degree of predictability. One would be able to say, for example, that an electric arc steel melting furnace requires a "Class 2A" collector; that a smelter bag house needs a "Class 4B" collector; that a foundry sand-handling system needs a "Class 1Z" collector; etc. A comprehensive rating system eventually could be developed.

There are 200 people present at this meeting. There were about 30,000 significant pieces of air pollution control equipment bought in 1973. Excluding the big million dollar jobs, most of it was bought by customers who are relatively unsophisticated and shouldn't have to become highly sophisticated in the black art of predicting the performance of control equipment. "I have here in my hand," (as the rabble-rouser would say) for example, an advertisement of a magic wet collector. I'll call it the wet sponge collector, which is advertised to collect 99.9 percent of anything and everything with a pressure drop of not more than 4 inches. The advertising literature list of customers reads like the Fortune 500. At some place along the line this kind of unbridled exaggeration has got to stop.

The Harvard Air Cleaning Laboratory, for quite a few years, performed tests somewhat along these lines for the Atomic Energy Commission, and the EPA has contractors performing similar test programs on occasional pieces of equipment today. But this is not the way to do it. In the first place, the government shouldn't have to do it. In the second place, the government has all kinds of restrictions and budgetary and political problems in this kind of an operation. Government-issued brand-name class ratings for commercial equipment would create all kinds of repercussions. On the other hand, it would seem that the Industrial Gas Cleaning Institute and the reputable manufacturers, who stand to lose from either unethical competition or by mispurchase and misapplication of their own equipment, would be in favor of such an impartial rating system. The Air Pollution Control Association; the American Society of Heating, Refrigerating and Air-Conditioning Engineers; American Society of Mechanical Engineers; the American Society of Chemical Engineers; the EPA; many industrial trade associations should be interested in this kind of an impartial, dependable rating system for the application of pollution control equipment.

The first objection to the plan is that truism which we've heard several times this week: that the laboratory does not attain the same dispersions, the same contaminants under the same conditions, as is found in the field. This problem is quite real. If one is going to test a piece of equipment on open-hearth fume, one has a choice of building an open-hearth furnace in the laboratory or moving the test equipment to some existing open-hearth furnace; and the choice there is obvious. But the field testing will be done, is being done, and if we have a simultaneous, well-planned, broad spectrum challenge presented to equipment in the laboratory, I am quite confident that good correlations for good predictability on a class basis can be achieved. The charlatanism and the witchcraft will be reduced. The customer, especially the small unsophisticated customer who is not large enough to support a strong technical staff will get more for his money. The enforcement activity and the plans approval activity will be simplified. There will be less dependence on the individual expertise, personal experience and opinion of the individual engineer who is reviewing plans at the state and local level for permit application, and we will have something to back up his decisions.

Another long-range benefit that would be achieved is the reduction of the routine stack testing that really should be accomplished for specific compliance with state plans in the absence of a rating system. The total market for air pollution control equipment for 1973 was $320 million, and the average sale was probably on the order of $10,000 to $20,000. That means 30,000 units that really should have been tested last year. A good stack test costs at least $2,000 and more often about $5,000; it is neither logical nor equitable to expect an acceptance test costing $5,000 to be performed on equipment averaging $10,000 to $20,000 in cost. The whole situation seems to be ripe for a certification laboratory-type rating plan.

Also this laboratory should not directly engage in research and development work, and certainly not in the same premises or with the same staff. The Harvard Air Cleaning Laboratory used to mix up the two functions to a degree, but that was the nature of their contract. They would at least vary the adjustable operating features of a given piece of equipment, and usually with the manufacturer's blessing, because he got some information out of it also. I propose that the certification laboratory, the "underwriter's laboratory," not do this type of thing. The whole field has advanced since the day when Harvard used to do that kind of work. Most of the reputable manufacturers have their own lab and their own development facilities. Let them do their own development work or let them hire a consultant to work with them; the certification lab would be strictly a rating laboratory.

Of course, there would need to be some kind of a sizable financial investment to get started. It should be started at a viable rather than minimal level. It has to be done right, and on a large enough scale to be useful, or it will not get the support of the industrial community and the professional community. I feel that if it is done right, it will get that support and that once it has proven its worth, the laboratory could and should become self-supporting through service charges and fees (again just copying the underwriter's laboratory idea).

The application of this idea should get rid of a lot of uncertainty in our technology. At the present time we have many literature-reported field tests which are not comparable because they were done by different methods and omit or perhaps even conceal, for competitive reasons, important parameters. A lot of tests are made which are not reported in the literature and are used for competitive purposes; the quality of such tests varies from excellent to horrible. There is quite a bit of word-of-mouth reporting of acceptability within the user industries, which is usually based on the lack of maintenance difficulties rather than upon emission control effectiveness. Last but not least are these unsubstantiated but also irrefutable advertising claims by the less reputable members of the vendor community. Thus the proposed lab would help rid us of all this wasted effort and wasted money.

When a "polluter" spends his money and gets something that doesn't work, not only is it an economic hardship on him, but the community continues to have the air pollution. It is usually some several years until all the arguments and lawsuits are finished and the dust settles, if you'll forgive the pun, and he goes on to the second round of trying to fix his problems. A simplified analogy can be made with the DOP (dioctylphalate) test for HEPA filters. HEPA filters are almost never used for filtering DOP out of the air. They're used for filtering ordinary atmospheric dust, dust which may be carrying microbiological infection, radioactive particles, etc. The fact that the application of the filter is not to the substance on which it is tested does not seem to hinder in any significant way the usability of that kind of test, specifications, or rating. The comparison is, admittedly, a vast oversimplification relative to air pollution control equipment. I think that the difficulties can be overcome and the long-range advantages are worth the very serious consideration of both the industrial and professional groups involved.

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16. ABSTRACT

The proceedings document presentations made during the Symposium which was aimed at describing the fine particulate control potential of existing fabric filter systems for the benefit of regulatory and user groups and suggesting to manufacturing and research organizations those areas where performance levels most need improving. The primary purpose of the Symposium was to better define the role of fabric filter systems for the control of fine particle emissions. Experts from Government, Industry, and University groups discussed the theoretical and practical aspects of filtration and important related areas such as particle behavior, fabric selection, and system evaluation. The effectiveness of fabric filter systems for controlling particulate emissions from industrial sources is well accepted in the pollution control field. However, the vast majority of available performance data depict overall weight recoveries with only minimal information on the capture efficiencies for particles in the equal to or less than 1 micrometer size range.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Particle Shape	Air Pollution Control	13B
Filtration	Particle Density	Stationary Sources	07D
Fabrics		Fine Particulates	11E
Aerosols		Fabric Filters	
Cost Effectiveness		Emission Standards	14A
Particle Size		Particle Behavior	

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