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APPLICATION OF FOAM SCRUBBING TO FINE PARTICLE CONTROL, PHASE II

Industrial Environmental Research Laboratory
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U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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APPLICATION OF FOAM SCRUBBING TO FINE PARTICLE CONTROL, PHASE II

by

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ABSTRACT

This report summarizes the knowledge, the experience, and the data gained to date relative to the application of foam scrubbing to collection of fine particles from gaseous streams. Experimental data obtained on a 0.236-m^3/s (500-cfm) pilot-scale foam scrubber facility are presented. Economic analysis indicates that a foam scrubber can be competitive with other fine particle collection devices. Areas for further foam scrubber development are recommended.

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FIGURES

FIGURES (continued)

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SECTION 1

SUMMARY

This report summarizes the results achieved while investigating the application of foam for removal of fine particles from gaseous phase. In the first phase of the program, the investigation was initiated by theoretical evaluations of collection mechanisms involved in fine particle collection by foam. Then, the theoretical findings were verified on a bench-scale foam scrubber apparatus (1.2×10^{-3} m^3/s; 2.5 cfm).[1] Utilizing the experience gained during the bench-scale verification, a pilot scale (0.236-m^3/s; 500-cfm) foam scrubber was erected and operated. Significant improvements in the scrubber operation and economics were achieved during the pilot-scale testing and demonstration. These improvements verify the foam scrubber as a viable device for removal of fine particles from gas streams, and warrant its further development. Specific areas needing further investigation and testing are outlined.

Section 2 summarizes the conclusions and recommendations made on this program. After the introduction in Section 3, the pilot-scale foam scrubber facility is described in Section 4. Section 5 summarizes the experimental results achieved during the pilot demonstration. Finally, the foam scrubber economics are compared with the economics of conventional particle collectors in Section 6.

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[1]Ctvrtnicek, T. E., R. F. Walburg, C. M. Moscowitz, and H.H.S. Yu. Application of Foam Scrubbing to Fine Particle Control--Phase I. EPA-600/2-76-125, U.S. Environmental Protection Agency Research Triangle Park, North Carolina, May 1976. 152 pp.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

These conclusions and recommendations reflect the observations made during both phases of this program. The reader is encouraged to familiarize himself with the observations made during the program's first phase involving theoretical evaluations of the foam scrubber collection mechanisms, verification of these mechanisms in a bench-scale (1.2×10^{-3} m^3/s; 2.5 cfm) experiment, and preliminary economics.[1] Only then can the conclusions and recommendations presented here be truly comprehended.

1. After demonstration on a pilot scale (0.236 m^3/s; 500 cfm), the foam scrubber remains a viable method for removing fine particulates from gaseous streams. The method is simple, consisting of basic operations such as pumping the liquid and gas, and spinning a disk to destroy the foam. The foam is generated by forcing aerosol gas through a screen sprayed with a surfactant liquid. Particle collection is believed to take place mainly by diffusion and sedimentation, mechanisms that are predictable and rather well understood.

2. Collection efficiencies demonstrated on the pilot scale using industrial dust were between 50% and 75% by count for particulates in a size range between 0.056 μm and 1.0 μm. These collection efficiencies are averages from an experimental operation that covered 20 hours and used a scrubber residence time of 20.5 seconds. At this residence time, the averages are somewhat better than the theoretically predicted collection efficiencies (based on particle density of 2 g/cm^3, bubble diameter of 2 mm, and temperature of 23°C), ranging from 32% to 67% by count for particles in the size range of 0.1 μm to 1.0 μm. A further increase in scrubber collection efficiency can be easily achieved by an increased scrubber residence time as demonstrated by the bench-scale tests.

3. Significant improvements in the foam scrubber operation were achieved due to the scrubber scaleup and the experience gained in operating the scrubber for longer periods. These improvements include the ability to generate satisfactory foam with (1) a surfactant concentration of 0.25% (1% to 2% on bench scale), (2) a scrubbing liquor feed rate of 6.83×10^{-4} m^3/s (10.8 gpm) per 0.259 m^3/s (550 cfm) of gas (this

is equivalent to 19.6 gallons per 1,000 cfm versus 38.4 gallons per 1.000 cfm achieved on the bench scale), and (3) a scrubbing liquor which was continuously recycled and contained up to 2 kg/m^3 of solids. In addition, the pilot foam scrubber operated at a lower pressure drop of 1.84 kPa (7.4 in. H_2O; 9 in. H_2O on bench scale), and the power consumption for the foam destruction was reduced by a factor over 400 (847 watts/m^3 of foam on bench scale versus 2.1 watts/m^3 of foam on pilot scale). The improvements in the foam scrubber operations, however significant, were realized without an organized and conscientious effort to optimize foam generation and foam destruction steps. They are a result of an organized and conscientious effort to demonstrate the foam scrubber as a viable system on a pilot scale. It is therefore believed that further improvements of the foam scrubber are yet possible.

4. Foam and foam scrubber liquor can be restored to their original condition by filtration.

5. Economic evaluations based on the results of this program indicate that the foam scrubber can be made competitive in terms of capital investment and operating costs with conventional particle collectors including fabric filter, high energy scrubber, and high efficiency electrostatic precipitator.

Based on the favorable results obtained during this two-phase program, it is recommended that further studies of the foam scrubber be made. These studies should be performed on a pilot or larger scale foam scrubber unit and should primarily concentrate on the following areas:

- Optimization of the foam generation step with respect to foam generation screen size, surfactant concentration, characteristics of particles in gas feed (size, solubility, surface properties), and scrubber liquor spray (surfactant liquor recycle under no-leak conditions, regeneration of the liquor through removal of collected solids, and liquor spray distribution and rate).

- Optimization of the foam destruction step with respect to minimization of secondary aerosol formation, consumption of energy, and design for large-scale applications.

- Verification of foam scrubber operations under conditions actually existing in the field such as elevated temperature and presence of gas contaminants (SO_x, NO_x, CO_2, CO, HC, etc.).

SECTION 3

INTRODUCTION

A variety of air pollution equipment is available to industry for containing solid particulate emissions (e.g., electrostatic precipitators, baghouses, inertial separators, wet scrubbers, settling chambers, impingement separators, and panel filters). In terms of mass removal efficiency, a majority of the commercially available particulate control devices are adequate, with mass removal efficiencies up to +99%. However, submicrometer particles are not captured by this equipment; they pass readily into the atmosphere, creating hazards to human health, as well as visibility and smog problems.

New concepts and technology for the control of fine particles are needed to help remedy this situation. In this category is foam scrubbing. Prior investigations, performed under the first phase of this contract, established theoretical and technical feasibility for the foam scrubber.[1] The mechanisms involved in collecting particles via a foam scrubber were defined and quantified. Theoretical collection efficiencies were then verified experimentally on a 1.2×10^{-3} m^3/s (2.5 cfm) bench-scale apparatus. Experimental results agreed well with those theoretically calculated.

Preliminary and limited economic evaluations indicated that the foam scrubber could be competitive in terms of capital investment costs with conventional particle collection devices, including fabric filter, high energy scrubber, and high efficiency electrostatic precipitator. However, the operating costs for the foam scrubber appeared substantially higher than those required for the aforementioned conventional devices, mainly due to the cost of surfactant. Based on the encouraging bench-scale experimental results and the lack of data on larger scale, it was recommended that foam scrubbing be evaluated on a pilot scale. This evaluation was done during the second phase of this contract, and the results achieved are presented in this report.

SECTION 4

EXPERIMENTAL APPARATUS

This phase of the program involved design, erection, and operation of a pilot-scale foam scrubber, scaled up by a factor of 200 from the bench-scale device developed in Phase I. The three major objectives of this phase were to: 1) investigate the feasibility of improving the process economics by recycling foam liquor solution continuously, 2) determine scrubber performance with a real-life solid fine particulate aerosol, and 3) determine the effects of scale up on scrubber performance and economics.

4.1 DESIGN CONSIDERATIONS

The primary scaleup requirement was a gas-handling capacity of 0.236 m^3/s (500 cfm). Other important criteria considered early in the design stages of this equipment were inlet gas conditions, and aerosol type and loading. One major objective of the second phase was to evaluate scrubber performance on solid particulate aerosols from an existing source (e.g., powerplant, foundry, pulp and paper mill, etc.), simulating as closely as possible an industrial stack containing fine particulates. This departed from bench-scale experiments where "ideal" liquid droplet aerosols were generated and used. To increase the chances for successful simulation of an industrial effluent, several practical attributes were required of the particulate dust that was to be used in pilot-scale demonstration experiments. The dust had to: 1) contain a large mass concentration of fine particles (<3 μm), 2) be representative of an actual emission source, 3) be nonmagnetic so as to not to interfere with particle sampling instruments, 4) be uniform in composition, and 5) have desirable feeding and handling qualities (nontoxic, noncaking, easily dispersed, insoluble, etc.).

After considerable searching, a suitable dust was found. The source of this dust is a stoker and coal-fired powerplant, in Nucla, Colorado, operated by the Colorado Ute Electric Association (Nucla Plant). Details concerning the origin and properties of this dust were previously described.[2,3] In the Sem[2] study, the Nucla Plant was sampled for submicrometer particles before and after the baghouse collector on boiler unit 2. Figure 1 shows typical loadings of fine particles between about 0.05 μm and 1.0 μm in diameter upstream of the baghouse particle collector. These data are averages of 19 runs taken during 35 minutes of boiler operation at near full load on two separate days.

The data in Reference 2 were taken during relatively constant boiler operation. Even so, the concentrations of fine particles fluctuated by as much as ± 93% in the particle size range of the lowest particle loading (0.562-1.0 μm) to ± 31% in the smallest particle size range. The concentration of total particles for all size ranges (0.0562-1.0 μm) fluctuated by ± 45%. It should be noted that although nearly 90% of the particles by number in the stack are less than 0.18 μm in diameter. These same particles constitute only 18% of the total mass loading.

The last important design criterion was scrubber residence time. As previously established, particle collection efficiency is a strong function of the time the particles reside within the foam.[1] Figure 2 shows theoretical trends for one set of experimental conditions (bubble diameter, 2 mm: particle density, 2 g/cm^3; atmospheric pressure; and temperature, 23°C). Curves for other sets of conditions were also calculated.[1] As shown in Figure 2, the particle collection efficiencies follow curves that steadily increase with time and asymptotically approach 100%. After a certain time, the gain in particle collection efficiency that would result with a further increase of residence time becomes rather negligible, and gets within the range of experimental error. To operate the pilot scrubber in this region would greatly reduce the possibilities to observe the effect of influential variables on the scrubber collection efficiency. Consequently, the pilot scrubber was designed for a shorter residence time of between 20 and 30 seconds where the particle collection curve is relatively steep and changes in collection efficiency can be observed more readily. Operating the pilot foam scrubber at these residence times meant that high scrubber collection efficiencies obtainable with longer scrubber residence times were sacrificed for the

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[2]Sem, G. J. Submicron Particle Sizing Experience on a Smoke Stack Using the Electrical Aerosol Size Analyzer. Presented at the Seminar on In-Stack Particle Sizing for Particulate Control Device Evaluations, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, December 3-4, 1975. 18 pp.

[3]Bradway, R. M., and R. W. Cass. Fractional Efficiency of a Utility Boiler Baghouse--Nucla Generating Plant. EPA-600/2-75-013-a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, August 1975. 148 pp.

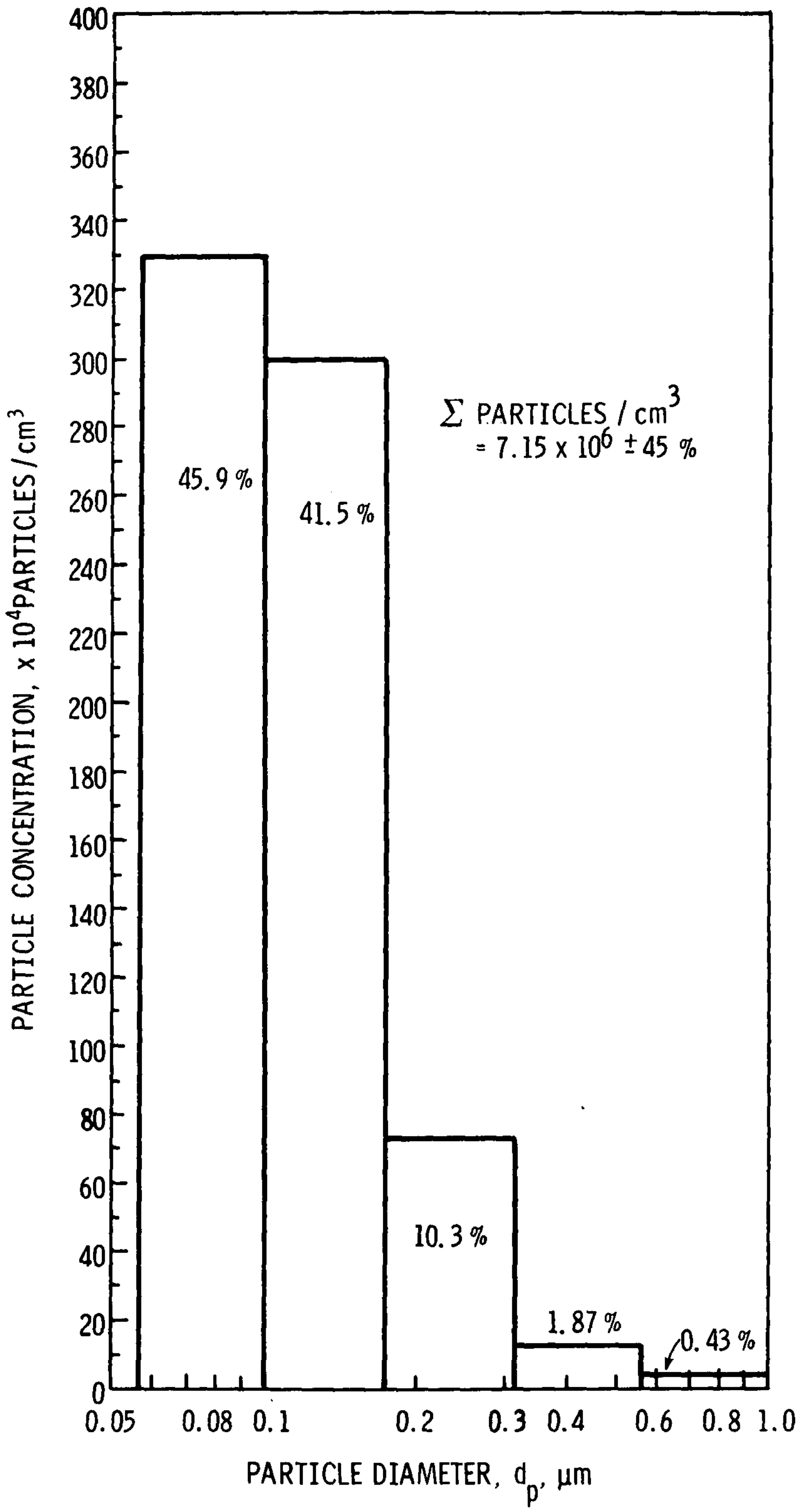

Figure 1. Typical number concentration of fine particles from a 12-MW coal-fired boiler unit at 92% load.[2]

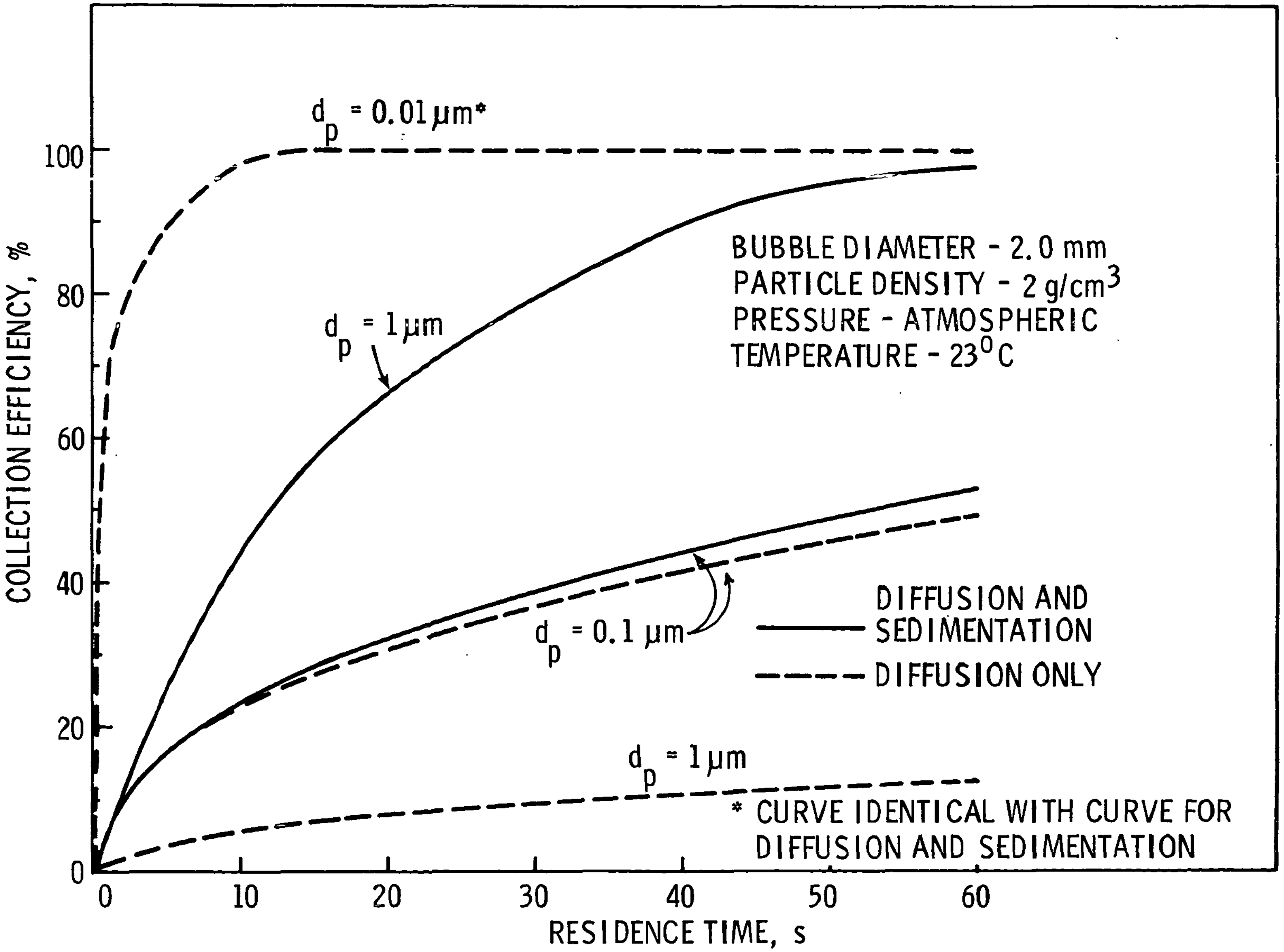

Figure 2. Particle collection efficiencies applicable to collection of particles by foam scrubber.[1]

purpose of having a more feasible pilot test facility. This should be borne in mind when pilot scrubber collection efficiency data are reviewed.

4.2 THE PILOT FOAM SCRUBBER FACILITY

The pilot-scale foam scrubber process consists of the operational steps diagrammatically shown in Figure 3. Filtered room air is intimately mixed with aerosolized fly ash fines and this mixture proceeds to the foam generation section. In this section, foam is made by passing the air laden with particlates through a 250-mesh stainless steel screen onto which the surfactant solution is uniformly sprayed. As the foam is formed, it encapsulates the dust particles and proceeds toward the foam destruction chamber, flowing in essentially plug-flow fashion. The ductwork between the foam generation section and the destruction chamber is large enough to provide a foam scrubber residence time between 20 and 26 seconds. The foam holdup period allows the encapsulated particles to migrate to the bubble walls for capture.

The foam then enters the destruction chamber where it is mechanically destroyed by rapidly rotating disks. The foam liquid produced from foam destruction is returned to the foam generator, and the cleaned air containing some residual particles and secondary aerosol from the foam destruction operation proceeds from the scrubber into the induced draft fan where it is finally exhausted outdoors. Due to some liquor recycle pump leaks and mist losses up the stack, a fresh surfactant solution is supplied using a makeup liquor.

During the course of an experimental run, the inlet and outlets of the scrubber are sampled periodically for particulate concentrations.

A more detailed process layout is shown schematically in Figure 4. The process is broken down into the following subsystems:

- dust aerosolization
- bulk air supply
- foam generation
- foam destruction
- scrubber liquor supply and recycle
- fine particle instrumentation
- scrubber operation

These subsystems are described in Appendix A.

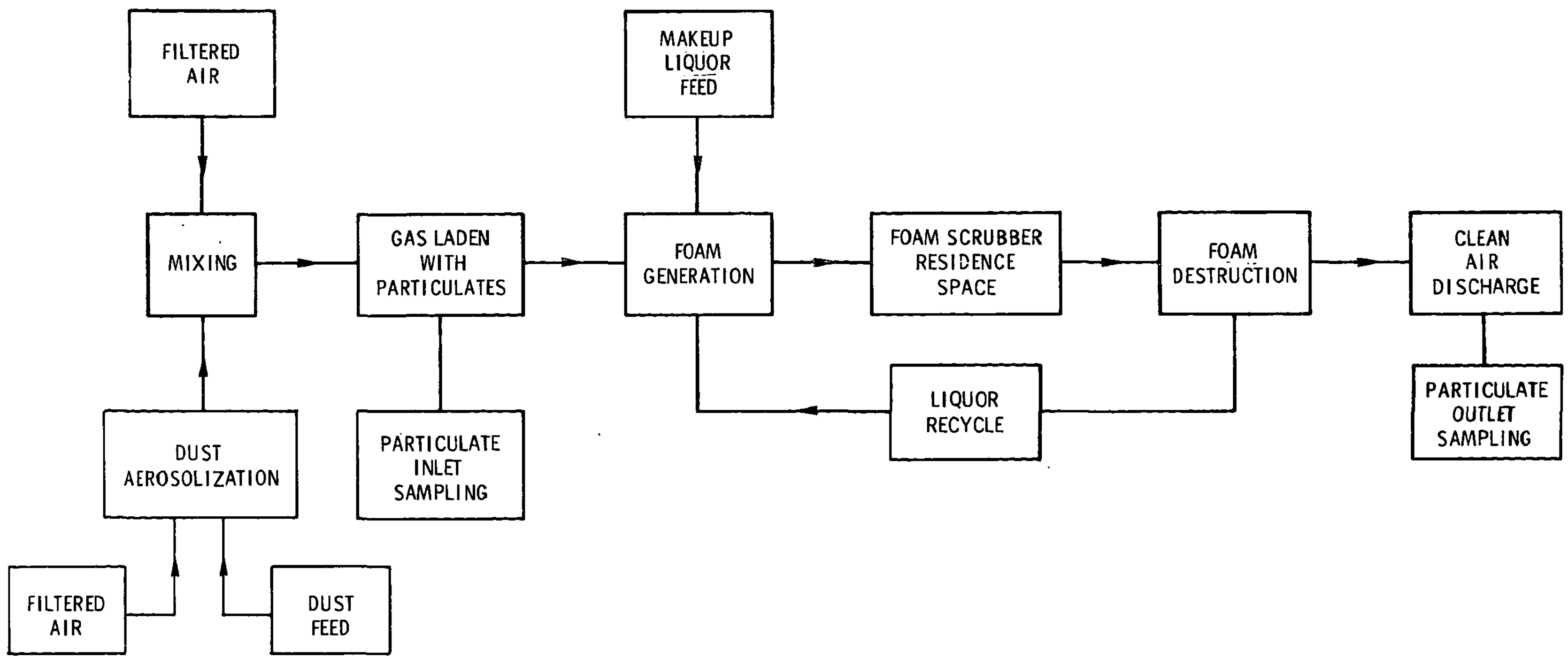

Figure 3. Experimental process block diagram of pilot-scale foam scrubber.

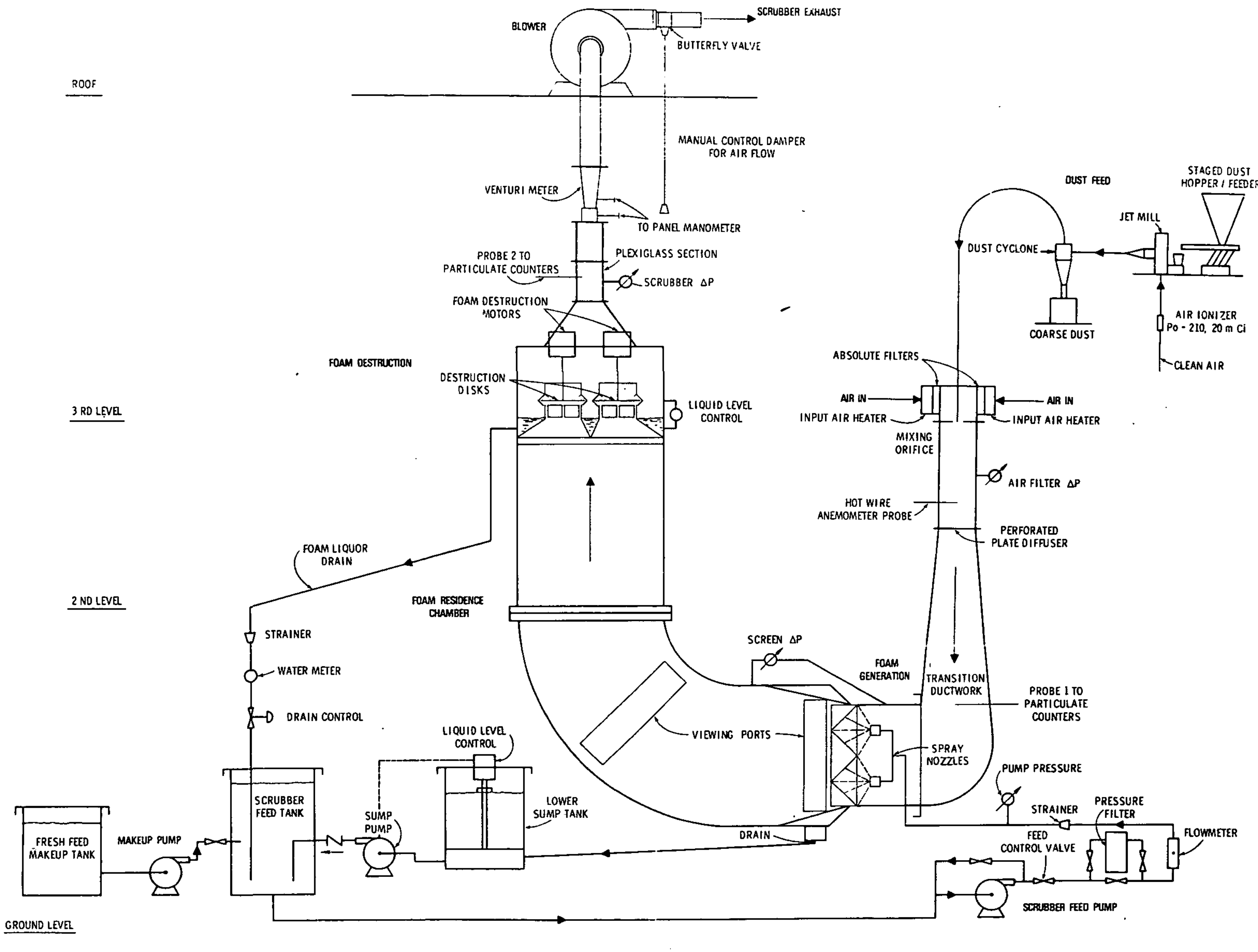

Figure 4. Pilot-scale foam scrubber process layout.

SECTION 5

EXPERIMENTAL RESULTS

In view of the conclusions reached during Phase I of this program[1] and the objectives for this second phase (see Section 4), the most critical variable for a successful foam scrubber was the process operating cost. Even with 99% recycle of the scrubbing liquor, the operating cost of the foam scrubber was an order of magnitude greater than that of the most expensive conventional control method (high energy wet scrubbing). Due to limited capabilities of the bench-scale experiments, no experimental data were available to demonstrate that 99%, or perhaps even higher, recycle of the scrubbing liquor solution is feasible.

The initial efforts of Phase II, therefore, concentrated on two important factors:

(1) Use of the best engineering judgment and experience to scale up the foam scrubber from the bench scale (1.2×10^{-3} m^3/s; 2.5 cfm gas-handling capacity) to the pilot scale (0.236 m^3/s; 500 cfm), and

(2) Use of this scaled up facility to investigate and demonstrate high recycle of the surfactant liquor while maintaining a scrubber particle collection efficiency close to that theoretically predicted (see Section 4.1).

Based on the results presented below, both of these factors were implemented with a great degree of success.

5.1 FOAM SCRUBBER SCALEUP

The most important items in the scaleup of the foam scrubber were the foam generation step, flow of the foam through ducts of large diameters, and the foam destruction step. All three of these are unique with the foam scrubber and are not known to be used in industry. Consequently, no data could be found which would suggest and provide direction for correct scaleup.

Additional data were developed on the effectiveness of foam destruction by high-speed disks using the bench-scale apparatus. Disks of different shapes and sizes were tested for energy consumption at the point where foam of constant qualities was being effectively destroyed. These data were then used to specify and design the foam destruction section of the pilot-scale foam scrubber. A brief summary of the foam destruction data is presented in Appendix B.

After thorough engineering analysis of the foam generation phenomena previously discussed and quantified,[1] it was concluded that a proportional scale up of the foam generation section relative to air throughput would be proper.

Flow of the foam through ducts of large diameters was a serious concern. The actual scale up was based on keeping constant the velocity experimented in the bench-scale scrubber. Velocity was chosen over Reynolds number because air velocity is a critical parameter for foam generation. An additional problem with scaling up through, for example, constant Reynolds number would be the large physical dimensions of a pilot-scale unit [diameter 19.5 m (64 ft), height 4.8 cm (2 in.)]. Scale up through velocity involved some amount of risk since the Reynolds number for the pilot-scale scrubber in comparison to bench scale increased about fourteenfold. This higher turbulence could cause flow channeling and foam collapse due to frictional forces. Some such turbulence was observed during the bench-scale experiments whenever there was an increase in foam flow velocity. This was probably due to peculiar characteristics of the foam; however, no significant increase in turbulence of foam flowing through the pilot-scale facility was observed.

Using these three scale up principles, the foam scrubber was designed and erected ready for further experimental work. Additional comments on troubleshooting this apparatus and making it acceptable for pilot demonstration tests are presented in Appendix C. The subjects discussed include:

- foam quality
- scrubber dust feed
- particle collection of surfactant spray, and
- foam baseline aerosol

5.2 SCRUBBER RESIDENCE TIME

As the foam is generated, it flows horizontally into an elbow-shaped ductwork and then proceeds vertically to the foam destruction chamber. During the pilot-scale experiments, it appeared that the physical configuration of the scrubber and the peculiar foam flow characteristics caused distortion of the normal plug-flow velocity profile of the foam, thus making it necessary to measure residence time experimentally. Figure 5 attempts to illustrate this problem. Although somewhat exaggerated, the figure shows that the foam travels in the path of least resistance in the horizontal and elbow sections. Foam, unlike gas, exerts a significant weight force on the lower portions of its flow, causing these portions to remain stagnant. Once the foam weight becomes uniform in the vertical section, a full plug flow develops.

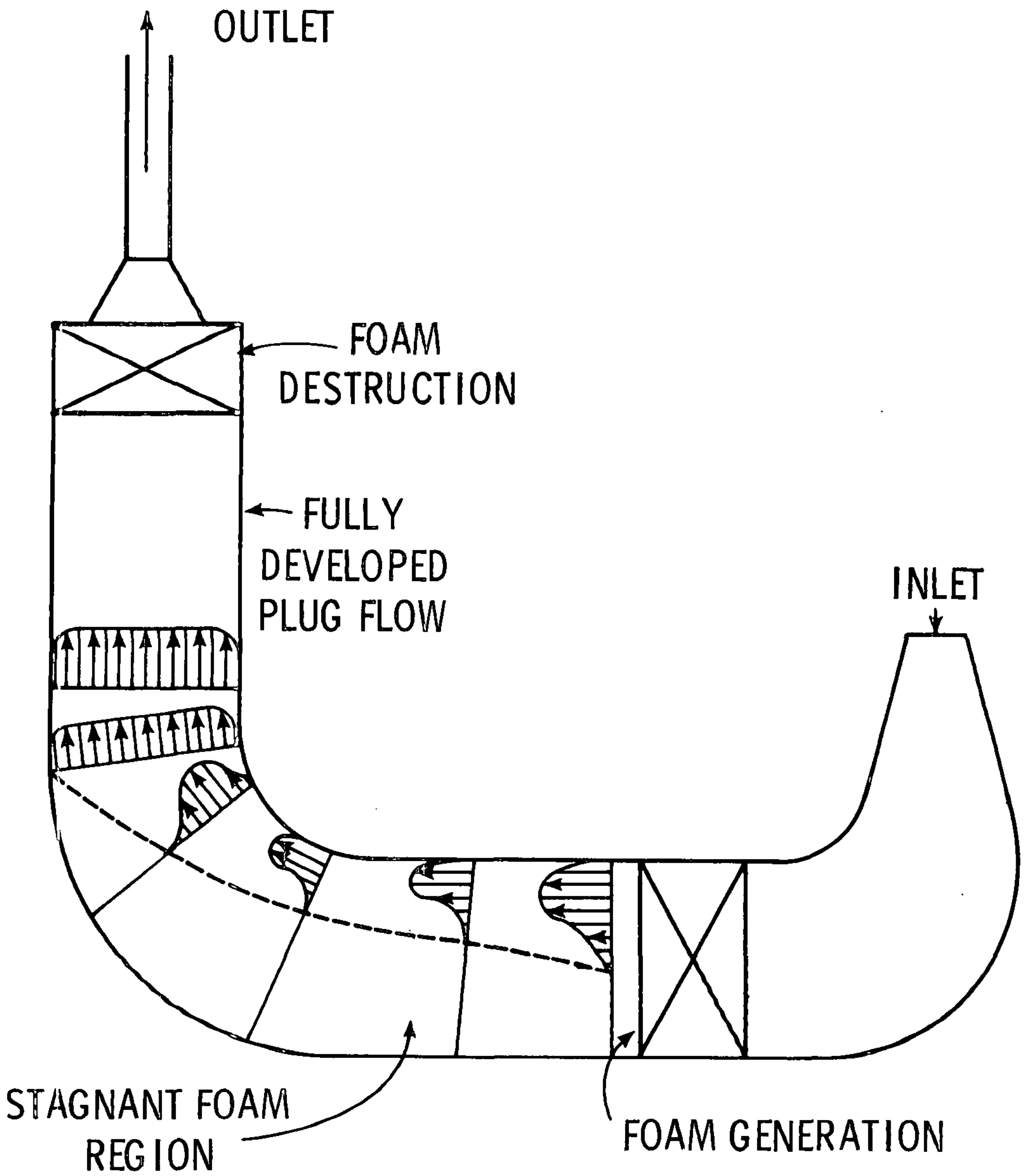

Figure 5. Approximate scrubber velocity profile at steady state.

The actual residence or space time was measured for 0.25% and 1% Tergitol foam by using a dye injection technique. A concentrated solution of methylene blue in 0.25% or 1% soap solution was placed in a pressurized bomb. After steady conditions were attained in the scrubber, the dye was injected into the inlet of the foam liquor feed pump. The time required for the dye to travel from the foam generation step to the destruction chamber was defined as the foam or scrubber residence time. A series of experiments indicated that the actual residence time is around 20-25 seconds. This value is far from the time required to observe high scrubber collection efficiency (refer to Section 4.1), and it is about 62-78% of the calculated space time (volume/air flow rate). Actual scrubber residence times observed during specific particle collection experiments are presented in Section 5.3.

5.3 PARTICLE COLLECTION EXPERIMENTS

Once the pilot scrubber was operational, it was tested for fine particle collection capabilities. The first crude collection efficiency measurements showed efficiencies ranging from 32% to 57% on a count basis (i.e., 32% for 0.78-μm particles). Efficiencies were measured at a dust loading of 0.8 g/m^3 (0.4 gr/acf).

Theoretical calculation of the collection efficiency involves three important parameters: foam bubble size, particle density, and scrubber residence time. The foam bubble size could be only very crudely estimated by visually observing the foam flowing around the viewing ports; its bubble size was estimated to be about 3 mm in diameter. The size of the bubbles in the bulk of the foam flow could not be estimated. The second important parameter, particle density, also was not precisely determined. But scrubber residence time, the third parameter, was actually measured and determined to be 25 seconds for this experiment.

Considering the limited knowledge of accuracy of these important parameters and referring to the calculated collection efficiencies in Figure 2 (bubble size 2 mm, particle density 2 g/cm^3) for the 25-second residence time, the collection efficiencies of particles in the size range between 0.1 μm and 1 μm should be between 38% and 76%. This means that the collection efficiencies experimentally determined are in agreement with those predicted by the theory. In order to increase the collection efficiency, longer residence times are required. (Refer to Section 6 to see how the residence time influences the scrubber cost.)

The pilot scrubber was purposely designed for shorter residence times, as was explained in Section 4.1.

After the first collection experiments were completed, an attempt was made to demonstrate the scrubber operation for a longer period of time and establish whether or not the recirculation of surfactant liquor affects two important variables, the foam characteristics (stability, bubble size) and the scrubber collection efficiency. Of course, during the recycle, the collected particulates would also accumulate in the surfactant liquor, and it was necessary to determine if this factor also has an influence on the two variables mentioned above. This was done successfully in an experiment lasting for about 20 hours.

During this 20-hour run, the particle collection efficiency of the scrubber was periodically measured. A summary of the 12 collection efficiency measurements is presented in Figure 6. The results of the 12 individual measurements, as well as a summary of scrubber operating conditions while obtaining these results, are presented in Appendix D. Specifically, the scrubber air throughput was 0.259 m^3/s ± 1.8% (550 acfm), the scrubber liquor feed was 6.83 x 10^{-4} m^3/s ± 1.2% (10.8 gpm), and the scrubber ΔP was 1.84 kPa ± 7% (7.4 in. H_2O).

Operating the foam scrubber for longer periods provided the operators with more experience and the ability to improve the scrubber performance. This is illustrated by the collection data. While the initial collection efficiencies for particles in the range of 0.14 μm to 0.78 μm were between 32% and 57% by count, later efficiencies covering the broader particle size range of 0.056 μm to 1.00 μm were between 50.0% and 75% by count, Figure 6. In addition, the latter collection efficiencies were obtained at a scrubber residence time of 20.5 seconds (versus 25 seconds in the first experiment). Corresponding theoretical collection efficiencies (Figure 2) for particles in the size range between 0.1 μm and 1.0 μm and for this shorter residence time are 32% to 67% by count.

This means that the improved average collection efficiencies over the period of 20 hours agree with those predicted theoretically even better than the data of the first experiment. The improvement is primarily due to the ability to generate foam with better characteristics (small bubbles and more stability) and maintain these characteristics with time. The surfactant concentration during the 20-hour experiment was kept at 0.25% by weight. This is another significant improvement over the bench-scale phase where about 2% surfactant solutions were needed to generate satisfactory foams. In addition, the surfactant liquor requirements were reduced from 5.17 x 10^{-3} m^3 per m^3 of gas (38.4 gpm per 1,000 cfm) to 2.64 x 10^{-3} m^3 per m^3 of gas (19.6 gpm per 1,000 cfm). These observations are very important. They indicate the limited nature and applicability of the results generated in the bench-scale experiments. More importantly, however, they indicate that the costs for surfactant, which are the major factor in the foam scrubber operating cost, can be significantly reduced (refer to Section 6).

During the 20-hour run, the surfactant liquor was recirculated, suggesting that its consumption can be reduced even further. As a consequence of the recirculation, the concentration of particles in the scrubbing liquor steadily increased as indicated in Figure 7. This concentration should not be considered

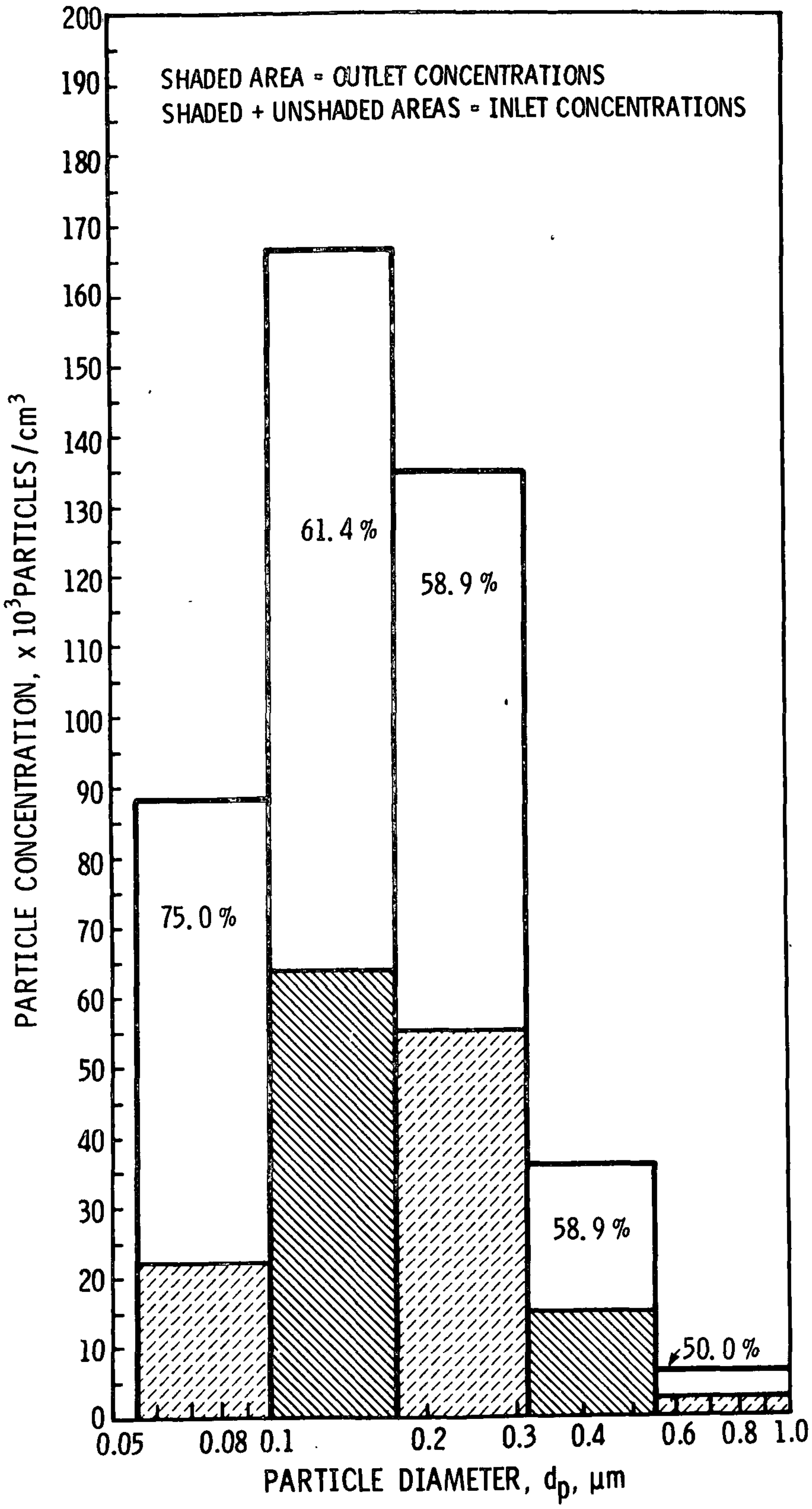

Figure 6. Average particle collection efficiency data (12 runs). Percent collection shown inside the unshaded area.

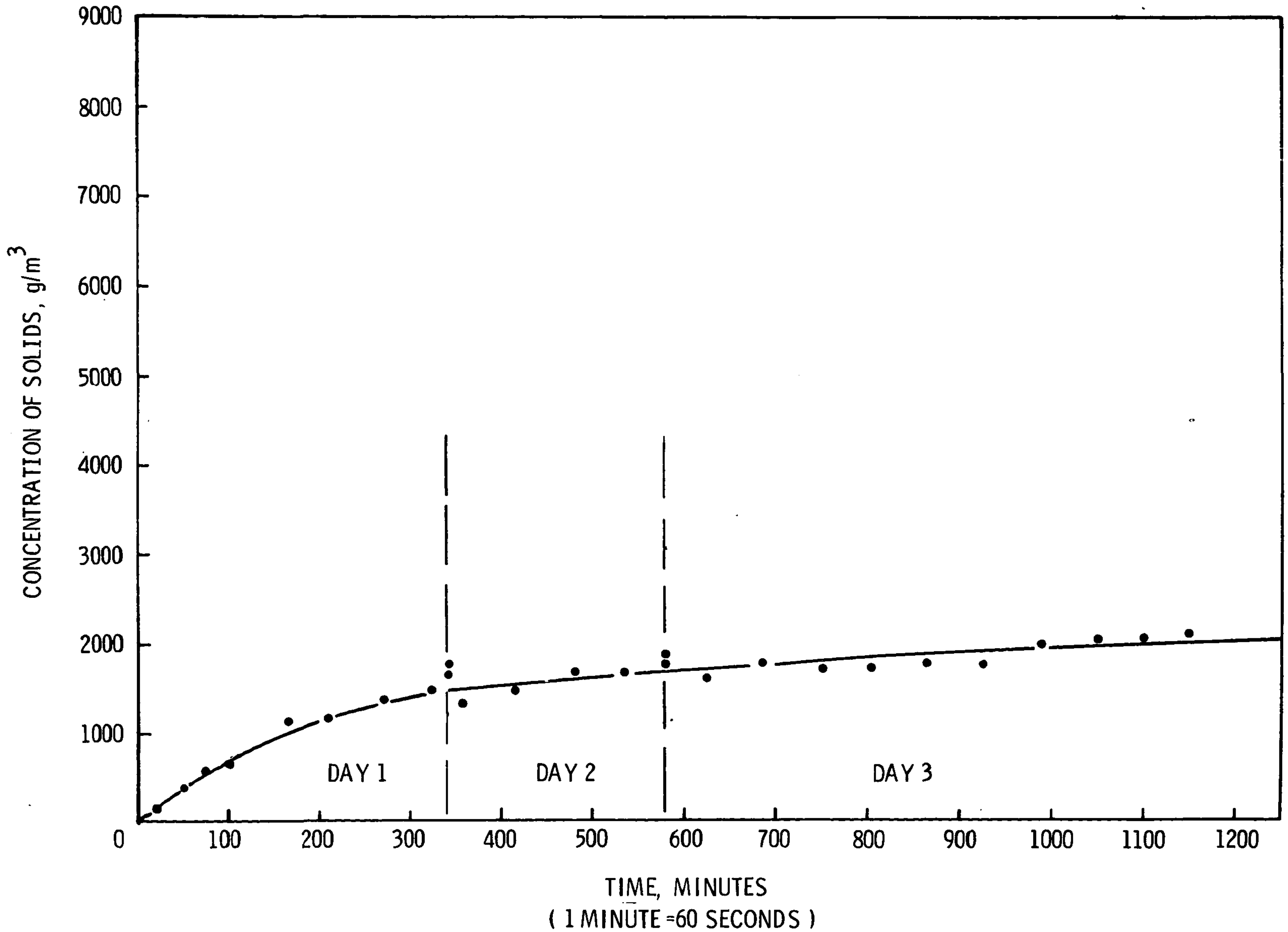

Figure 7. Concentration of solids in scrubbing liquor as a function of time.

absolute since there was some accumulation of solids in the scrubber sumps. Ideally, under steady state conditions (stable particle concentration in the scrubber gas feed and stable particle collection efficiency), the increase in particle concentration with time should follow a straight line. This was not the case in the 20-hour run (see Figure 7) due to some pump leakage of the scrubber liquor. To compensate for this leakage, as well as the losses of the scrubber liquor through the scrubber exhaust, a steady makeup stream of surfactant liquor was needed [about 1.23×10^{-5} m^3/s (0.2 gpm)]. In the 20 hours, the concentration in the scrubber just about reached the steady state as Figure 7 illustrates. At that time, the amount of particulates collected in the scrubber liquor became equal to the amount of particulates lost through the leakage and accumulation so that no further increase in solids concentration in the scrubber liquor was observed.

The particle collection efficiencies in Figure 6 are based on particle count rather than mass. Expressing the particle collection efficiencies on a mass basis has some limitations, since collection of a few larger particles can account for high mass collection while no significant collection of particles in the fine size range is realized. In this respect, the foam scrubber has demonstrated a strong capability to collect fine particles.

The collection mechanisms utilized in foam scrubbing are those of diffusion and sedimentation.[1] These mechanisms are rather well understood and are not subject to human error. As such, they will function in any environment with gravitation field and concentration gradient. Proper operation of the foam scrubber is thus reduced to control of foam characteristics and creation of a practically acceptable environment to permit these mechnisms to function. For these reasons, it is important that future development of the foam scrubber include further investigation of the foam generation step. This step has not been fully explored and optimized.

Even though significant improvements in foam generation and foam characteristics were achieved during the pilot-scale demonstration, they only suggest that additional efforts in the area of foam generation on a large scale are warranted. These efforts should primarily concentrate on (1) optimization of the foam generation screen mesh (refer also to Appendix C, Section 1, for further comments), (2) optimization of the scrubbing liquor spray (spray pattern, liquor spray rate, and surfactant concentration), and (3) the flow of the foam through the scrubber (foam stability, turbulence, and channeling).

Also, the collection efficiencies in Figure 6 represent collection of the injected dust. The background liquid aerosol levels produced in foam destruction were substracted from the particle levels escaping from the foam scrubber. Additional data on foam are presented in Appendix C, Section 4. The formation of the secondary aerosol in the foam destruction step is another factor which needs further investigation. Just as the other important areas of the foam scrubber operation reported above enhanced particle collection efficiency, foam generation with lower surfactant concentration, ability to recycle the scrubber liquor), it is believed that the area of foam destruction can also be greatly improved. Appendix C, Section 4 indicates the scope of such improvements. The potential improvements should concentrate on minimization of secondary aerosol formation and minimization of energy consumption. Both of these variables were observed to be a strong function of disk design and speed, surfactant concentration and overall geometry of the foam destruction chamber. The effect of geometry on the secondary aerosol formation, particularly, is not adequately understood.

While operating the foam scrubber for 20 hours, no deterioration in foam characteristics was observed. It is believed that the length of the run could have been extended with no significant change in scrubber collection efficiency. Of course, as already mentioned, some leaks of the surfactant liquor accompanied this experimental run, requiring a steady makeup of fresh surfactant. This led to some difficulty in determining the maximum number of surfactant liquor recycles. Nevertheless, being able to reduce the surfactant liquor concentration from 2% to 0.25% while maintaining satisfactory foam characteristics lowered the cost of surfactant eightfold. Through recycling the surfactant liquor, it was possible to reduce the consumption of 0.25% surfactant liquor to about 1.23×10^{-5} m^3/s (0.2 gpm). The effect of these factors on the foam scrubber economics will be further discussed in the following section.

It should be possible to reduce the consumption of the surfactant liquor even further. The recycling basically produces a buildup of collected particulates in the scrubber liquor which eventually should influence the foam generation and perhaps the foam characteristics. During the 20-hour experiment, the solids built up to about 2 kg/m^3 of the liquor, and with this concentration of solids, no signs were observed which would suggest worsening of foam generation conditions or foam characteristics.

Temperature is another very important variable for the foam scrubber development, and it was not experimentally verified. Due to a proportional relationship of the particle diffusion coefficient and the temperature, an increase in collection efficiency with an increased temperature may be expected. Changing the gas temperature, however, may influence other factors involved in the foam scrubber operation. A discussion of these factors was presented in the Phase I report[1] (Section 4.3.2 on Thermophoresis and Diffusiophoresis). Furthermore, temperature may influence the surface properties of foam. This can subsequently affect foam flow characteristics, stability, bubble size, and the like. Most of the factors which may be influenced by the changes in gas temperature are not easy to quantify. Consequently, it is recommended that the foam scrubber be operated at various temperatures and the effect of these temperatures on foam scrubber operation and collection efficiency be properly evaluated.

Before completing the 20-hour experiment, an attempt was made to restore the scrubber liquor to its original condition via filtration. This was accomplished by in-line filtration of the scrubber liquor containing about 2 kg/m^3 of suspended solids through a pressure filter while maintaining foam generation. No difficulties were observed during the filtration. Removal of the suspended material from the scrubber liquor restored the foam to its original white appearance.

The improvements in the foam scrubber operation, however significant, were realized without an organized and conscientious effort to optimize the foam generation and foam destruction steps. They are a result of an organized and conscientious effort to demonstrate the foam scrubber as a viable system on a pilot scale. It is therefore strongly believed that further improvements of the foam scrubber performance and economics are yet ahead and may be discovered when additional efforts are undertaken as recommended above.

SECTION 6

ECONOMICS

Preliminary data on foam scrubber economics were previously reported.[1] These data were based on results achieved during the foam scrubber bench-scale testing. In comparison with those results, significant improvements were noted while testing the foam scrubber on a pilot scale as discussed in the previous sections of this report. All these improvements in the foam scrubber operation strongly affected the foam scrubber economics. Consequently, this section revises and updates the foam scrubber economics to reflect the findings from the pilot-scale tests.

As before, the costs generated were compared with costs for three conventional particulate control techniques. The cost estimates for the conventional devices were obtained from the open literature and it should be recognized that the comparison presented here is only as good as the available estimates. In addition, even though the foam scrubber has been tested on a pilot scale (0.236 m^3/s; 500 cfm), its scaleup to a full size facility still remains to be demonstrated. As such, there are no accurate scaleup data from which to verify the reliability of the foam scrubber economics presented in this report.

The assumptions used in preparation of all cost estimates, their sources, and the deficiencies and limitations of the cost estimates presented are discussed and reported below. The three conventional particle collection techniques are high efficiency electrostatic precipitation, fabric filtration, and high energy wet scrubbing.

6.1 ACCURACY OF ESTIMATES

The accuracy of the foam scrubbing cost estimates is limited by the amount of information gained during the pilot testing. Pilot test results were the only source of data used to estimate the foam scrubber economics on the scale several magnitudes larger than the pilot-scale facility. Hence, the accuracy of the estimates for the foam scrubber is judged to be about ± 50%. Additional information used to determine the foam scrubber costs was taken from Modern Cost-Engineering Techniques edited by H. Popper[4] and Plant Design and Economics for Chemical Engineers by M. S. Peters and K. D. Timmerhaus.[5]

The costs for conventional control devices were obtained from three journal references: Dust Collection Equipment by G. D. Sargent,[6] A Systematic Procedure for Determining the Cost of Controlling Particulate Emissions from Industrial Sources by N. G. Edmisten and F. L. Bunyard,[7] and Estimating the Costs of Gas-Cleaning Plants by J. R. F. Alonso.[8]

Even though the economic data for the conventional devices should be representative of fabric filtration, high energy scrubbing, and high efficiency electrostatic precipitation, the corresponding collection efficiencies of these devices in the fine particle range are questionable. They all are defined as high efficiency collectors based on total particle mass collection. Since fine particles in most industrial gases represent only a small fraction of the total particle mass (e.g., an estimated 68% of fine particles in the range between 0.01 μm and 3 μm from pulverized-coal-fired powerplants are in the 1 μm to 3 μm range on a mass basis, while the same size range represents less than 1% of particles on a number basis),[9] these devices may not remove fine particles even if a very high overall mass collection efficiency (99%+) is obtainable as claimed. As a result, the economics of a foam scrubber device collecting fine particles might be compared with a conventional collector whose collection efficiency in the fine particle range is not very significant. Nevertheless, the economic data for the three conventional control techniques

[4]Modern Cost-Engineering Techniques. H. Popper, ed. McGraw-Hill Book Company, New York, New York, 1970. 539 pp.

[5]Peters, M. S., and K. D, Timmerhaus. Plant Design and Economics for Chemical Engineers, Second Edition. McGraw-Hill Book Company, New York, New York, 1968. 850 pp.

[6]Sargent, G. D. Dust Collection Equipment. Chemical Engineering, 76(2):130-150, 1969.

[7]Edmisten, N. G., and F. L. Bunyard. A Systematic Procedure for Determining the Cost of Controlling Particulate Emissions from Industrial Sources. Journal of the Air Pollution Control Association, 20(7):446-452, 1970.

[8]Alonso, J. R. F. Estimating the Costs of Gas-Cleaning Plants. Chemical Engineering, 78(28):86-96, 1971.

[9]Shannon, L. J., P. G. Gorman, and M. Reichel. Particulate Pollutant System Study. Volume II-Fine Particle Emissions. APTD-0744, U.S. Environmental Protection Agency, Durham, North Carolina, 1 August 1971. 348 pp.

are based on extensive past experience in design, construction, and operation and are believed to be accurate to within 25% to 30%.

6.2 BASELINE COLLECTION EFFICIENCIES

The following discussion substantiates the questionability of collection efficiencies for the three conventional devices in the fine particle range. In a study of fine particulate emissions performed by Midwest Research Institute,[9] collection efficiency data for the conventional devices to the submicrometer particle size range were extrapolated. These are presented in Figure 8. For convenience, the collection data from bench-scale experiments for the foam scrubber are also included.

The collection efficiencies for wet scrubbers and fabric filters in the particle size range between 0.1 μm and 1 μm can be sufficiently supported by experimental data. Data from at least 10 scrubbers and 6 fabric filters of different designs were compiled to produce the extrapolated curves. The curve for fabric filters was produced using data with 0.1-μm particle penetrations between about 0.5% and 65%. Thus, this curve represents a questionable average with a relatively large spread rather than a typical fabric filter operation. Wet scrubbers show a fairly steep curve with collection efficiencies in the particle size range quickly decreasing with the decreasing particle size.

The collection curve of electrostatic precipitation extrapolated to the particle size range between 0.1 μm and 1 μm can be supported by only one experimental datum measured for particles of about 0.7 μm. The rest of the experimental data were taken in the range above 1 μm.

The collection curves for the foam scrubber do not extend below the 0.1-μm particle size, but as indicated by the theoretically calculated collection efficiencies[1] (and the theoretical collection efficiencies were found to agree with those determined experimentally), reasonably high collection of particles in this range may be expected.

In conclusion, the collection of fine particles by the three conventional devices is questionable and will need further experimental verification. This may lead to changes in the cost estimates if these devices should collect significant amounts of particles in the fine particle size range. The changes are more likely to increase than to decrease the costs presented here. The costs for the foam scrubber are based on pilot-scale tests and can increase or decrease in the future. The bench and pilot tests were designed to demonstrate technical feasibility, not to optimize operating conditions and costs. Regardless of this, a significant reduction in foam scrubber costs was achieved as a result of scaleup from bench to pilot scale.

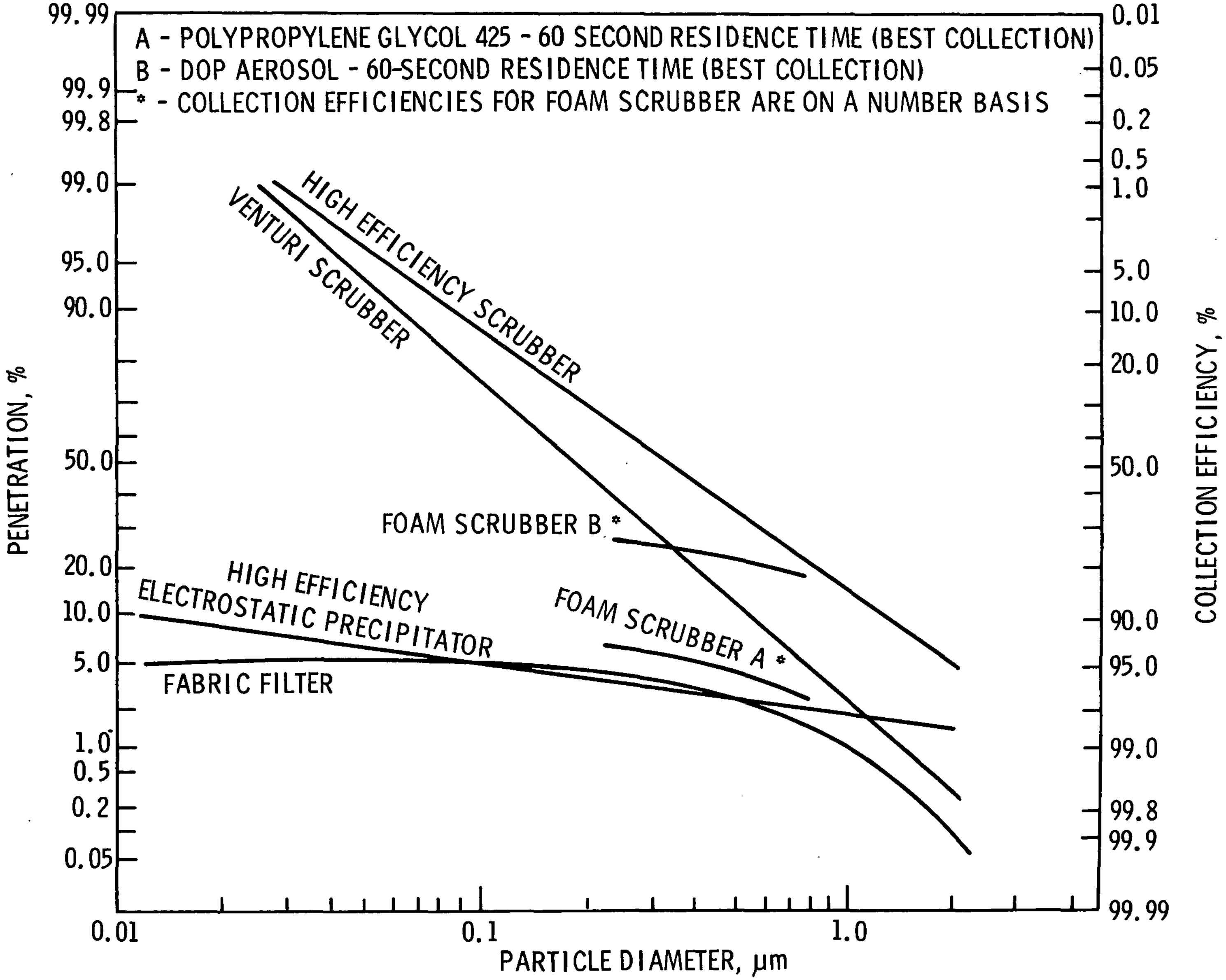

Figure 8. Extrapolated fine particulate control efficiencies.

To obtain a meaningful comyarison of capital and operating cost estimates for particulate control alternatives, the estimates should be based upon consistent parameters and have similar accuracy. This was attempted here insofar as the available information permitted. Because it allows order-of-magnitude comparisons with conventional control techniques and identifies critical cost-sensitive areas, an economic analysis of foam scrubbing provides direction for further experimental work. This was strongly demonstrated by the previous cost estimate[1] which identified the significance of surfactant cost. But the previously mentioned limitations of any of the cost estimates and comparisons presented here should not be overlooked.

The economic analysis of foam scrubbing and comparison with the three conventional control devices follow. General assumptions applicable to all cost estimates are listed in Table 1, followed by the assumptions for each specific type of control equipment in Tables 2 through 5.

6.3 RESULTS

The results of the capital cost estimates are presented in Table 6 and Figure 9. Table 6 presents percentages of foam scrubbing capital costs as a function of residence time for a 26.3-m^3/s (50,000-acfm) unit, and Figure 9 depicts the capital costs for foam scrubbing as well as for conventional controls as a function of unit capacity. Table 6 shows that the largest capital cost is incurred for the scrubber itself (from 30% to 56% of total capital requirements). Figure 9 indicates that capital costs for foam scrubbing are similar to the costs for conventional devices. Depending on foam scrubber residence time, the capital cost for foam scrubbing is generally above that for fabric filtration or high energy wet scrubbing and below that for eletrostatic precipitation.

Table 7 and Figure 19 present the results of the operating cost analysis. Foam scrubbing operating costs as a percentage of total operating costs are presented in Table 7 as a function of scrubber capacity. The operating cost is relatively independent of foam scrubber residence time since the operating costs resulting from the installed equipment cost are insignificant compared to the cost of the surfactant.

TABLE 1. COST ASSUMPTIONS

General

Capital and operating costs do not include waste treatment and disposal.

Gas temperature, gas composition, grain loading, and control efficiency were not considered as variables due to insufficient information concerning their influence on cost.

Labor costs for both operation and maintenance are contained within the estimates of maintenance labor and materials.

Time reference 1976 — Marshall and Stevens index 470

Chemical Engineering facribated equipment index 200

Capital

Cost scaling exponent 0.6

Installation charge includes field installation, start-up cost, working capital, and interest on construction loan.

Operating

Stream time 8,000 hours/year

Pump and air mover efficiency 50%

Utility costs

- electricity $0.015/kWh
- water $0.079/m^3$ ($0.30/$10^3$ gal)

Depreciation - 7% installed cost

Capital charges - 10% installed cost (includes interest, taxes, insurance, overhead, general and administration, etc.)

TABLE 2. FOAM SCRUBBING ASSUMPTIONS

Capital

Minimize surface area of scrubber (length = diameter) with maximum diameter of about 9 m (30 ft) - if larger add another scrubber train

Scrubber - 6.35 mm (1/4 in.) carbon steel with cost as function of weight (spray nozzle 45 kg, 100 lb)

Screen - 96 m^2/m^3 (29 $ft^2/10^3$ ft^3) 316 stainless 250 mesh screen - \$65/m^2 (\$6/ft^2)

Foam destruction system (10% of scrubber cost)

Residence time 10-60 seconds

Surfactant makeup vessel or surge vessel with recycle 10 minute capacity

Pump requirement 2.6 $m^3/10^3$ m^3 (20 gal/10^3 ft^3)

Installation charge - 100% purchase cost

Operating

Pressure drop 1.8 kPa (7.4 in. H_2O)

Solution nozzle pressure 359 kPa (52 psig)

Maintenance labor and materials - 4% installed cost

Surfactant solution (0.25%) consumption - 0.05 $m^3/10^3$ m^3 (0.4 gal/10^3 ft^3); and none

Energy required for foam destruction - 74 watt/m^3(2.1 watt/ft^3)

Surfactant - 0.25% solution utilized for Tergitol

Cost on 100% basis

Tergitol \$1.43/liter (\$5.40/gal)
Aerosol \$1.27/liter (\$4.80/gal)
Sterox \$0.53/liter (\$2.0/gal)
Alkanol \$3.17/liter (\$12.00/gal)

TABLE 3. ELECTROSTATIC PRECIPITATION ASSUMPTIONS

Capital
References listed in text
Installation charge - 70% purchase cost
Operating
Maintenance labor and materials - \$64/m^3 s^{-1} (\$0.03/acfm)
Pressure drop 249 Pa (1.0" H_2O)
Contact power 9 watts/m^3 (0.00034 hp/acfm)
For costs based on installed cost, use high end of range

TABLE 4. FABRIC FILTER ASSUMPTIONS

Capital
References listed in text
Installation charge - 75% purchase cost
Operating
Maintenance labor and materials - \$170/m^3 s^{-1} (\$0.08/acfm)
Pressure drop 1.99 kPa (8.0" H_2O)
For costs based on installed cost, use high end of range

TABLE 5. HIGH ENERGY WET SCRUBBER ASSUMPTIONS

Capital

References listed in text

Installation charge - 200% purchase cost

Operating

Maintenance labor and materials - $\$127/m^3\ s^{-1}$ (0.06/acfm)

Pressure drop 14.9 kPa (60" H_2O)

Liquid head 1.79×10^5 Pa (26 psig)

Liquid circulation - 2.67 m^3/1,000 m^3 (20 gal/10^3 acf)

Makeup water - $6.68 \times 10^{-5}\ m^3/m^3$ (0.03 gal/acfm hr)

For costs based on installed cost, use high end of range

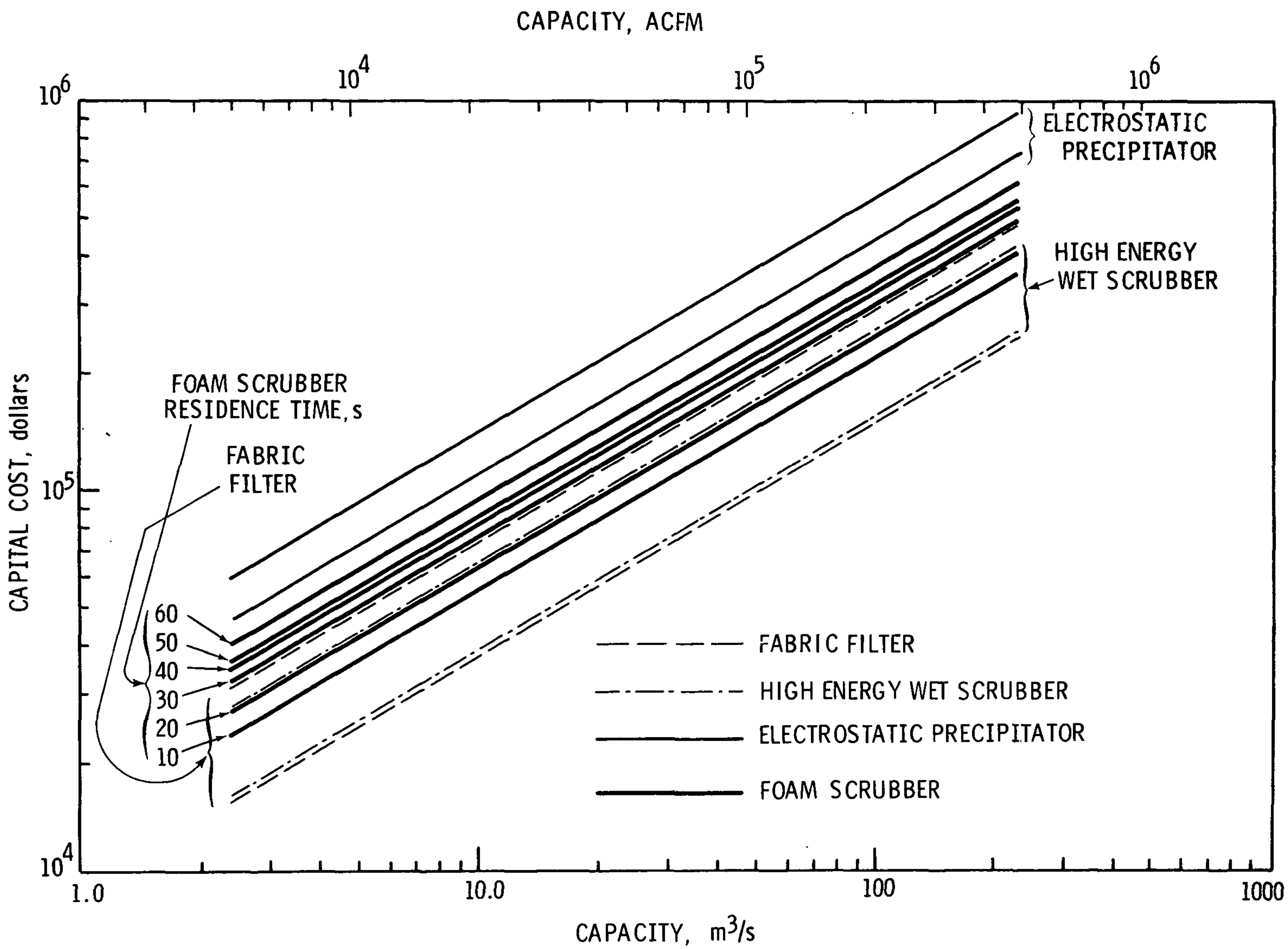

Figure 9. Capital cost for particulate control devices.

TABLE 6. FOAM SCRUBBING CAPITAL COSTS AS A FUNCTION OF SCRUBBER RESIDENCE TIME, EXPRESSED AS PERCENT OF TOTAL PURCHASE COST
Capacity - 26.3 m^3/s (50,000 acfm)

	Residence time, s					
Component	10	20	30	40	50	60
Scrubber	30	38	47	51	52	56
Screen	19	16	14	13	12	11
Destruction system	3	4	4	5	5	6
Mixing/storage vessel	40	35	29	26	26	23
Feed/recycle pump	8	7	6	5	5	4
Total purchase cost	100	100	100	100	100	100

TABLE 7. FOAM SCRUBBING OPERATING COSTS FOR 40-SECOND RESIDENCE TIME AS A FUNCTION OF CAPACITY, EXPRESSED AS PERCENT OF TOTAL OPERATING COST

	Capacity, m^3/s (cfm)		
Component	2.63 (5,000)	26.3 (50,000)	263 (500,000)
Surfactant	53	66	74
Utilities	14	17	19
Maintenance	6	3	1
Depreciation	11	6	2
Capital charges	16	8	4
Total operating cost	100	100	100

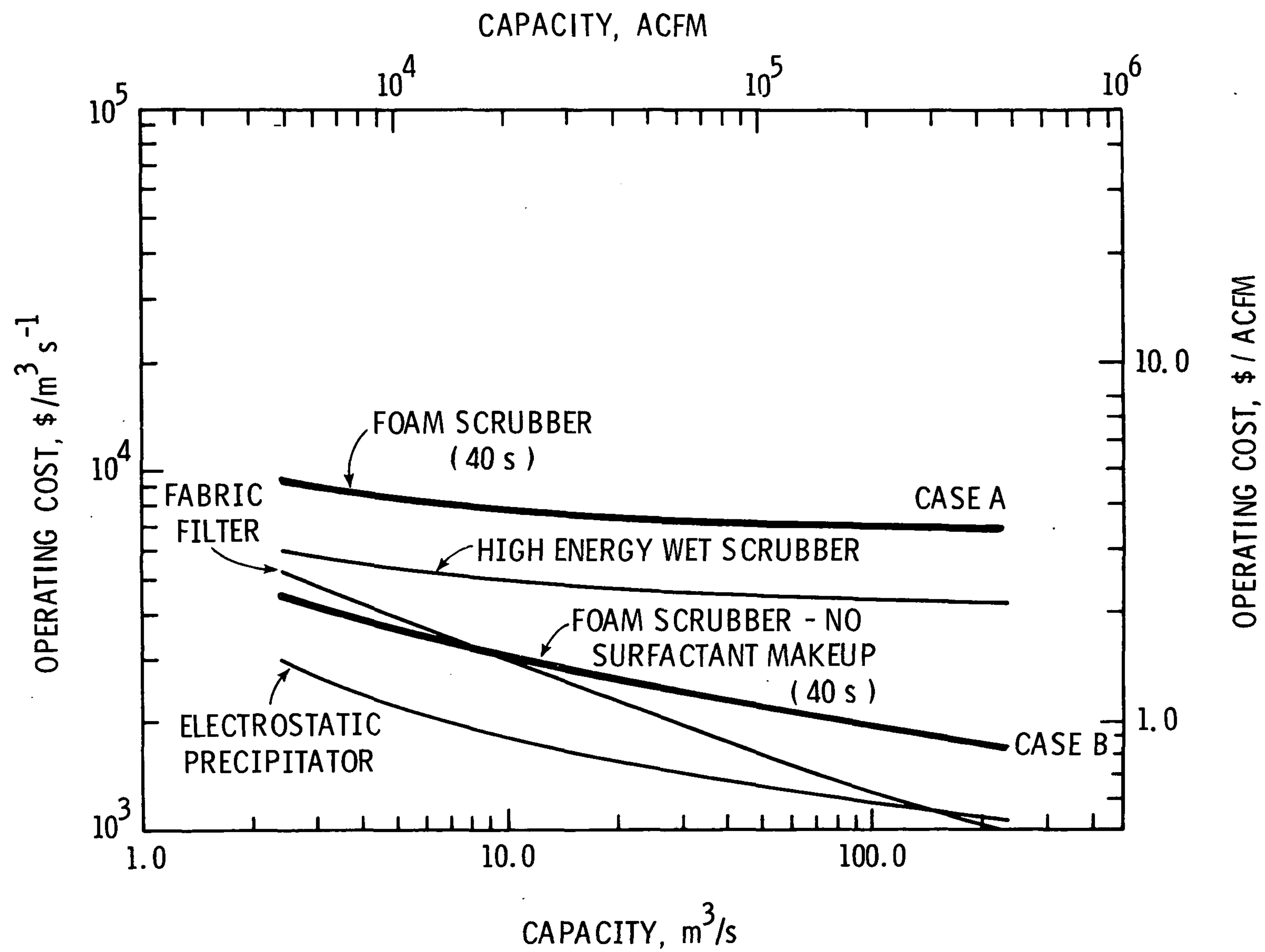

Figure 10. Operating cost for particulate control devices.

Surfactant costs for this estimate, based on using Tergitol, amount to 53% to 74% of the total foam scrubber operating costs. Costs for other surfactants were listed in Table 2. Figure 10 presents a comparison of operating costs for foam scrubbing with the conventional collection methods. A 40-second residence time was arbitrarily chosen since operating costs are not extremely sensitive to residence time.

There are two curves indicating foam scrubber operating cost in Figure 10, Cases A and B. Case A represents the operating cost based on scaling up the pilot-scale scrubber to a unit of identified full capacity. The full-capacity unit would then operate at conditions identical to those experienced on the pilot scale except for the scrubber residence time which would be 40 seconds. The pilot scale scrubber operated at 20.5 second residence time. Identical operating conditions include scrubber pressure drop, gas throughput per unit square area of foam generation screen, liquid-to-gas ratio, surfactant concentration, energy consumption of foam destruction disks per unit foam volume, and scrubbing liquor makeup per unit of scrubber liquor feed rate.

The scrubber liquor makeup during the pilot-scale testing was 1.23×10^{-5} m^3/s (0.2 gpm) which still represents a significant operating expense (53% to 74% of the total operating cost; see Table 7). As discussed in the previous section, it should be possible to reduce the consumption (makeup) of the surfactant liquor further. The makeup of 1.23×10^{-5} m^3/s observed during the pilot test was almost completely the result of pump leakage. Some efforts were made to eliminate this leakage (the pump packing was tightened and replaced). However, due to the strong ability of Tergitol surfactant solutions to dissolve oils, greases, and lubricants, the leakage was not completely stopped. Using a pump with a mechanical seal could have eliminated the leakage. However, this type of pump was not available at the time of testing.

At the leakage and scrubber surfactant makeup rate of 1.23×10^{-5} m^3/s (0.2 gpm), the concentration of solids in the scrubber liquor built up to about 2 kg/m^3 of the liquor. With this concentration, no influence on foam scrubber operation (deterioriation of foam quality) was observed. This indicates that lower surfactant makeup rates and subsequent lower scrubber operating costs should be attainable. With less surfactant makeup and multiple liquor recycles the concentration of collected particulate would increase and could negatively influence the foam quality. Should the foam quality deteriorate, surfactant soluion could be restored to its original condition and recovered for further usage by filtration as mentioned earlier.

Case B represents the foam scrubber operating cost with no surfactant makeup. At present, the minimum surfactant consumption required for a troublefree foam scrubber operation is not known. Since it is believed that the surfactant consumption may be reduced significantly the actual foam scrubber operating cost should be lower than that represented by the Case A curve. At the same time, some surfactant losses may be expected. Consequently, the actual operating costs will be higher than those represented by the Case B curve.

Once surfactant consumption is at its minimum, the utilities become the next highest operating expense (see Table 7). With the successes attained during the pilot-scale testing, it is strongly believed that future experimentation may also demonstrate additional reduction in foam scrubber utilities requirements and lead to further lowering of the Case B curve.

The foam scrubber capital investment cost is competitive with that for existing conventional particulate collectors. Considering the potential for further improvement, the foam scrubber operating cost is also well within the competitive range. Consequently, further development of the foam scrubber is highly recommended.

REFERENCES

1. Ctvrtnicek, T. E., R. F. Walburg, C. M. Moscowitz, and H. H. S. Yu. Application of Foam Scrubbing to Fine Particle Control--Phase I. EPA-600/2-76-125, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, May 1976. 152 pp.

2. Sem, G. J. Submicron Particle Sizing Experience on a Smoke Stack Using the Electrical Aerosol Size Analyzer. Presented at the Seminar on In-Stack Particle Sizing for Particulate Control Device Evaluations, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, December 3-4, 1975. 18 pp.

3. Bradway, R. M., and R. W. Cass. Fractional Efficiency of a Utility Boiler Baghouse--Nucla Generating Plant. EPA-600/2-75-013-a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, August 1975. 148 pp.

4. Modern Cost-Engineering Techniques. H. Popper, ed. McGraw-Hill Book Company, New York, New York, 1970. 538 pp.

5. Peters, M. S., and K. D. Timmerhaus. Plant Design and Economics for Chemical Engineers, Second Edition. McGraw-Hill Book Company, New York, New York, 1968. 850 pp.

6. Sargent, G. D. Dust Collection Equipment. Chemical Engineering, 76(2):130-150, 1969.

7. Edmisten, N. G., and F. L. Bunyard. A Systematic Procedure for Determining the Cost of Controlling Particulate Emissions from Industrial Sources. Journal of the Air Pollution Control Association, 20(7):446-452, 1970.

8. Alonso, J. R. F. Estimating the Costs of Gas-Cleaning Plants. Chemical Engineering, 78(28):86-96, 1971.

9. Shannon, L. J., P. G. Gorman, and M. Reichel. Particulate Pollutant System Study. Volume II--Fine Particle Emissions. APTD-0744, U.S. Environmental Protection Agency, Durham, North Carolina, 1 August 1971. 348 pp.

10. Ström, L. Transmission Efficiency of Aerosol Sampling Lines. Atmospheric Environment, 6:133-142, 1972.

APPENDIX A

DESCRIPTION OF PILOT FACILITY SUBSYSTEMS

The entire scrubber system is housed in a three-story building having a 6.4 m x 6.1 m floor plan. The scrubber geometry was altered to meet the physical constraints of this building. The scrubber is arranged in a "U" shaped configuration (Figure 4). The right leg of the "U" contains the dust feeding, gas conditioning, mixing, and foam generation operations, while the left leg contains the foam residence chamber, foam destruction chamber, air blower, and feed and recycle liquor control loops.

Except for the exhaust duct, the scrubber is square. The inlet air enters a 30 cm square stainless steel mixing duct 91 cm long. The mixing duct is connected to a diverging duct section which slows the air velocity and changes the flow direction 90° into the 91 cm square foam generation section. As foam is generated, it diverges into a 120 cm square ductwork elbow which changes the foam flow direction 90° upward. The foam continues to flow upward in a 120 cm square duct about 2.5 m long. Several viewing ports installed in the scrubber walls permit the foam flow through the scrubber to be observed.

1. DUST AEROSOLIZATION

Before the dust is aerosolized, the fly ash fines are loaded into the high-capacity hopper of a vibratory feeder. A second feeder (not shown in Figure 4) links the main hopper feeder to a modified jet mill, Figure A-1, which serves to disperse the feed material into a stream of ionized air. Ordinarily, a jet mill serves as a particle classifier, breaking up coarser material with the opposing high-pressure air jets designated "O" and "P" in Figure A-1. For the foam scrubber experiments, however, the jet mill was modified to disperse the dust into an air stream rather than to intensely pulverize it.

The feed dust material in the vibratory feeders is air aspirated into the impact chamber and through the upstack into the classification chamber where the air flow pattern swirls the mixture onto the discharge port. Large particles or agglomerates are reentrained at the impact chamber entrance.

Prior to entering the jet mill, the "P" jet air flows through a "static eliminator" radioactive source (Po-210, 20 mCi) which

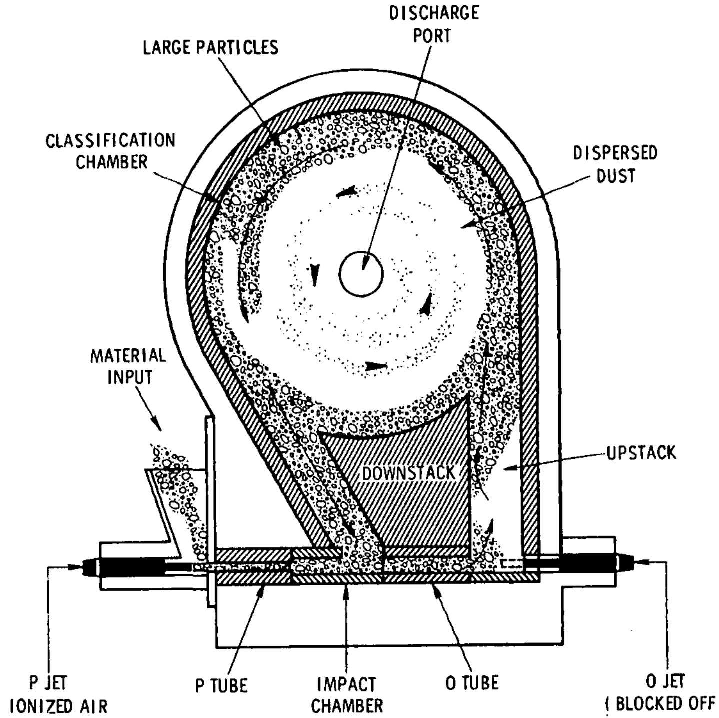

Figure A-1. Jet mill modified for dispersing fly ash fines.

serves to lower static attractive forces between dust particles arising from particle motion and helps to lower particle agglomeration.

To prevent large particles from entering the scrubber, a metal dust cyclone was installed downstream of the jet mill discharge port to cut the coarse material fraction out of the scrubber inlet stream. The coarse gritty material and highly charged agglomerates are deposited into a hopper installed at the bottom of the cyclone while the fines are sent to the scrubber inlet. At the scrubber inlet, the suspended dust is mixed with the bulk scrubber air. A mixing orifice is located in the scrubber duct just downstream of the scrubber air inlet and the dust tube exit. The orifice mixes the relatively slow-moving bulk air with the high-speed dust jet.

Further mixing occurs in a 30 cm square, 90 cm long stainless steel scrubber entrance duct. A thin stainless steel perforated plate oriented normal to the air flow at the end of this duct serves to diffuse and homogenize the bulk dust mixture.

2. BULK AIR SUPPLY

The bulk air for the scrubber is sucked from the room by means of the induced draft fan mounted on the roof of the building. The inlet room air is filtered by four absolute filters prior to mixing with the test dust. This ensures proper control of the particulate concentration entering the scrubbers. Penetration tests made on the absolute filters indicated that when no dust is fed, the scrubber air at the scrubber inlet is perfectly clean. The particle count was below the detectable limits of the electrical mobility analyzer. The total flow rate through the scrubber is monitored by a venturi meter installed in the round scrubber exhaust duct.

3. FOAM GENERATION

As the air/particulate mixture proceeds through the scrubber, it enters the foam generation section. The bulk scrubber air feed loaded with the particulate generates the foam by passing through a 250-mesh screen continuously sprayed with surfactant solution. The screen is arranged in a zigzag fashion normal to the air flow, Figure A-2.

4. FOAM DESTRUCTION

After the foam-encapsulated and particulate-laden gas has flowed through the main scrubber residence chamber, the foam is destroyed and the clean gas is exhausted through the stack. The foam is destroyed with high-speed disks. This method of foam destruction was selected, used and investigated during the bench-scale phase of this program.[1] Practically, the foam is funneled upward toward the destruction disks driven by electrical motors. The motors are on the outside of the destruction chamber, with shafts extending into the chamber. High shear force exerted on the foam by the rotating disks causes the foam to collapse, forming a liquid which carries the collected particulate matter and drains into the lower portion of the destruction chamber. Under normal operation, the scrubber is under vacuum. Therefore, some liquid level is maintained in the destruction chamber to provide a seal and a head for draining the liquid into the scrubber feed tank for recycle. A view of the foam destruction chamber is shown in Figure A-3.

5. SCRUBBER LIQUOR SUPPLY AND RECYCLE

Altogether, the scrubber liquor supply and recycle subsystem consists of three pumps and three tanks (shown in Figure 4). The scrubber feed pump delivers the scrubber liquor from the scrubber feed tank through a flowmeter and a flow control valve to the foam generation section. Here the liquor is evenly sprayed on the foam generation screen (see Section 3 of this appendix). During foam generation, a portion of the liquor drains from the screen and flows by gravity to a lower sump tank. The tank is equipped with a liquid level control to maintain liquid in the tank and assure a permanent liquid seal between the scrubber under vacuum and ambient conditions. As the liquid in the lower sump

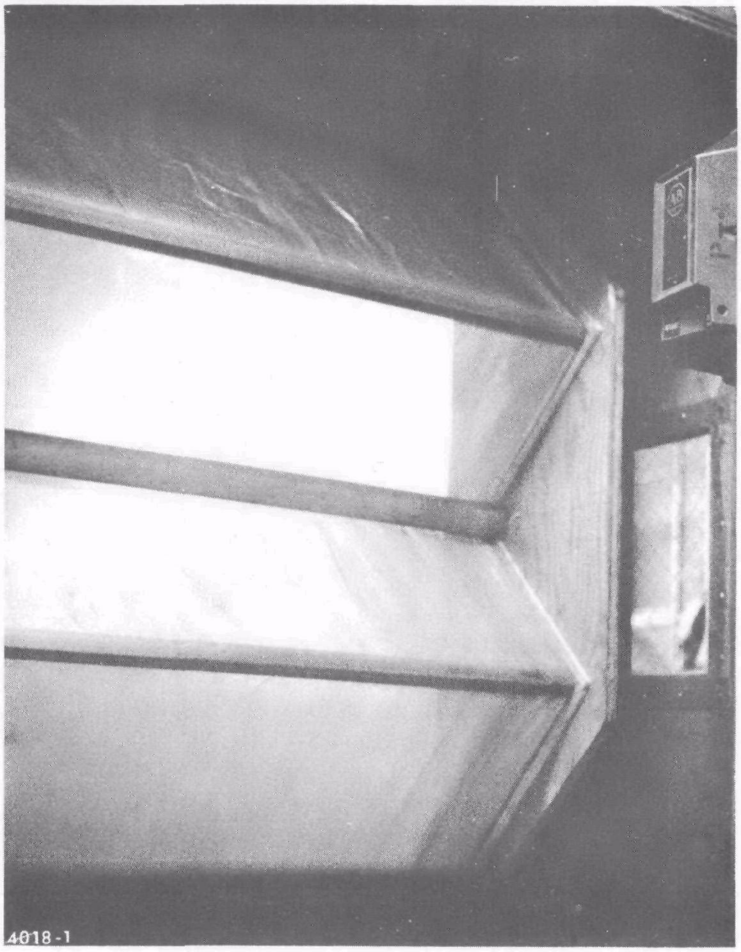

Figure A-2. Foam generation screen arranged in a zigzag fashion.

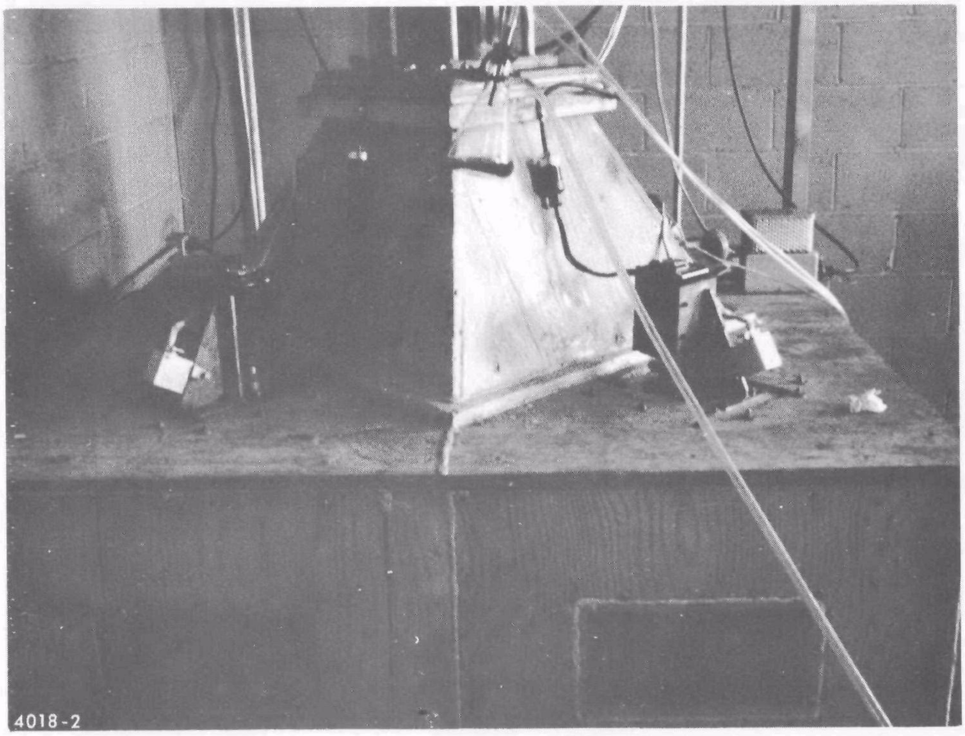

Figure A-3. A view of the foam destruction chamber.

tank accumulates, the level control activates the sump pump which transfers the excess liquid from the sump tank into the feed tank.

The liquor drained from the scrubber foam destruction section also accumulates in the feed tank. Finally, a fresh surfactant solution is supplied from the fresh feed makeup tank into the feed tank as needed. A transfer pump is used for this purpose.

6. FINE PARTICLE INSTRUMENTATION

Particle counters available for use on this program were described in the previous report.[1] They include the model 3030 electrical mobility analyzer (EM counter) manufactured by Thermal-Systems, Inc., model 220 optical counter manufactured by Royco, Inc., and model 100 condensation nuclei counter (CN counter) manufactured by Rich, Inc. The EM counter, Figure A-4, counts the number of 0.025, 0.044, 0.078, 0.139, 0.247, 0.44 and 0.78 micrometer particles in the sample stream. The optical counter counts the number of 0.3, 0.5, 0.7, 1.0 and 2.0 micrometer particles in the sample stream, and the CN counter gives the total count of particles.

The aerosol dilution and sampling system was optimized for the inlet and outlet conditions of the foam scrubber. Aerosol sampling of both inlet and outlet streams was performed using 9.5 mm bore Tygon tubing at a Reynolds number of approximately 2,300. This Reynolds number is optimum, according to L. Ström, for minimizing sample deposition on tubing walls, as well as for minimizing the breakup of larger particles (>2 μm).[10] In addition, both inlet and outlet sampling lines are of equal length. The sampling probes are made from 9.5 mm bore stainless tubing with uniform radii. Both the inlet and outlet probes are pointed upstream and located in the center of the main air mass.

7. SCRUBBER OPERATION

Due to its simplicity, the operation of the scrubber is straightforward. With the equipment at rest, the sump of the foam destruction chamber is filled with surfactant solution to the level that both permits the liquid level control to function properly and maintains gravity siphoning of the foam liquor produced in foam destruction.

The lower sump tank is then filled to the level where its liquid level control functions properly and where a seal between the scrubber and ambient conditions is established. The scrubber feed tank and fresh feed makeup tank are filled. The dust hopper

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[10] Ström, L. Transmission Efficiency of Aerosol Sampling Lines. Atmospheric Environment, 6:133-142, 1972.

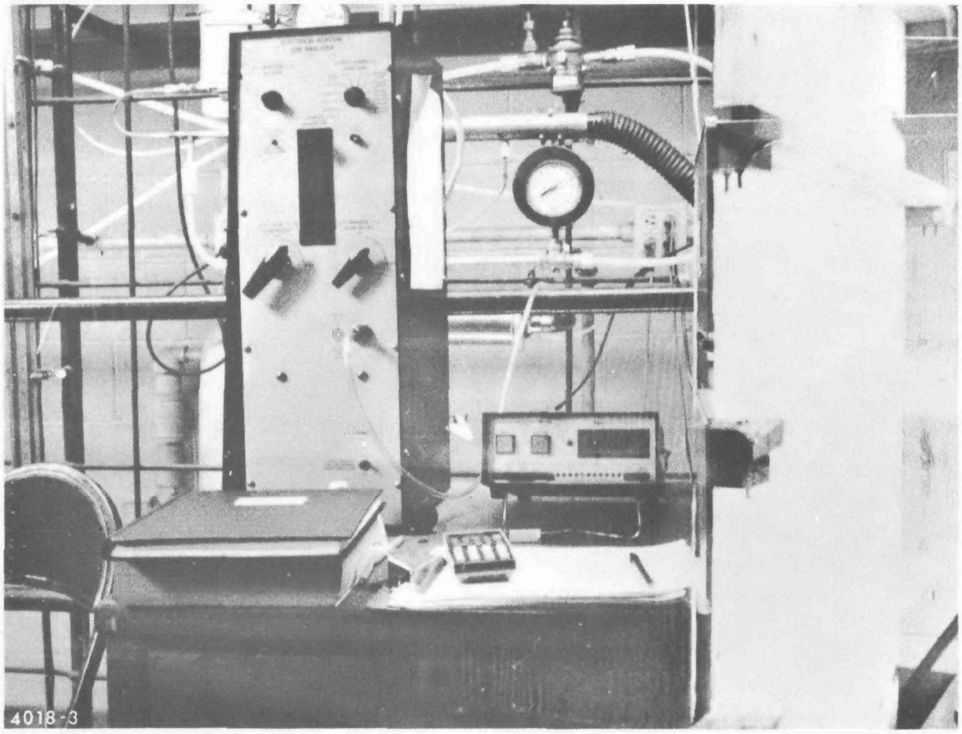

Figure A-4. Electrical mobility analyzer used for foam scrubber particle collection efficiency evaluations.

is then filled with solid particulate dust which is to be fed into the scrubber, and the scrubber facility is ready for operation.

Before each experimental run, the induced draft fan is started up and the dry air flow through the scrubber is allowed to stabilize. Room air is sucked through the absolute filters on the scrubber inlet. These filters are very efficient; and provide clean air to the scrubber at or near the detectable limits of the fine particle instrumentation. If necessary, the scrubber air flow is calibrated.

The scrubber feed pump is then switched on and adjusted to provide the required solution spray rate and spray nozzle pressure. At this point, the total scrubber pressure drop starts to increase. The air flow is adjusted upwards to compensate for the increased pressure drop created by the wet spray on the foam generation screen. Foam generation commences immediately upon wetting of the screen. Air flow characteristics through the scrubber stabilize when foam reaches the destruction chamber. The foam destruction disks are then turned on, dust feeding is initiated, and the scrubber is ready for testing and experimental data collection.

APPENDIX B

EXPERIMENTAL DATA ON FOAM DESTRUCTION

A three-point experiment was designed and performed to establish trends useful for scaling up the foam destruction operation. In this experiment, the degree of foam destruction was determined visually. Three disk diameter sizes were employed in the experiment: 10, 14.6, and 19.7 cm. For purposes of control, the foam impingement velocity was maintained constant at a nominal value of 0.125 m/s for all sizes of disks used. Impingement velocity is the foam velocity normal to the blade prior to destruction.

The experimental runs measured power input to the high-speed universal motor, speed of the spinning disk, and foam flow rate. Power consumption was measured with a direct reading watt meter accounting for the motor's power factor ($E \cdot I \cdot \cos \zeta$). Speed of the disk was measured stroboscopically, and air and surfactant solution flow rates were determined from calibrated rotameter and pump curves, respectively. Foam used for the experiment was made from Tergitol® TMN surfactant and water, mixed as a 2% surfactant solution. Bubble size for all runs appeared consistent and comparable to the 0.8-mm-diameter foam obtained in previous bench-scale experiments.

The results of the experiment are shown in Figure B-1. Data accuracy is approximately ± 20% because during defoaming, power input can fluctuate by this amount. Motor size for a full-scale defoamer can be extrapolated from a plot of power versus disk diameter in Figure B-1. As no distinct difference in power consumption with speed were noticed for the same size disk, the values of power were averaged. The curve holds for a range of speed between 5,000 rpm and 10,000 rpm.

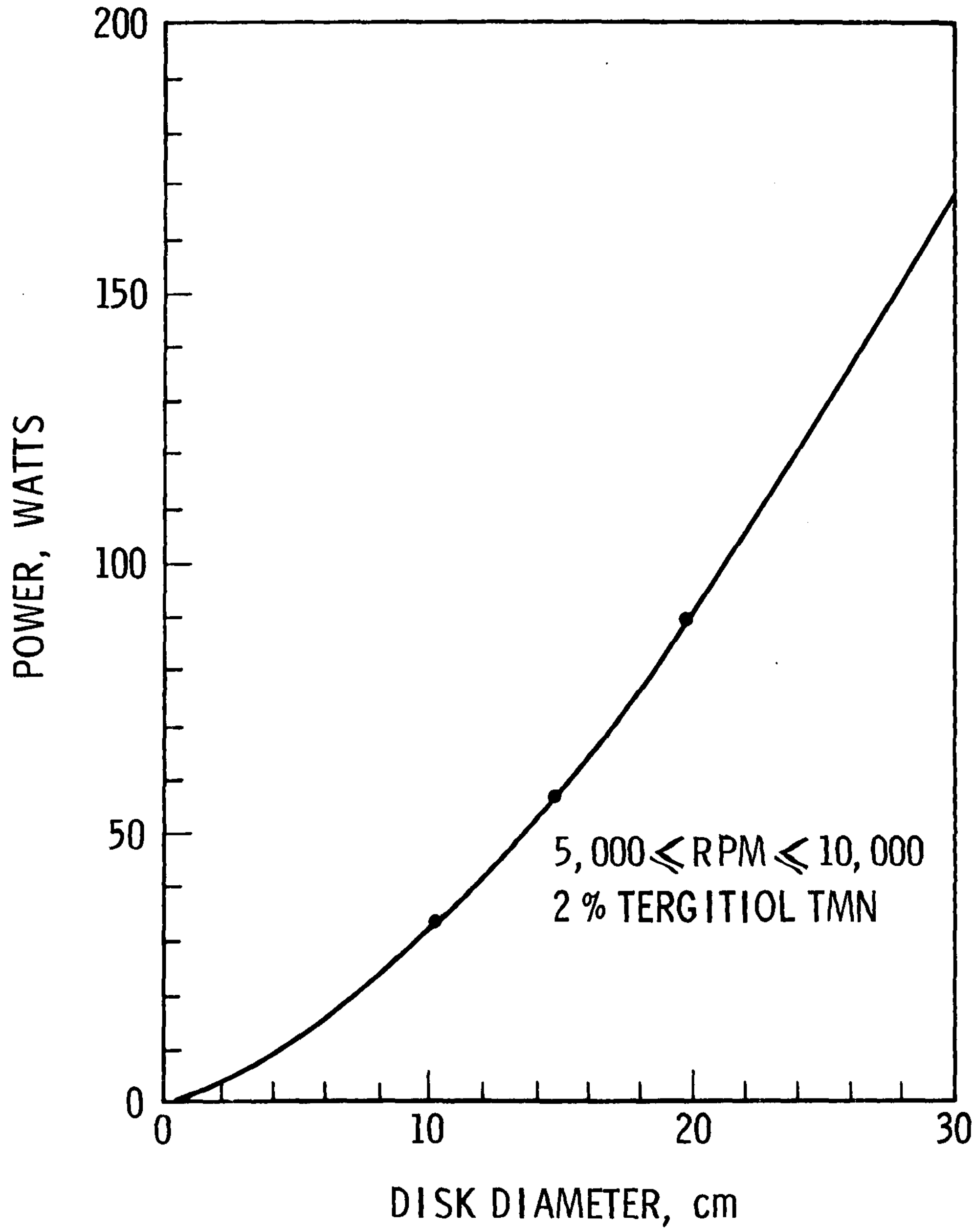

Figure B-1. Power requirements for foam destruction.

APPENDIX C

TROUBLESHOOTING OF THE PILOT-SCALE FOAM SCRUBBER

1. FOAM QUALITY

Initial experiments performed with the pilot-scale scrubber revealed the problem of poor foam quality. Foam could be made, but it was of large bubble size (>10 mm), and it contained many air pockets and striations. The problem was attributed to poor coverage of the screen with the scrubber liquor spray and to insufficient and nonuniform air velocity through the screen. It appeared that the foam liquid spray was not covering the edges of the screen and that it was not of a uniform density. It was further observed that the liquid was draining off of sections of the screen (runoff) without penetrating the screen mesh. Installation of multiple spray nozzles, which gave better and more uniform coverage of the foam generation screen, solved this part of the problem.

The reason for insufficient and nonuniform air flow through the foam generating screen was readily observed and defined as air leaks in the scrubber system. As discussed previously, the air feed to the scrubber is supplied by an induction fan connected to the scrubber outlet. Consequently, the scrubber operates below atmospheric pressure. The total air flow is measured with a Dall tube flowmeter connected between the fan and the scrubber outlet. During each experimental run, the air flowmeter was set at a specific flow rate, e.g., 0.236 m^3/s (500 acfm). Thus, when foam was being generated, it was difficult to determine whether the entire amount of air measured at the scrubber outlet passed through the foam generation screen. Any air leakage downstream from the foam generation screen would cause a reduction in the absolute flow of air through the screen.

A system was devised to quantify the scrubber leakage rate. A hot wire anemometer with probe accessory was installed in the scrubber inlet. The induced draft fan was then started, and the outlet air flow was set at 0.236 m^3/s (500 acfm) on the Dall tube flowmeter. The screen was kept dry so that the negative pressure in the scrubber would be negligible. Under these conditions, the inlet and outlet air flows were nearly identical. The inlet hot wire velocity reading was noted to indicate an anemometer reading of 0.236 m^3/s (500 cfm).

The scrubber operating pressure was next simulated by carefully blocking off a portion of the inlet air suction ports while maintaining constant (0.236 m^3/s) air flow at the outlet. Next, the total air flow at the outlet was increased until the anemometer read the velocity equal to that measured at the negligible scrubber negative pressure (0.236 m^3/s at the scrubber inlet). This was done while maintaining the scrubber operating (negative) pressure constant. The air leakage rate was estimated to be the difference between the two total air flow readings on the Dall flowmeter.

Our initial experiment showed a leakage rate of 0.090 m^3/s (38%) at 0.236 m^3/s (500 acfm) of air flowing through the screen. This leakage appeared to be one of the reasons for poor foam quality. The air leakage rate was reduced considerably by sealing the detectable air leaks to a value less than 10% of the total flow.

As a result of stopping the majority of scrubber air leaks, providing proper screen air velocity, and changing to the multiple spray nozzle configuration, acceptable foams were generated with surfactant liquor concentrations ranging between 0.25% and 2% by weight. Foam was judged acceptable by visual observation of uniform bubble size and minimal air pocketing.

Another reason for poor foam quality was plugging of the foam generation screen with large dust particles. The Nucla dust, although highly concentrated in fines, contains a small fraction of large size particles, roughly 4% by weight >20μm. Foam quality degradation and increased screen pressure drop with loss of scrubber collection efficiency were some results observed as the screen began to plug. To solve this problem, a cyclone to remove large size particulates was installed in the dust feed line. One may argue that the same problem may exist with all industrial streams containing particulate matter. This warrants further discussion.

Based on our observations, it is important that the foam generation screen be kept clean. Otherwise, the foam generation conditions are altered, resulting in poor foam quality and lowered scrubber particulate collection efficiency. These are associated with a reduced open area of the screen due to physical plugging, changed gas velocity through the screen, and, ultimately, non-optimum foam generation conditions. (It is not expected that this problem would exist with soluble particulate.)

a. Selection of Foam Generation Screen Mesh to Eliminate Plugging

The screen plugging was observed during the pilot-scale experiments only when working with the Nucla fly ash and with a 250-mesh screen. Feeding fine particles only into the scrubber eliminated the problem on the pilot scale to the extent that in the 20-hour experimental run, no deterioration of foam characteristics was observed. It is quite likely that a simple solution such as properly selected screen mesh for dusts with different particulate size distributions may completely prevent the screen plugging.

The selection of the optimum screen mesh will be a tradeoff between the scrubber residence time and the screen plugging for each specific dust stream. When a screen with very fine mesh is used, plugging may become severe depending on dust particle distribution. At the same time, fine screen mesh produces foams of small bubble size which reduces the time required to obtain high particle collection efficiency.

When the dust contains a high number of large particulates, a screen with rather large openings will be needed to prevent plugging. It was determined during the bench-scale phase that such screens produce foams with relatively large bubbles.[1] This may lead to longer scrubber residence times in order to achieve high particle collection efficiencies. Presently no specific guidelines can be given as to selection of the proper screen mesh as a function of particle size distribution. It is highly recommended that this problem be investigated further.

It is very important to recognize that the main purpose of the foam scrubber is to collect particles in the fine particle size range (<3 μm). It was demonstrated that the collection of these particles by the foam scrubber can be successful, and that such collection is technically and economically feasible.

The foam scrubber was not intended as a universal collection device for collection of all particulate of any size. Since all existing particle collectors operate best in certain specific types of applications, the foam scrubber will most likely be no exception. At present, the best application conditions for the foam scrubber are not fully defined, nor was it the objective of this program to define them. Additional efforts could easily develop the necessary data in this area.

b. Removal of Large Particle Sizes from the Dust Stream Prior to Entering the Foam Scrubber

Many particle collectors function rather well for large particle sizes. They utilize various principles of operation and range widely in collection efficiency, initial cost, operating and maintenance costs, space requirements, arrangement, and materials of construction. Examples of these devices include inertial separators, settling chambers, impingement separators, and panel filters. More expensive types of collectors are wet collection devices, baghouses, and electrostatic precipitators.

It is not expected that the use of the more expensive collectors would be an attractive alternative for removal of large size particles in combination with the foam scrubber. The cost of such an alternative would most likely be prohibitive.

The use of the other, more economically attractive devices, however, may be feasible. A cyclone inertial separator successfully removed large-size particles from the Nucla dust during the pilot-scale experiments. It should be recognized that the selection of a particle collection train for a specific application is a function of many important variables including dust characteristics, carrier gas characteristics, space availability, influence on production cost, and the like.

The question of what is feasible economics for a fine particle control technology has not yet been answered (refer to the Phase I report for further information[1]). Based on the economic evaluations, the foam scrubber has been shown to be economically competitive with conventional particle collectors (see Section 6). But further investigation is needed to determine when the foam scrubber has to be combined with a "precleaner," and what type of "precleaner" is necessary. Then, the potential of the foam scrubber, whether with or without a "precleaner," can be determined more accurately. It is therefore recommended that, after the data on foam generation screen selection are available, a study be made to determine both the necessity for gas precleaning, and its impact on foam scrubber economics.

c. Mechanical Cleaning of the Foam Generation Screen

It was observed during the pilot-scale experiments that the screen can be mechanically cleaned should it get plugged with large-size particles. This solution, then would involve development of a continuous mechanical cleaning concept for the foam generation screen. When this is done, the effect of the mechanical cleaning on the foam scrubber economics should be evaluated.

2. SCRUBBER DUST FEED

As already mentioned, aerosol consisting of the Nucla fly ash fines was dispersed into the scrubber inlet with staged vibrating feeders and a jet mill. Figure C-1 gives a typical stability trace of the inlet aerosol fed to the foam scrubber. This is a high sensitivity trace made with the EM counter, and it shows that the dust feeding system is reasonably stable in performing collection efficiency measurements.

3. PARTICLE COLLECTION OF SURFACTANT SPRAY

Prior to running collection efficiency experiments with foam, an attempt was made to measure the collection efficiency of the wet screen only. It had been observed during bench-scale testing that some particles had been collected on a water-wetted screen. Pure tap water at the rate of 6.33×10^{-4} m^3/s sprayed on the clean screen. The fan was set to deliver 0.258 m^3/s air flow. An incomplete series of particle data was taken because, with the negative pressure in the scrubber, the limits of scrubber design were reached. The pressure drop across the screen and the negative scrubber pressure increased markedly when tap water was sprayed on the screen. One percent surfactant solution produces a pressure drop about three times lower than when pure water is used. The higher viscosity and surface tension of water explains this phenomenon. As a result of the excessive pressure drop, the wet screen particle collection effect for the pilot scrubber could not be determined. Based on the data generated on the bench scale, however, collection by the foam generation spray alone should be insignificant.[1]

4. FOAM BASELINE AEROSOL

The amount of baseline aerosol generated from the foam destruction was measured. The particle baseline is measured at the scrubber outlet with foam being generated and destroyed, but with no dust feed. The baseline aerosol originates from two sources, the first being the foam destruction disks. The high-speed disk blades break the foam into liquid which is returned to the feed tank. The shearing and chopping of the blades may result in a net generation of aerosol. In addition, the leakage of room air into the scrubber resulted in a net count of fine particles in the outlet stream.

The average foam baseline counts for the 20-hour experiment are shown in Figure C-2. The counts made when running 1% Tergitol solution and approximately 6,500-rpm disk speeds indicated 10^6 particles/cm^3 in the particle size range between 0.025 μm and 0.78 μm. Attempts were made to reduce baseline counts. It was found that the baseline could be reduced nearly 10 times by switching to a lower concentration of surfactant (0.25% versus 1%) and decreasing disk speed from 6,500 rpm to 4,000 rpm. Under these conditions, foam was sufficiently stable and at the same time was easily liquefied, even at the lower destruction disk rpm's.

The above observation is very important. It indicates the potential improvements that can be realized due to the scaleup. Based on bench-scale experiments, 0.25% surfactant solutions did not generate acceptable foams. But reduction of the surfactant concentration during the pilot experiments not only had a dramatic influence on the operating cost of the foam scrubber, it also produced foams which are much more readily destroyed, as indicated

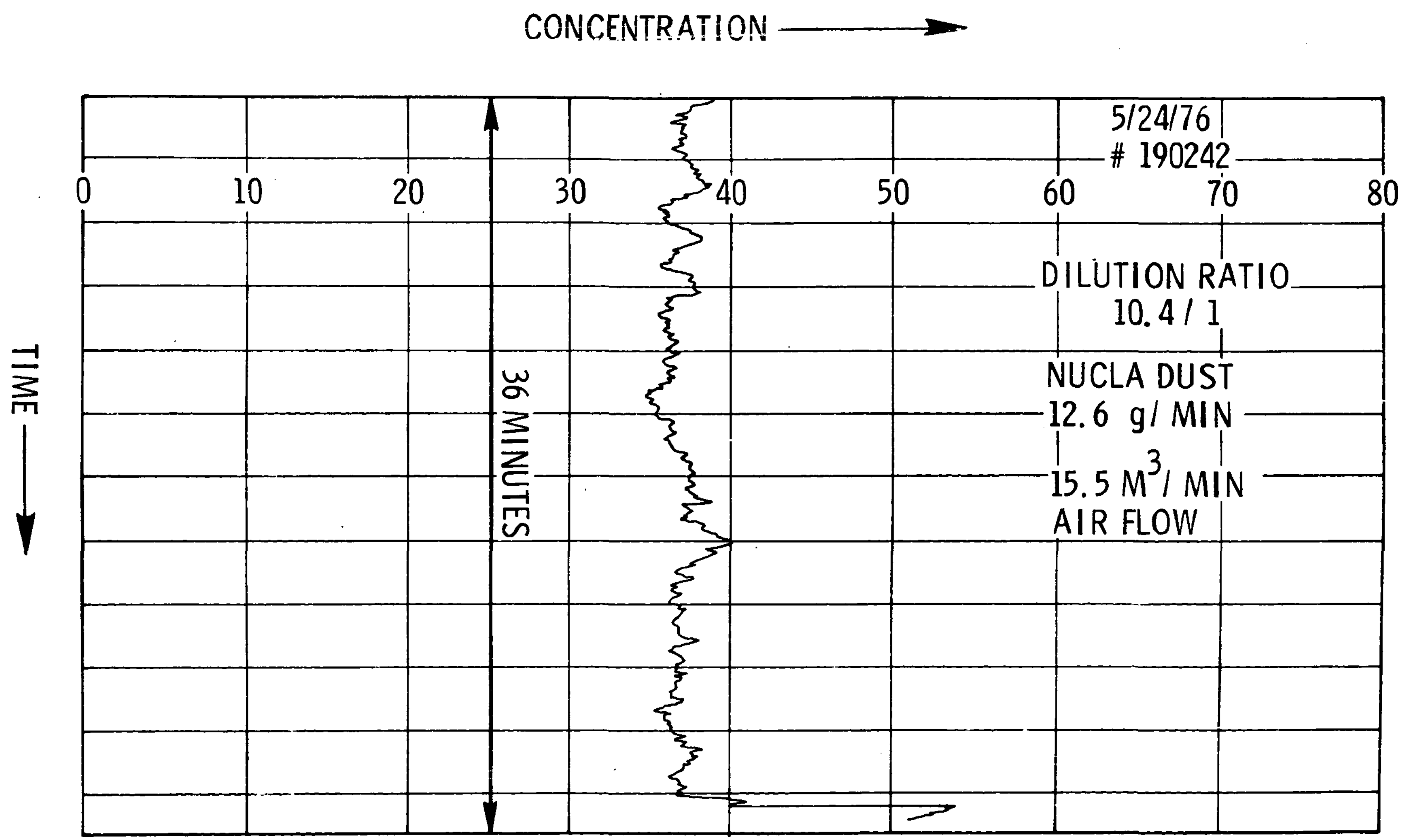

Figure C-1. Aerosol stability.

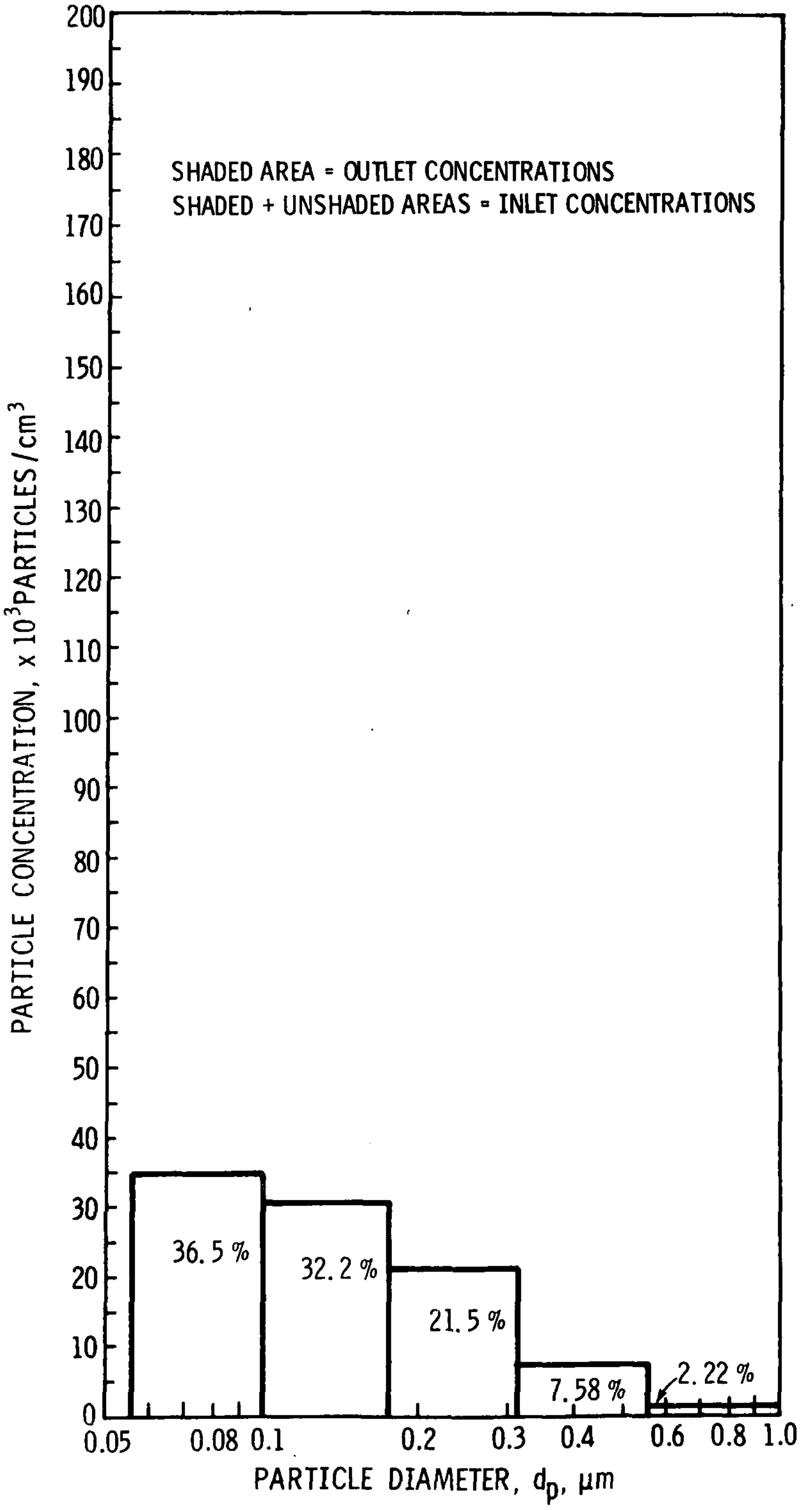

Figure C-2. Average foam baseline counts (11 runs). Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol. Disk speed: 4,000-5,000 rpm.

by lower destruction disk rpm requirments. The lower speed also had a significant influence on the secondary (baseline) aerosol formation. Ultimately the power consumption by the destruction disks was reduced.

It is strongly believed that even further improvements of foam destruction (reduction in secondary aerosol formation and power consumption) are achievable once the foam destruction step is more thoroughtly understood. It is therefore highly recommended that the foam destruction step be investigated further.

APPENDIX D

FINE PARTICLE COLLECTION DATA AND FOAM SCRUBBER OPERATING CONDITIONS FOR THE 20-HOUR EXPERIMENTAL RUN

During the 20-hour experiment, the scrubber particle collection efficiency was measured 12 times. The results of these 12 measurements are presented in Figures D-1 through D-12. A summary of the data was presented in Figure 6.

Several variables important for foam scrubber operation were periodically monitored. The most important of these are summarized in Table D-1. The table indicates the ranges as well as the averages for each important variable. As can be seen, the operation of the scrubber during the 20 hours was very stable with rather minor fluctuations in the scrubber gas flow throughput, scrubber ΔP, and scrubber particle feed.

TABLE D-1. RANGES AND AVERAGES FOR IMPORTANT PARAMETERS OF THE FOAM SCRUBBER OPERATIONS, 20-HOUR DEMONSTRATION

Parameter	Range	Average
Barometric pressure, kPa	98.37-99.00	98.74
(in. Hg)	(29.13-29.32)	(29.24)
Wet bulb temperature, K	291-294	293
(°F)	(65-70)	(68)
Dry bulb temperature, K	298-303	301
(°F)	(76-86)	(81)
Relative humidity, %	41-56	47
Air throughput, m^3/s	0.255-0.261	0.259
(cfm)	(540-555)	(550)
Liquor feed, 10^{-4} m^3/s	6.75-6.90	6.83
(gpm)	(10.7-11.0)	(10.8)
Scrubber ΔP, kPa	1.74-1.97	1.84
(in. H_2O)	(7.0-7.9)	(7.4)

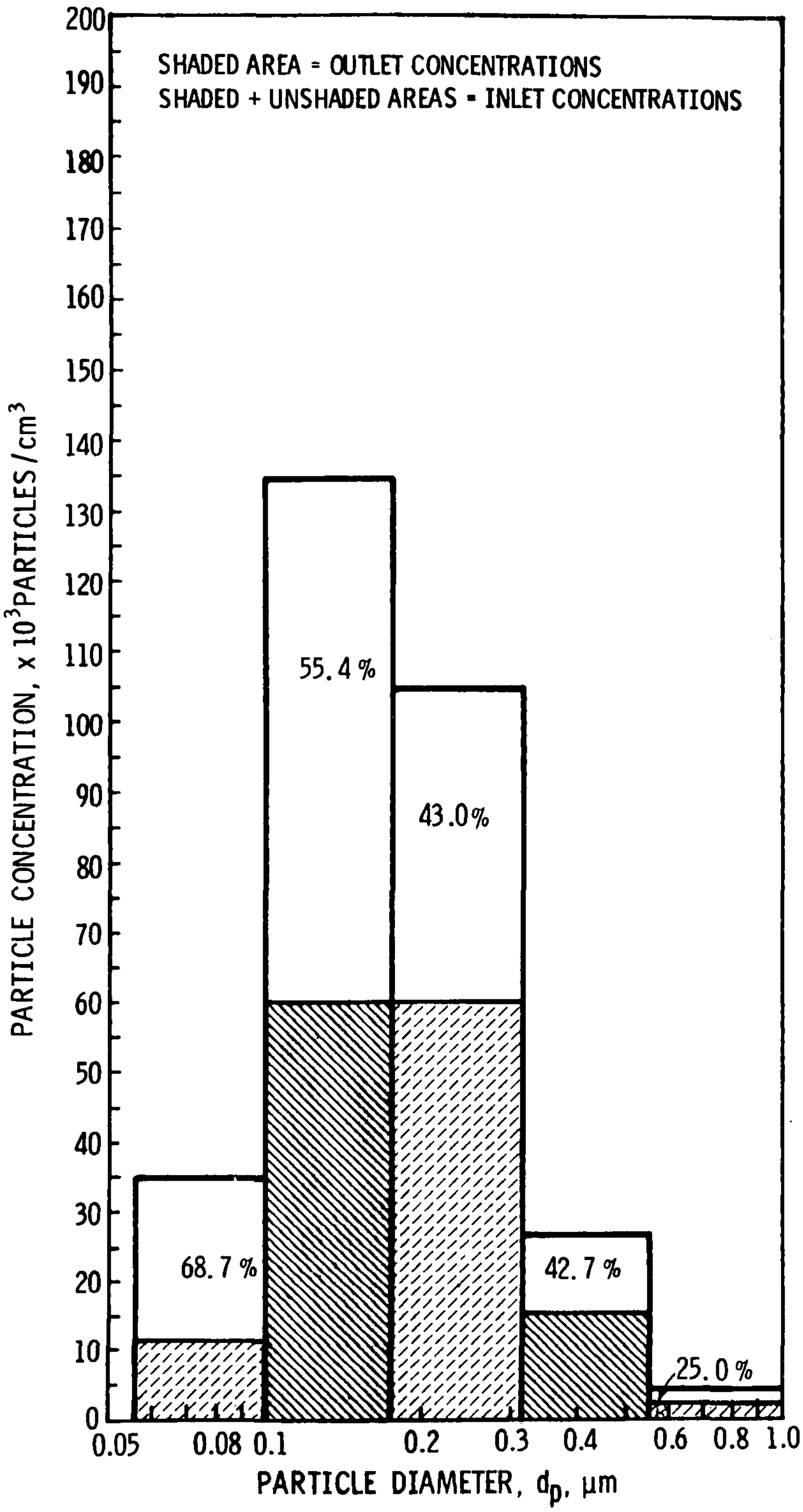

Figure D-1. Particle inlet and outlet concentrations and collection efficiencies (Run 1). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

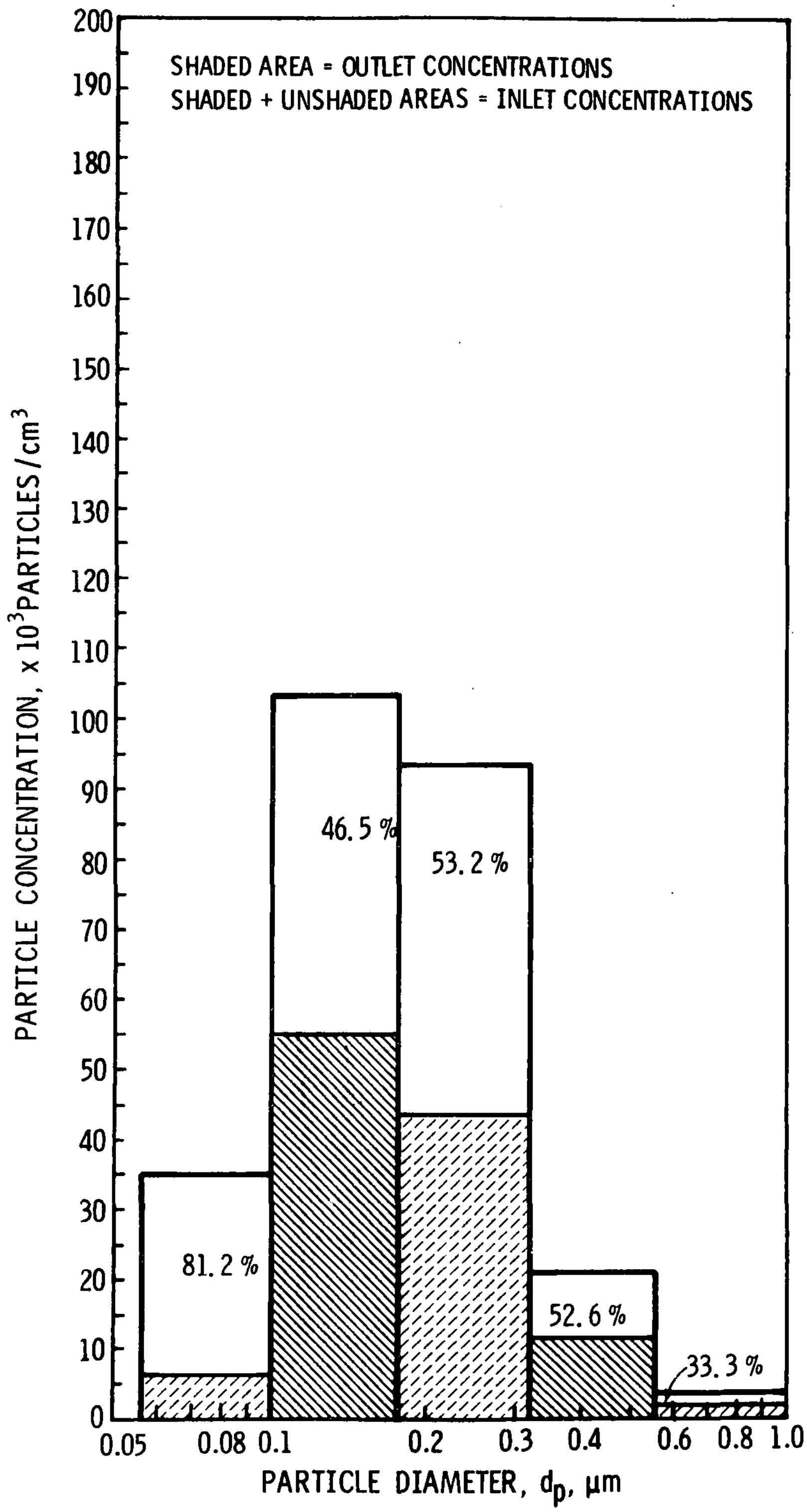

Figure D-2. Particle inlet and outlet concentrations and collection efficiencies (Run 2). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

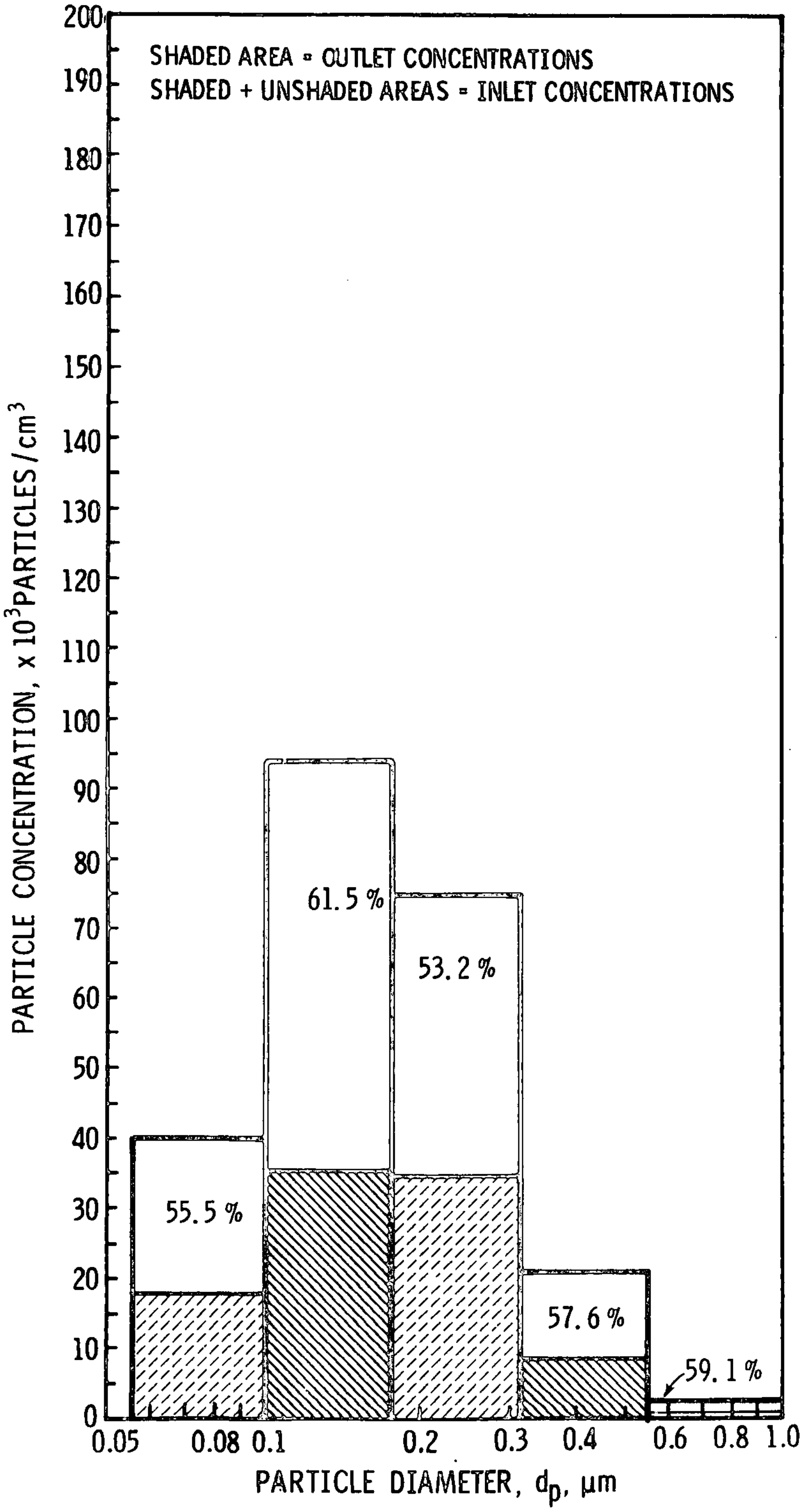

Figure D-3. Particle inlet and outlet concentrations and collection efficiencies (Run 3). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

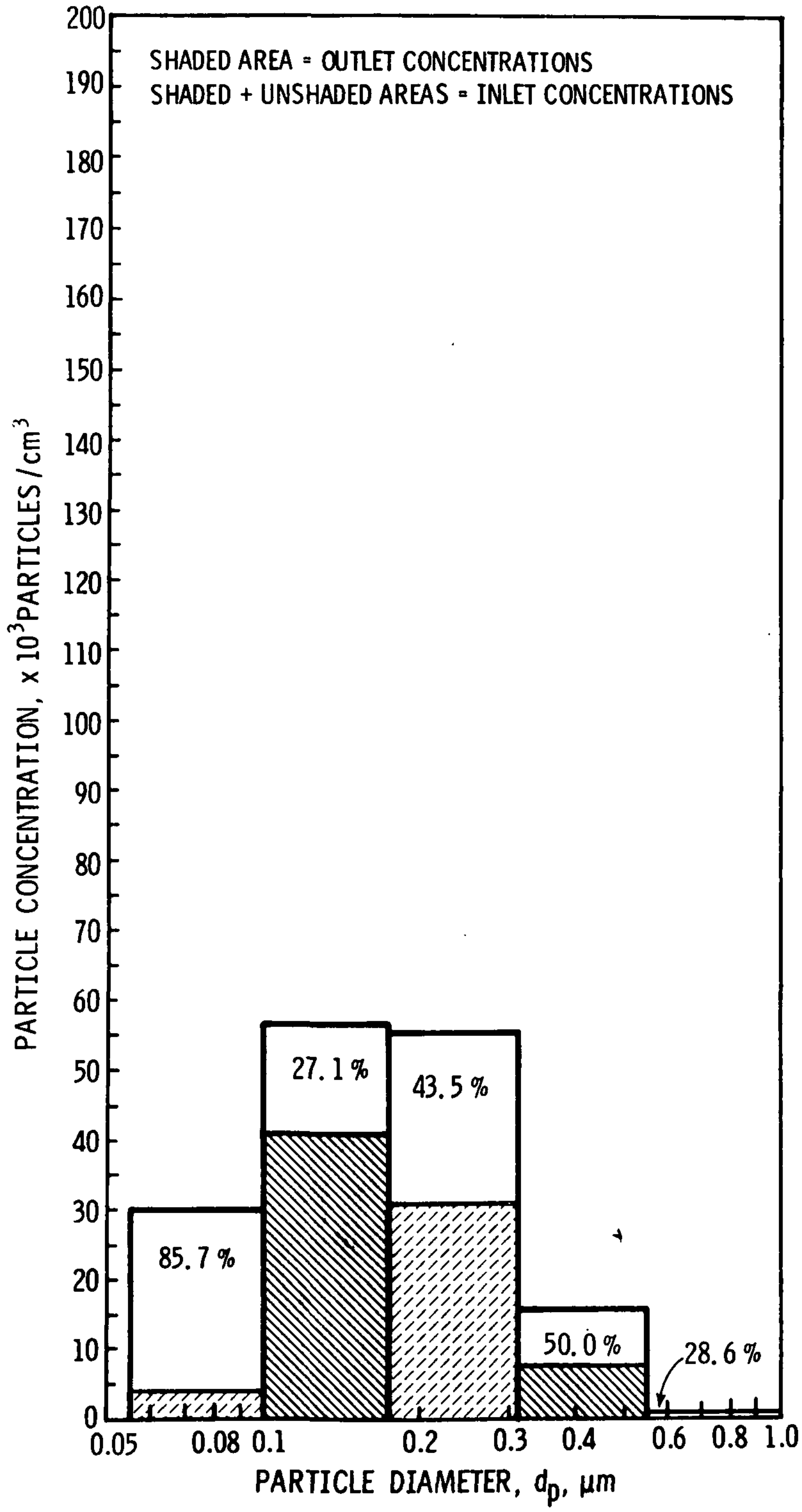

Figure D-4. Particle inlet and outlet concentrations and collection efficiencies (Run 4). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

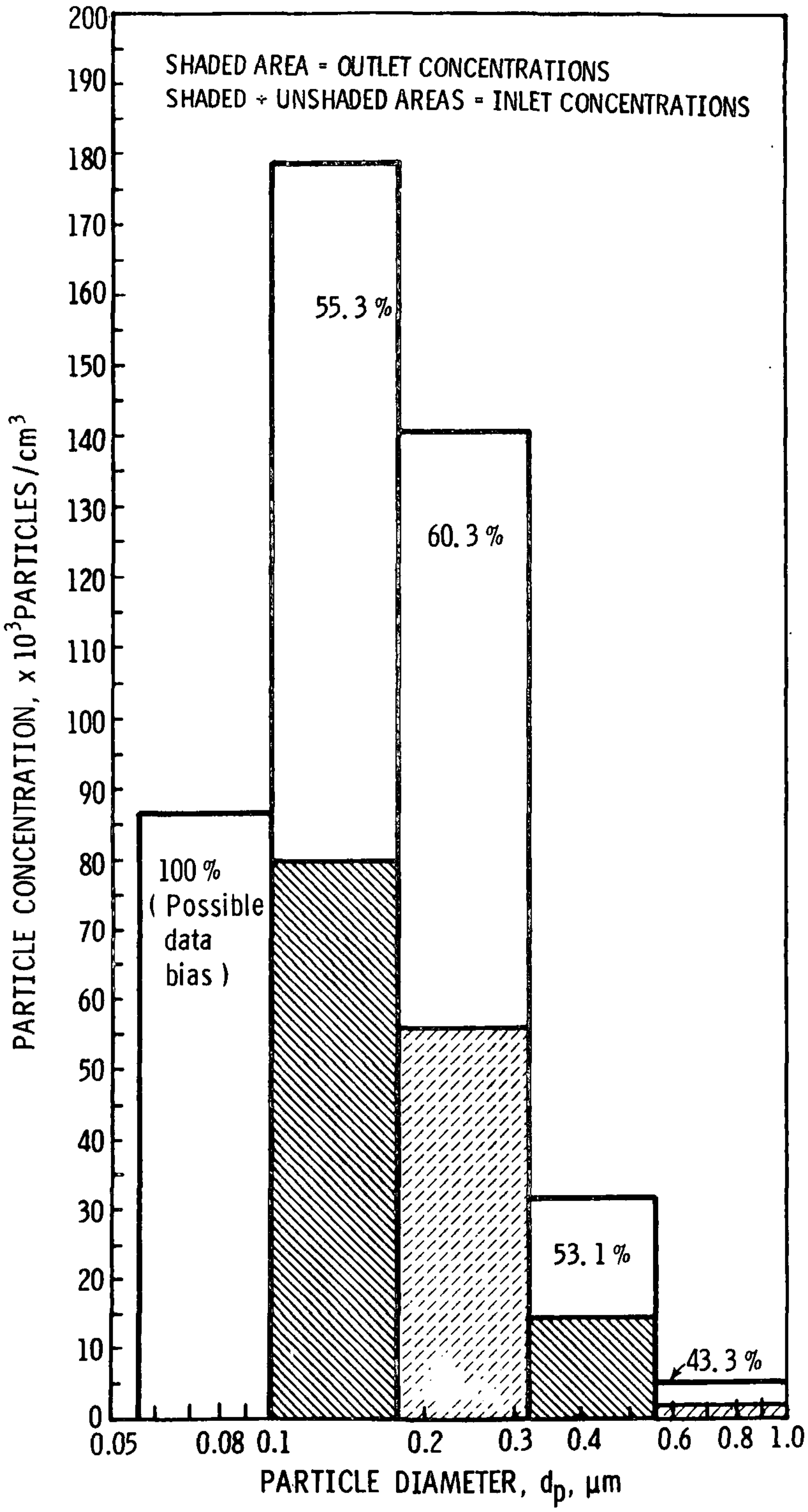

Figure D-5. Particle inlet and outlet concentrations and collection efficiencies (Run 5). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

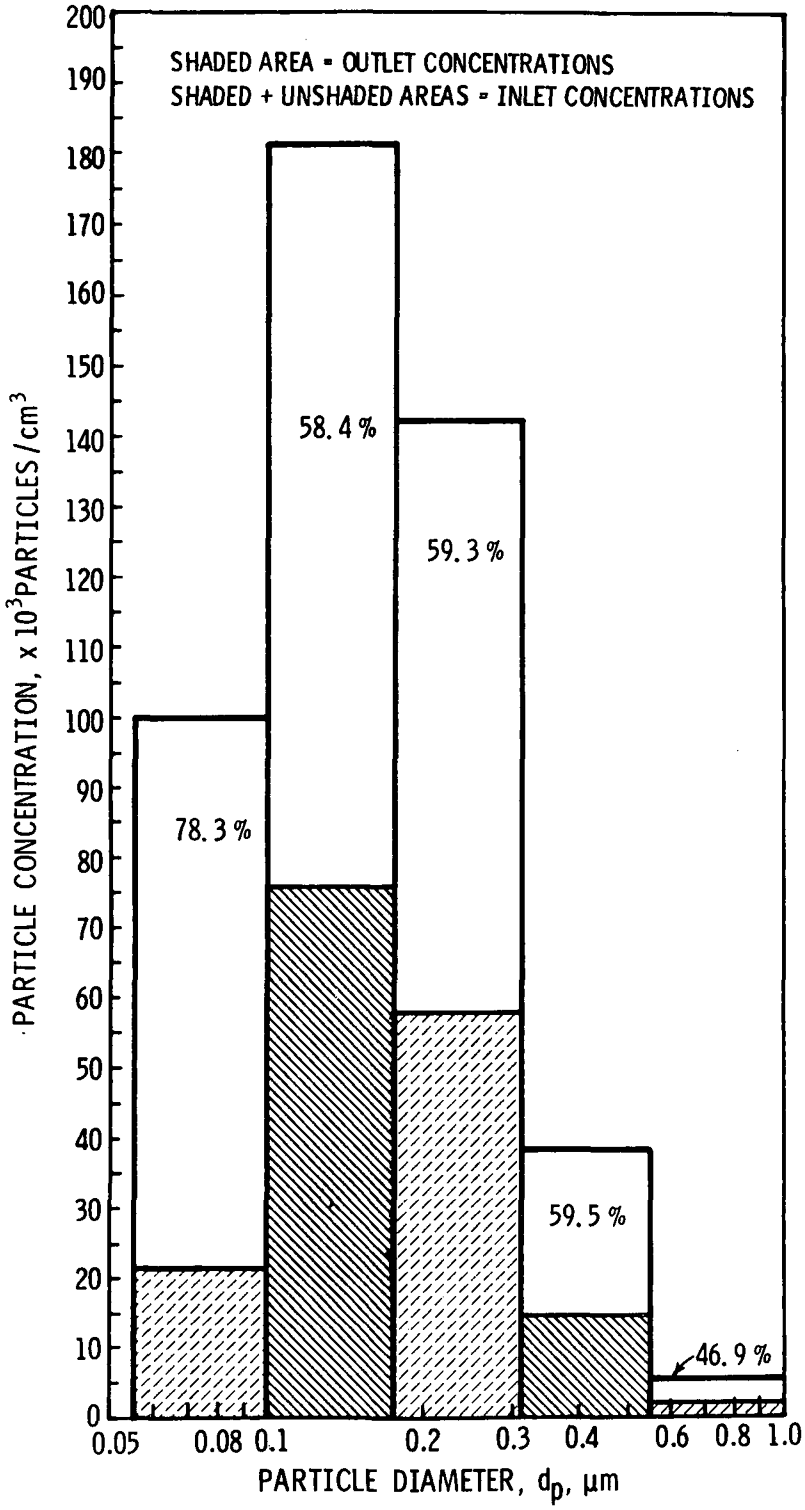

Figure D-6. Particle inlet and outlet concentrations and collection efficiencies (Run 6). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

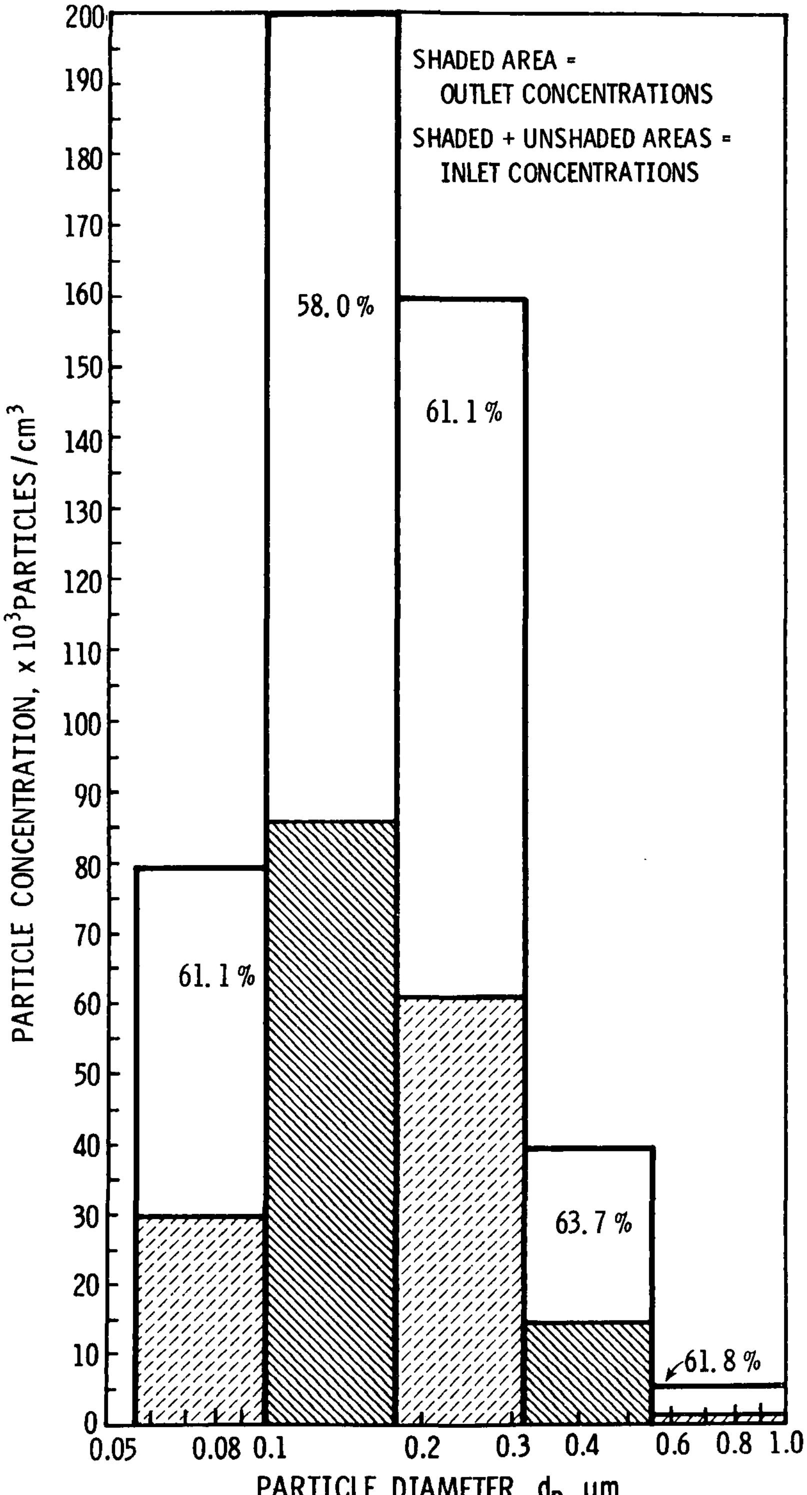

Figure D-7. Particle inlet and outlet concentrations and collection efficiencies (Run 7). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

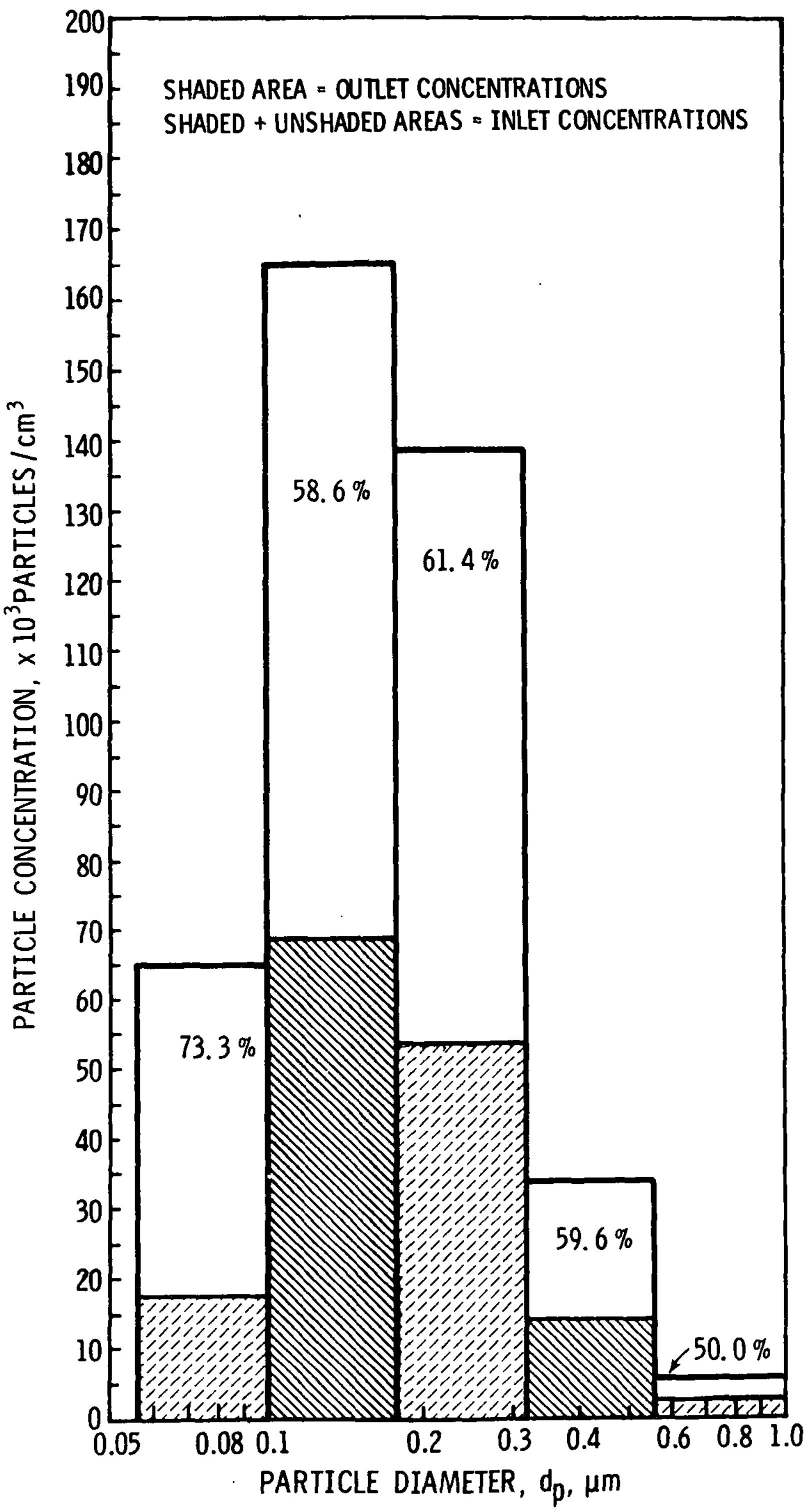

Figure D-8. Particle inlet and outlet concentrations and collection efficiencies (Run 8). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

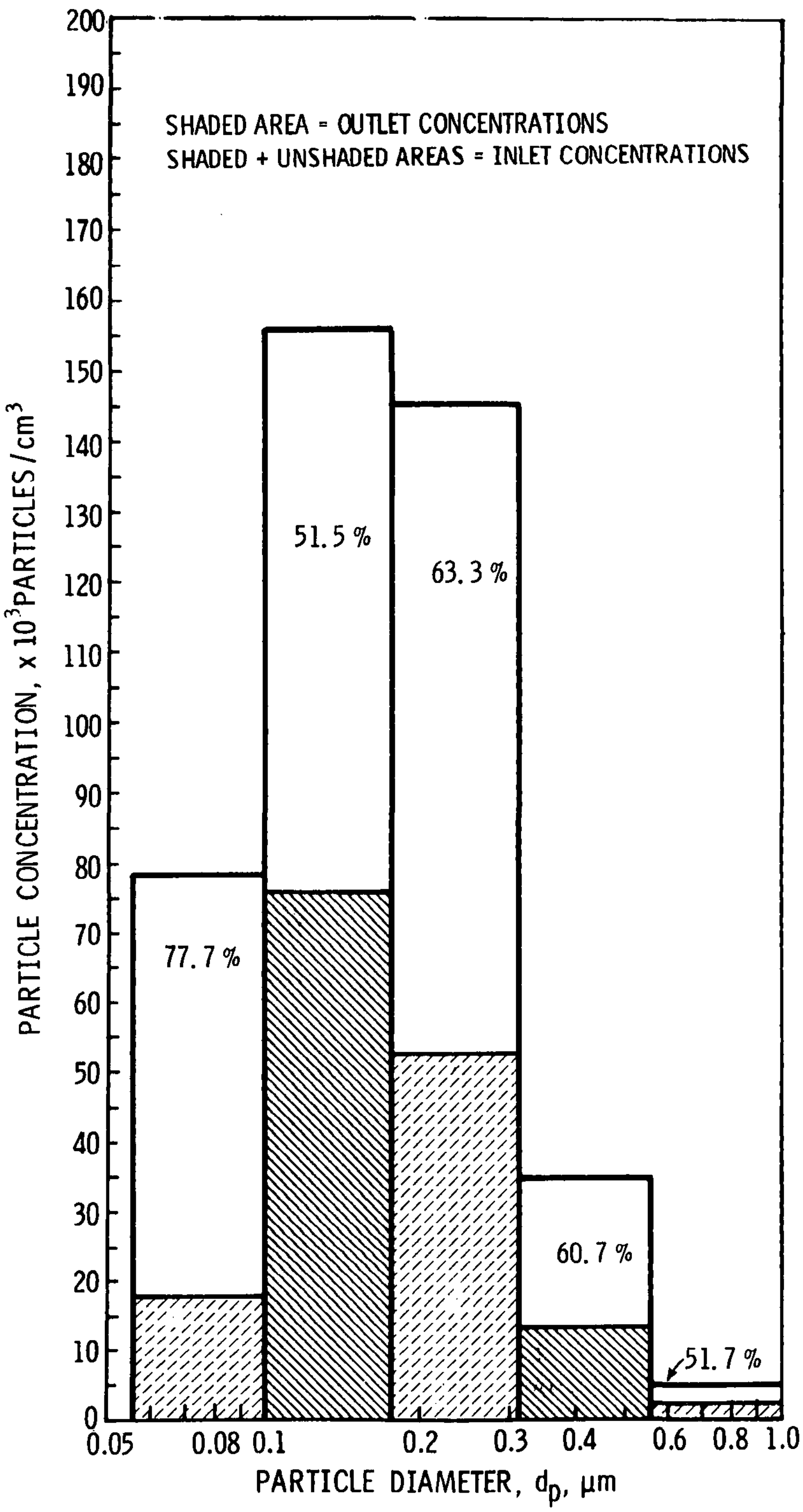

Figure D-9. Particle inlet and outlet concentrations and collection efficiencies (Run 9). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

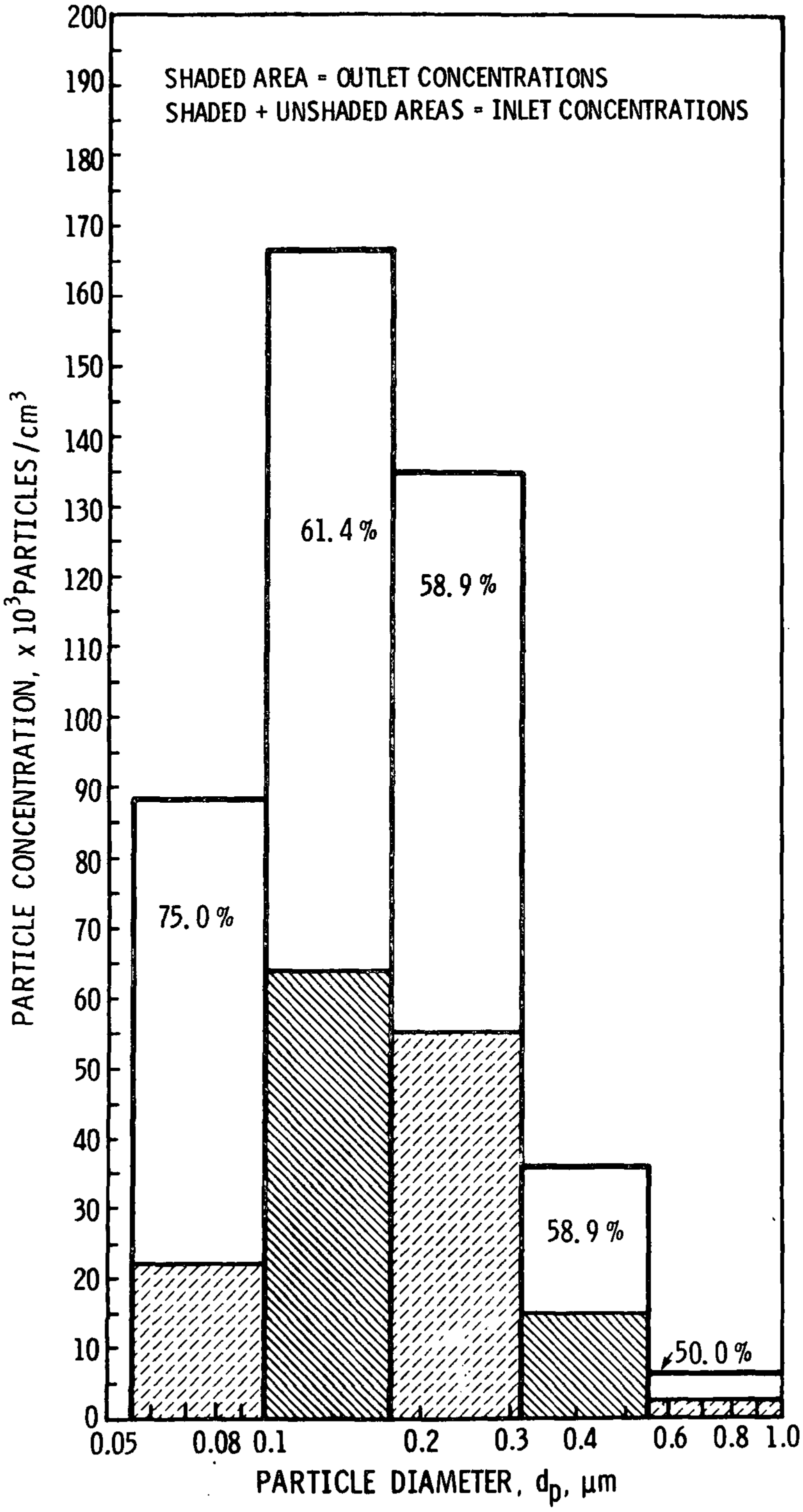

Figure D-10. Particulate inlet and outlet concentrations and collection efficiencies (Run 10). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

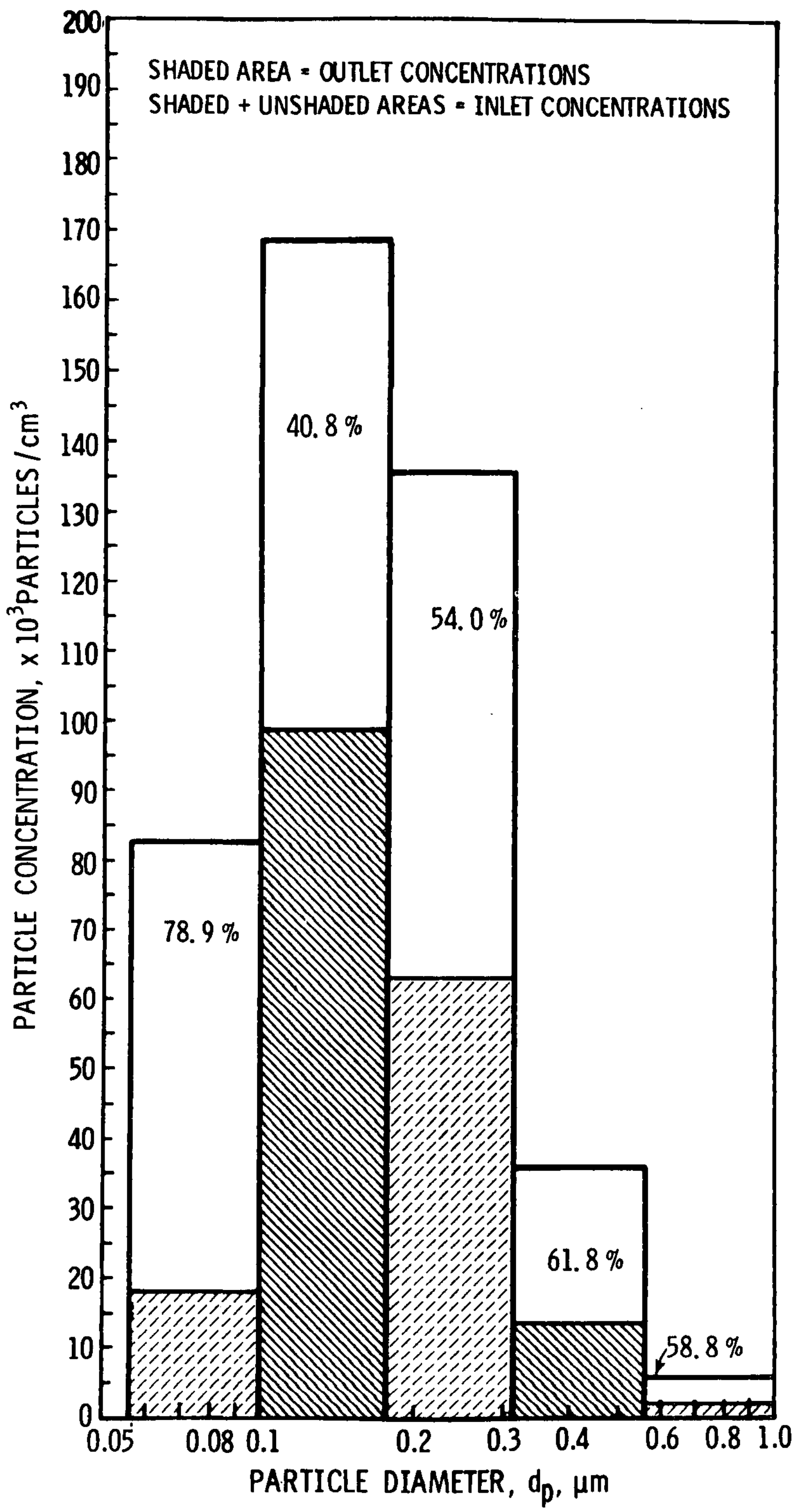

Figure D-11. Particulate inlet and outlet concentrations and collection efficiencies (Run 11). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

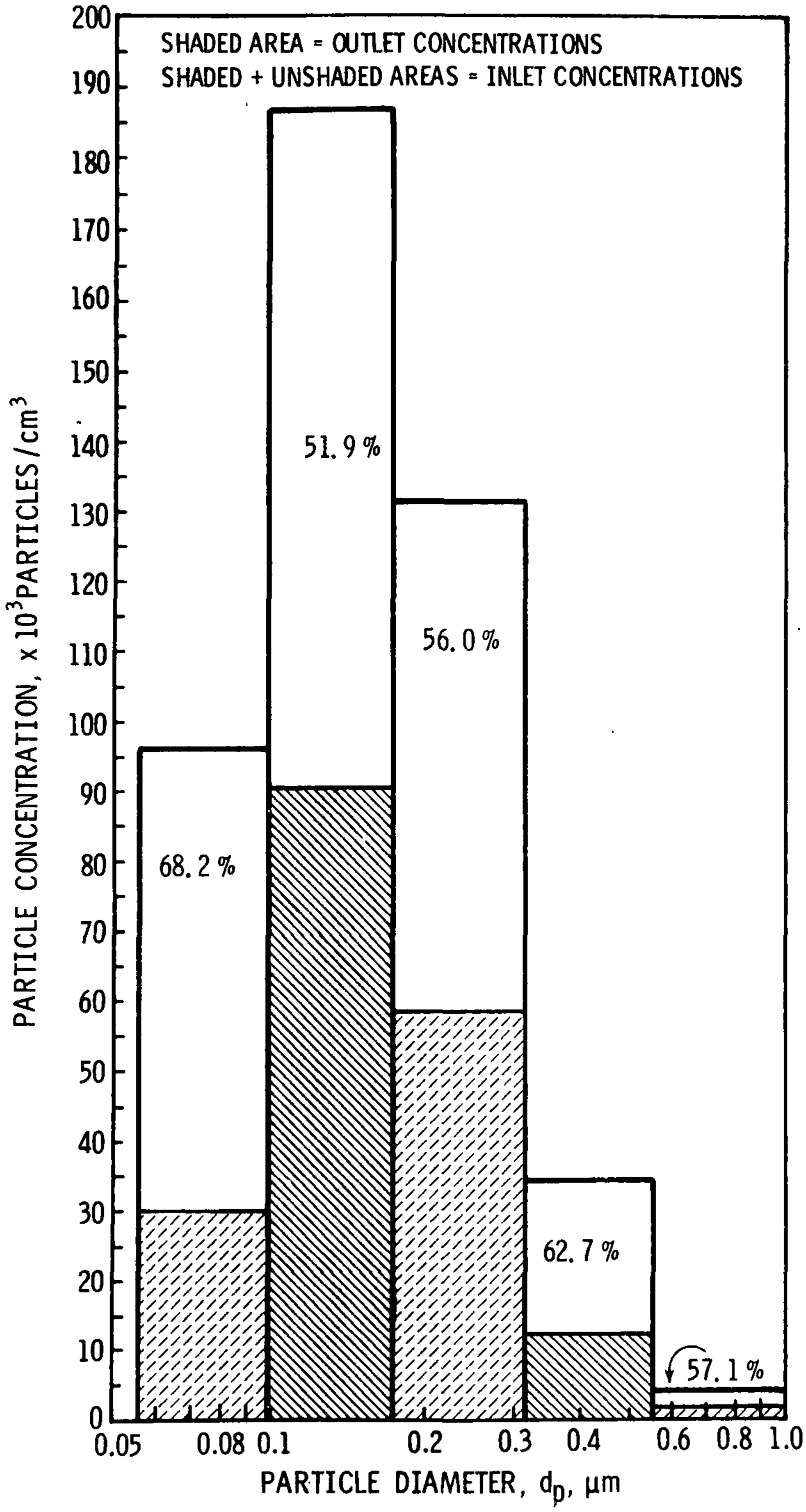

Figure D-12. Particulate inlet and outlet concentrations and collection efficiencies (Run 12). Percent collection shown inside the unshaded area. Scrubber residence time: 20.5 seconds. Surfactant concentration: 0.25% Tergitol.

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16. ABSTRACT The report summarizes the knowledge, experience, and data gained to date, relative to the application of foam scrubbing to collecting fine particles from gaseous streams. Experimental data are presented obtained on a 0.236-cu m/s (500-cfm) pilot-scale foam scrubber facility. Economic analysis indicates that a foam scrubber can be competitive with other fine particle collection devices. Areas for further foam scrubber development are recommended.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Air Pollution Control	13B
Scrubbers	Stationary Sources	07A
Foam	Particulate	11G
Dust	Fine Particles	
Gases		07D

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