THE FILTER TEST PROGRAM, AN INSTALLATION MANUAL, AND FILTER RESEARCH

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During the Air Cleaning Seminar at Idaho Falls two years ago, those of you who attended will recall that defective high-efficiency filter units were discussed at great length. Mr. George Hurwitz of the Army Chemical Center and I gave a paper outlining the types of defects we had found in a sampling of high-efficiency filter units. Our evidence had been confirmed by the condition of various filter stocks held by the atomic energy program.

Subsequent investigation by the filter manufacturers traced the breakdown primarily to the corrugated separator used in the filter unit. The separator had been made of four-pound asbestos paper. This paper basically had very little capacity to hold its shape after corrugation. In the process of manufacture, therefore, the asbestos paper was run through laundry starch. Upon drying, the starch held the shape of the corrugations in the separator. The continuing hydroscopic nature of the starch had not been reckoned with. With separators assembled into the filter unit, the starch coating absorbed moisture over a period of time, even while the filter unit still was in stock. The effect was the same as exposing your starched shirt collar to the rain. Corrugations in the separator flattened out and the internal pack or core of the filter unit sagged. The thin filter paper broke at the edge of the frame or along the topmost separator from the weight of the sagging pack. These were examples typical of the damage being found two years ago.

You will remember also that inspection and testing stations for high-efficiency filter units were being scheduled at Edgewood, Maryland, and Hanford, Washington. The stations were started to assure that filter units delivered to the atomic energy program would be initially reliable. The inspection and testing facilities were made available to program installations on a voluntary basis. This policy of voluntary use continues today. There are very few plants and laboratories that are not taking advantage of the service.

Inspection and testing stations have been in operation for 22 months. I want you to see their testing experience with the high-efficiency filter units that have passed through the stations.

Fig. 1. This will give you the percentage of filter units rejected by the stations for all causes except shipping damage. Shipping damage, incidentally, has been one-half of one per cent. The first bar deals with filter units made and delivered before the testing program began. These were withdrawn later from stock and sent to stations for inspection and test. Note that nearly 49 per cent of these units were rejected. The second, third, and fourth bars reflect the rejection of new filter units for each of three six-month periods of station operation. You will observe that eight per cent of all filter units were found unacceptable in the first half of 1960, a greater percentage in the second half, and almost 14 per cent in the first half of this year. The next two figures will show that the filter manufacturing picture is not as gloomy as this slide indicates.

Fig. 2. Here are the rejections of new filter units delivered in the three semi-annual periods following start-up of the testing program. Note, however, that these rejections were made solely for excess penetration or lack of efficiency in the filter unit. You see that these percentages decreased successively.

Fig. 3. Alongside rejections for penetration, we now have the percentage of new filter units rejected for excessive resistance or pressure drop. Rejections for this cause have been mounting continually. Greater pressure drop in the filter unit can be traced partly to heavier filter paper now used in its construction. The seven-mil filter paper is becoming obsolete. The additional pressure drop can be attributed also to more rigid operating requirements which the filter unit must meet. For example, Hanford required humidity-resistant paper in filter units for their reactor confinement. We understand that Savannah River will require waterproofed filter paper for units in their reactor containment program. Other installations also have a need for waterproofed filter paper. It is only logical then that increased pressure drop will result when filter paper must be made to meet these needs. The number of rejections for excessive pressure drop outstrip rejections for penetration by far. This accounts for successive increases in total rejections that you saw in the first slide. This is why I said that the filter manufacturing picture is not as gloomy as the Figure 1 indicated.

Fig. 4. Here are our filter manufacturers, X, Y, and Z, and the percentage of new filter units that inspection stations have rejected for penetration. These rates were established in 18 months of testing by the stations.

One of these three manufacturers has given us a continuing authorization to destroy all of his filter units which inspection and testing stations reject for excessive penetration. When filter units of the other two makers are rejected for this cause, the units are returned. We do not know how the two manufacturers dispose of these rejected filter units. Presumably they can be funneled into uses where extreme high-efficiency is not required of the filter unit. Whatever the disposition, we want to eliminate every potential avenue through which these rejected filter units can find their way back into the atomic energy program. We therefore recommend to those few plants and laboratories who are not participating in the quality assurance program that they start sending their filter deliveries through the inspection stations for testing.

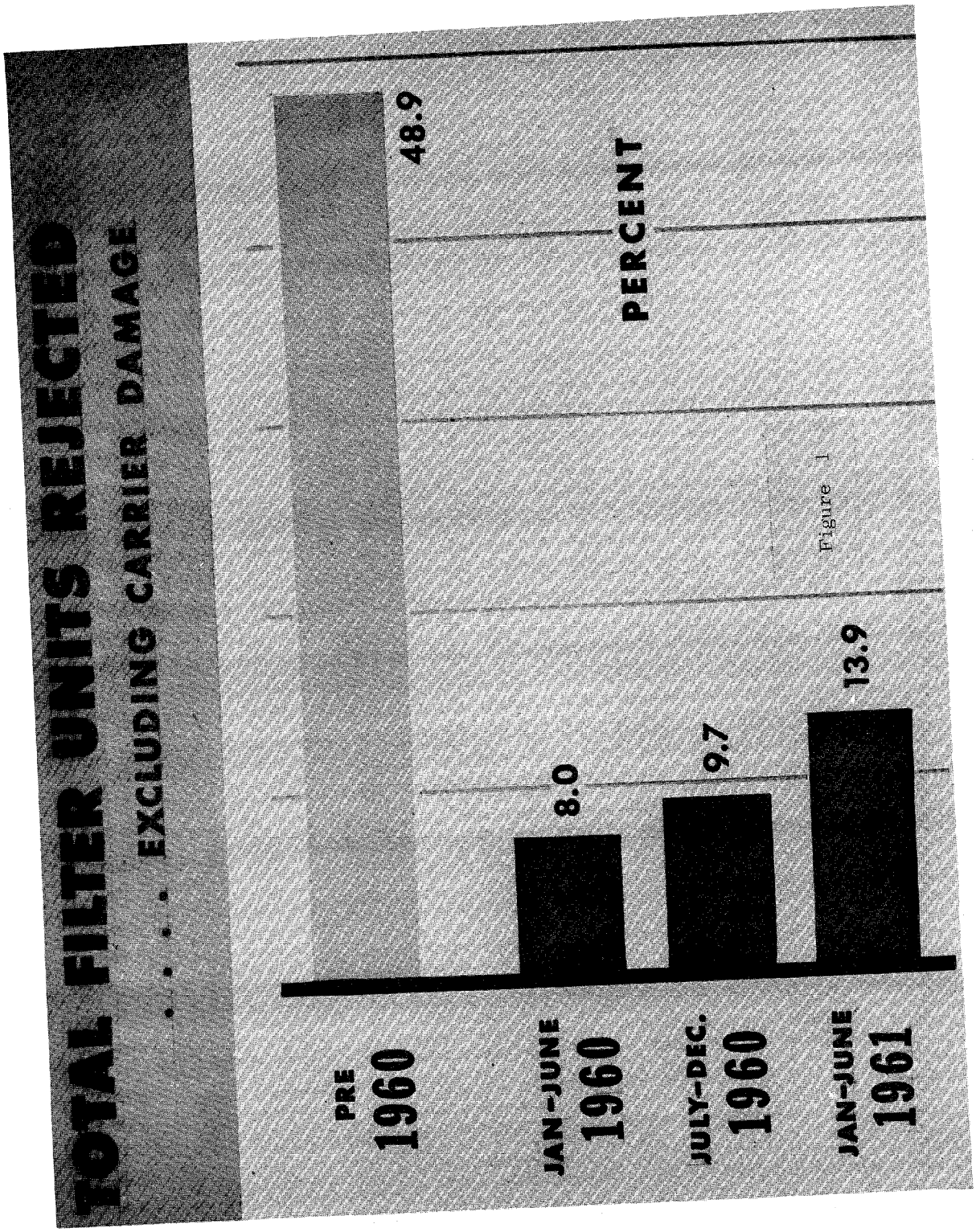
TOTAL FILTER UNITS REJECTED
. . . . EXCLUDING CARRIER DAMAGE
PERCENT
48.9
8.0
9.7
13.9
PRE 1960
JAN-JUNE 1960
JULY-DEC. 1960
JAN-JUNE 1961

Figure 1

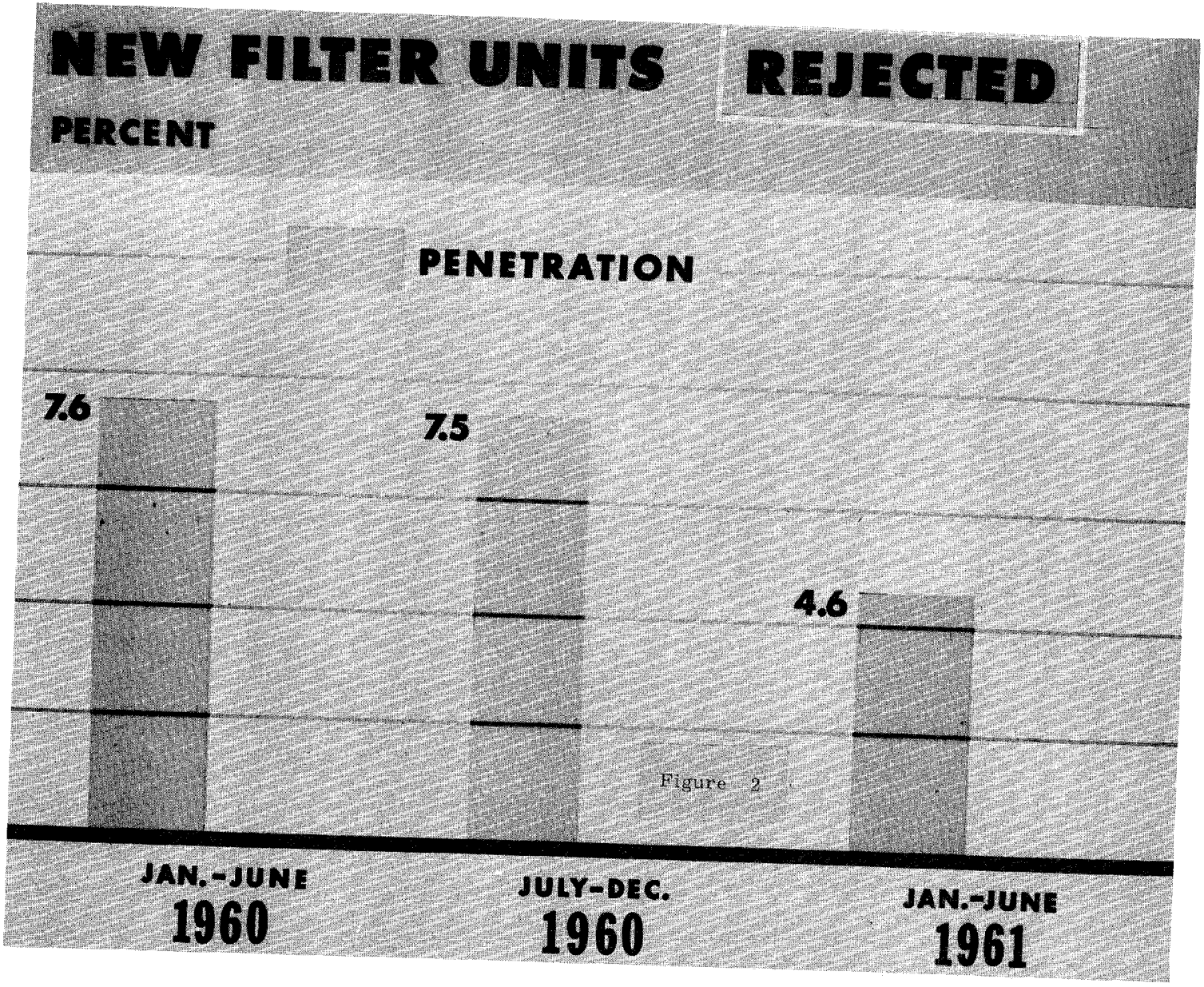
NEW FILTER UNITS
REJECTED
PERCENT
PENETRATION
7.6
7.5
4.6
JAN.-JUNE
1960
JULY-DEC.
1960
JAN.-JUNE
1961

Figure 2

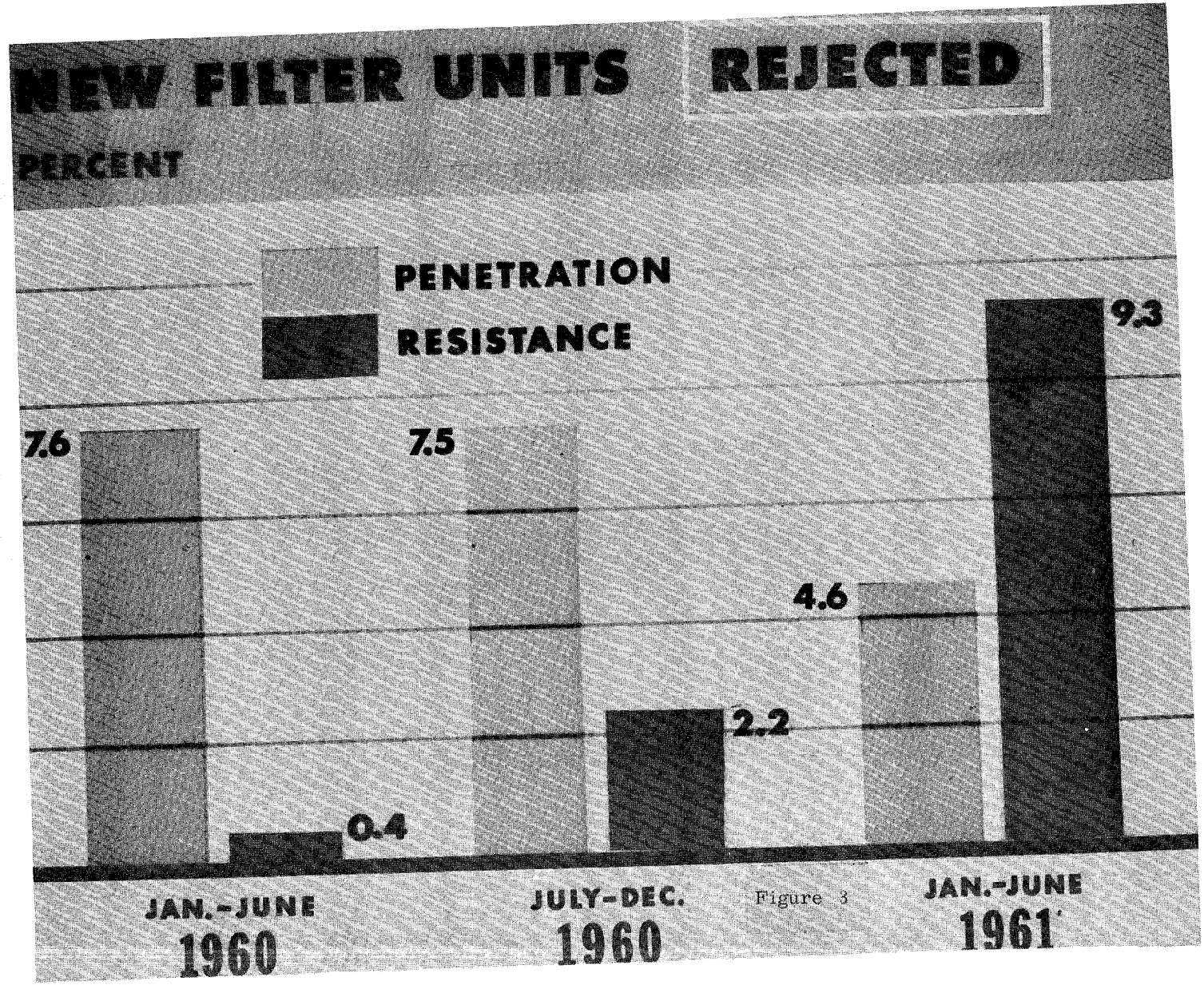
NEW FILTER UNITS REJECTED
PERCENT
PENETRATION
RESISTANCE
7.6
0.4
7.5
2.2
4.6
9.3
JAN.-JUNE
1960
JULY-DEC.
1960
JAN.-JUNE
1961

Figure 3

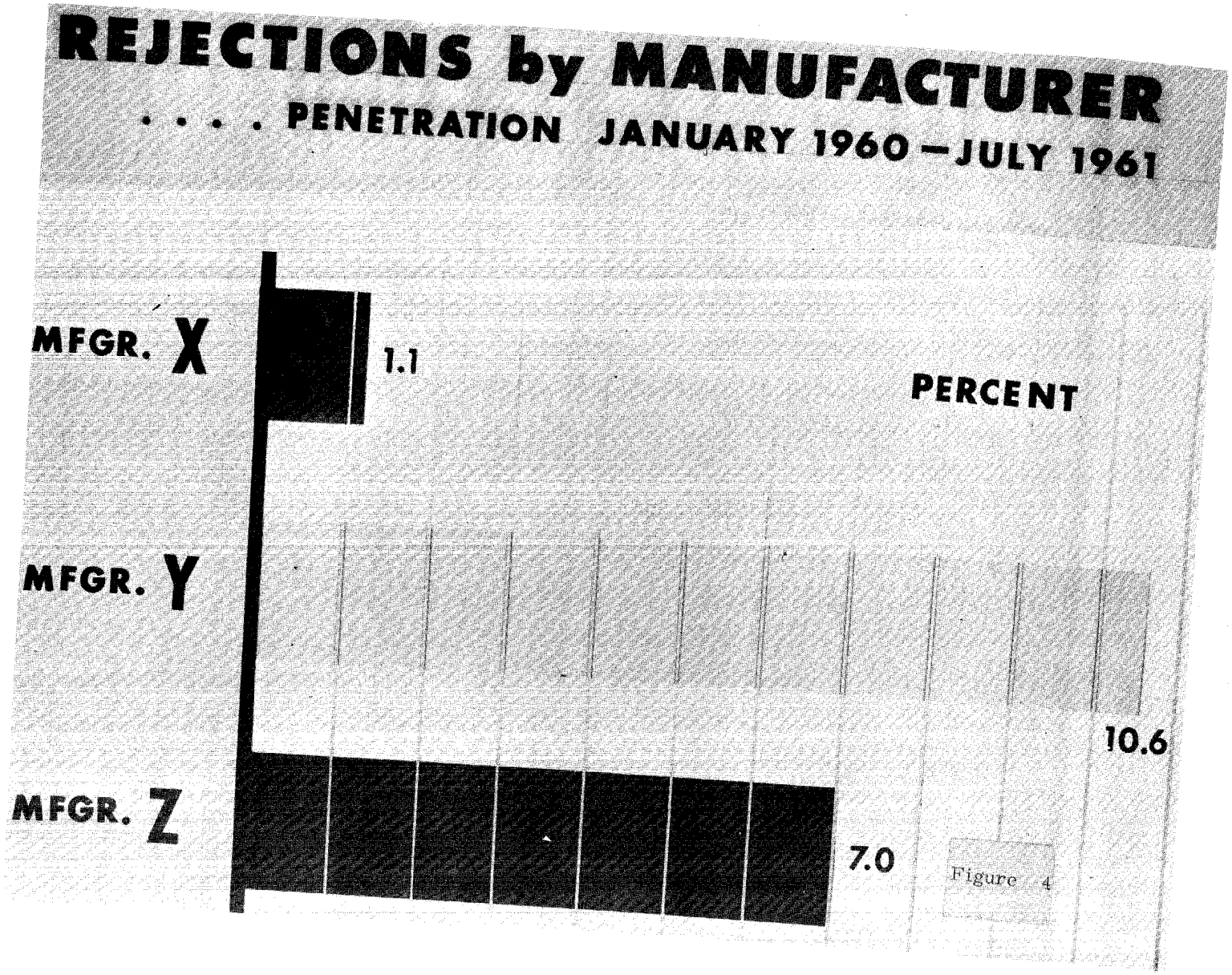
REJECTIONS by MANUFACTURER
. . . . PENETRATION JANUARY 1960 — JULY 1961
MFGR. X
1.1
PERCENT
MFGR. Y
10.6
MFGR. Z
7.0

Figure 4

Even after filter units have been purchased on rigid specification and have been sent through inspection and testing stations, there still is a serious source of damage from in-plant handling. Mr. James H. Palmer has brought out evidence of this damage on several occasions in prior years. The damage obviously stems from workers who have not been taught to appreciate the highly efficient function that the filter unit performs and who are now aware of the delicate nature of the filter unit. Frequently the care required to install it is not understood. To meet this problem, Mr. Palmer and I have assembled a manual covering inspection, storage, handling, and installation of the high-efficiency filter unit. The manual also includes a few recommendations on design of systems for these units and their protection against fire. Although the manual is brief and is directed primarily to the workers who are most closely associated with this damage, the manual should be useful to others who have an interest in this type of air cleaning. It is written simply for easy understanding, it is illustrated with 24 photographs, and it will be reproduced in 6- by 9-inch size for convenient carrying in the pocket of clothing. The manual will be identified as TID-7023. It is scheduled for release to the regular health and safety distribution list near the close of next month, November 1961. A special distribution will be made to reach mechanics and other crafts handling high-efficiency filter units in plants and laboratories.

In addition to indoctrination of filter handlers, there are other actions to assure the performance of high-efficiency systems. One in particular is the testing of filter units after installation. I will leave this subject to Dr. Young and others who will follow me on the program. Still other actions affect research and development for better filter units, which I will treat only briefly.

The U. S. Army Chemical Corps, Naval Research Laboratory, fabricators of filter units, and manufacturers of various filter components are devoting considerable effort to research and development in this area. To this can be added the work of Harvard Air Cleaning Laboratory. Further, I am confident that you will hear papers at this meeting which will impress you with the extent of activity in this field by various atomic energy plants and laboratories.

The aggregate of all of these efforts already has produced a stronger filter paper, more reliable separators, and generally improved filter construction. One recent example is a filter unit constructed with ceramic cement combined with a glass fiber pad to replace the rubber cement normally used for the sealant. This make-up is not yet in regular production but exhaustive tests have demonstrated the additional reliability of this type of construction. I believe that this filter unit will permit us to increase the maximum operating temperature to 500° Fahrenheit.

The time I have been allotted does not permit an extensive discussion of the materials and assemblies proposed for investigation or now under research. It is sufficient to say that the field of filter research is vibrant and the trend to better air cleaning devices is most promising.

In summary, then, we faced a most discouraging period with undependable filter units at the time of the preceding Air Cleaning Seminar. We have instituted inspection and testing to assure the integrity of our filter deliveries. A few installations in the atomic energy program are not using the service but should do so to confirm the quality of their purchases. Manufacturing technology and filter components have been improved continually in the past two years so that today we have a much more reliable product, even with the more rigid and unusual operating requirements that the high-efficiency filter unit must meet. There has been a great impetus for research and development in the high-efficiency area of mechanical air cleaning and the future promises us an even better filter unit that will operate under even more rigid conditions.

DISCUSSION

BILLINGS: We would like to interrupt the schedule briefly at this point and have Dr. Silverman talk about in-place filter testing research at Harvard.

SILVERMAN: We don't want to become an example of the lack of communication between AEC facilities. We are not aware, however, that the Health and Safety Laboratory in New York knew that we were asked by the Fire and Safety Branch to look at a simple way to prepare uranine aerosols for test in the field. At Mr. Gilbert's request, some time ago, we conceived an in-place filter test using a uranine aerosol package. Mr. Gilbert arranged through a custom aerosol filter, as they are called, to perpare us mixtures of various types. A little history on this subject might be useful at this juncture. We have a research contract with AEC, which is still in existence, for developing a face fit test for respirators.

In starting out, we used a typical Magnaflux aerosol disperser can which is used for inspecting quality of castings. We set up an aerosol with this source and determined the leakage that might take place around the face fit of a mask.

We actually found we couldn't make this commercial aerosol much smaller than 0.5 u and used it only for qualitative leak testing. We went over to the uranine generation, which was adapted from meteorological stack work, for our respirator evaluation. The uranine cans we have are very simple. The can is actually the type used for household products. A half or a quarter pound aerosol dispenser, with a uranine placed into it as an aqueous suspension and we determine the particle sizes we have by air sampling. I have three results so far from our package design. They are listed below:

Uranine-Freon Aerosol Package

Package Design	Uranine Concentration, %	Mg, u+	σ_g	% Fluorescence*
A	2.3	0.54	1.93	37.6
B	0.50	0.47	1.87	55.0
C	0.10	0.33	1.73	53.0

* Compared to uranine-water solutions.
\+ Optical sizing.

We still have microscopy of the last dilution under investigation.

This is a can that anybody can squirt into a duct and take samples up and downstream without the complications of requiring a compressed air supply.

I think if we have one other application for this type of disperser, if we can get a Magnaflux can with the right fluorescent material that will fluoresce in the ultraviolet, we believe we can spot the leaks with a black light. At the moment, the method of analysis is the one where you simply wash the filter papers and put it in a spectrophoto fluorimeter. If we go back to the Magnaflux type, we believe a very simple apparatus can be used in the field. It is a reflection photometer with a ultraviolet light. The filter is placed in a holder and the light reflected from its surface to a photo cell with a meter. One can put the filter disc in a holder, illuminate it and read the fluorescence from the surface of the filter deposit. This can be a hand-held package, but you may need about a 110-volt line. We can measure about a microgram of this fluorescent material with this surface fluorescence. Our figures on analysis of the uranine, from the dispersal can indicates the loss in fluorescence due to packaging and standing isn't enough to be serious as yet. We can detect 10^{-9} grams in solution. In this technique it is possible to get efficiencies of several 9's after the decimal point in a matter of four or five minutes of sampling with the filter paper in a sample holder.

With a better analytical method, we believe a hand pump might even be used for sampling onto the filter paper. We thought we would report this because it was stimulated by Mr. Gilbert's desire to have a fairly simple package that anybody could use in the field. We think that black light fluorescence method may indicate the location of leakage and the goodness of fit of the framing. I also neglected one important credit here. Two of our staff that are not here that assisted in this work: they are Mr. William Burgess and Mr. Felix Stein. They certainly deserve credit for our laboratory efforts on this project.

EVALUATION OF HIGH-EFFICIENCY AIR FILTER SYSTEMS

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INTRODUCTION

My subject is high-efficiency air filtration. For this purpose, pleated, glass-paper filters are finding increased use in process systems, ABC shelters, glove boxes, laboratory hoods, white rooms, reactor confinement and a growing list of similar applications. There have been many problems in the use of these filters such as filter efficiency and resistance, filter strength, service life, maintenance, fire hazards, etc. However, I shall limit my discussion to the one problem which to date has received the least attention but, in fact, should be considered the most important. Millions of dollars have been spent on high-efficiency air filtration, but very little in proving that the specified efficiency has, in fact, been achieved by the filter system. This discussion then, is concerned with "the proof of the pudding" -- the in-place evaluation of a filter system. I shall review briefly the methods developed at the Naval Research Laboratory for this purpose. We shall consider first the techniques used, then describe as an example of this work the evaluation accomplished recently at one of the AEC sites of a number of filter systems, and finally list and discuss briefly a number of suggestions and recommendations which have been obtained from the numerous evaluations we have made of a wide variety of filter systems.

DISCUSSION

The techniques used for the in-place evaluation of a filtration system have been developed over the past ten years by the group I represent at the Naval Research Laboratory. Our interest in this subject arises from our responsibilities in the field of Chemical and Biological warfare defense. The method we use consists of the generation of an aerosol of dioctylphthalate upstream of the filter. The aerosol concentration ahead of the filters and that downstream is detected and measured by the use of a light-scattering meter. The equipment used is similar to that used by the two testing stations at Edgewood and Hanford for the acceptance testing of filters purchased under AEC specification No. 120. The in-place evaluation should be considered as supplemental to the acceptance testing and does not remove the requirement for the work at the two facilities. Our equipment is simplified in order to be portable and thus practical for field use. The DOP aerosol is generated by the use of an appropriate number of air-operated nozzles immersed in the liquid DOP. The aerosol produced by the NRL Model II generator used for

these studies has an average particle size of about 0.8 microns. Detection and measurement of aerosols is accomplished instantaneously by the NRL E-3 light-scattering meter. The overall sensitivity of this equipment is one part in 10^5. That is, with the upstream concentration set at 100% on the meter, a downstream concentration of 0.001% is measurable. Since the specifications for this type of filter is set at 0.05%, the sensitivity of the equipment is well within this requirement.

In practice the aerosol is generated at the intake of the filter system or in a supply plenum. The only precaution here is to assure a well mixed sample truly representative of the overall upstream concentration. In similar fashion, an air sample is taken downstream of the filter and compared to the upstream concentration. If the downstream sample has an aerosol concentration equal to, or less than, 0.05% of the upstream sample, we then have conclusive evidence of an acceptable system. Unfortunately, this is usually not the case.

The next step is to determine the leakage sites. The sample probe is connected to the meter and the aerosol generated as usual upstream. The meter is set on the most sensitive scale and the probe is moved in a systematic pattern over the face of the filter, around the filter gasket and the filter housing. Leaks are readily detected since the leak allows the high upstream aerosol concentration to pass. In a very short time -- no more than 15 minutes for a filter bank containing 6 filters -- the leakage sites are spotted. Thus, one is quickly able to ascertain whether the filter is at fault, or whether it is poor gasket seal, or if the trouble occurs at the housing. This information generally enables one to correct the trouble and provide a satisfactory filtration system.

Next, I should like to illustrate the method by discussing an evaluation recently accomplished at one of the AEC sites. We were asked to check these systems to insure that the high efficiency required was actually being achieved. There were two types of systems -- one included 6 filters each rated at 1,000 cfm while the second contained 30 filters of the same rating.

Figure 1 is a view down the access manhole of a Type A system showing the six filters in place. The plywood cover was used during the evaluation to facilitate the placement of probe and sound powered phones to the outside where the light-scattering meter was located. It should be noted here that minor, temporary, alterations such as this one are often required to facilitate the filter testing.

The filter housing is shown in Figure 2 before the high-efficiency filters were inserted. The large pleated filters on the left are the upstream, coarse prefilters which are used to prolong the life of the high-efficiency filters. Although I shall mention it later, the design of these systems whereby the whole bank (6 units in this case) is secured as a unit is always the

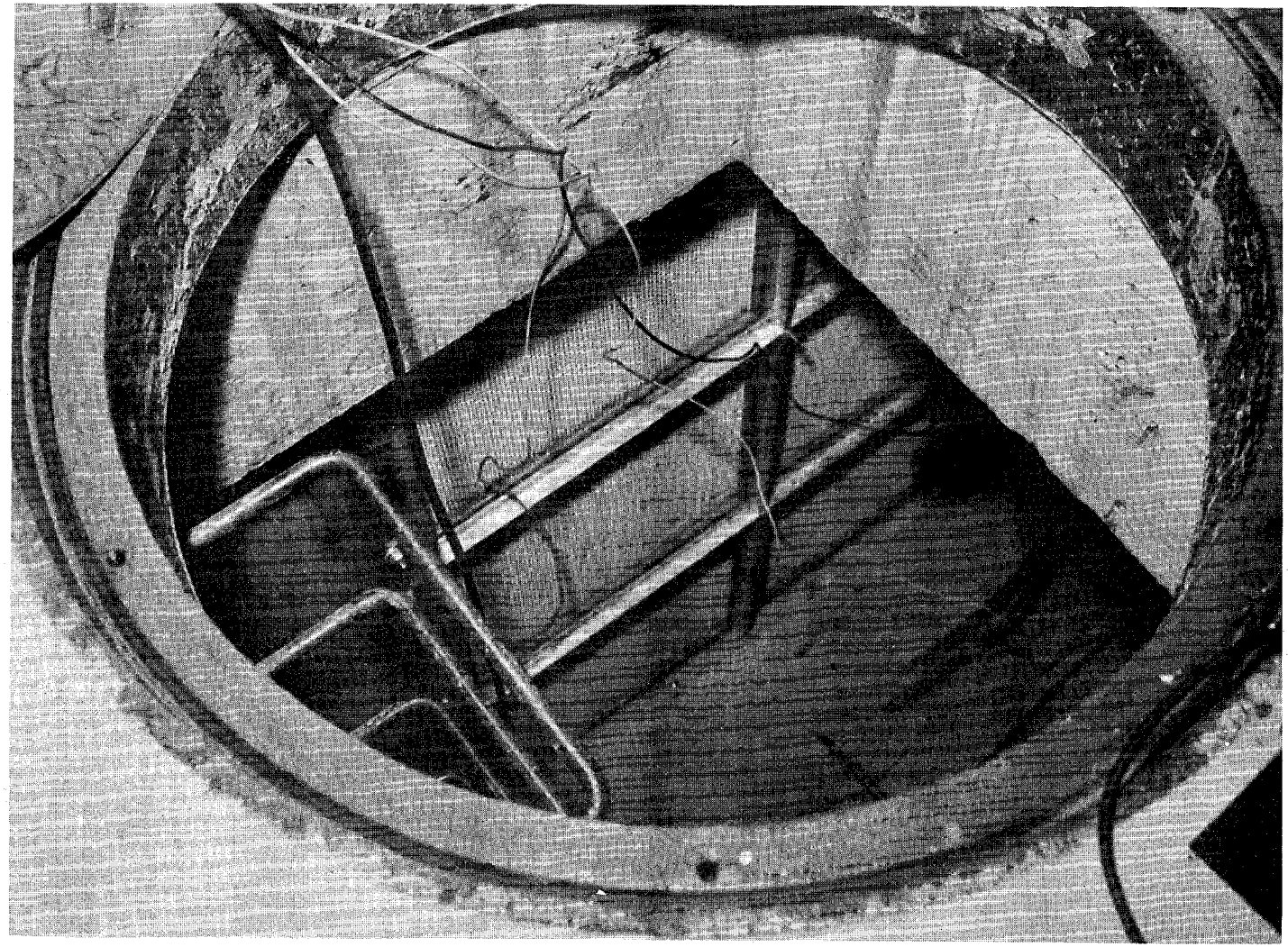

Figure 1 Access to Filter Bank of Type A System

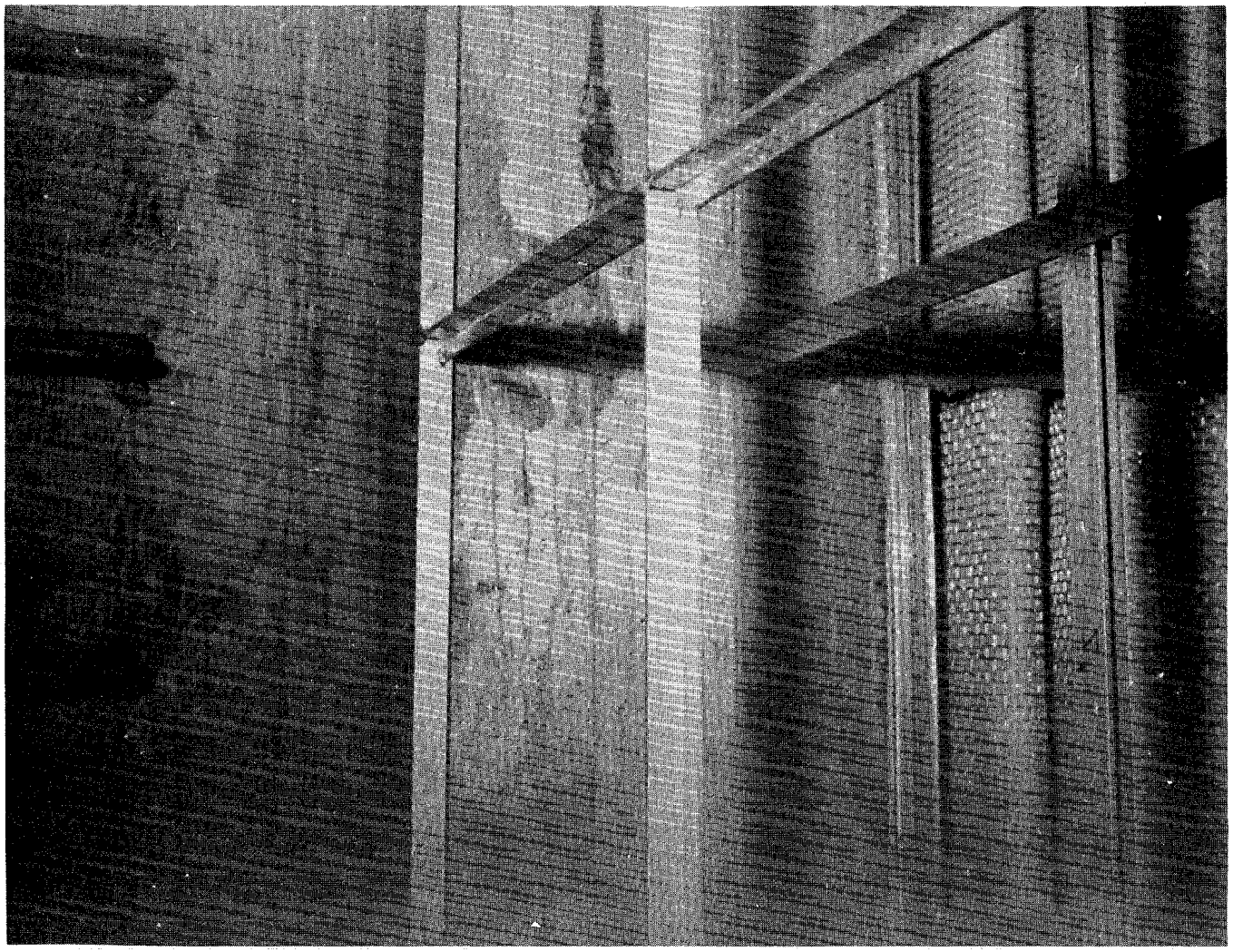

Figure 2 Filter Housing and Prefilters

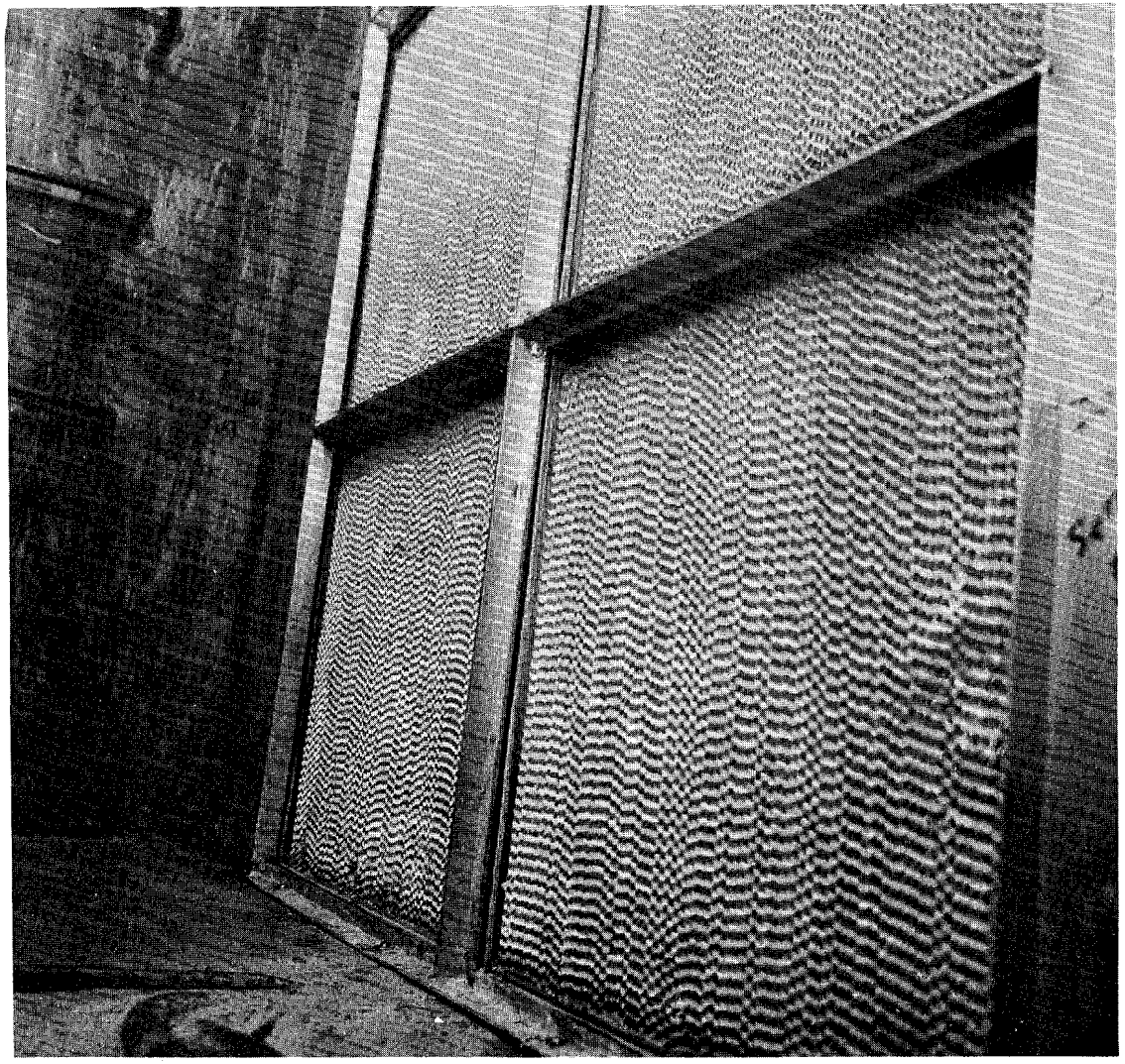

Figure 3 High-Efficiency Filter Banks of Type A System

most difficult to obtain a good seal.

The third figure, a close-up of the filter bank, shows this point more clearly. The predicted difficulties did in fact occur. Poor seals were found around the filter frame and at the filter gaskets.

Three of the four NRL Model II generators are shown in Figure 4. The ventilation air supply was secured for this picture to show the aerosol more clearly. Although not shown in the figure, a tarp or other temporary cover is usually used to insure maximum delivery of aerosol to the vent opening. An opening is provided in this temporary cover and when the intake is outdoors, this opening is oriented in the direction of the prevailing wind. These arrangements are required to obtain a constant and uniform aerosol supply at the ventilation intake. Each of the Model II generators contain six nozzles immersed in liquid DOP and the average particle size of the aerosol produced at an operating air pressure of 15 psi is about 0.8 microns.

Figure 5 is an overall view of the topside operation. The air compressor is on the right and the light-scattering equipment on the left. Probes from the meter lead upstream and downstream of the filter system. The temporary cover is shown partially draped over the intake screen.

Figure 6 is a close-up of our portable light-scattering equipment. The light cell is above, the indicator is below. Not shown is the vacuum pump which is used to pull the sample through the light cell.

Figure 7 is a photograph of the second type of system that was evaluated. This system contains 30 of the 2 ft x 2 ft filters. Again, the defects were readily detectable. The main leakage occurred between the support frame and the concrete structure, at the V, and at a few intermediate points. The attempt to seal 30 filters in a bank in one operation is exceedingly difficult. It requires perfect alignment (which is rarely achieved). It requires uniform gasket pressure over long spans (which is just as rare).

The probing operation is shown in Figure 8. As one operator moves the probe slowly over the filter and housing in a preset pattern, the meter is monitored for large scale changes, indicating the leakage sources.

The last figure (9) is a resume of the data obtained from these systems. Systems A - E are essentially alike in design. System D was run first and the penetration was shown to be 0.081% which is unacceptable. An efficiency of 99.95% would, of course, correspond to a penetration of 0.05%. We use penetration figures since that is what we measure directly and also because we believe that what we need to worry about is how much aerosol is getting through the system. Probing filter System D revealed that the extensive penetration came from three sources:

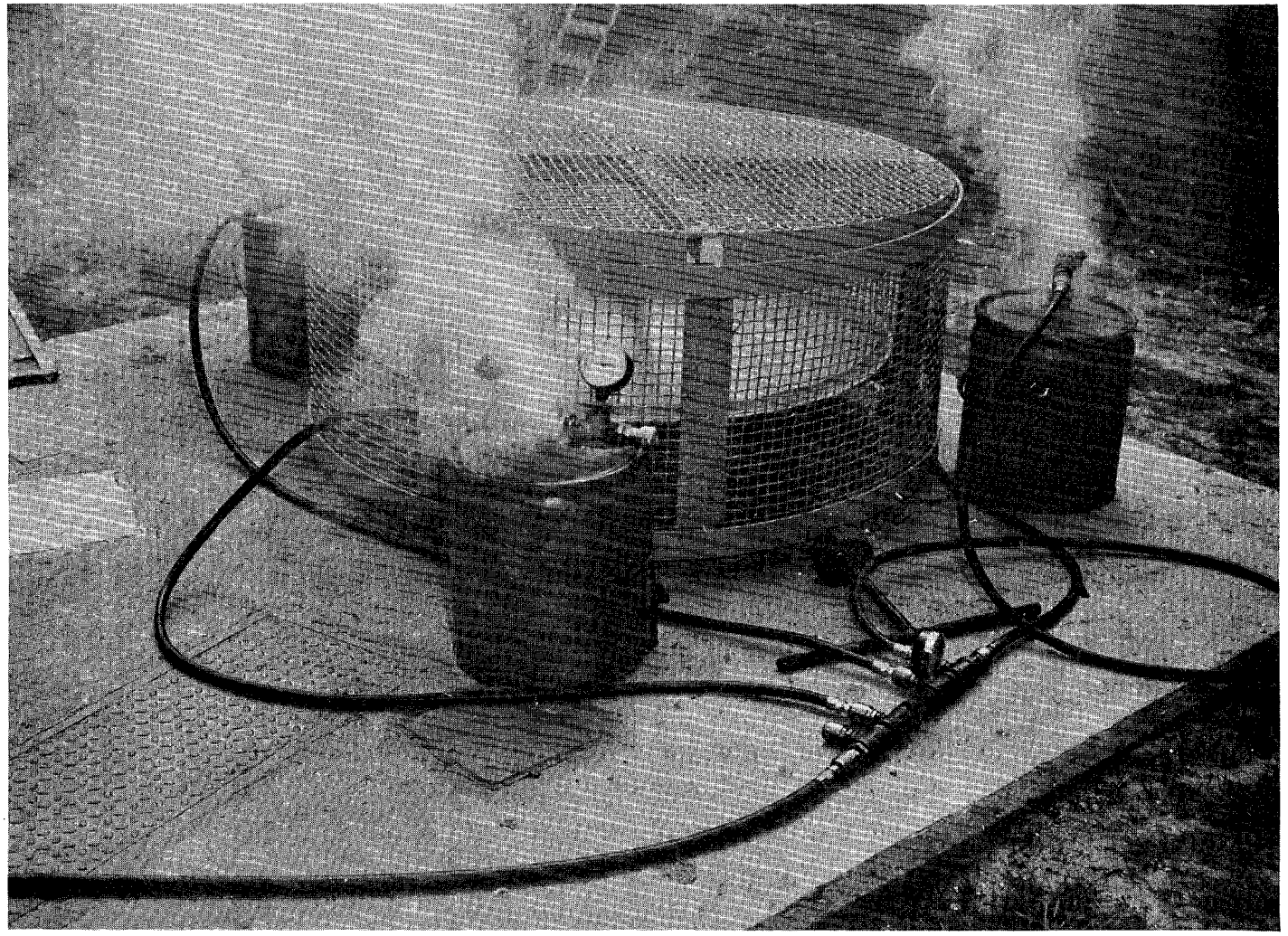

Figure 4 Ventilation Intake With Aerosol Generators

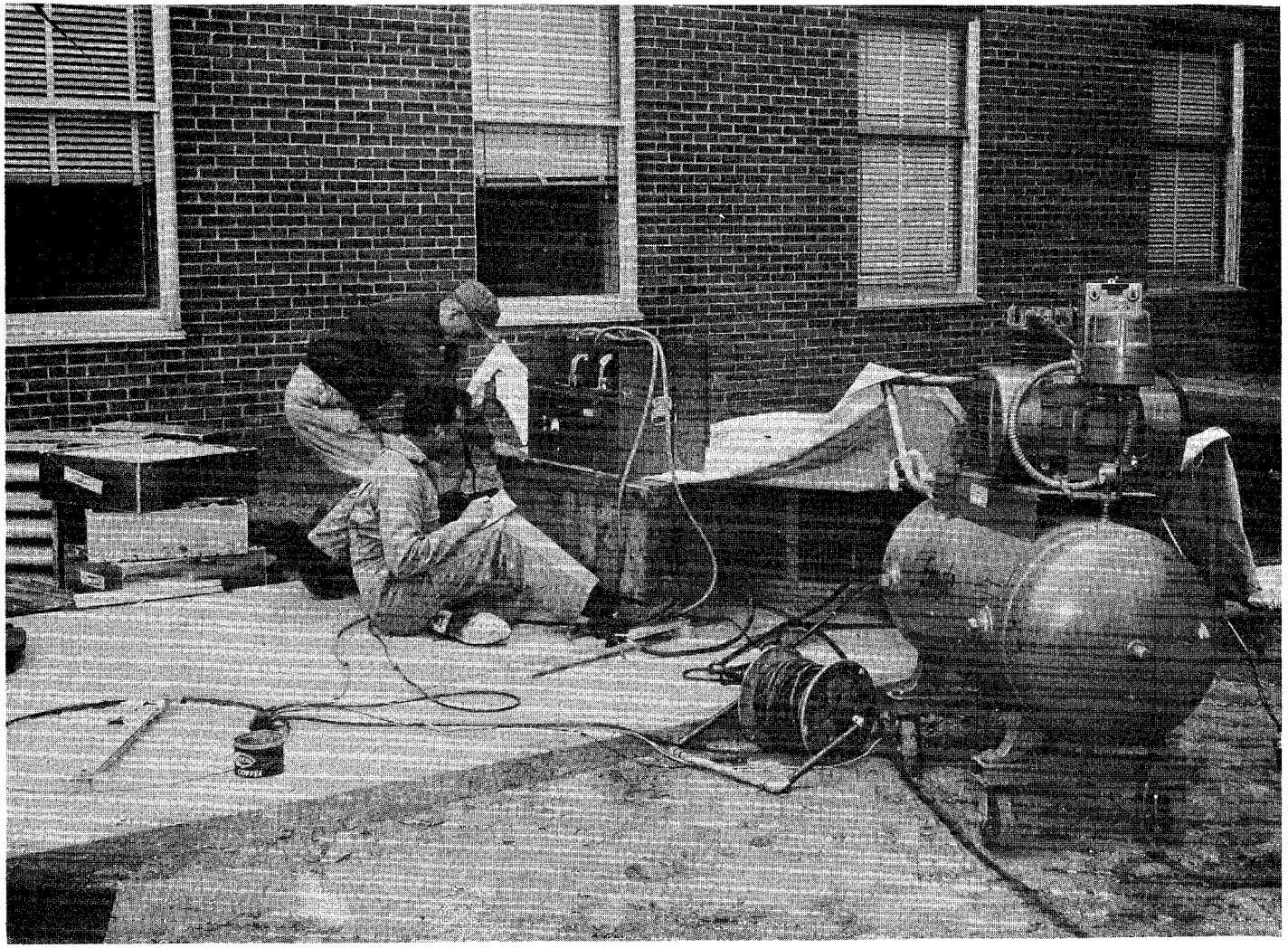

Figure 5 Topside Equipment for Filtration Evaluation

Figure 6 NRL Portable Light-Scattering Meter

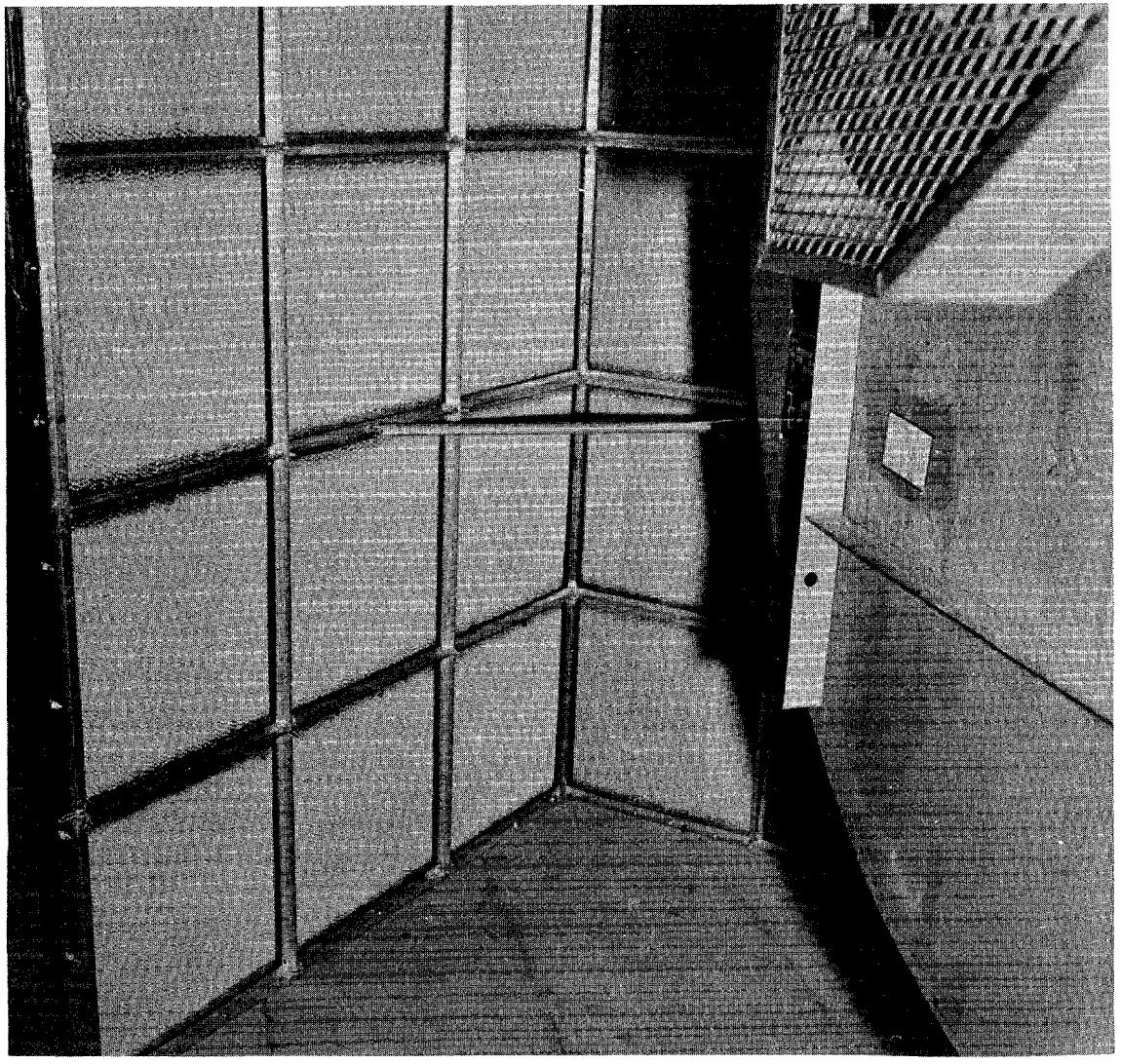

Figure 7 High-Efficiency Filter Banks of Type B System

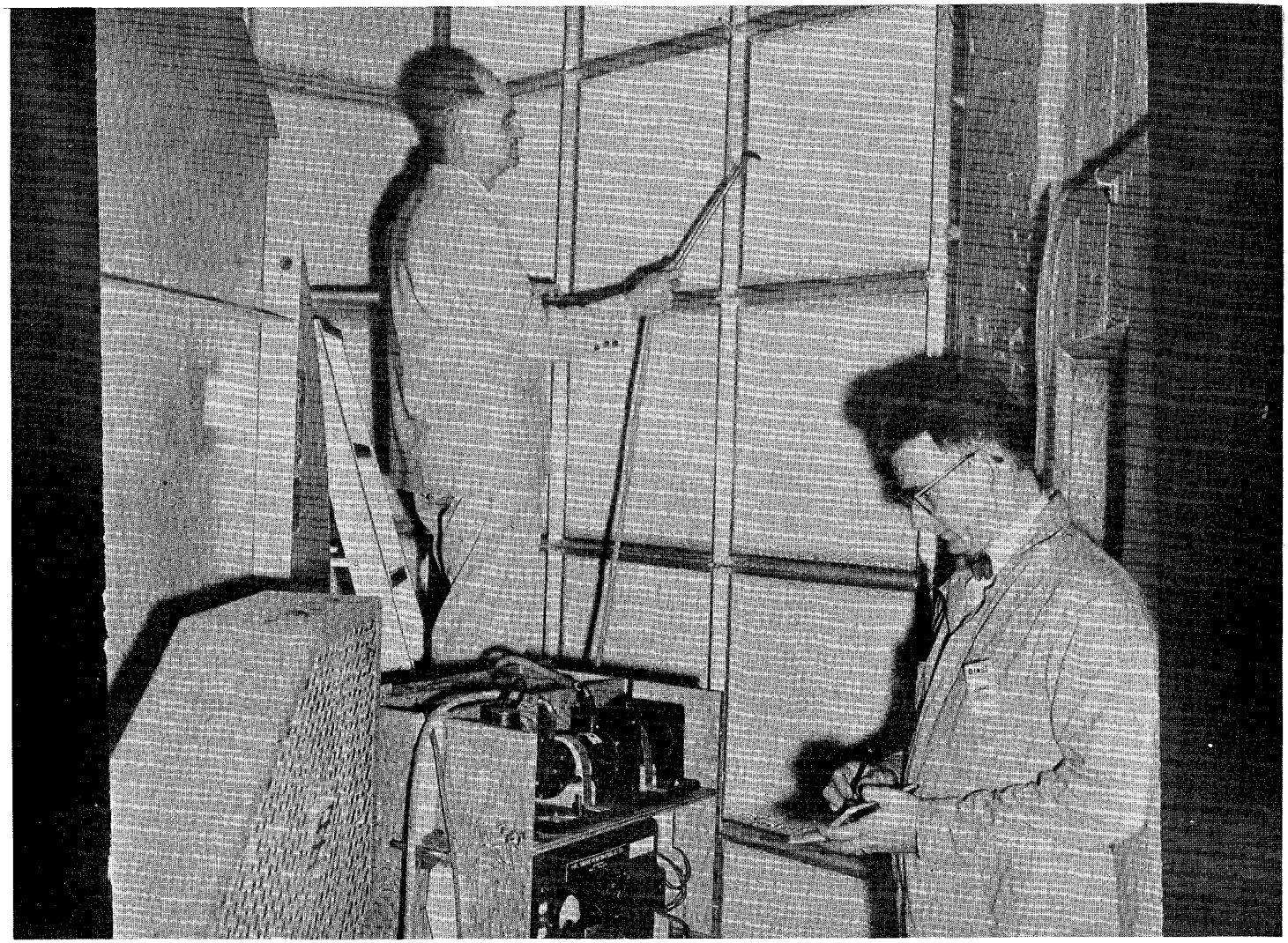

Figure 8 Probing Operation for Leak Detection

SYSTEM	TYPE	AIR FLOW	OVERALL PENETRATION
A	A	4, 000	0. 007
B	A	5, 000	0. 030
C	A	5, 000	0. 042
D	A	4, 000	0. 081 - 0. 006
E	A	4, 000	0. 009
F	B	24, 000	0. 035

Figure 9 Aerosol Penetration Data for Six Ventilation Systems

(1) The gasket seals between the filter and frame.

(2) The seal between the frame and the concrete housing.

(3) A leak through an electrical junction box which had coax-cable leading from the upstream side to the protected area.

Each of the filters in all these systems was shown to have penetrations with this aerosol of the order of 0.005%. After correcting the defects in System D by regasketing and reseals, the overall penetration was determined to be 0.006% which is, of course, quite acceptable.

The information gained from the measurements of System D was used as guidance in effecting a resealing of the other systems. Even so, three of the systems, B, C, and F were found to be acceptable, but still have leaks. In each case, probing was accomplished to assist in pinpointing the leakage sources with further sealing to be accomplished.

One other factor which is readily discernible from these data is that the operation of the filter at less than rated flow provides a measure of insurance. It is doubtful if Systems B, C, or F would be acceptable for this installation if they were being operated at 1,000 cfm per filter instead of the reduced flows shown. Of course, another reason for the use of extra filters is to allow reduced flows to increase their service life.

I should like now to discuss briefly with you some recommendations regarding the design of filtration systems. These conclusions have been amassed from our evaluations over the past eight years of a large number and variety of filtration systems.

The first recommendation is that high-efficiency filtration systems be utilized only where an efficiency of that order magnitude is required. These filters and these systems are premium price items and should be used only where necessary.

Second, foresight in the planning and design stage of the filtration system by considering problems of evaluation, replacement of filter and maintenance can be most helpful in achieving and maintaining the required efficiency. Particular items in this regard are:

(1) System should include built-in probe holes to facilitate testing and monitoring.

(2) Modular or unitized sealing of the filter is more effective than attempting to seal a large number of filters simultaneously.

(3) Sealing methods should be at least semi-automatic, that is, one cannot rely on the judgment of the installer to determine the tightness of bolts and screws or that an effective seal has been made. This is a notorious source of trouble.

(4) Little reliance should be placed on tape and caulking compounds. The best and only sealing that should be required in a well-designed and well-constructed housing is the gasket seal of the filter to the framework. It is also preferred that this framework be an integral part of the housing.

(5) Increased filter life and the chance of attaining the desired efficiency is possible if the filters are derated by using larger numbers or reducing the air flow rate. This is, however, not absolute -- as we saw from Filter System D.

(6) And last, with the facility such as ours available for the in-place evaluation, it is strongly recommended that acceptance of the filtration system be subject to such testing. That is, to include this type of acceptance testing as a part of the specification of the construction contract.

In conclusion, I have reviewed briefly our methods for in-place testing of filtration systems. Perhaps the important thing to remember is that filter units with aerosol penetrations of 0.05% or less are readily available, but to achieve an efficiency of 99.95% for a filtration system -- the installation of these filters must also be this good or better.

DISCUSSION

BILLINGS: It would seem appropriate at this time to have a discussion of the last three papers simultaneously.

FIRST: Each of the speakers who has talked on this subject has proposed a different test for the filters, in place, and each of these tests is different from the ones performed by the manufacturer. Is it proposed that the manufacturers will use a different test or are these to be correlated?

GILBERT: When we are talking about in-place testing, I think we are talking about qualitative testing.

FIRST: That was not my impression.

GILBERT: It can be made quantitative, but it is a difficult thing because of your aerosol generation.

YOUNG: It is quantitative, as far as what you have with the aerosol. You have to realize that it is different from a manufacturer's aerosol simply because you can't make that system portable. A 0.3u size cannot be made portable. Our aerosol was 0.8u. The filtration system can be measured quantitatively with that but it is not designed to replace the manufacturer's test or the quality acceptance test. It is simply a way for a person to assure himself, with this aerosol, that this is a good system. We are not trying to replace anybody's technique or method.

GILBERT: The manufacturer is supposed to put a 0.3 test aerosol on the unit and give you a stamp on the frame indicating the penetration at a given air flow. My slides indicated that there is a sufficient number of these where this is not entirely reliable, as they come to us.

The way the quality assurance program works is that the people in the program who buy units buy them subject to passing the inspection and test criteria, which is also in the purchase order, at either of the two stations, and if they don't pass, they don't belong to them; they belong to the manufacturer.

This screens out the stuff which you accepted and you can't see it 90 per cent of the time -- any faults in it -- from having to put this stuff in there and then find it with an in-place test. The damage in in-plant handling has been terrific. That is why we put this manual together. We were not writing for

our own edification; there is a need for it. We want at least to orient the interested personnel to this job and maybe we can cut out some of this damage. There are a lot of pictures of damage on units that are already in place. Where mounted, these filters have big scratches across them.

We want to take units which initially were good and put them in there, but this doesn't tell you a thing -- the test at the station doesn't tell you a thing about the condition of the mounting, even if they were good then. Whether air can by-pass the gasket -- like one outfit, we got a 1/8th tolerance in the unit and they put up a bank that has no tolerance -- the final test is to do an in-place test when they are already mounted to be sure that you have the efficiency that you bought initially.

FIRST: But why accept a 0.5 penetration that has a different meaning than the acceptance test? You are talking about a 0.5 penetration being acceptable for 0.3u, and Dr. Young is talking about it being acceptable for 0.8 DOP on the finished installation. What I am confused about is what do all these tests mean? Then, of course, we have the test with the dyes. Shouldn't somebody be pulling this all together?

GILBERT: It would be wonderful if we could pull a lot of things together, but we are doing the best we can just by the educational process. We have here a quantitative test. These stations match numbers with the manufacturer.

Usually you will find out that the in-place test, and I take this figure to be 95 per cent of the time, is a go or no-go test. In other words, you can throw a cat through the hole, if there is a hole, where they mount it. That would be an exaggeration, but is definitely appropriate. You can get an aerosol, a larger aerosol, through and around a gasket where you have these gaps in your system, and it is just to be certain you have a sealed system.

PALMER: I think the measurements on your portable machine vary -- you must remember that your DOP is not homogeneous. It is not as accurately controlled as in the standard machine.

SILVERMAN: I would simply want to comment on this question of differences in the aerosol. You will all recognize that the uranine method is a weight method for a solid aerosol. The size range can be placed in the same bracket as the manufacturer's present 0.3u test. We still represent, however, that the result we get is an integrated result. In other words, we are not taking an instantaneous reading, which is true of Dr. Young's, and any other smoke penetrometers. It really boils down the question of the correlation between the solid aerosol and DOP aerosol, especially if they have the same size range, which we believe we can make readily.

In our tests with respirator filters (which are the same as space filters but in addition have activated carbon packed in the canister), we have been able to show a correlation between the uranine test at 0.2u with the manufacturer's DOP test at 0.3u. Out of this will come a factor which would represent the correction factor. I have to agree with the other two speakers, that one is an

installation evaluation and the other is a filter evaluation. I think the two things have to be viewed in that light and they could be brought together, but it is a question of how much time and effort should be extended in this direction.

We don't think the holes are big enough to put a "microcat" through, but they still can be measured in terms of uranine penetration.

Some of these little holes pull down the filter from that last 0.5 to the first 9 and I think Dr. Young will give this audience credit for being able to subtract from a hundred, so they will be able to figure out penetration.

BILLINGS: These proposed techniques can be calibrated against the standard that the manufacturers are now using, but the important objective is to be able to use it as a means of detecting or assessing what you have done in the field, which is something not presently available.

FIRST: I don't see how you can measure the installation without at the same time measuring the filter performance. You are measuring the sum. This is why it seems to me you should have a correlation, so that you will be able to evaluate your installation without taking into consideration what the filter performance is contributing to it.

BILLINGS: Both of the papers given on the uranine approach are completely experimental at this point, and will have to be calibrated undoubtedly.

SILVERMAN: There is one point to add here. In a system with 30 filters, with 30 manufacturers' penetration values on it, you must admit that some place you have to make an integration of those. Even if the installation was 100 per cent perfect, you are not going to get anything but some number which represents the integral of all those penetrations, so it is the worst filter in the lot that turns out to be the one that pulls down the average results.

FIRST: But we don't really know what the installation test means since the filter cartridges may be giving only .0001 percent penetration and the rest of the aerosol penetration is then caused by an installation deficiency. What puzzles me is why the AEC spends so much money to purchase and retest filters capable of retaining 99.95% of 0.3u DOP and then is satisfied to accept a much lower penetration standard from the finished installation?

SILVERMAN: I would like to add one thing that Dr. Young perhaps might have brought out -- it was brought out a long time ago in the original testing -- after these high efficiency and most other filters are in place their efficiency rises because they plug. If the installation then begins to leak you lose performance. As the pressure drop rises, you may increase leakage through the existing holes. We do need a correlation between the unit filter test, in the long run, and the method used to test the installation.

SHAVER: Was there any test work with the filters plugged to give a determination of the bypassing of the particles around the filters?

YOUNG: In the past we haven't evaluated many plugged filters. We expect the efficiency to increase. The one thing I should have stressed more is that when we measure the aerosol penetration of a filter system, we usually find that practically all the penetration is coming around the filter. Through an undamaged filter, the penetration will approximate 0.005% or lower, while a hole or leak will show penetrations of 5% or higher.

SHAVER: My reason for the question was that as the filter plugs you might get more bypassing around it.

YOUNG: This is possible.

SHAVER: I wondered if the filters were clean -- if you did any correlation between the dirty filter, to evaluate the bypassing --

YOUNG: An increase in bypassing as the filter resistance builds up is no doubt a contributing factor.

SHAVER: You are bringing out exactly the point I wondered about: If you have a bypass around the gasket and the pressure drop increases through the filter itself, you are going to get a higher percentage bypass?

YOUNG: Yes.

SHAVER: Shouldn't your test correlate the plugged or dirty filter condition to evaluate this bypass?

YOUNG: We have not done any extensive evaluation of this effect. But we have found that gasket problems or other physical change due to age also contributes to an increase in bypass.

ELECTROSTATIC PRECIPITATORS FOR NUCLEAR SUBMARINES

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ABSTRACT

While there is little available knowledge on the physiological effect of aerosols on men for long periods of exposure, there is no question of their undesirability; their deleterious effect on delicate instruments is well recognized. Electrostatic precipitators for the control of aerosols in nuclear submarine atmospheres are described. Measurements of the atmosphere composition as well as effectiveness of the precipitators under operational conditions are included.

The utilization of nuclear power for submarine propulsion has made possible an entirely new method of submarine operation. The length of submergence will now depend almost entirely on the ability of men to live and work efficiently in closed spaces.

Sixty-day submergences of the POLARIS submarines illustrate the fact that nuclear-powered craft travel undersea for long periods of time without contact with the earth's atmosphere. We would like to discuss with you some of the problems arising from the accumulation of finely divided particles of solids and liquids (aerosols) suspended in the air of the submarine. While there is little available knowledge on the physiological effects of aerosols on man for long periods of exposure, there is no question of their undesirability and their deleterious effect on delicate instruments and equipment is well recognized.

The very presence of the nuclear reactor might suggest that radiation would be a problem that must be considered. In reality, the reactor shielding and confinement is so efficient that the operating crews receive less direct radiation than their surface shipmates receive from cosmic sources. Studies have shown that the exposure of the crew averages less than 10 milliroentgen equivalents per week, considerably less than the 100 mr level permissible. Early in the program the evolution of radioactive radon gas originating from luminescent radium-painted dials and signs presented a problem. Gaseous radon diffuses easily from apparently well-sealed components and enters the ship's atmosphere. Here it decays into its radioactive daughter elements which become associated with aerosol particles suspended in the air. Figure 1 shows the dramatic increase in air-borne beta activity with time submerged as a result of only six small sources. The curve

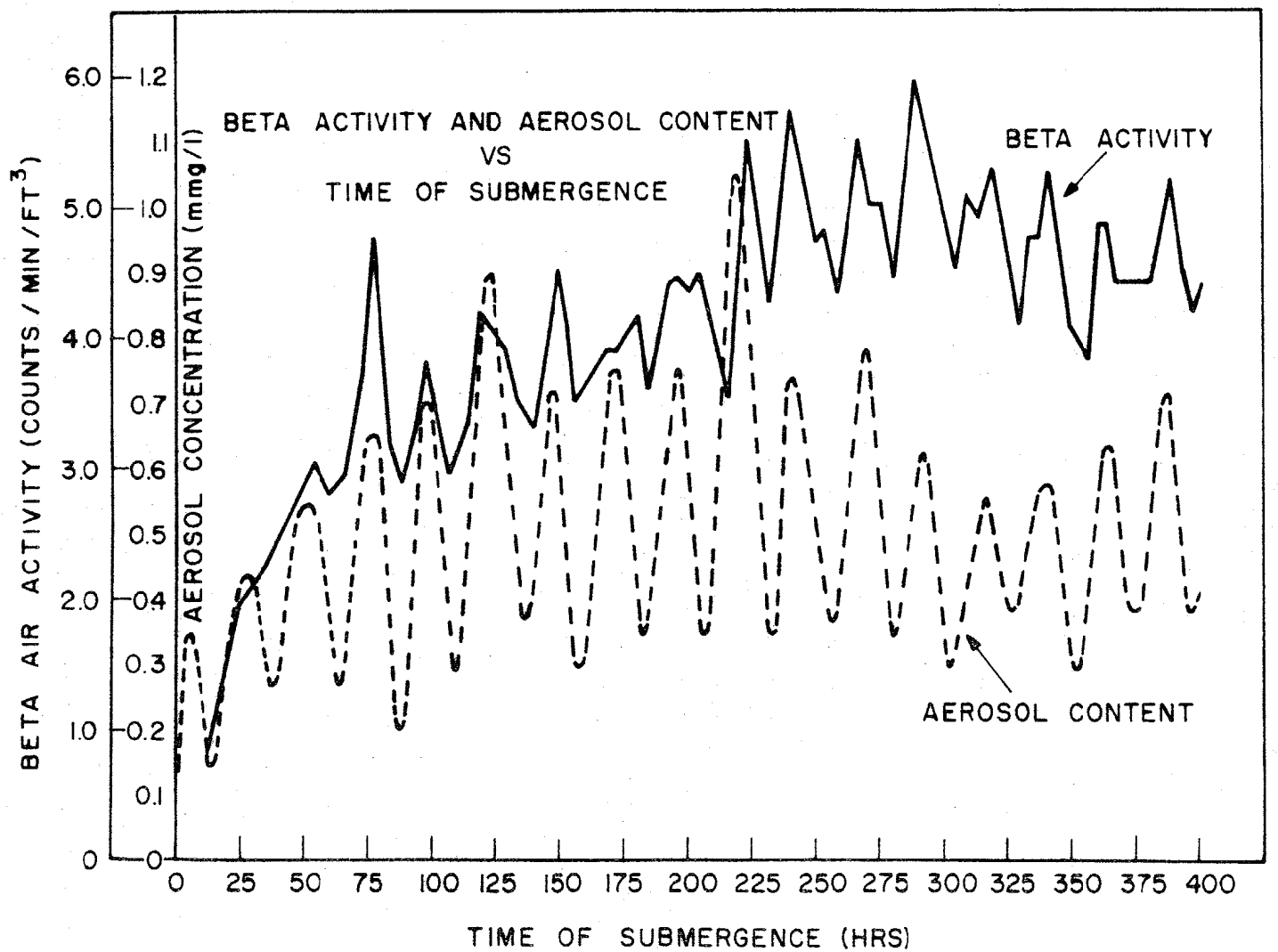

Figure 1 Air-borne Beta Activity vs. Time of Submergence

shows a gradual leveling off as equilibrium is approached. At equilibrium, levels are about 30 times higher than when surfaced. Apart from the possible biological hazard, this represents a nuisance since radiation monitoring equipment does not distinguish between the activity from the radon and that due to the serious condition of a reactor leak. The only solution was to remove all such sources from the ship, and, indeed from the entire submarine supply system to prevent their reappearance aboard.

The control of aerosols aboard the nuclear submarine was anticipated when it was learned that unlimited smoking would be permitted. Intiial samples from the ships showed by chemical analyses that about 75% of the particulate matter originated from cigarette smoking. Average aerosol concentrations were about 0.4 micrograms per liter; the manner in which the concentration varies with time is shown in Figure 2. It should be noted that the concentration gradually increases for the first 100 or so hours at which time an equilibrium concentration is reached. The absolute value of this equilibrium concentration is directly related to the amount of aerosol filtration equipment present. The present concentrations were achieved with only 1200 CFM of electrostatic precipitators (ESP). As seen later, installations with increased ESP capacity show markedly lower equilibrium concentrations. It can also be noted that a daily variation is observed with the concentration lowest in the early morning hours and highest in the early evening. This effect can be observed on the instantaneous concentration of aerosols over a 24-hour period as shown in Figure 3. High concentrations are observed at the time the watches are changed; for example, 0400, 0800, 1200, 1600, etc. Likewise, high concentrations are observed when all hands are up and working and during recreation periods. To be more specific there is a direct relationship between aerosol concentration and personnel activity.

The particle size distribution of the aerosol in the nuclear submarine is shown in Figure 4. It can be seen that the median number distribution is about 0.45 micron diameter with less than 1% greater than 1 micron. These sizes are characteristic of aged tobacco smoke.

There have been several instances when smoking was temporarily banned abroad a nuclear submarine. Of special interest is one which occurred during the TRITON round the world trip. The aerosol concentration versus time for this period is shown in Figure 5. It can be seen that the concentration decreased to about one-third its original concentration, thus indicating about two-thirds of the aerosol originated from tobacco smoking. The agreement between this figure and the 75% from chemical analyses of the filters is considered good. A slight increase in concentration as the smoking ban continued indicates that perhaps the body was stronger than the spirit and a few "cheaters" resulted. The very high concentration immediately after the smoking ban was lifted is understandable, especially to the smoker. The increase in irratibility, the shortness of tempers and the general psychological let-down during the no-smoking ban was clear evidence that cigarette smoking could not easily be eliminated.

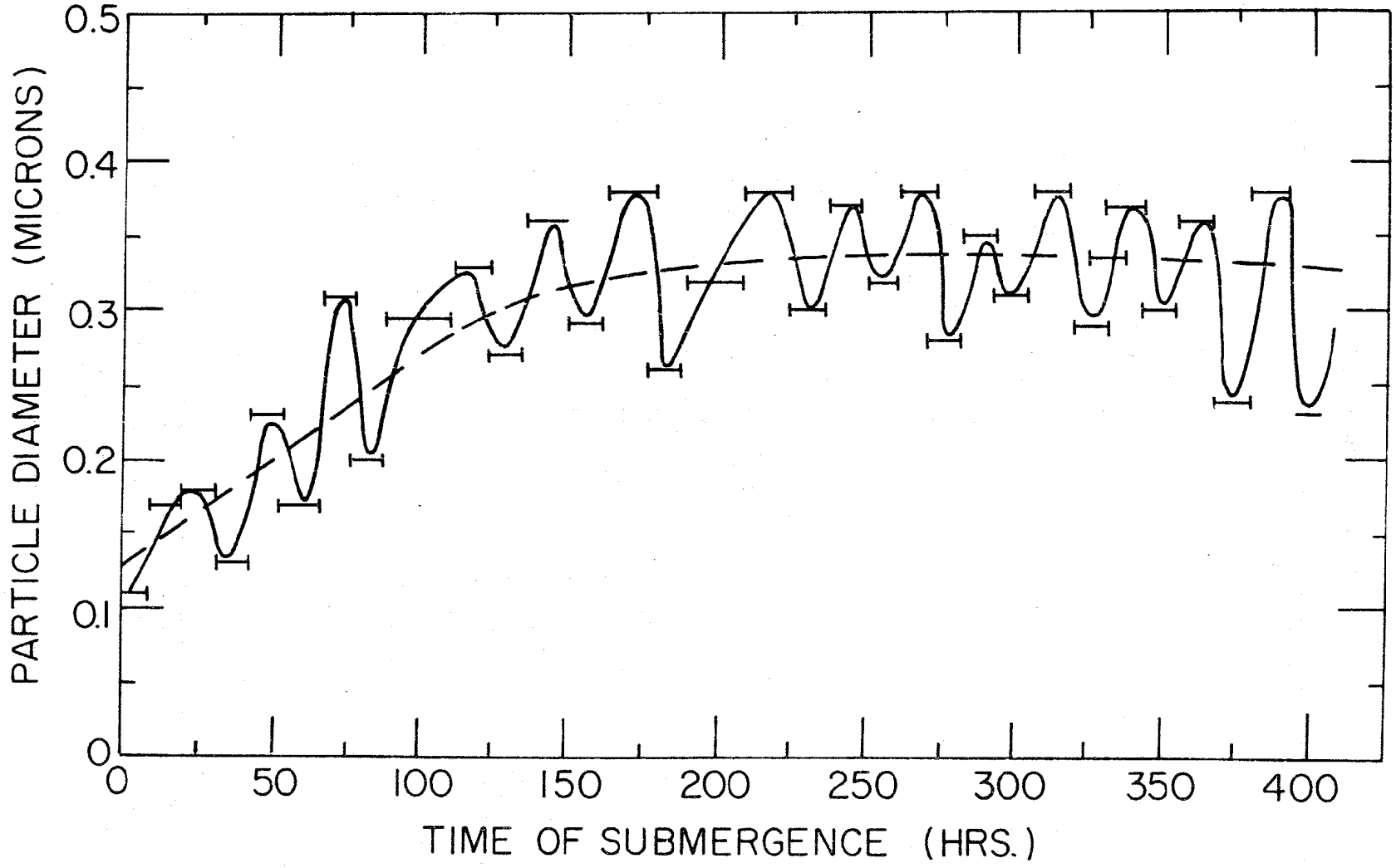

Figure 2 Aerosol Content vs. Time of Submergence

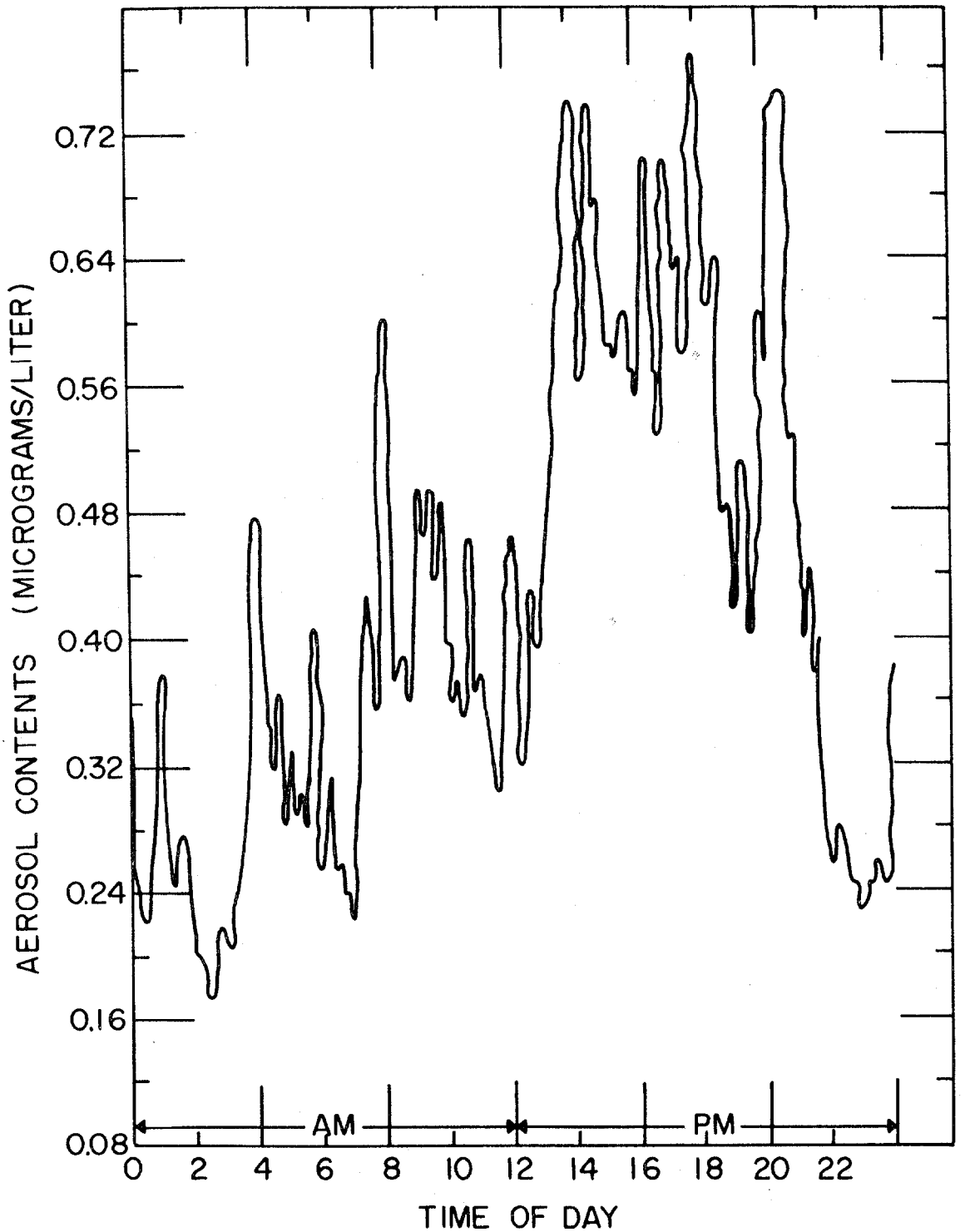

Figure 3 Daily Variation of Aerosol Content

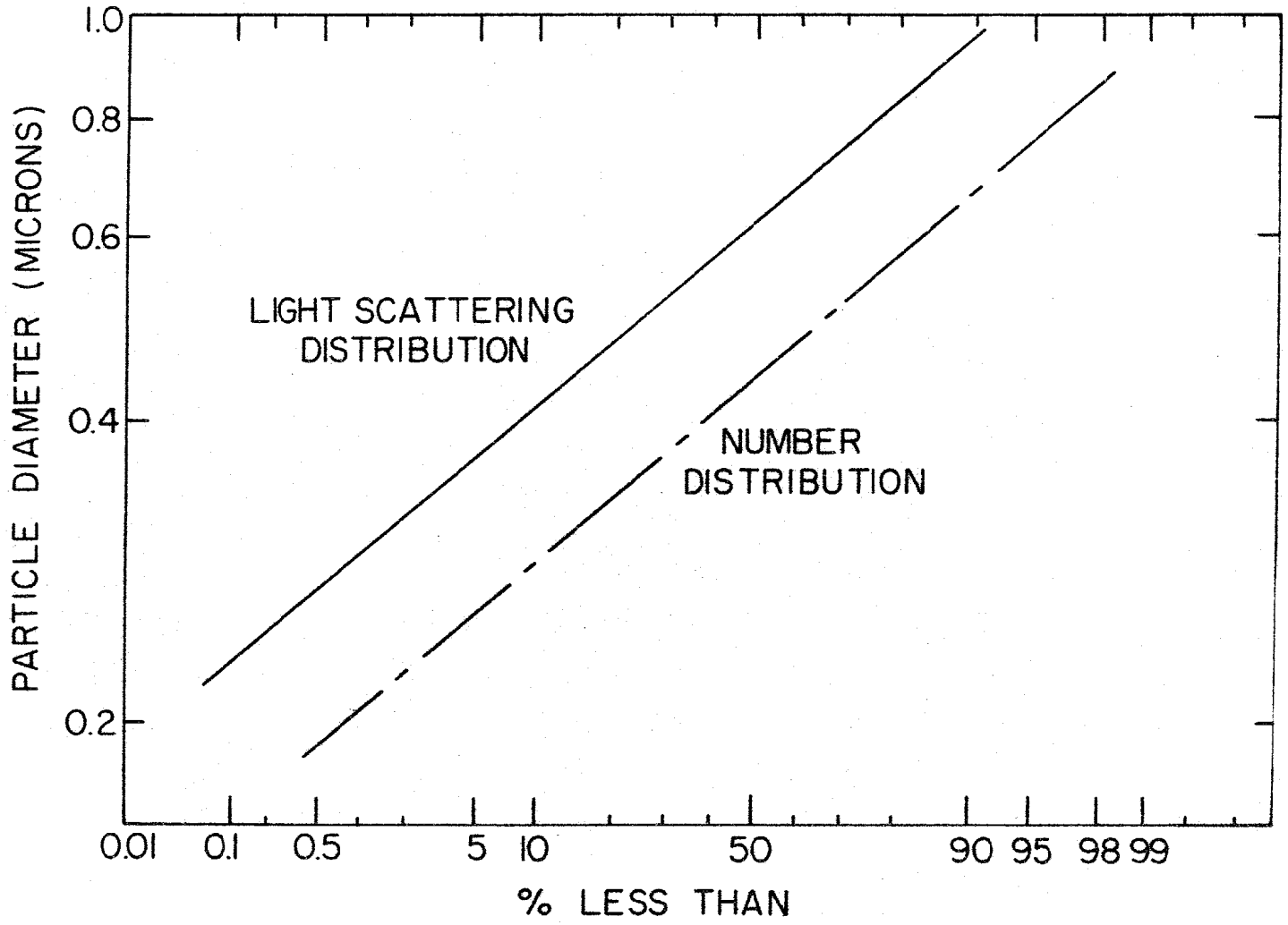

Figure 4 Particle Size Distribution of Submarine Aerosol

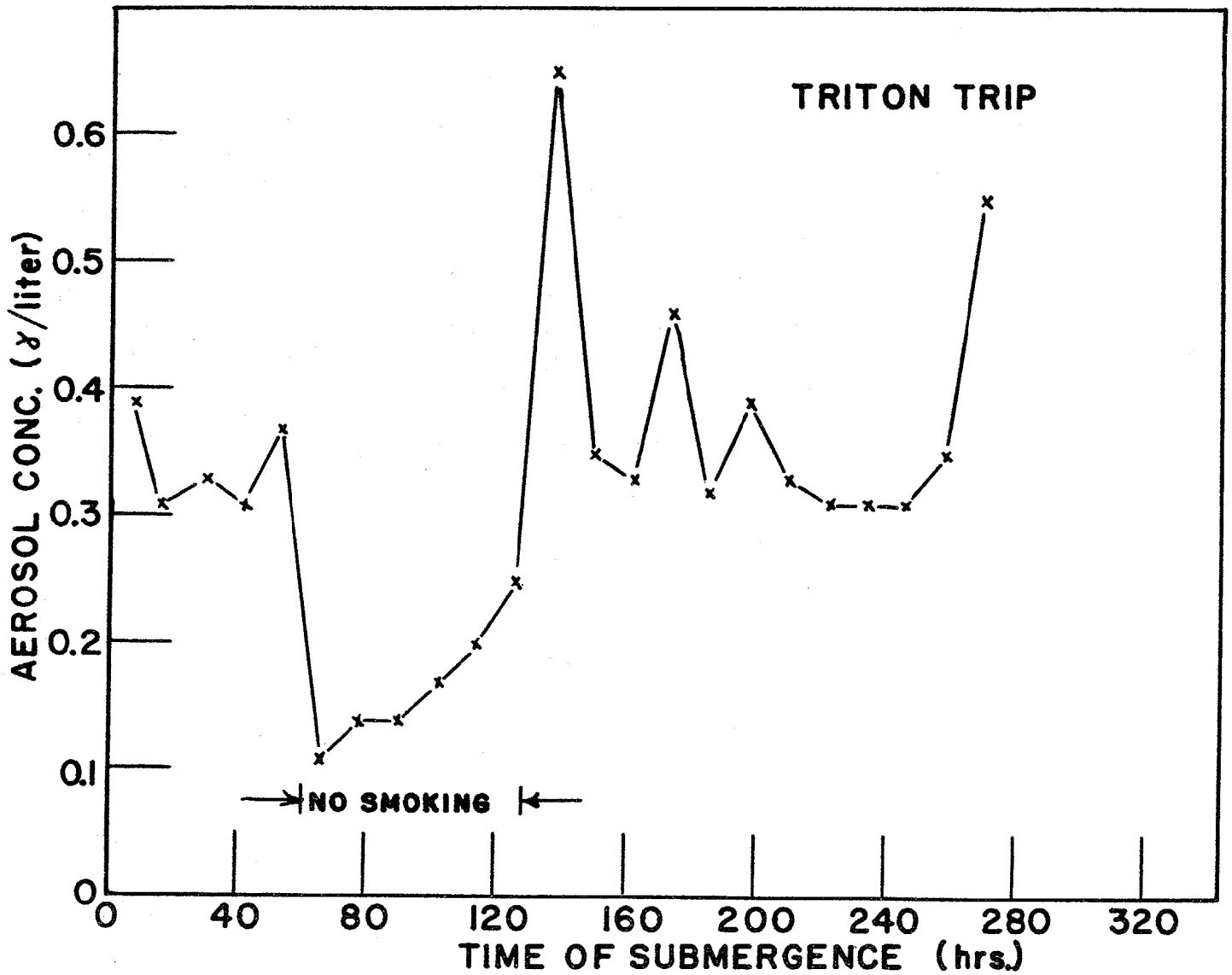

Figure 5 Effect of Smoking on Submarine Aerosol Concentration

Knowing the characteristics of the aerosol to be removed, the type of filtration device which is best suited for submarine service can now be considered. Inasmuch as space is critical, it is reasoned that a device of high filtration efficiency and low resistance to air flow is indicated. The device must be one which requires a minimum of replacement parts and must be capable of being cleaned in place. The only known device which meets all these requirements is the electrostatic precipitator (ESP).

ESP's are generally either of two designs; plate type or tube type. The plate type is by far the more common and because of its construction is often referred to as the two-stage precipitator. An exploded view of this type unit is shown in Figure 6. This type of ESP consists of a short ionizing section followed by a larger collecting section. The ionizing section consists of a number of ducts formed by parallel aluminum plates, which are grounded. In the center of each duct, and perpendicular to the air flow, is a discharge electrode of tungsten wire. These wires are negatively energized by the power supply to a level of about 15,000 volts. The collecting section consists of parallel aluminum plates which are grounded. In the center of each pair of grounded plates, and parallel to them, is another aluminum plate energized negatively to a level of 5,000 to 6,000 volts.

The second type of ESP, tube type, utilizes the same type of ionizer but has a different design of collecting cell. The tube-type collector cell is an assembly of concentric tubes and rods that act as high tension electrodes. The outer tubes which may be stacked in a honey comb array, are grounded to the shell. The inner rods are energized to a level of about 15,000 volts. The washed-in-place system makes it possible to wash the plates and/or tubes of the ESP without removing the unit from its duct system.

For a large majority of applications, the plate-type collector cell is generally perferable from the standpoint of compact size, manufacturing tolerances and cost per cubic feet of air to be treated. However, in some cases, unusual installation or performance requirements indicate the use of a tube-type unit. It is to be expected that there will be an area of performance requirements where the choice is arbitrary if cost considerations are eliminated.

Thirteen models of precipitators have been developed to cover the different sizes rating and configurations of submarine construction. These units are now commerically available. They are basically as described previously but consist of various numbers of ionizing and collecting sections. The primary reason for making the ionizing and collecting sections in separate components and for segmenting these components is to facilitate their installation into the submarine. All precipitators or portions thereof must be capable of passing through a 25-inch hatch. A picture of a unit consisting of five separate ESP sections together with the required power supply is shown in Figure 7. This unit is capable of handling 11,000 CFM of air at better than 95% removal efficiency and less than 0.10 in. WG pressure drop.

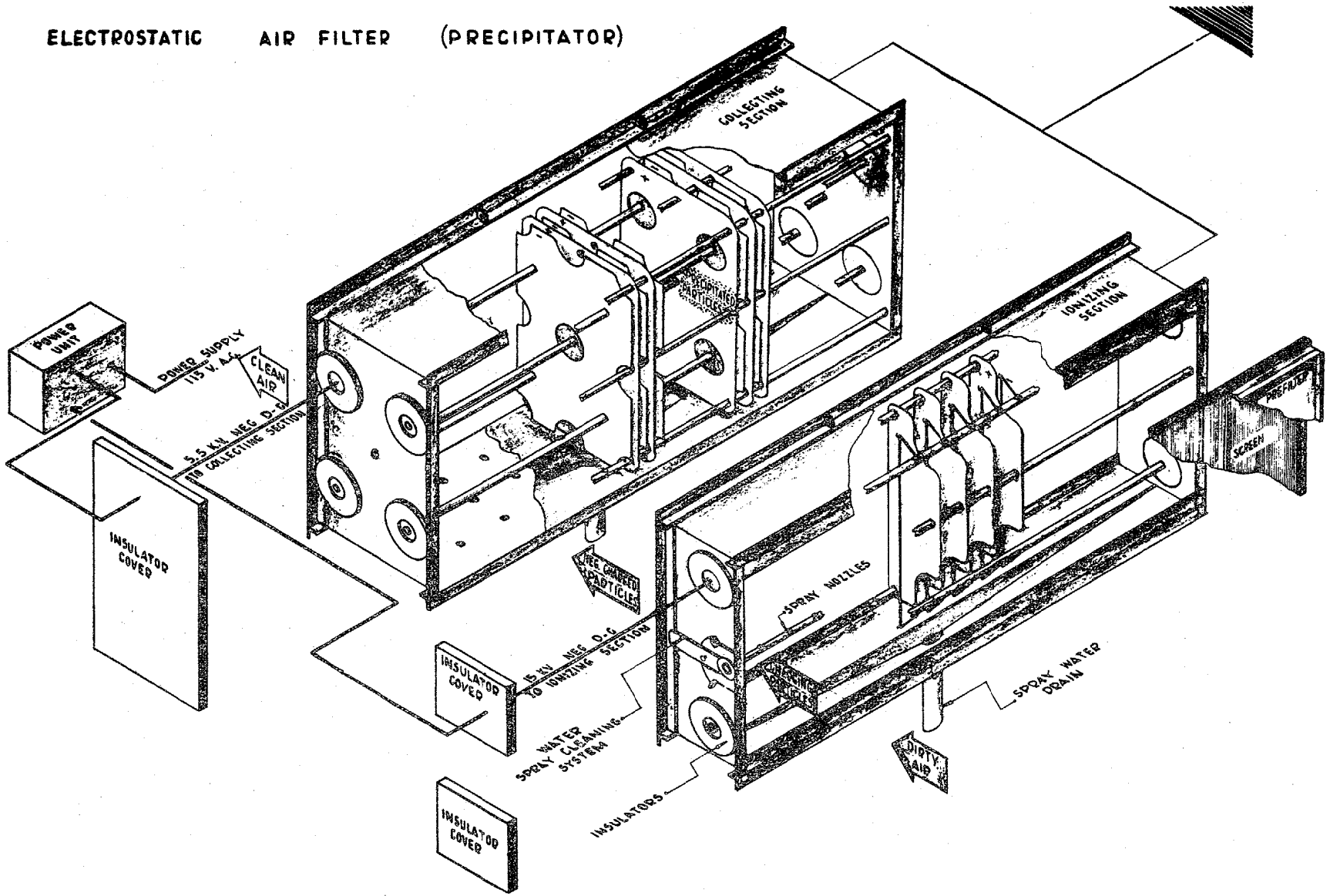

Figure 6 Two-stage Submarine Electrostatic Precipitator (exploded view)

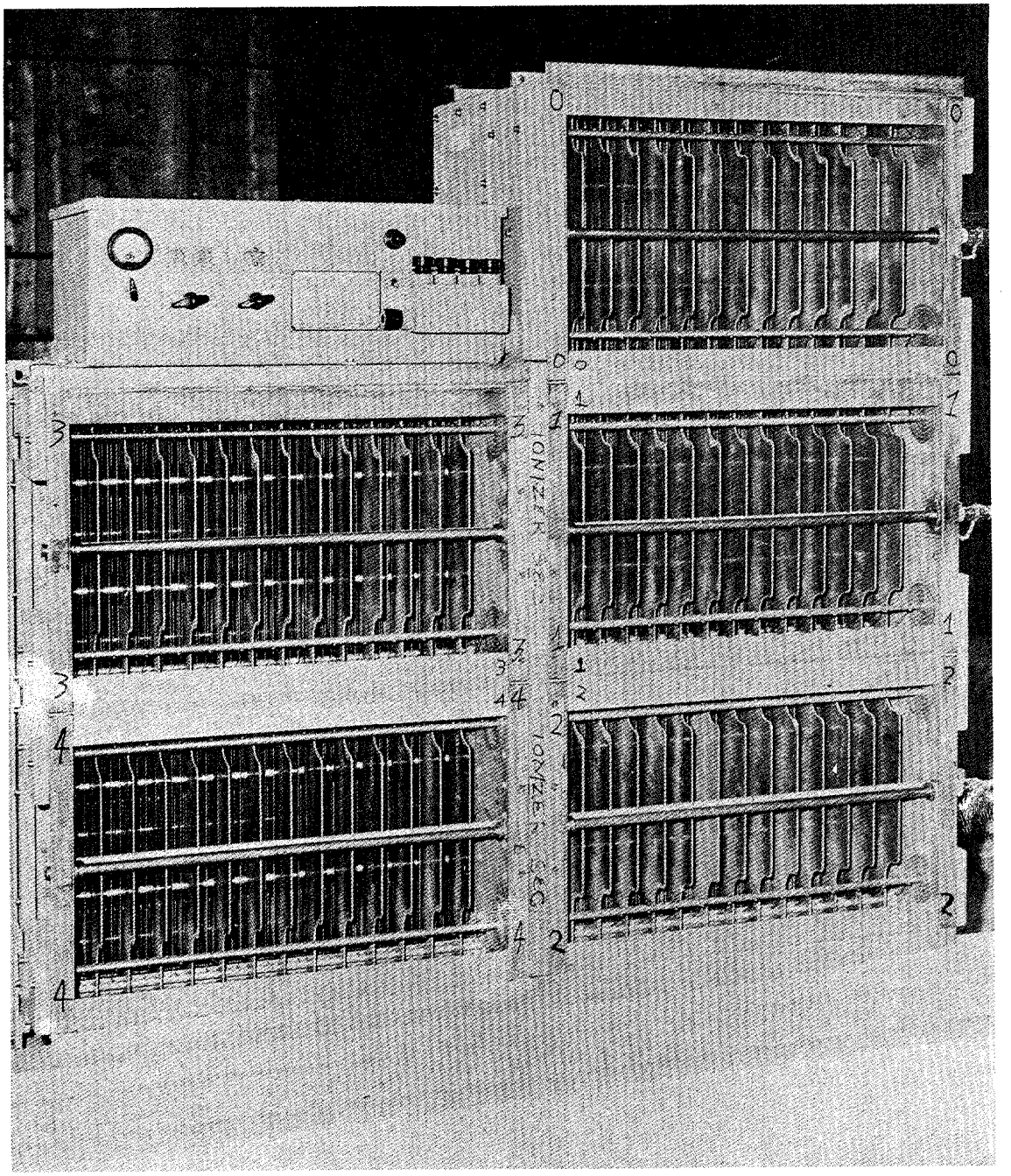

Figure 7 Nuclear Submarine Precipitator Installation

The design criteria for these units have been determined and depending upon the performance required and the physical space available a variety of units may be specified. Flow rates from 1000 to 11,000 CFM and with linear rates of 10 to 30 feet per second can be effectively handled; removal efficiencies of 80 to 99.98% are possible at ozone generation rates of less than 0.1 ppm. It is believed that the design variables have been sufficiently established that units can be reliably designed for most any application.

A number of our nuclear submarines have been fitted with this type precipitator. The effectiveness of the units for aerosol control is seen in Figure 8. The single high point on the lower curve was obtained by securing the precipitators for a short time to assure that the lower concentrations were due to the precipitators. Aerosol reductions in nuclear submarine atmospheres of over 80 percent have been achieved.

In summary, the essential design criteria and performance for a series of commercially available precipitators have been established. Modular construction allows the stacking of basic units to achieve the desired capacity of filtered air. Dependent upon air flow rates and/or space requirements, removal efficiencies as high as 99.98% are practical.

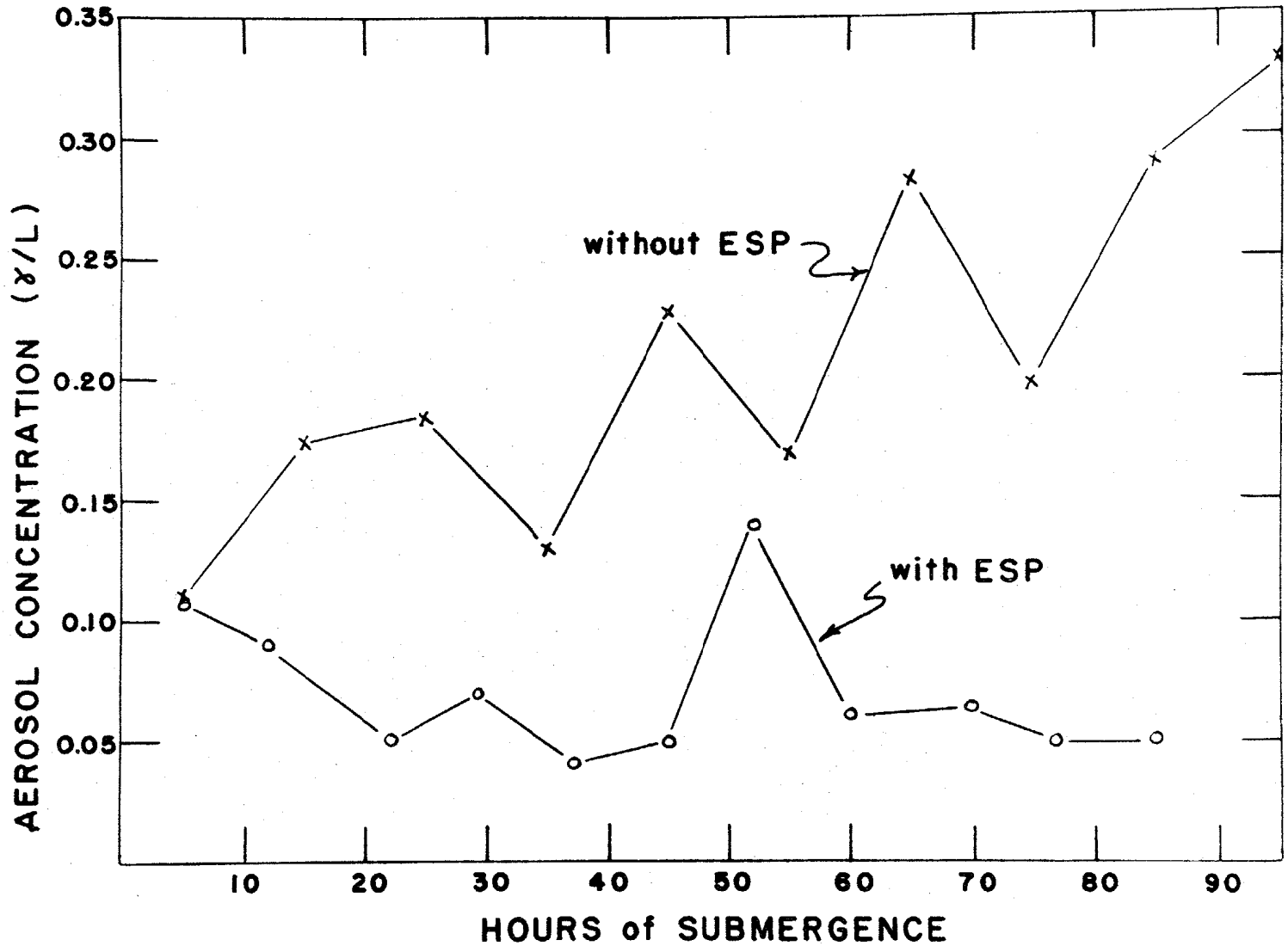

Figure 8 Effect of ESP of Aerosol Concentration

DISCUSSION

BILLINGS: Are there questions relating to Dr. Anderson's presentation?

THAXTER: What effect does this have on the bacterial count?

ANDERSON: An indication of the reduction of bacteria in submarine atmospheres can be obtained from the decrease in airborne beta activity. Since this activity has been shown to be associated with particulate matter, any reduction in it should reflect similar reductions in bacterial organisms. We have not been able to take an incubator and associated equipment on a ship, but we feel that airborne organisms have been reduced by 90 to 95% by the precipitator installation. There is a program now underway to install a bacteriological laboratory on one of the ships. This installation should obtain the specific information you ask about.

BALLS: Have you run any tests at greater than 0.4 of a microgram per liter?

ANDERSON: Yes we have performed such tests. Under certain operational conditions we have measured concentrations as high as 5 to 10 micrograms per liter. These concentrations were observed while the ship was operating under a condition called ultraquiet. During this operation, all air-moving and filtering equipment is shut down and localized aerosol concentrations may get quite high. As soon as electrical power is restored to the air-moving equipment, the precipitators are very effective in quickly reducing the aerosol concentrations. This points out one disadvantage of the precipitator, i.e., it doesn't have the fail-safe principle. Outside of this, we feel that it will do an extremely good job of removing particulate matter of all particle sizes at relatively low air flow resistance.

DENNIS: I would like to know (a) if the ozone figure is based upon an equilibrium value and, (b) was equilibrium reached in the system with activated charcoal.

ANDERSON: No. It is a specification of the precipitator itself and is measured directly in the output of the precipitator. Present specifications state that ozone concentrations shall be less than 0.1 ppm in the outlet and that ozone equilibrium concentrations shall not exceed 0.05 ppm in the ship itself. The carbon bed in the ship is present for organic and odor removal and is not intended for ozone control.

SHAVER: I am curious about the sloughing off of the material collected in a precipitator. Did you do any test work with any after filter to check this out and where did you actually make your measurements that you indicated on your draft?

ANDERSON: The electrostatic precipitator installation contains both a pre-filter and an after-filter. These items are of the low resistance metal screen variety. The pre-filter prevents the accumulation of lint-type materials in the precipitator while the after-filter is present to collect the large size blow-off particles from the collector plates. The measurements of submarine concentrations reported were made in the ambient submarine atmosphere. On the other hand, efficiency measurements were made both fore and aft of the unit itself. Our studies are somewhat inconclusive, but it appears that we are getting some increase in reliability of our complex electronic system. We feel that this is attributed to the aerosol material being accumulated by the precipitator rather than in the high voltage equipment itself.

LIFE-LOADING TESTS ON CERTAIN FILTER MEDIA

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ABSTRACT

A study is reported of six selected roughing filter media and a high-efficiency medium to determine their life-loading characteristics. Accelerated life tests using a natural dust test aerosol were designed and performed to simulate anticipated operating conditions in proposed reactor confinement ventilation systems for which these filters were being considered. Test findings were correlated with actual confinement system performance. Reasonable agreement is noted. Test data indicated the inadvisability of using roughing filters due to the increased pressure drop of the high-efficiency filters per unit of loading and to the relatively difficult task of roughing filter changes.

To determine the most desirable filter arrangement which would predispose to long life and economical operation, selected filter media contemplated for use in HAPO reactor building exhaust ventilation systems which are better known as reactor confinement systems, were subjected to accelerated life-loading tests by the Occupational Hygiene Operation to provide data for this purpose. The primary filtration system consisted of high-efficiency, fire-resistant filters although some consideration was given during early design stages to the possible use of roughing or prefilters upstream from the high-efficiency filter banks.

Certain aspects of this study on high-efficiency media were reported by D. E. Wisehart at the 6th Annual Air Cleaning Conference at Idaho Falls. The data reported at that time will not be repeated here except as it is important to the discussion of life expectancy and actual performance which is being experienced with these systems.

For the sake of clarity the testing facility and procedure will be reviewed briefly. Figure 1 shows the over-all testing facility comprising a dust generator, a settling chamber and a filter holder assembly. The dust generator is shown in greater detail in Figure 2.

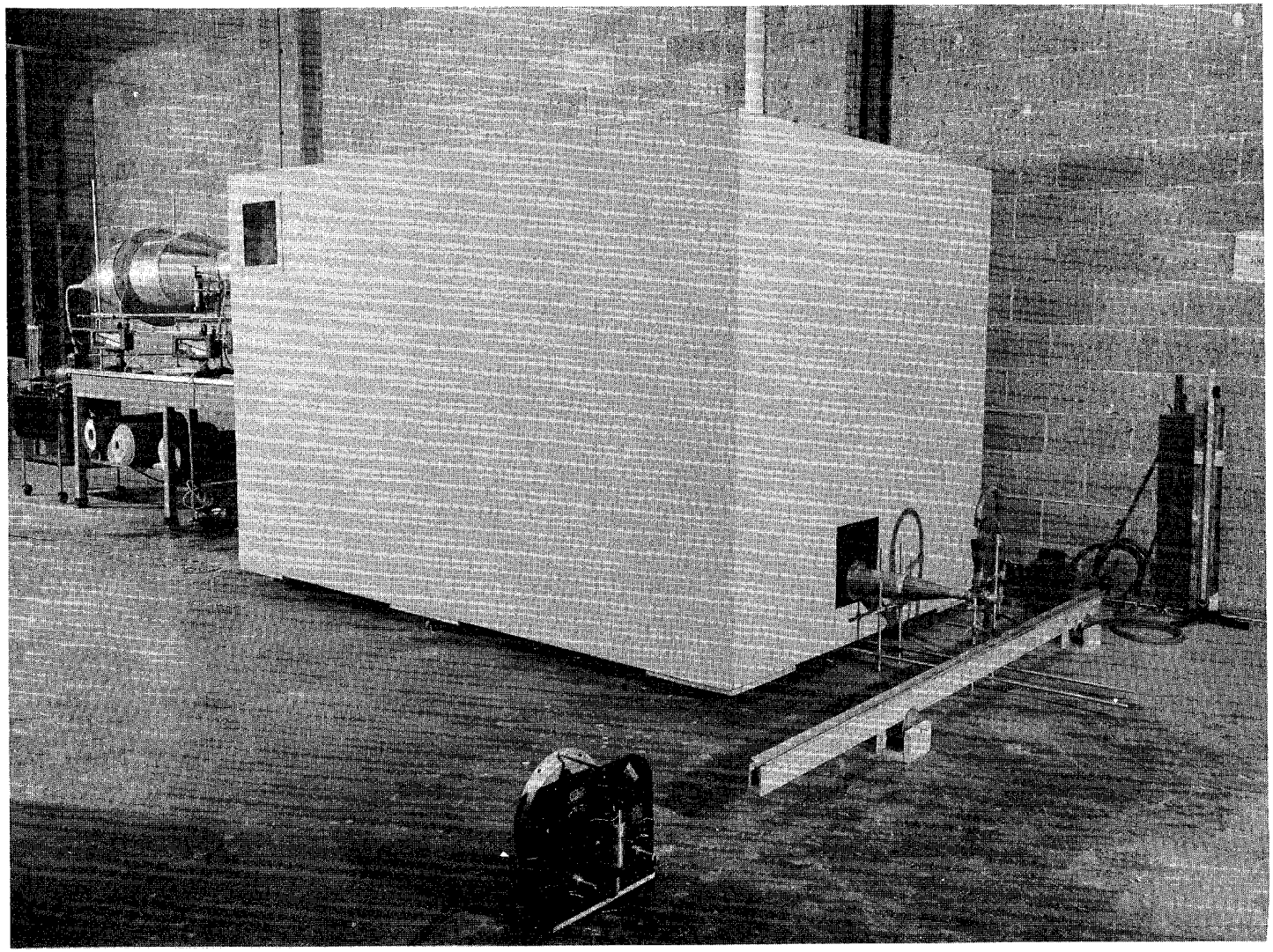


Figure 1 Filter Testing Facility

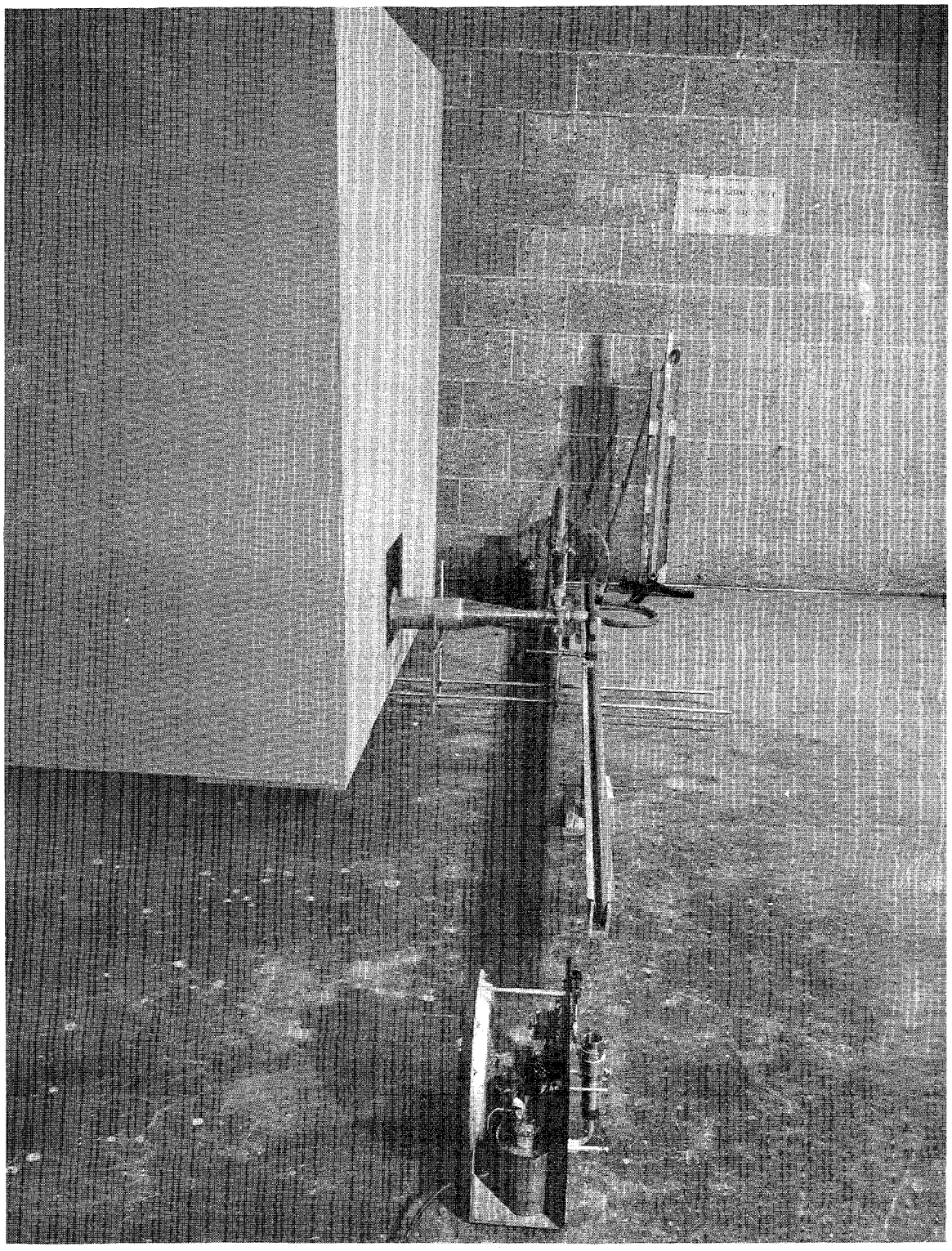


Figure 2 Dust Generating Device

The test dust consisted of natural settled dust which had accumulated in the attic space of a project building over a number of years and was readily collected in sufficient quantity by vacuum cleaning. This dust was loaded uniformly in a V-shaped trough (Figure 2) from which the dust was picked up by an air aspirator and ejected into the chamber. The air stream from the aspirator discharged into the front of the chamber at a low level, permitting the coarser size fraction of the dust to settle and remain in the chamber. The airborne fraction was drawn from the top at the rear of the chamber and from there was drawn through the test filter assembly. The rate at which this dust was discharged into the chamber and passed into the filter assembly was directly proportional to the depth of dust in the V-shaped trough. The mass mean size of the resulting test aerosol was about 5.5 microns and the average dust concentration of the test atmosphere was approximately 200 mg/m^3. For comparative purposes a sodium chloride test aerosol was used which had a particle size of about 0.5 micron and a standard deviation of 1.5. Airflow rates through the various media were maintained at levels consistent with that designed for the confinement filter systems. Pressure drop readings were taken across the media by inclined manometers during test runs. Filter loadings were determined indirectly during each test run by isokinetic sampling upstream and downstream from each medium under test. Sampling filters were analyzed gravimetrically from tared papers. As a check, each test filter was weighed at the termination of each test to check the integrated air sampling results. Good correlation was found in each instance.

Several different commercial prefilter media were tested, five of which are discussed in this report. These media were each subjected to the test aerosol until their pressure drops reached 1.0 in. wg. While the load was building up, pressure drop readings were made periodically and the incremental dust load was estimated from concurrent serial dust samples collected from the airstream. The loading characteristics of the five prefilter media are shown in Figure 3. It is evident that one medium had a relatively favorable dust holding capacity. Wisehart's previous report on this study indicated that by reducing the filtering velocity by 50%, the life of the medium was more than doubled. This medium was selected for further consideration for possible use in conjunction with the high-efficiency filters. The appearance of typically loaded test filter media can be seen in Figure 4.

The high-efficiency, fire-resistant filter paper tested was that which was commercially available at that time in the manufacture of such filters. It was an all-glass fiber medium. Tests were next performed on this medium using aerosols of three different sizes. Initial testing was made by exposing the filter to the 5.5 microns dust directly from the chamber in the same manner as for prefilters. Another series was made with the selected prefilter upstream of the high efficiency medium. Size analyses of the dust passing the prefilter indicated it had a mass mean size of about 2.0 microns. The average concentration of this prefiltered dust was 40 mg/m^3. A third series was run using a sodium chloride fume having a mass mean size of about 0.5 micron. During each of these tests incremental loadings were determined by sampling the test airstream as described previously. The results of loading tests on the high-efficiency filter can be seen in Figure 5 in which the increase in pressure drop is related 1) to a loading of the natural test dust, 2) to a loading of the prefiltered dust and 3) to a loading of the NaCl fume.

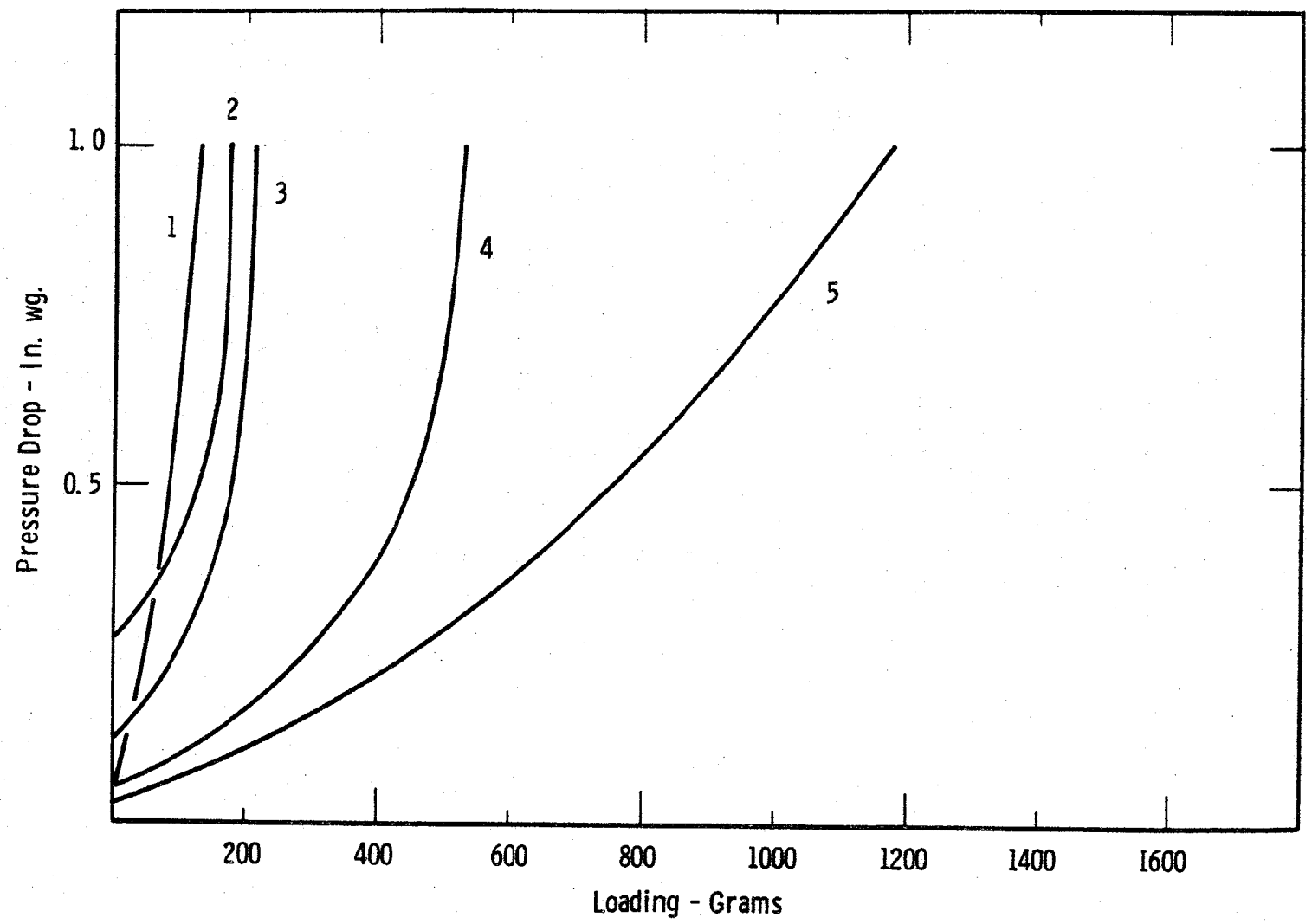


Figure 3 Prefilter Loading Characteristics

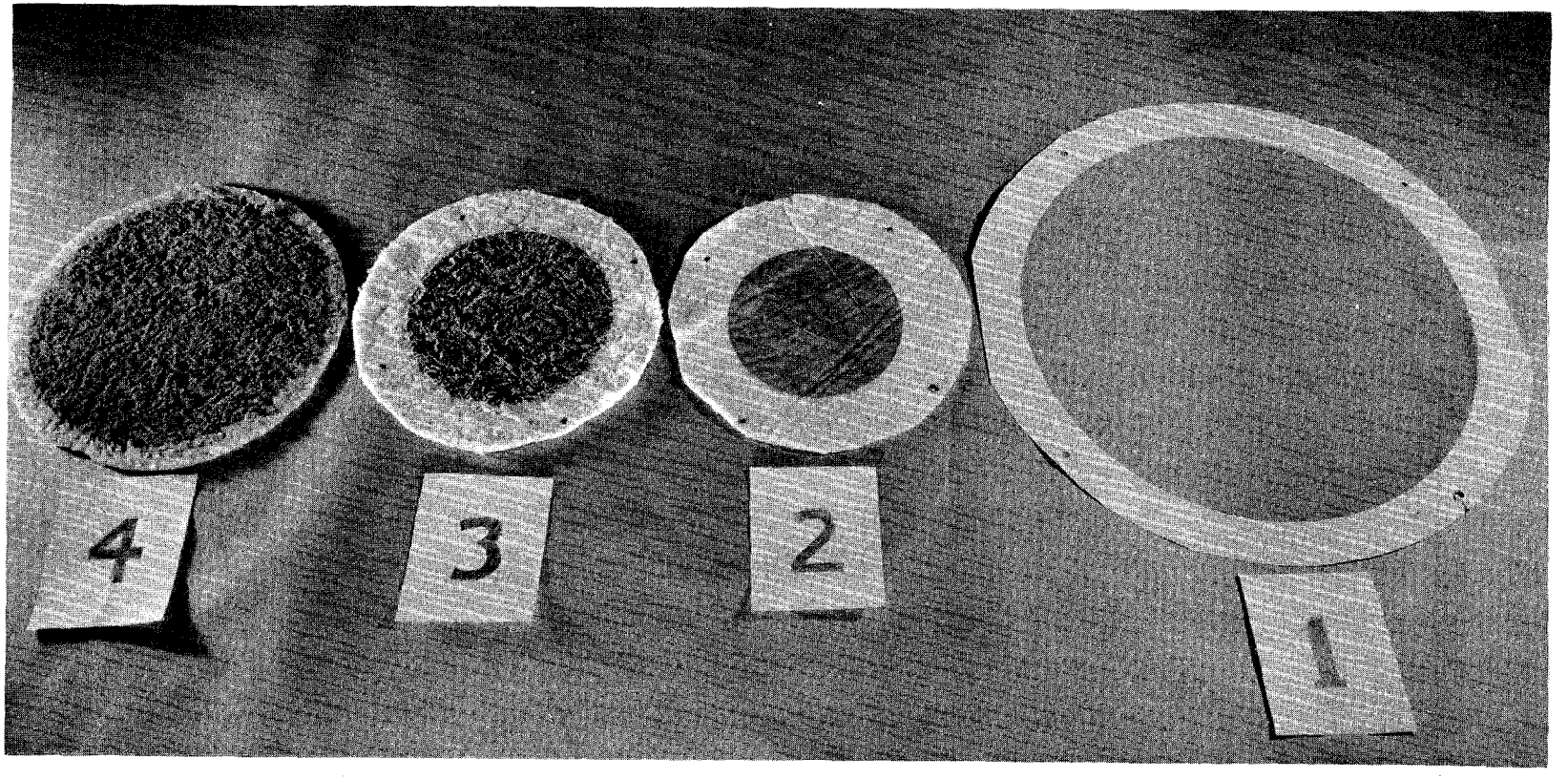


Figure 4 Typical Loaded Test Media

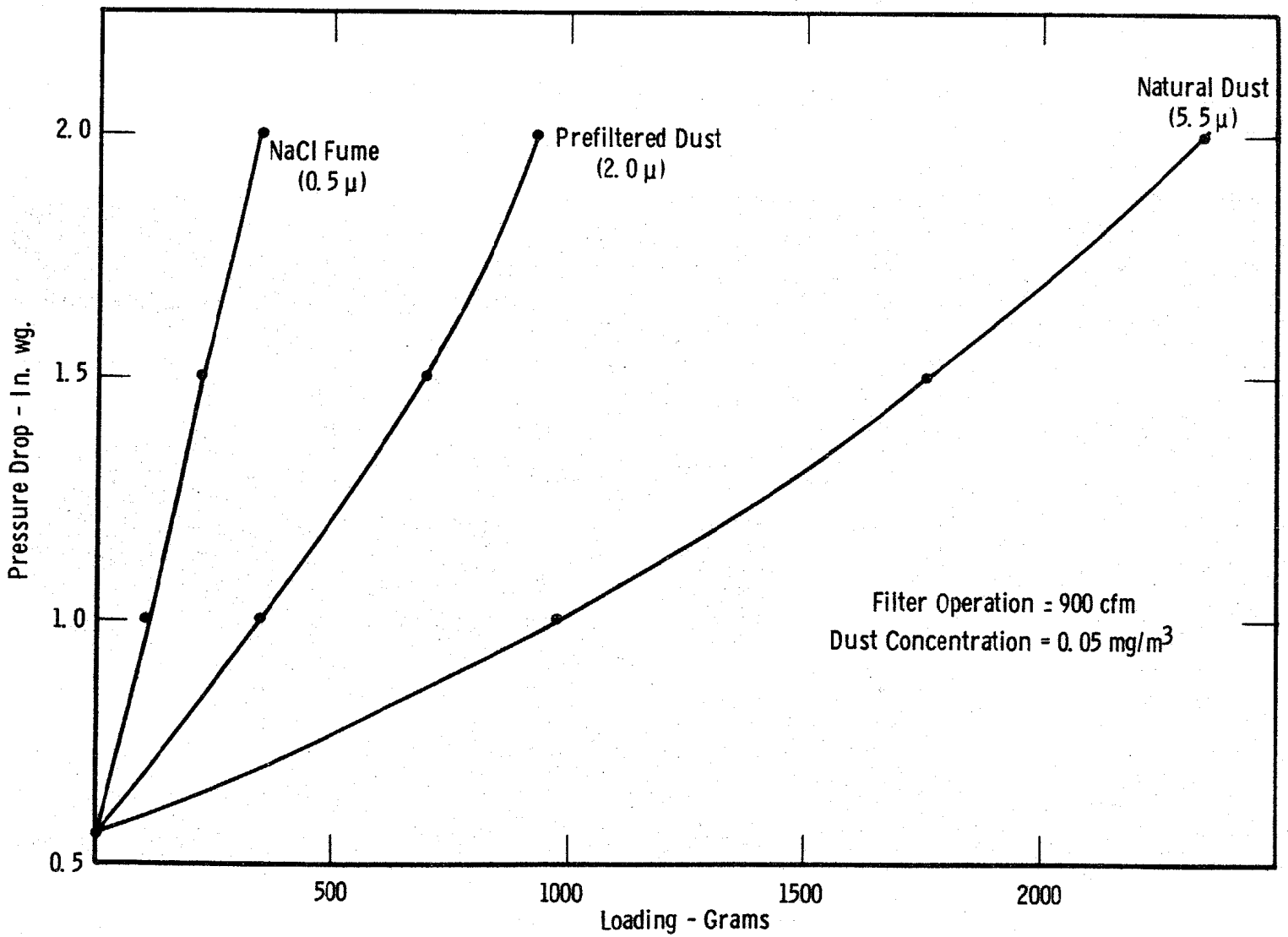


Figure 5 Effect of Particle Size on Loading of High-Efficiency Media

It is noted, as expected, that for a given dust loading the pressure drop increase was considerably greater with prefiltered dust which was of a selectively smaller size. This was more apparent with the NaCl fume.

The particulate concentrations to which filters would be exposed in the reactor ventilating systems were measured in several instances. Difficult sampling conditions, however, permitted only limited data. It was found that the concentrations ranged between approximately 0.05 mg/m^3 and 0.005 mg/m^3. Applying the loading-pressure drop relationships shown in Figure 5 to an estimated air-stream loading of 0.05 mg/m^3, it is possible to project the anticipated life expectancy of the high-efficiency filter units. This is seen in Figure 6 for the three aerosols previously discussed. Assuming the actual dust to be in the size range of the chamber test dust, the life expectancy of these filters is about three years if the maximum permissible pressure drop is 2.0 in. wg. This, of course, would be influenced by the building activities as well as outdoor dust levels which can be strongly influenced by wind and construction activities. (1) Based on the data compiled from the tests on prefilter and high-efficiency filter media and from other technical considerations related to problems associated with replacing contaminated roughing filters, it was decided that the most economical filter arrangement was to use only the high-efficiency filters.

At the time of initial planning of these air cleaning facilities, a test assembly consisting of a roughing filter, a high-efficiency filter and a back-up activated charcoal filter cell for halogen gas removal was installed by the Irradiation Processing Department in one of the reactor exhaust ventilation systems so that the "stack gases" could be drawn through the filters at their rated airflows. It was hoped that this full scale prototype unit would provide supplementary data for the design of these facilities. Each of the filter components was of commercial type and size under consideration. These tests lasted for approximately one year during which time pressure drop readings were periodically taken. Part way through this test period, a high-efficiency filter was substituted for the roughing filter, thus making two high-efficiency filters in series. Since the new upstream high-efficiency filter was operating under conditions essentially identical to a single bank of high-efficiency filters, the data which were obtained were correlated with accelerated life test findings. It was found that the in situ test indicated a 40% shorter life expectancy than that indicated by the accelerated life tests and noticeably shorter than that being presently experienced by the reactor systems as shown in Figure 7.

About January, 1961, installation of the filter systems was commenced. The typical installation consisted of a single bank of filters as described by Mr. Heacock. All these systems are presently operating although building ventilation balancing, fan capacity adjustments, etc. are still in progress. The loading performance of these filter banks is shown in Figure 7. The accelerated life expectancy data and the full scale prototype test unit data are superimposed in Figure 7. It was not possible to obtain data on all reactor buildings at the time of this writing although 10 of the 16 filter banks are shown. It should be mentioned that the prototype data represent tests conducted at the normal rated filter capacity of 1000 cfm rather than at 900 cfm, the design and operating airflow. These data would make this performance curve relatively high with respect to the other curves which are

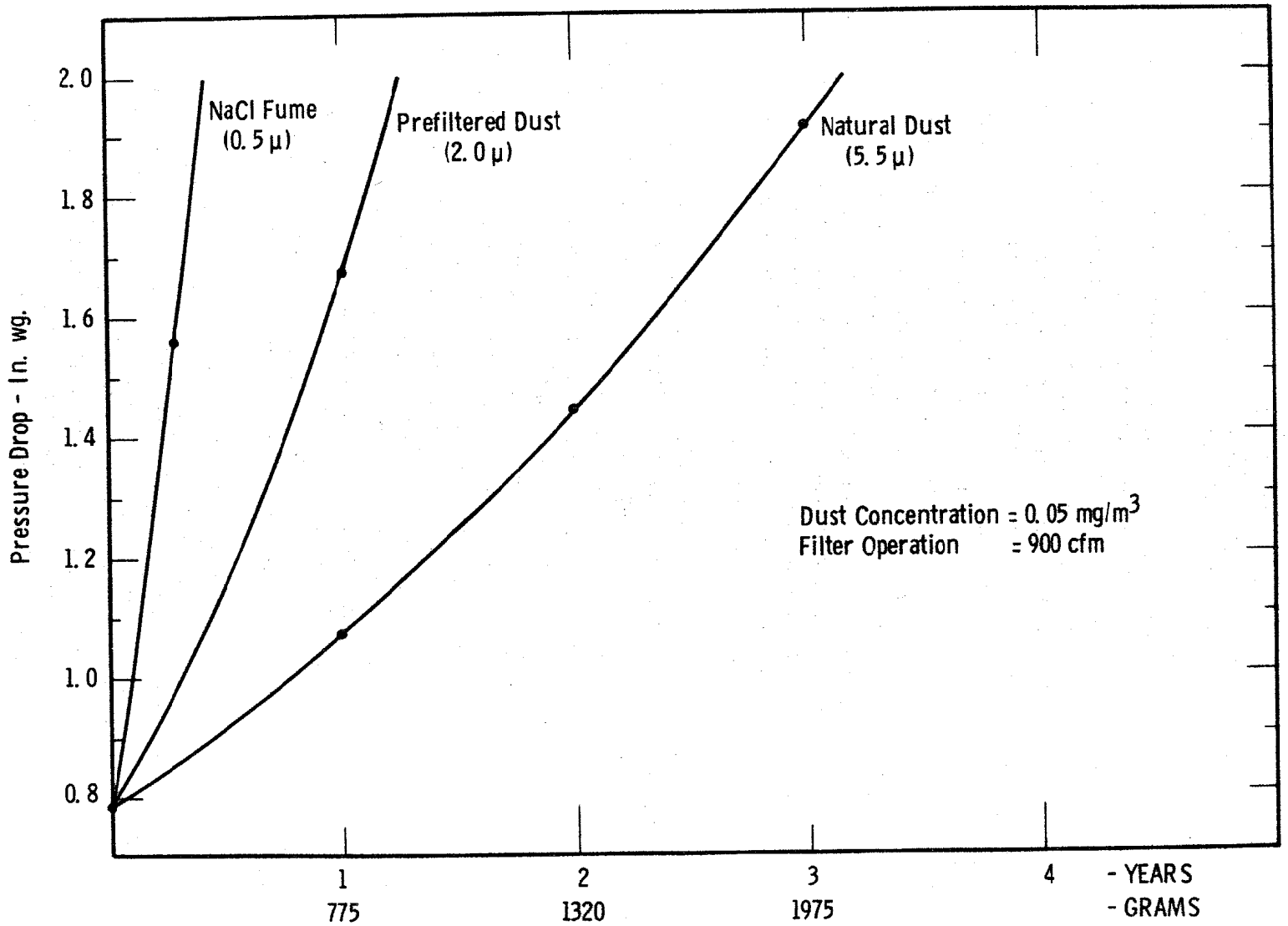


Figure 6 Effect of Particle Size on Life of High-Efficiency Filter Units

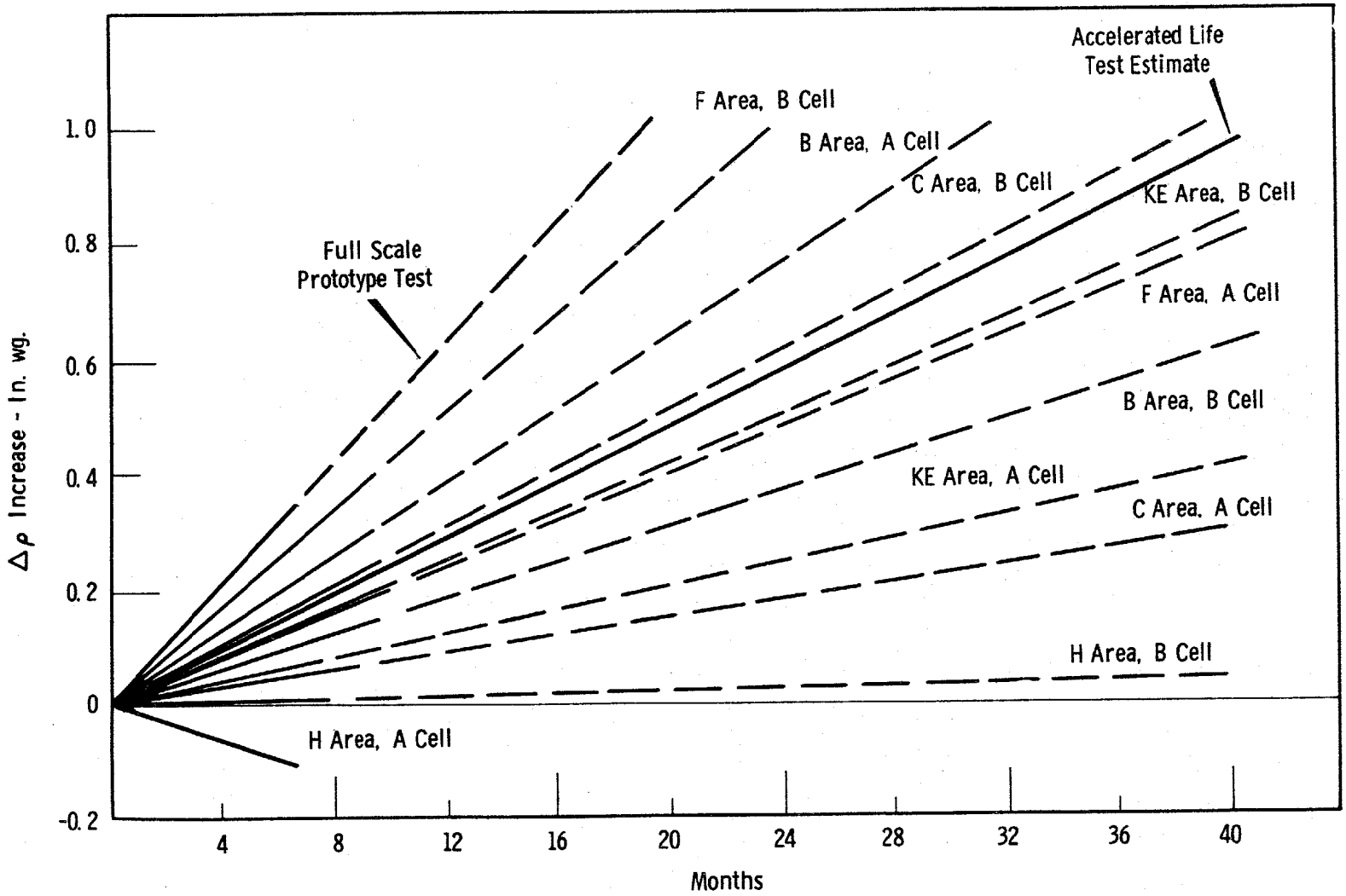


Figure 7 High-Efficiency Filter Performance

based on airflows of 900 cfm. The actual performance of the individual systems obviously varies markedly and this is felt to be reflecting the variations in ventilation airflows resulting from system balancing and fan adjustments which are still in progress. It should also be pointed out that in actual performance, the extrapolated lines as presented in Figure 7 will probably be typical loading curves rather than straight line projections due to the more rapid pressure drop increase per unit of loading as the filter life progresses. This will tend to shorten the expected life which are predicted in Figure 7. It appears that in the majority of instances the high-efficiency filter life will exceed the estimated three years.

REFERENCE

1. Adley, F. E., and Gill, W. E., Atmospheric Particulate Background in a Rural Environs, American Industrial Hygiene Association Journal, August, 1958.

TURBULENT DEPOSITION IN SAMPLING LINES

L. C. Schwendiman and A. K. Postma
General Electric Company
Hanford Laboratories Operation

INTRODUCTION

Obtaining a truly representative sample from a gaseous stream carrying radioactive particles is often difficult, sometimes impossible. One contends with ductwork and passages designed with little consideration to sampling requirements. Under some sampling conditions, the local radiation levels are so great that to obtain any sample requires long sampling lines, and compromises are often made in sample integrity without knowledge of the degree of the compromise. In the more conventional industries, standards for sampling have been written with recognition of the errors of non-isokinetic flow, deposition in sampling lines, and with recognition of differences in particle characteristics. Although these standards for aerosol sampling are well founded, they are frequently too idealistic for application in sampling radioactive aerosol streams in nuclear materials processing plants. In these circumstances where exact compliance with the idealized sampling arrangement can not be realized, knowledge of the degree of error introduced is important.

OBJECTIVE

The objective of this paper is to discuss briefly the significance of turbulent deposition of particulates in sampling lines, and to present experimental data which permit the deposition to be estimated.

DISCUSSION

The motion of particles in a turbulent stream of gas is extremely complex as each particle is subject to the ever-changing eddy velocities of the gas. Because of its mass the particle cannot always faithfully follow the gas eddy. The few attempts to describe theoretically the behavior of a particle and its deposition probability have required assumptions which are only approximations to the actual situation. The best work to date appears to be that of Friedlander and Johnstone who derived theoretical expressions for the deposition velocity, K.[1] The deposition velocity is the quotient of the number of particles deposited per unit time per unit area of the wall divided by the number of particles per unit volume in the gas stream. These authors attempted to verify the theory with experimental measurement. Their model visualized small particles faithfully moving with the eddies in the turbulent core of the conduit and in the buffer region.

The particle was assumed to approach the conduit wall with a radial velocity equal to the mean fluctuating velocity of the gas just outside the buffer region. Under the assumption that turbulent eddies did not penetrate the laminar sublayer, particles would not have reached the wall under their experimental conditions, yet significant deposition did occur. Because of this inconsistency with the experimental observation, Friedlander and Johnstone then applied the diffusivity equations developed by Lin, Moulton, and Putnam[2] which take into account eddy disturbances in the laminar sublayer.

Their derived equation for K is supported reasonably well by the experimental data, although the simplifying assumptions in the equation, and the uncertainties in measurement of the important parameters reflect significant differences between prediction and experiment as might be expected.

The work to be presented was undertaken to obtain relations which might be used in a practical way to predict deposition in conduits under a variety of circumstances. Verification of theory was not a principal objective, however, fluid dynamic concepts of stopping distance and thickness of the laminar sublayer were drawn upon in establishing a correlation function.

EXPERIMENTAL

The objective of the experimental work was to measure K, the deposition velocity, under a variety of conditions of particle size, average conduit velocity, and a few conduit diameters. As suggested by the definition of K the number of particles of a given size deposited on unit area per unit time of those in unit volume of the gas passing through the conduit were measured using the apparatus shown in Figure 1.

The particulatate material used in most of the experiments was fluorescent grade ZnS. (U.S. Radium Corporation No. 2210) Some measurements were made with 30u glass spheres. The dry powder was dispersed by an air jet impinging on a tube of the powder vibrated to expose a fresh surface to the jet. Added filtered air carried the fine powder into the mixing chamber where larger particles were dropped out due to gravity settling. The large chamber provided a reservoir of airborne particles uniformly distributed and of essentially constant concentration. The powder-laden air passed then into the vertical test section made of 1" or 3/4" pipe accurately machined as shown. Each half section could be removed after a run and a direct microscopic count made of the particles deposited in various size ranges, using a combination of ultra violet and white light for illumination. The concentration of particles of a given size range in the air stream was determined by collecting a known aliquot on a black membrane filter, and carefully measuring the number of particles in the size ranges of interest. The number in the size range divided by the fractional aliquot gave the number of particles of this size range in the total through-put of airborne material during the run. The number of particles of the size range per gram of the dry powder could then be computed. Depletion from the gas phase was kept to an insignificant level with respect to the average particle concentration. Re-entrainment was also insignificant under the conditions of the experiments. For zinc sulfide particles in the size ranges examined

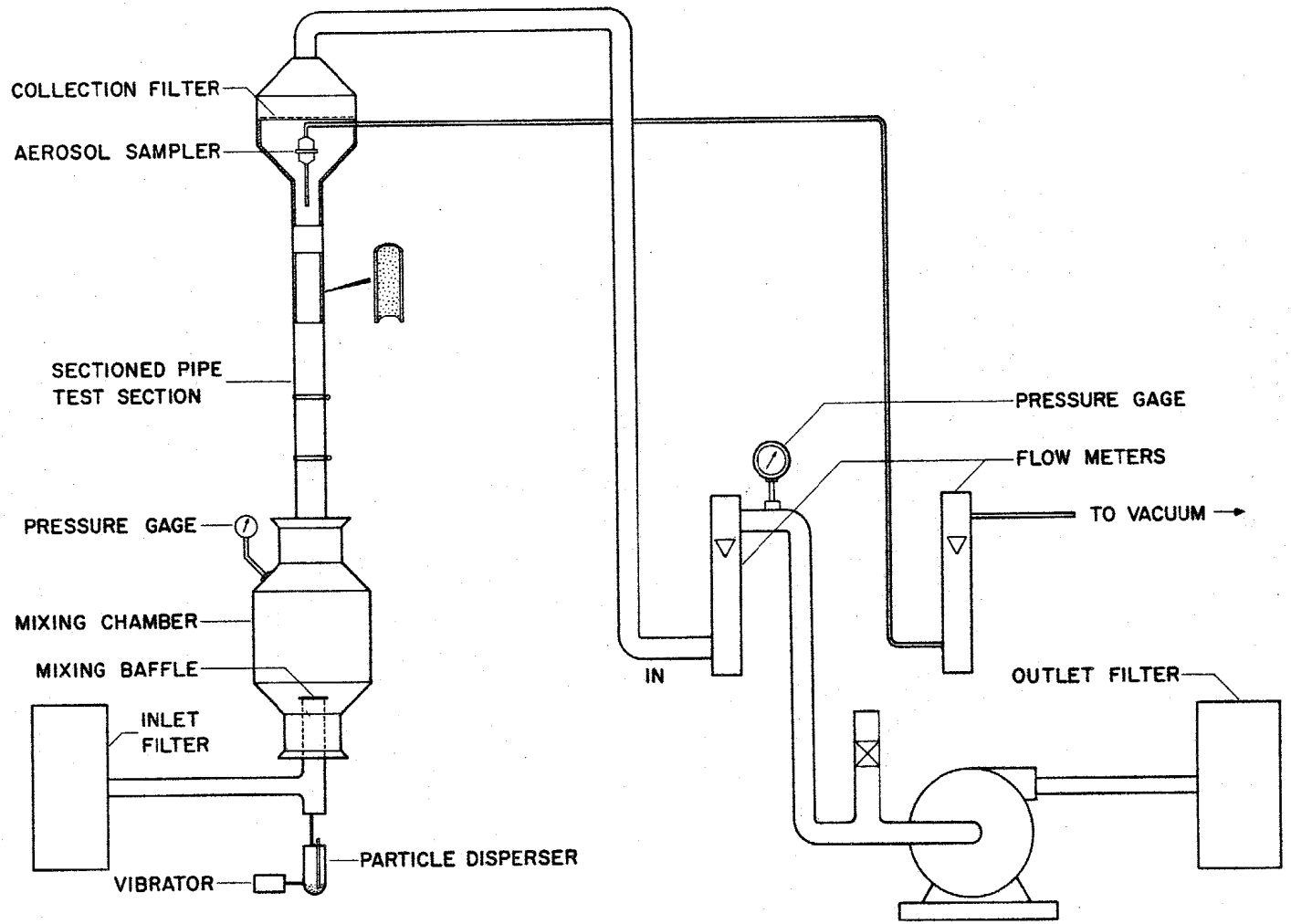


Figure 1 Experimental Arrangement

(2 and 4 microns), no effect of surface preparation on deposition was noted. The larger 30u glass beads were measurably re-entrained from the metal wall and the inside surfaces were coated with a high viscosity silicone oil to minimize re-entrainment.

RESULTS

Typical results of these measurements are displayed in Figure 2, in which the deposition velocity K in cm/sec is plotted as a function of Reynold's number. It is noted that a power function exists with high order dependence on the Reynold's number. The Reynold's number, however, is the product of conduit diameter, average velocity, gas density and reciprocal of viscosity, hence a plot of K vs. Reynold's number for a given diameter does not necessarily illustrate the dependence (or independence) of deposition velocity on duct diameter. The dependence shown in Figure 2 is really that of K with average velocity in the conduit.

A function was developed with which the deposition velocity divided by duct velocity could be reasonably correlated. The function is

$$(D)^{0.84} \left[\frac{\rho_p \, \rho_g \, f \, d_p^2 \, V_{av}^2}{\mu^2 \left(1 + \frac{13.5 \, \rho_p \, d_p^2}{\mu}\right)} \right]$$

The sumbols are defined as follows:

D = conduit diameter, cm
p = density of the particle, g/cc
g = density of the gas, g/cc
d_p = diameter of particle, cm
f = Fanning friction factor, dimensionless
V_{av} = average velocity in the conduit, cm/sec
u = gas viscosity, g/cm/sec

When this parameter is plotted against $\frac{K}{V_{av}}$, the data appear as shown in Figure 3.

The bracketed term defines a number proportional to the ratio of the stopping distance of a particle to the thickness of the laminar sublayer. As this ratio increased, so does the value of $\frac{K}{V_{av}}$, as might be reasoned intuitively.

Experimental error probably contributed materially to the lack of a higher degree of correlation, and more refined experiments are needed to establish the exact relation existing. It is pointed out that only two conduit diameters, one gas viscosity, and two particle densities are represented in the current data (open symbols of Figure 2). The data of Friedlander and Johnstone have also been plotted (close symbols). Additional

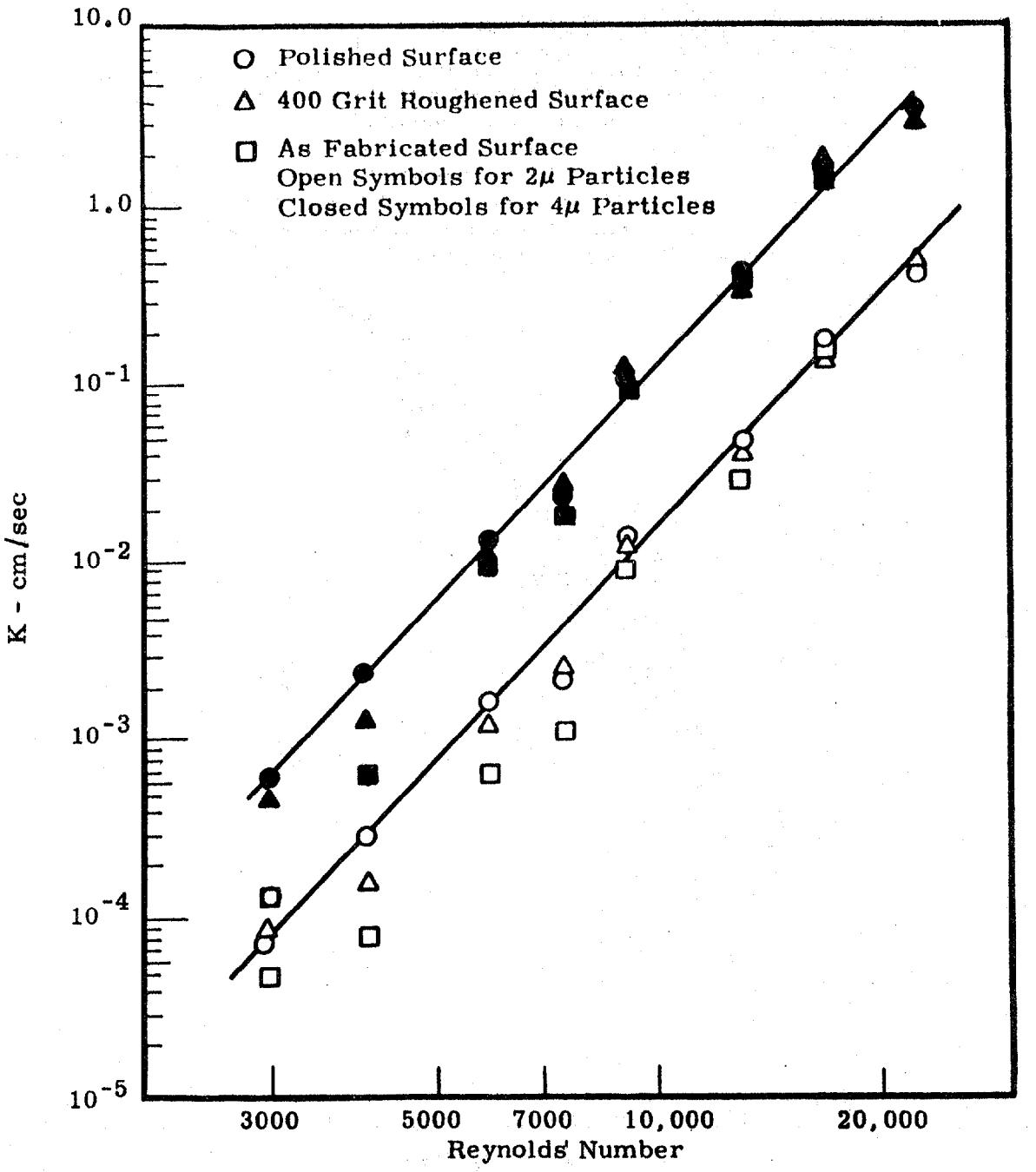


FIGURE 2

Deposition of Zinc Sulfide Particles in 3/4" Welded Stainless Steel Pipe

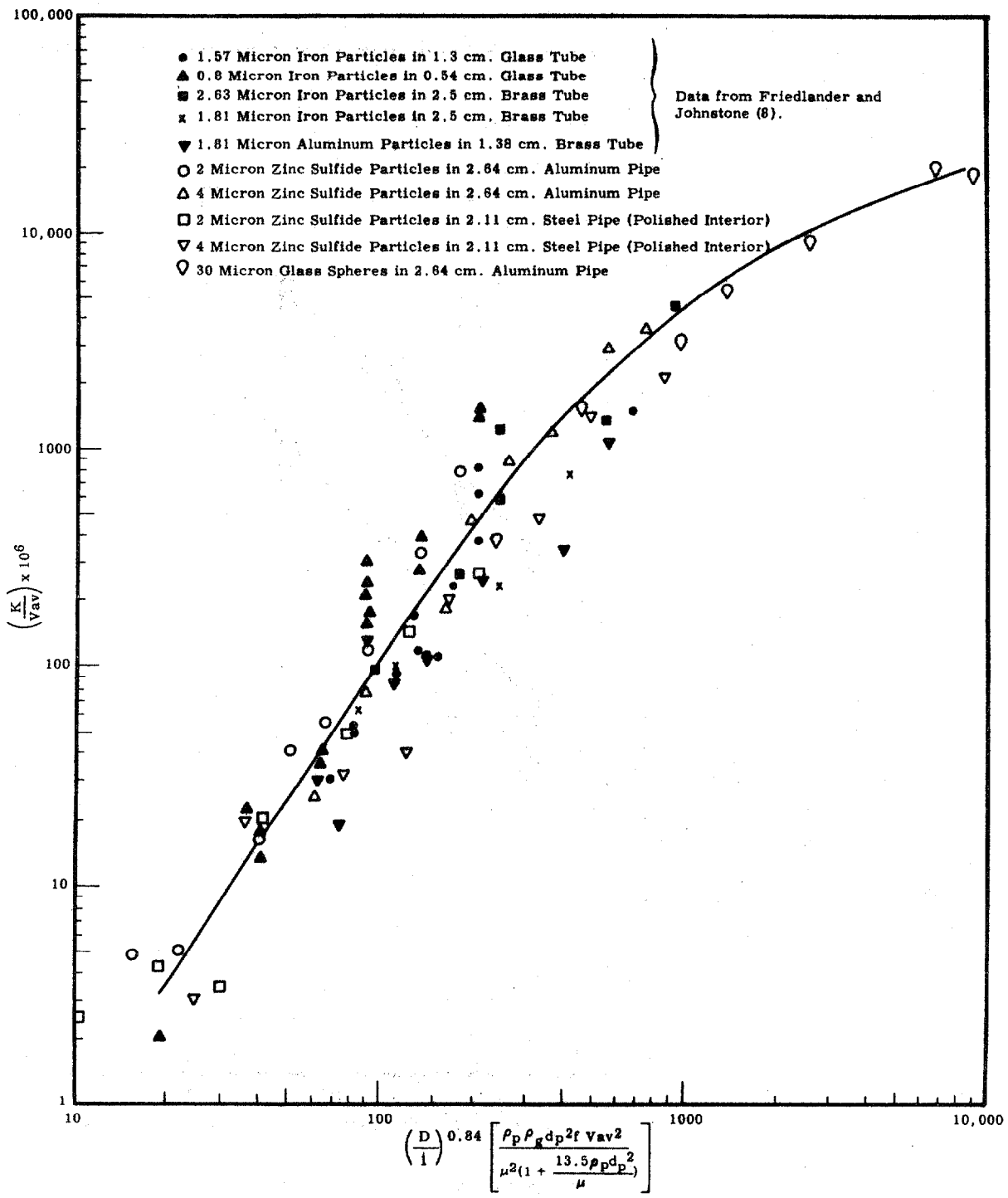


Figure 3 Relation Between Deposition Constant and Correlation Function

particle densities, and duct diameters are thus included, yet the points still seem to distribute themselves about the line.

The equation of the straight line portion of the curve from low values of $\frac{K}{V_{av}}$ to a $\frac{K}{V_{av}}$ of about 1×10^{-3} is

$$K = 6.00 \times 10^{-9} D^{1.79} \rho_p^{2.13} \rho_g^{2.13} d_p^{4.26} f^{2.13} \mu^{-4.26} \left(1 + \frac{13.5 \rho_p d_p^2}{\mu}\right)^{-2.13} V_{av}^{5.26}$$

substituting $\mu = 1.84 \times 10^{-4}$ poise, and $\rho_g = 0.0012$ g/cc,

$$K_{air} = 29.42 D^{1.79} \rho_p^{2.13} d_p^{4.26} f^{2.13} (1 + 7.336 \times 10^4 \rho_p d_p^2)^{-2.13} V_{av}^{5.26}$$

All symbols have the definitions and dimensions stated earlier.

These equations point out the extreme dependence of K upon particle diameter and average duct velocity. Immediately apparent is the necessity to measure these parameters with precision if accurate values of K are to be inferred. The application of these relations to actual sampling situations likewise requires accurate knowledge of these parameters before prediction of particle losses to the conduit wall can be made. Application to parameter values beyond the range studied may result in additional errors in the calculated value of K.

APPLICATION TO SAMPLING LINES

Once the deposition velocity, K, is established by measurement or calculation, the ratio of entrance to exit concentration in a circular conduit may be calculated from the expression

$$\frac{C}{C_o} = \exp - \frac{4KL}{VD}$$

in which

C_o = entrance concentration
C = Concentration at a point L cm downstream
V = average velocity in cm/sec
D = diameter of the conduit in cm

(The derivation of this expression is given in the Appendix.)

One way of expressing the deposition is to calculate the length of a conduit in which 50% of the particles will be impacted on the wall. Thus

$$L_{1/2} = \frac{0.693\ VD}{4K} = \frac{0.693\ Re\ \mu}{4K \rho_g}$$

Figure 4 describes this function using experimentally determined K values.

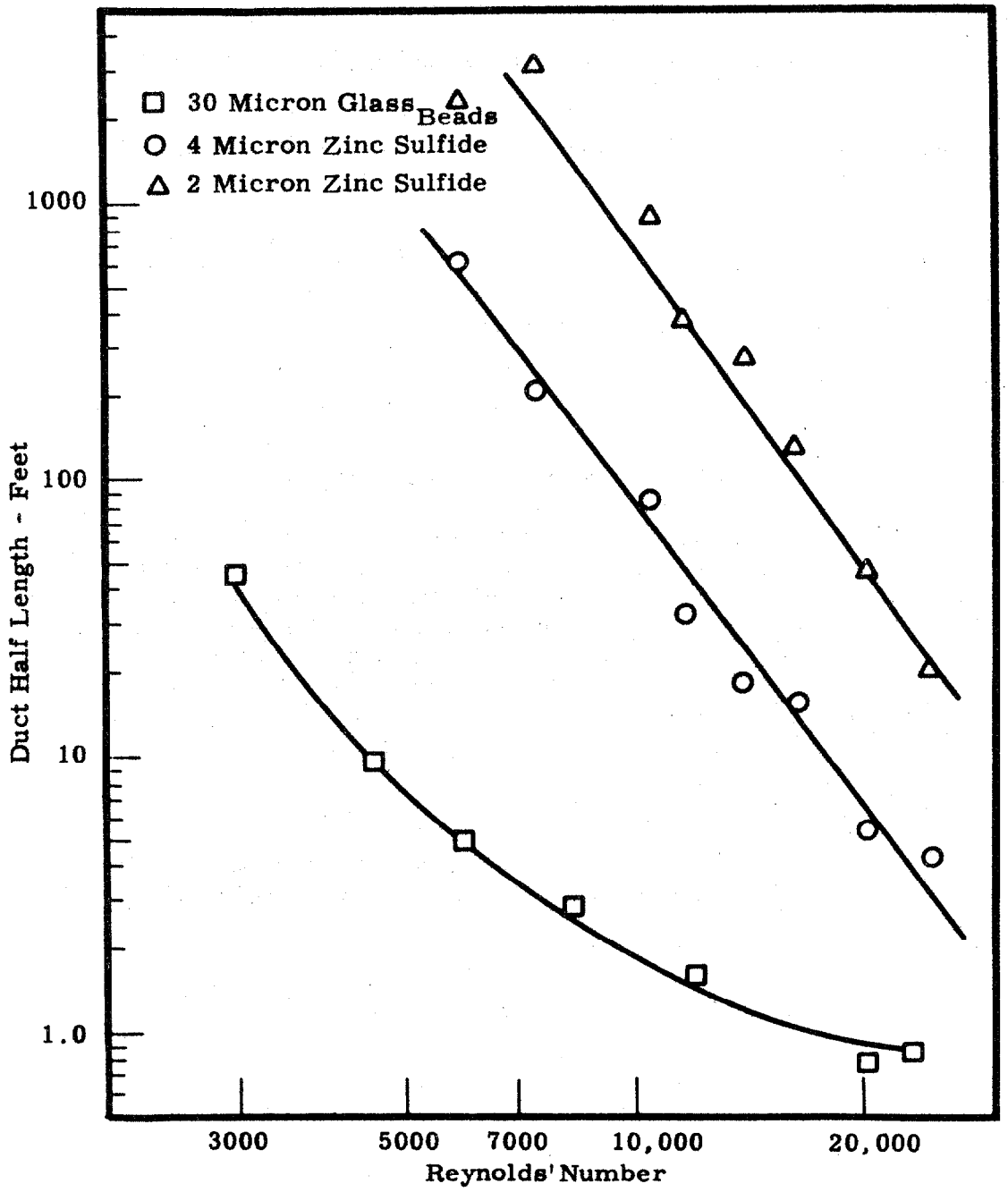


Figure 4

Duct Half Length for Particle Deposition in One Inch Aluminum Pipe

The actual retention within a one-inch line some 72 feet long was compared with the predicted retention. Zinc sulfide particles were used and a deposition constant determined for each of several particle diameter increments in the size distribution spectrum. Using these and the fraction in each size range, the retention of each size increment was calculated, then summed. This calculated retention was compared with the measured loss of all particles to the wall. Table I gives the results.

TABLE I

DEPOSITION OF PARTICLES IN A 1" LINE 72' LONG

Flow Rate	Predicted Retention Wt. %	Actual Retention Wt. %
13.6 cfm	92	87
8 cfm	72	66
8 cfm	93	86

The agreement indicates that the deposition rate data are of the correct order of magnitude, and suggests that particle re-entrainment of particles in this size range is insignificant.

CONCLUSIONS

Turbulent deposition of particles in sampling lines may cause appreciable errors in sampling systems. The degree of error can be estimated from the data presented. Deposition is extremely sensitive to particle size and sampling velocity, larger particles moving at high velocities have larger deposition constants. To minimize turbulent deposition, low velocities should be used, yet not so low that gravity settling will introduce errors. In every case sampling lines should be made as short as practicable.

Further theoretical and experimental work is necessary to provide the understanding and data to permit valid estimates of deposition to be made over a wide range of conditions and to improve accuracy. Re-entrainment phenomenon and retention on elbows and transistions are also areas requiring further study.

REFERENCES

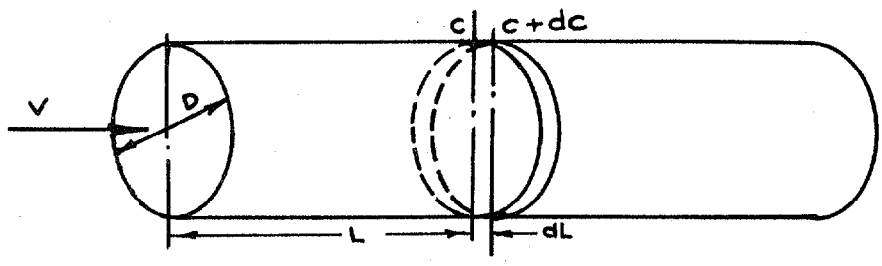
1. Friedlander, S. K. and H. F. Johnstone, Deposition of Suspended Particles from Turbulent Gas Streams, Ind. Eng. Chem. 49: Pt. 2, P. 1151.

2. Lin, C. S., R. W. Moulton, G. L. Putnam, Mass Transfer Between Solid Wall and Fluid Streams, Ind. Eng. Chem. 45: p 636-640 (1953).

APPENDIX

Derivation Of The Equation For Particle Deposition In A Conduit

Consider a differential section of a tube through which an aerosol is flowing as in the following sketch:



The number of particles entering the incremental volume per second:

$$\text{Input Rate} = \frac{\pi}{4} D^2 VC$$

D = tube diameter, cm
V = average gas velocity, cm/sec
C = average particle concentration in the gas particles per cm^3.

The number of particles leaving L + dL in the gas per unit time will be

$$\text{Output Rate} = \frac{\pi}{4} D^2 (C + dC)$$

During passage through dL, the wall deposition rate will be

$$\text{Accumulation} = \pi\ dL\ (C + \frac{dC}{2})K$$

L = distance along the pipe axis in cm

$$K = \text{deposition velocity} = \frac{\text{Number per } cm^2/\text{sec}}{\text{Number per } cm^3}$$

Writing a material balance for the elemental volume:

$$\frac{\pi}{4} D^2\ CV = \frac{\pi}{4} D^2\ V(C + dC) + \pi D\ dL\ (C + \frac{dC}{2})K$$

Solving the last equation, taking $C = C_o$ at $L = 0$, and $C = C$ at $L = L$ gives:

$$\frac{C_o}{C} = \exp \frac{4KL}{VD}$$

DISCUSSION

BILLINGS: I wonder if anybody familiar with Chemical Corp or Navy programs would like to say anything about this particular research.

MITCHELL: The Army Chemical Corps sponsored this work at Battelle Memorial Institute.

BILLINGS: You have approached this same problem for a different purpose and have gotten results?

MITCHELL: Right, and we are preparing to publish that.

BILLINGS: This problem is an older one for which there has been continuing interest, from the standpoint of sampling, but also from the standpoint of conveying material through ducts.

FIRST: I would like to know if the sampling ducts were thoroughly grounded during these experiments.

SCHWENDIMAN: Yes. These were metal tubes, either aluminum or stainless steel, and we had them grounded. Dr. First is suggesting that the electrostatic effects would operate and I can't tell him unequivocally that they were not operating, even with grounding. The particle is a poor conductor itself. We want to go into these other factors in future studies.

CRAIG: Are these equations applicable to the range of half a micronsize particle?

SCHWENDIMAN: Since we were working with particles much larger than one-half micron (2 and 4u size), I would be hesitant to extrapolate down to a half micron particle.

For very small particles, of course, this equation would predict very, very low depositions. Qualitatively, this is what you would expect. However, Brownian motion gets to be more important as you go to smaller and smaller particles. There are equations which might predict deposition, but I would hesitate right now to extrapolate down to a 0.5u particle with the equations presented.

BILLINGS: The electrostatic effect can be very significant for submicron particles. Some work was done at Harvard with respect to the image force and a theory was derived which will predict deposition due to this effect.