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TESTS OF HIGH-EFFICIENCY FILTERS AND FILTER INSTALLATIONS AT ORNL

E. C. Parrish
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INSPECTION ENGINEERING DEPARTMENT

DIRECTOR'S DIVISION

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E. C. Parrish

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TESTS OF HIGH-EFFICIENCY FILTERS AND FILTER INSTALLATIONS AT ORNL

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ABSTRACT

High-efficiency filters are used in air handling systems as the primary means of minimizing the amount of radioactive particulate matter released to the atmosphere. The feasibility of measuring the filtration efficiency of "systems" containing such filters has been established at ORNL. Since the middle of 1962 the efficiency of more than 650 systems has been successfully measured in situ using an aerosol of dioctyl-phthalate and a forward light scattering photometer. In addition, over 1500 new filters have been checked prior to being placed in ORNL stores stock. Tests have been made to determine (1) the linearity of the Naval Research Laboratory type photometer, (2) the precision of filter efficiency determinations, (3) the effect of prolonged exposure to aerosol on filtration efficiency, and (4) the effect of airflow rate on the efficiency of both efficient and defective filters.

1. HISTORY

High-efficiency filters have a wide and important use in atomic energy installations for the removal of sub-micron radioactive particulate matter. In most exhaust systems the high-efficiency filter is the primary means of minimizing atmospheric contamination during normal operation or during the accidental release of radioactive particulate matter. These filters, if in good condition, will remove 0.3-μ particles from an air stream with an efficiency of 99.97% or better.

Historically, high-efficiency filter papers were developed during World War II for use in gas masks and for other military purposes. When the paper was first used in gas masks by the Chemical Warfare Service (CWS), it was on the classified list. During 1946 and 1947 the Atomic Energy Commission (AEC) became interested in the potential uses of such papers, and a major development program was begun. In 1950 the filter

medium was declassified and made available to the industry. It is still often referred to as a CWS or an AEC filter.

From the time high-efficiency filters became commercially available until 1957, not all users of such equipment fully appreciated the fact that the filters were delicate and required special attention. At an Air Cleaning Seminar[1] at Harvard University in June 1957, one manufacturer of high-efficiency filters alleged that at least one of the other two manufacturers was using an efficiency-measuring instrument which needed calibration. On the basis of those remarks plus the fact that some information was available which seemed to bear out the allegation, AEC, in cooperation with the Army Chemical Center at Edgewood, Md., decided to test random samples from filter stocks of atomic energy plants. The survey disclosed a significant percentage of unsatisfactory filters stocked by the Atomic Energy plants. The filters could have been damaged during transportation or by handling, or the damage could have resulted from improper control during the manufacturing process. As a consequence of these findings, the AEC established two quality assurance stations to inspect and test high-efficiency particulate filters for the atomic energy program. The General Electric Company at Richland, Wash. (HAPO) was designated as the quality assurance station for installations west of the Mississippi River, and the Chemical Corps Arsenal, Edgewood, Md., provided service for locations east of this line. The availability of the filter testing service was announced[2] in December 1959. Use of the service was placed on a voluntary basis for participants in the atomic energy program.

ORNL participated in the quality assurance program, and all filters were independently inspected by the Chemical Corps Arsenal, Edgewood, Md., before shipment to the Laboratory. While a significant improvement in the quality of filters received was observed, shipping and handling damage continued to be a problem. As a consequence of this experience, ORNL embarked on an exploratory program to find a reliable and practical method of checking the efficiency of new filters prior to stocking. The program was intended to supplement rather than replace the service offered by the AEC quality assurance station at Edgewood, Md. The method of determining filtration efficiency employed by the quality control stations was modified to suit the needs of the Laboratory and in March 1961, ORNL's program became effective. Since March 1961, ORNL Inspection Engineering Department has checked over 1500 new high-efficiency filters prior to stocking, for conformance with specification requirements. While this is another step in the effort to minimize atmospheric contamination by particulate matter, it is obvious that having an efficient filter in its carton is relatively unimportant except as an interim measure in an overall comprehensive program.

The efficiency of an air handling filtration system not only depends on the individual filters but also on the installation as a whole; for example, sound filters must be properly installed in a structurally adequate system, and essentially all leakage paths must be eliminated. In the final analysis an adequate system can only be assured and attained by measuring the overall efficiency of the installation with the operational filters in place. Concurrent with the ORNL program of testing new filters for stock, a feasibility study was made on in situ testing of actual operative installations. The techniques used for testing individual new filters were applied to determining in situ, the filtration efficiency of systems, and during 1961 and 1962, the feasibility was established by tests. In November 1962, as a part of the ORNL radiation safety policy, it became a requirement that all filter systems containing high-efficiency filters be tested in situ at a frequency depending to some degree upon the particular installation, the process involved, and attendant operating hazards. To date, over 650 banks of filters have been tested in situ; the largest installation contained two hundred 24- by 24-in. filters and had a nominal operating capacity of 100,000 cfm of air.

Effective Jan. 1,1963, the ORGDP of Union Carbide Nuclear Company became an AEC quality assurance station to replace the filter inspection service formerly provided by Edgewood Arsenal.[3]

2. THEORY OF FILTRATION AND FILTRATION EFFICIENCY DETERMINATIONS

2.1. Introduction

The high-efficiency filter illustrated in Fig. 1 has an efficiency of 99.97% or higher based on 0.3-μ particles. The usual methods of measuring filter efficiencies, such as the dirt weight and discoloration tests, are wholly inadequate for testing CWS or AEC filters from the standpoint of time and particle-size requirements.

The AEC quality assurance stations use a machine[4] in which an aerosol of dioctyl-phthalate (DOP) is generated from the liquid to produce particles with an average size of 0.3 μ. The 0.3-μ particle was selected by the Army Chemical Center, since it is considered to be the most difficult to remove by filtration. In general, particles of this size are too small to be collected by impaction and too large to have a tendency to be caught by random Brownian motion. The filter under test is placed in an air stream containing these particles, and the concentration of the particles is measured before and after the filter by means of a photometer which measures the intensity of light forward scattered from the DOP particles.

Fig. 1. High Efficiency Filter 24 X 24 X $11\frac{1}{2}$ in.

2.2. Filter Test Rig

The method used by ORNL for measuring filter efficiencies approximates the system employed by the AEC quality assurance stations. Figure 2 shows the original ORNL installation for testing individual new filters for stock. A polydisperse aerosol is produced by atomizing liquid dioctyl-phthalate with compressed air in the chamber at the right-hand end of the rig. The aerosol is swept through the system by the incoming air, since the rig is on the suction side of the blower, passes through the filter under test, and is then discharged to the atmosphere. The efficiency of the filter is calculated from the concentration of the particles, measured by means of a photometer, in samples removed from upstream and downstream of the filter.

The rig was modified to include a long, straight downstream run of pipe to accommodate an orifice for airflow measurements and to induce thorough mixing of the particles with the air before the downstream sample tap. The modified rig is shown in Fig. 3. The pump for removing samples from the air stream and the photometer are shown in the foreground.

2.3. Forward Light Scattering Photometer

The concentration of particles (DOP) in a sample is measured by means of a forward light scattering photometer and amplifier combination. Figure 4 shows a cross section of a typical photometer and light scattering chamber. The interior surfaces of the chamber are dull black to minimize internal scattering of stray light. The air sample containing particulate matter is drawn into the chamber, passes through a pair of open-ended cones apex to apex, and is then discharged. The optical system in front of the light source is such that the beam of light forms a hollow cone, the center of which is a cone of darkness. The lens and phototube at the opposite end of the chamber are located within the diverging cone of darkness; thus only light which is forward scattered from particulate matter in the cone of light reaches the phototube.

Figures 5 and 6 show two different photometers used by ORNL. The one in Fig. 5 is manufactured by the Phoenix Precision Instrument Company, and Fig. 6 is a National Instrument Laboratory (NIL) instrument. The NIL photometer is a copy of an instrument designed by the U.S. Naval Research Laboratory.[5]

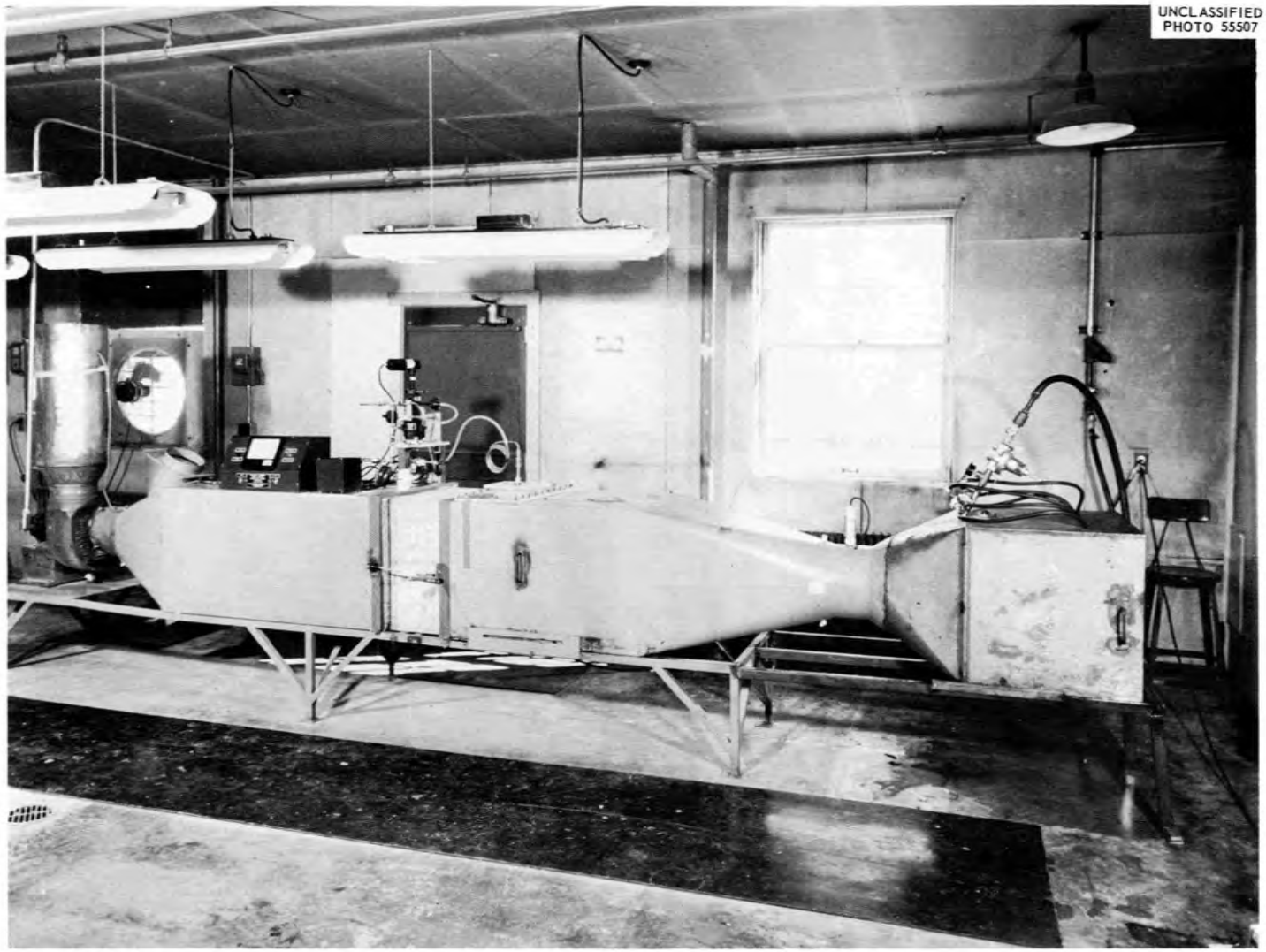

Fig. 2. Original Filter Test Rig for Testing New Filters.

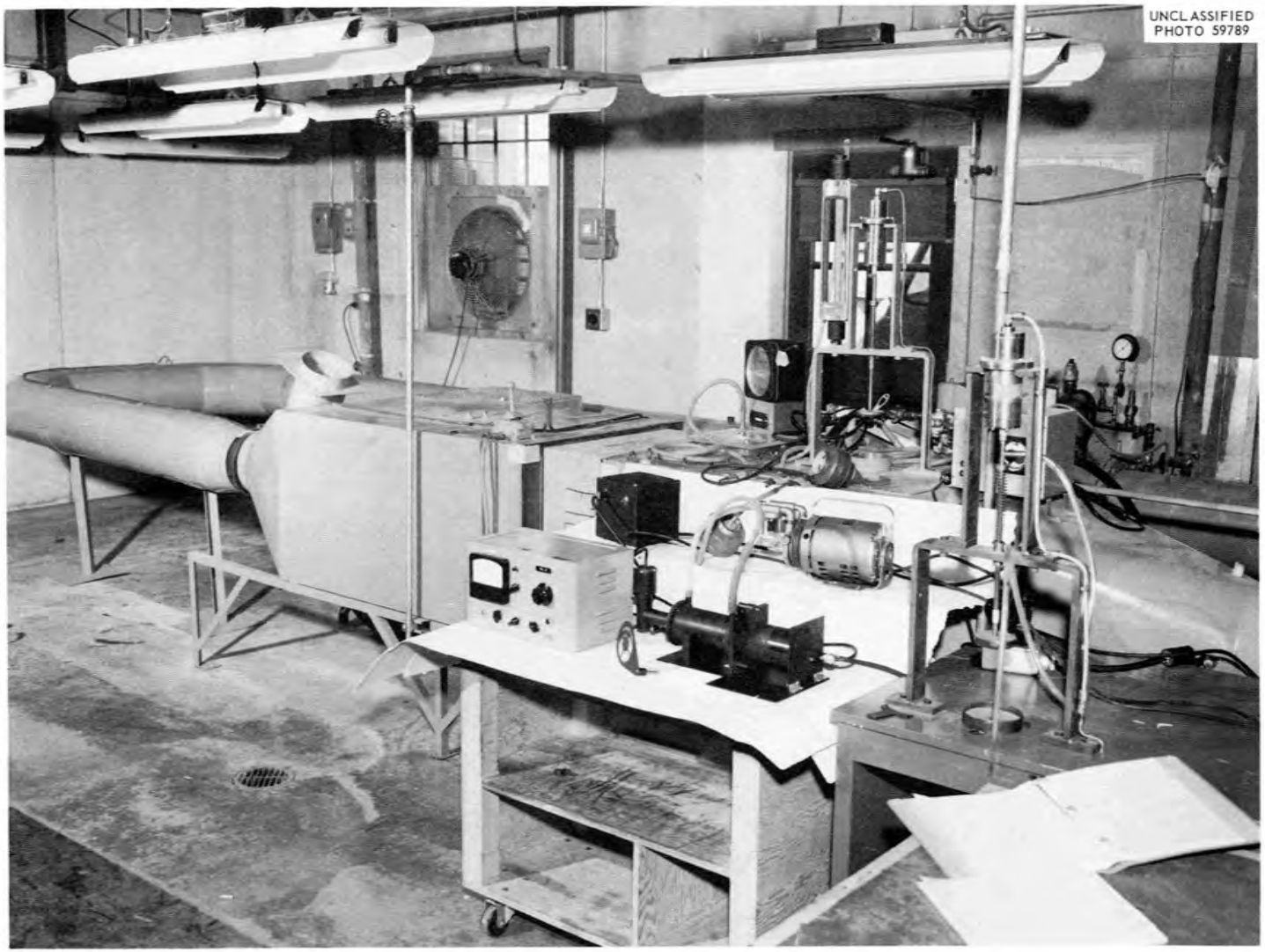

Fig. 3. Modified Filter Test Rig for Research and Testing New Filters.

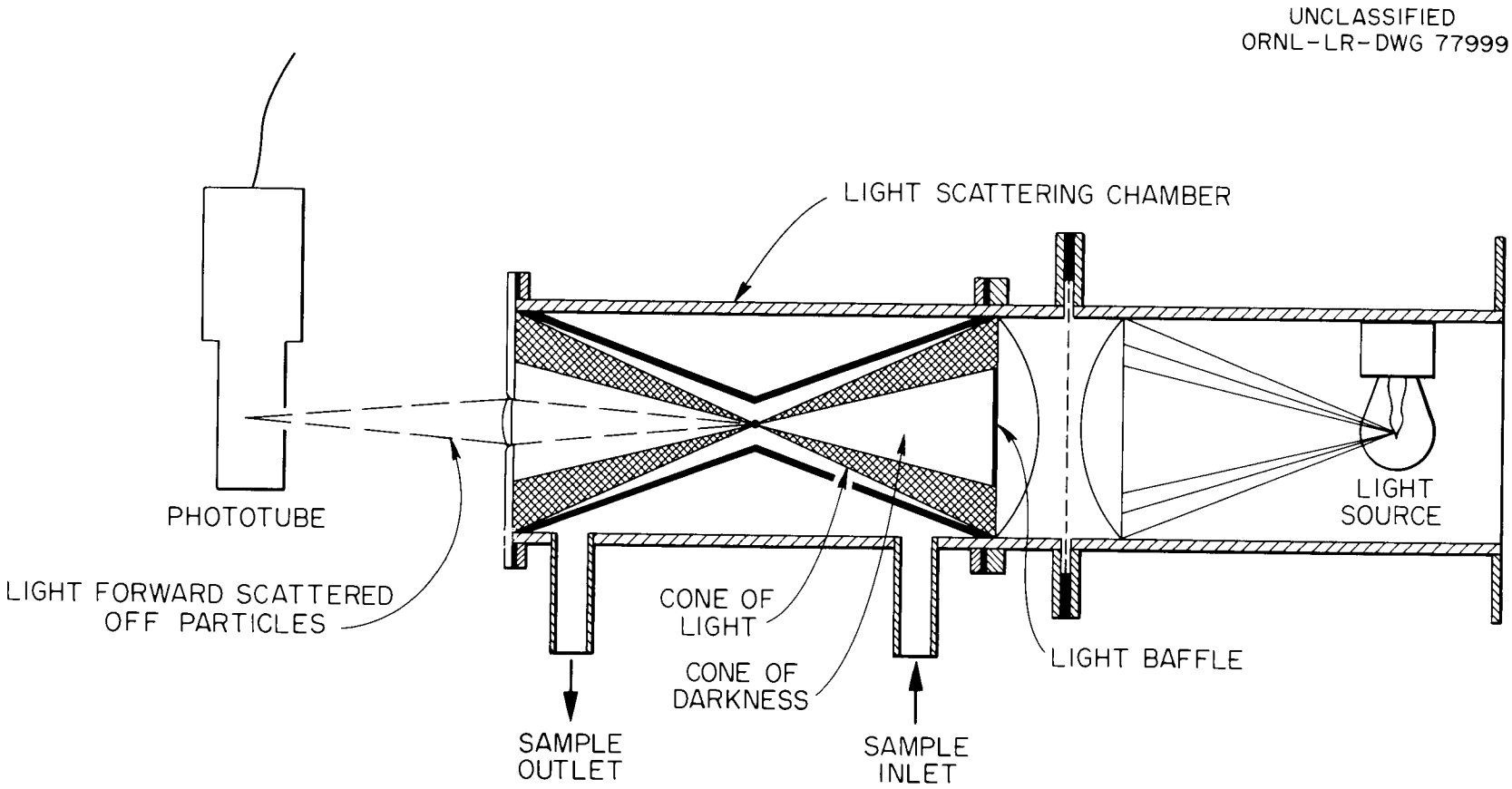

Fig. 4. Cross Section of a Forward Light Scattering Photometer.

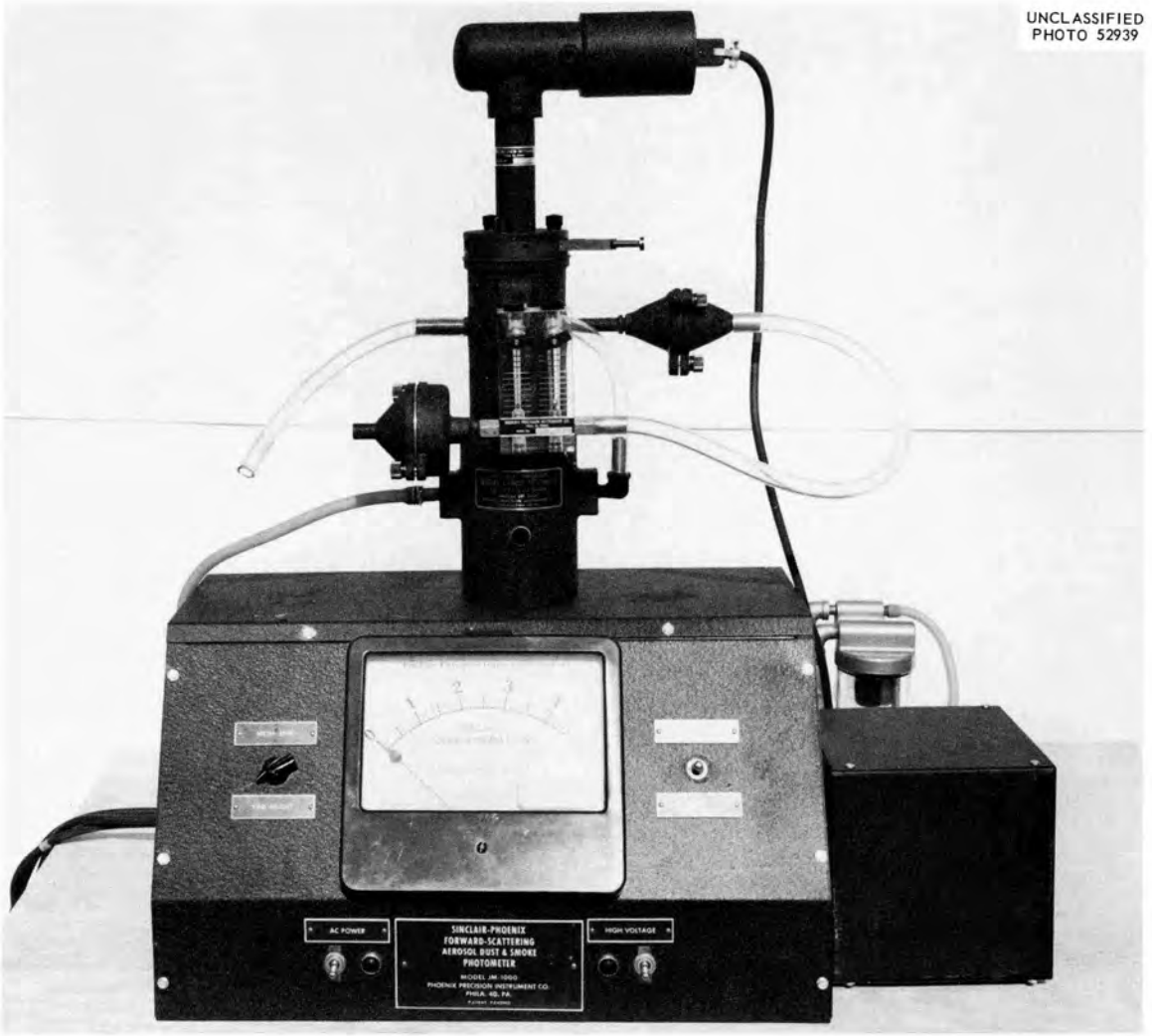

Fig. 5. Logarithmic Amplifier and Photometer.

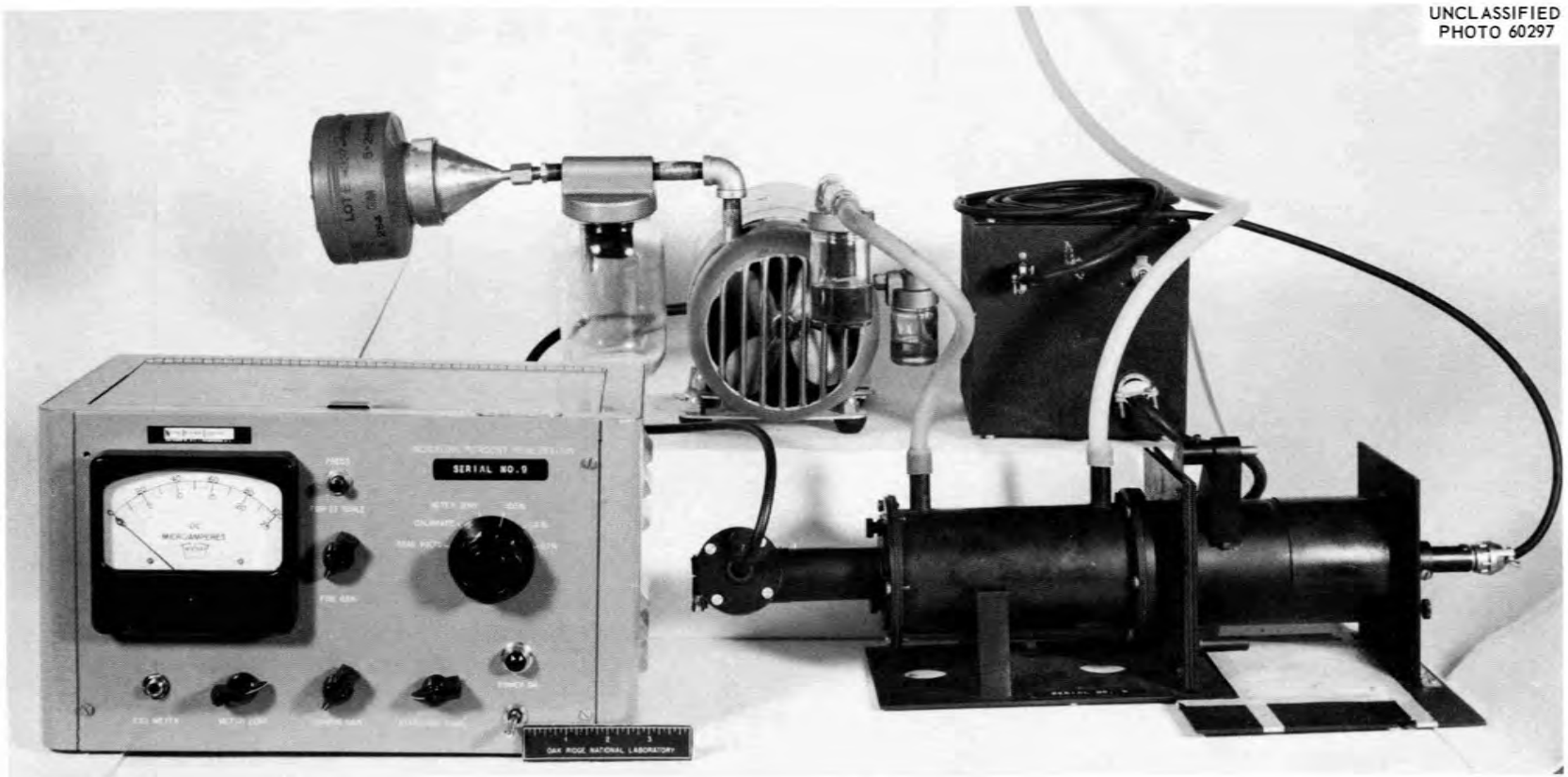

Fig. 6. Naval Research Laboratory Type Photometer, Amplifier, Transformer and Pump.

2.4. Aerosol Generators

The method which the AEC quality assurance stations use for generating the DOP aerosol produces a uniform smoke with an average particle size of 0.3 μ. However, because of its size and complexity, it is not a practical system for field applications. A simple inexpensive air-operated DOP generator was designed by the Naval Research Laboratory[6] to produce a smoke of comparable particle size, but, since particle-size separation is accomplished by impaction, the output is too low for most applications.

Figure 7 illustrates a high-capacity air-operated aerosol (DOP) generator recently designed by the Naval Research Laboratory.[7] The high output results from the six atomizer nozzles plus the omission of impactors. The same figure shows an exploded view of the high-capacity generator; the six nozzles appear at the open end of the 5-gal. container. The generators are operated with the level of DOP approximately $\frac{1}{2}$ in. above the atomizing nozzles.

To supply sufficient smoke for testing large multifilter installations, numerous generators are used in series or series-parallel arrangements. The 6-nozzle generator, shown in Fig. 7, has been modified by ORNL to include 12 nozzles, as illustrated in Fig. 8, to reduce the number of generators required for testing large-capacity installations.

The high-capacity air-operated generators produce large quantities of smoke due to multiple nozzles and the omission of impactors. The smoke produced by these generators is a polydisperse aerosol with an average particle size of 0.8 μ, as compared with the 0.3-μ smoke produced by the special generators used by the quality assurance stations. Tests have shown this difference in particle size to be relatively unimportant for practical testing applications within the precision of measurement requirements.

3. IN SITU TESTS OF INSTALLATIONS

3.1. ORNL Standard Technique

The same technique described in Sec. 2.2 for testing individual new filters for stores has been adapted by ORNL to in-place testing of filter systems. A polydisperse aerosol of dioctyl-phthalate, produced by atomization of the liquid with compressed air, is discharged into the system through any convenient air intake ahead of the filter bank. The

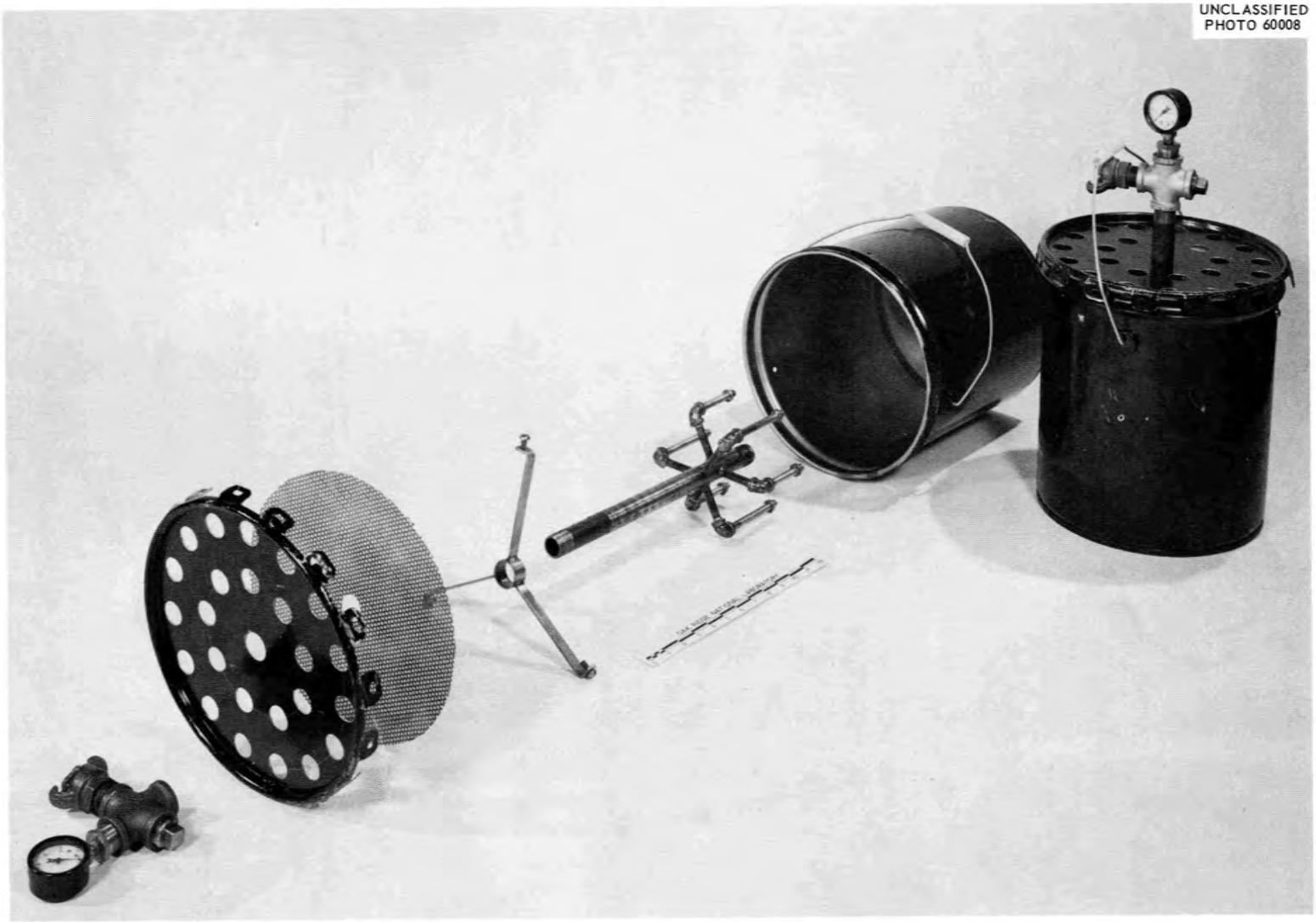

Fig. 7. High-Capacity Aerosol Generator.

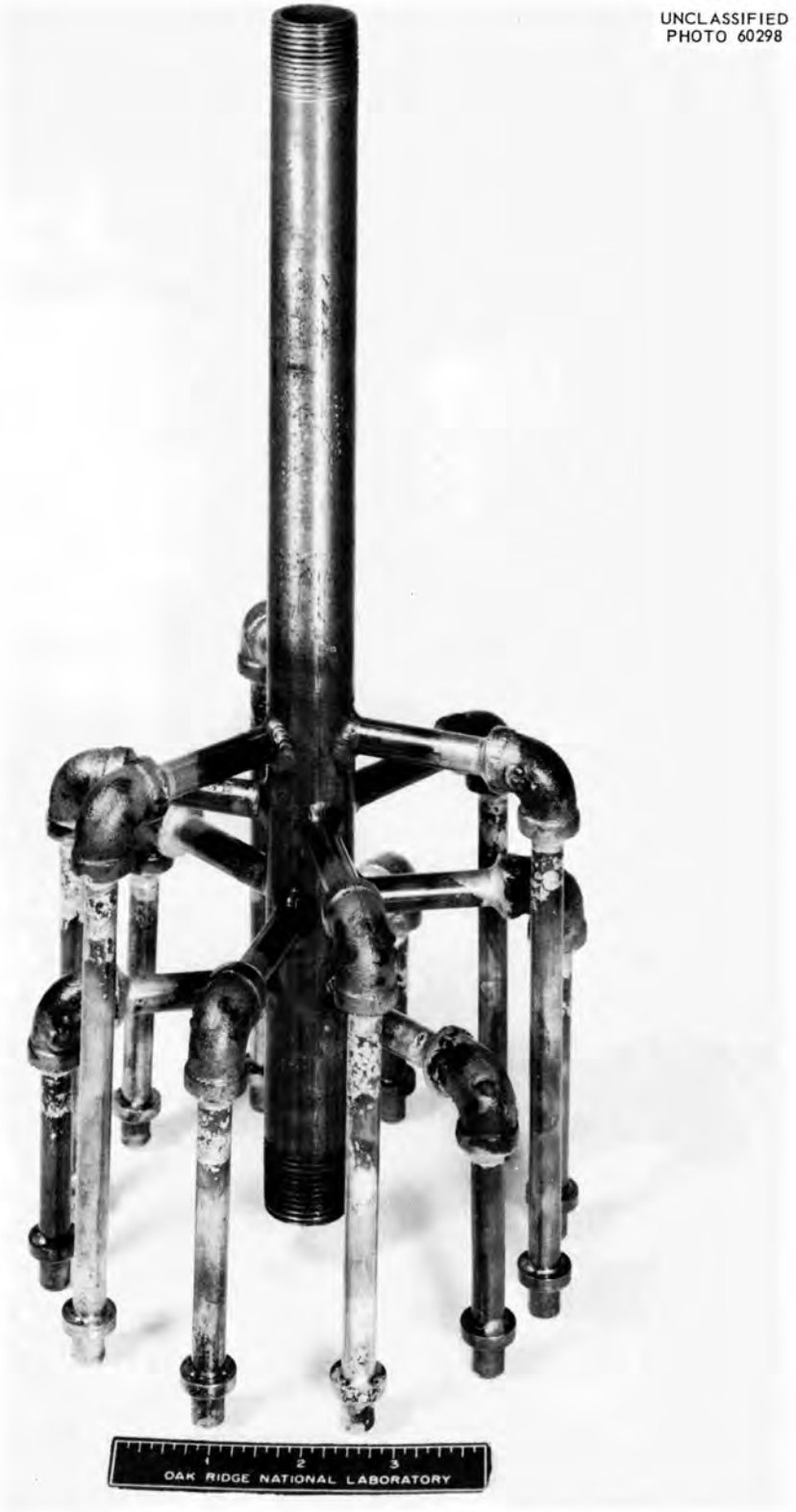

Fig. 8. Twelve-Nozzle Atomizing Unit for an Aerosol Generator.

concentration of the unfiltered smoke is then measured, by means of the forward light scattering photometer, from samples removed from the system ahead of the filter bank. The concentration of the aerosol in the filtered air is measured downstream of the filters. The efficiency of the filtration system is then calculated from the concentration of the aerosol before and after the filters.

Figure 9 shows one method of introducing the aerosol into a system wherein a plastic sheet is used as the collecting hood. Figs.10 and 11, respectively, illustrate the removal of an upstream (unfiltered) and downstream (filtered) sample from a system; the amplifier and light scattering chamber appear in the foreground. Due to the short length of duct between the filter bank and blower, the downstream sample is removed after the blower, where a homogeneous mixture occurs.

When an in situ test shows a system to have an unsatisfactory efficiency, corrective action is indicated. The source of leakage may be due to (1) damaged filters, (2) damaged or inadequately seated gaskets, (3) warped or rough filter mounting frames, or (4) other continuous paths between the two sides of the filter bank. Figure 12 illustrates one method of locating the source of trouble. The downstream side of the filter bank is probed with the probe connected directly to the photometer; leakage paths are readily detected by erratic behavior of the pointer on the amplifier. Aerosol is swept through the system during the probing operation but often at a reduced concentration (see Sec. 5.4).

3.2. Ramifications of the Standard In Situ Test

It is sometimes necessary to modify the basic technique to circumvent problems imposed by the physical arrangement of a particular system. The basic technique requires the removal of representative samples of the smoke (aerosol) before and after the filter bank under test. Accordingly, in order to conduct this test, there must exist a sufficient length of duct between where the aerosol is introduced and the filter bank, to induce thorough mixing of the air and the DOP particles. If diluent side streams exist, a sufficient length of duct is then required between the last side stream and the filter bank for complete mixing before the upstream or unfiltered sample is removed.

If a representative upstream sample cannot be obtained for the reasons indicated above, a reliable in situ test is still possible. In this instance the aerosol is introduced in the same manner (through a convenient intake), but only filtered samples are removed for concentration determinations. The equivalent upstream concentration is then measured indirectly by installing the smoke generators downstream of the filter

Fig. 9. Temporary Shroud for Introducing Aerosol into a System.

Fig. 10. Removal of an Unfiltered Sample for a Concentration Determination.

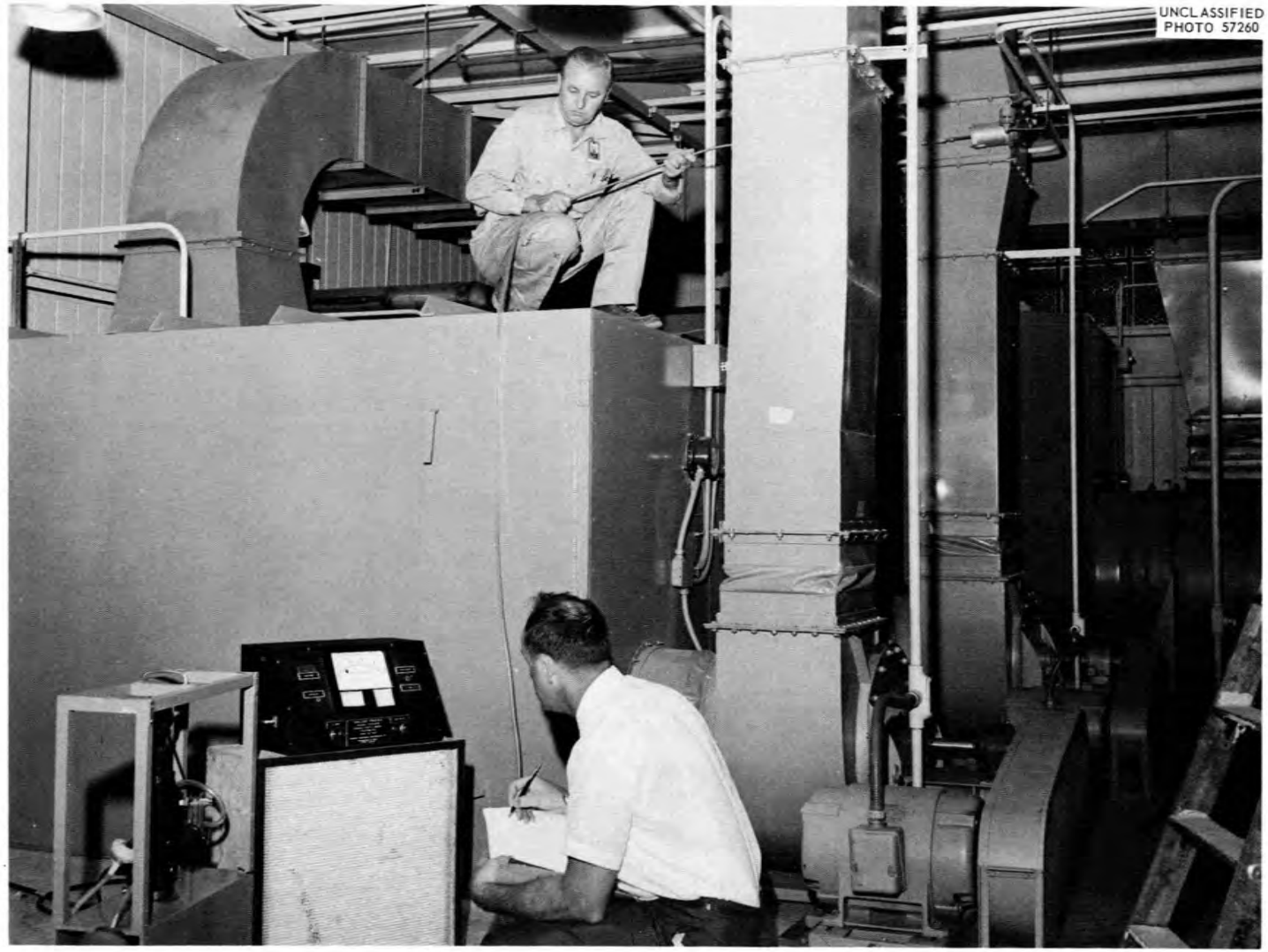

Fig. 11. Removal of a Filtered Sample for a Concentration Measurement.

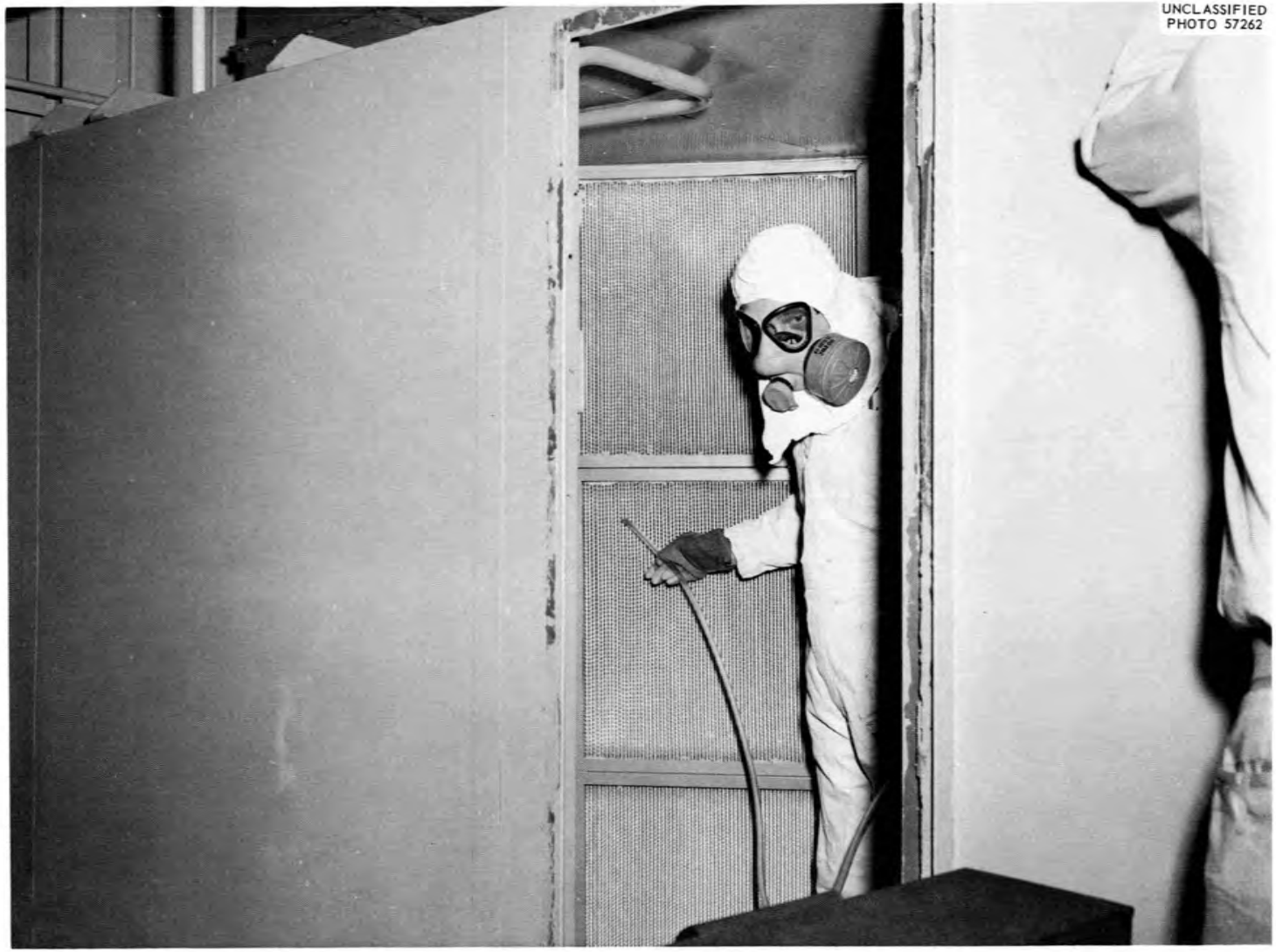

Fig. 12. Probing the Downstream Side of a Filter Bank.

bank and sampling further downstream before or after the blower. This indirect method is reliable if care is exercised in maintaining the output of aerosol and the airflow through the system constant during the testing period.

An alternate, indirect method of determining the upstream aerosol concentration is based on the fact that the output of a generator depends only on the pressure of the compressed air at the generator and the level of the DOP. Each smoke generator is calibrated in a system of known airflow, and an OUTPUT vs PRESSURE curve is drawn. Then, if the airflow in the system under test is known or can be accurately measured, the upstream aerosol concentration is calculable from the calibration curves.

In general, the in situ test can be applied to most systems using the standard technique or some modified version such as one of those discussed above.

3.3. Results of In Situ Tests at ORNL

Since the inception of the in situ filter testing program at ORNL, over 650 in-place tests have been made. Some systems or banks of filters were tested more than once as a result of repairs, modifications, or filter changes; thus retests are included in the 650 figure.

There are many ways available to present the results of the tests to illustrate differences which may exist between different types of systems. It appears that, on the average, small systems containing one or two high-efficiency filters should give a higher "first-test" efficiency than comparable systems with a greater number of filters. Likewise, it seems reasonable to expect that filters serving chemical laboratory exhaust hoods might have lower "first-test" efficiencies, due to the presence of corrosive vapors, than systems handling air that is essentially free of chemical vapors.

Table 3.3.1 presents the results of the first in situ test of 487 different systems. Two categories were selected for the reasons indicated above: (1) Chemical Laboratory Hood Exhaust Systems and (2) Cell Ventilation and Normal Building Exhaust Systems. Each category has been subdivided to indicate filter banks of one or two filters and banks containing three or more filters. The term "first test" is intended to mean the first in situ test of the particular system and bears no relation to the age of the installation or the length of time the particular filters were in service prior to the test. In some instances, filters in Category 2 may be subject to corrosive vapors and thus the classifications should be interpreted as representing "prime functions" only.

Table 3.3.1. Results of the First *In Situ* Test of Two Different Types of Systems Employing High-Efficiency Filters

Range of Efficiency (%)	Category 1 Chemical Laboratory Hood Exhaust Systems				Category 2 Cell Ventilation and Normal Building Exhaust Systems			
	1 or 2 Filters per Bank		3 or more Filters per Bank		1 or 2 Filters per Bank		3 or more Filters per Bank	
	Number	Percent of Total	Number	Percent of Total	Number	Percent of Total	Number	Percent of Total
100.00 - 99.97	263	76.0			72	79.0	15	30.6
99.97 - 99.95	5	1.4	1	100	3	3.3	3	6.1
99.95 - 99.90	15	4.3			2	2.2	4	8.1
99.90 - 99.0	25	7.2			5	5.5	20	41.0
99.0 - 95.0	22	6.4			7	7.7	4	8.2
95.0 - 90.0	7	2.0			0	0	1	2.0
90.0 - 80	4	1.2			0	0	0	0
80 - 0	5	1.4			2	2.2	2	4.1
Total	346		1		91		49	

Based on the data of Table 3.3.1 and an experience factor which the data do not reflect, the following conclusions may be drawn:

1. It is relatively easy to achieve a system efficiency of 99.97% or higher in single- and double-filter installations. No significant difference is apparent between Categories 1 and 2.

2. Relatively few existing, large multifilter installations had a satisfactory efficiency at the time of the first test. Only 31% of the systems containing three filters or more had an efficiency of 99.97% or better on first test as compared with about 78% for the one- and two-filter installations.

3. New systems of all sizes have a reasonably good chance of passing a preoperational in situ test if close attention is given to details of design and fabrication and if the filters are installed under close supervision.

The data shown in Table 3.3.1 were accumulated from in situ tests of the following installations:

Building	System
Building 2528	Vibratory compaction facility. Building and hood exhaust system.
Building 3003	ORNL Graphite Reactor off-gas system.
Building 3005	LITR off-gas filter system.
Building 3012	Hood serving mezzanine floor and foundry room exhaust system.
Building 3019	Three filter banks of filter house 3091.
Building 3026-C	Hood exhaust filter system.
Building 3026-D	Cell ventilation system for Building 3026-D and the hot cells in Building 3042.
Building 3042	Iodine trap filter.
Building 3044	General building exhaust and beryllium system.
Building 3092	Two filter systems to the caustic scrubber discharge.
Building 3106	Six filter banks in the filter housing.
Building 3108	Three banks of filters: east, middle, and west.
Building 3110	Two filter banks serving the cell ventilation system and the iodine cell ventilation system.
Building 3508	Exhausts for Rooms 1 to 5. Cell ventilation and glove boxes.
Building 3517	Main cell ventilation and cell ventilation bypass system.

Building 3592	Walk-in hood system and building ventilation system in the Volatility Laboratory Unit Operation.
Building 4500N	All exhaust systems in 4500N, Wings 1, 2 and 3.
Building 4500S	Chemical laboratory hoods and room ventilation systems.
Building 4508	Chemical laboratory hoods and room ventilation systems.
Building 7500	HRT cell ventilation system.
Building 9201-2	Cyclotron ventilation system.
Building 9204-3	General exhaust, components wash area, and glove box exhaust system.

Subsequent investigation of many of the low-efficiency systems disclosed the following to be the significant causes of leakage through or around the filters:

1. Improper sealing between filter and frame.

   a. Loose hold-down clamps.
   b. Damaged gaskets.
   c. Foreign material between gasket and frame.
   d. Rough or warped surfaces on the filter mounting frame.
   e. Insufficient number of hold-down devices or devices incorrectly positioned.

2. Defective filter medium.

   a. Deterioration from chemical attack.
   b. Punctured due to careless handling at time of installation.
   c. Sagged due to incorrect installation, that is, pleats horizontal instead of vertical.

3. Defects in filter frame and housing.

   a. Unwelded joints at corners and sides of frames.
   b. Absence of a frame member between two adjacent filters.
   c. No provisions for clamping filter to frame. (Designer apparently believed that the pressure drop across the filter would provide an adequate gasket seating force.)

4. PRECISION OF MEASUREMENTS

4.1. Introduction

To adequately describe the efficiency of an individual filter or a system, it is necessary to supplement the efficiency figure with a number which represents the confidence limit of the measurement. While the methods of determining confidence limits are straightforward statistical procedures, the problem is complicated, owing to the number of factors which can directly or indirectly influence the value, namely:

1. The difference between technicians conducting the test.
2. The calibration of the instrument (photometer).
3. Inherent differences between instruments.
4. Drift of the instrument during the test period.
5. Duration of test, since the efficiency of a filter decreases after prolonged exposure to an aerosol of dioctyl-phthalate.
6. Changing concentration of the aerosol as a result of fluctuations in the system airflow during the test period.
7. Rapid fluctuations of the photometer (amplifier) resulting from the inability of the system to attain equilibrium.
8. Absolute value of the concentration of aerosol upstream of the filters. (A constant error in reading the photometer is less significant when high concentrations of aerosol are used.)

Item 7 presents the greatest problem when attempting to specify confidence limits. When relatively inefficient filters or systems are tested, a type of instability exists downstream of the filter bank as a result of aerosol "pulsing" through leakage paths. In these cases the degree of instrument fluctuation appears to be a function of both efficiency and the means employed to induce mixing before the downstream sample is removed.

The data accumulated from tests of new filters for stores have been analyzed to approximate the precision of the measurements. In addition, statistical control tests were conducted in the test rig to experimentally determine confidence limits for both efficient and relatively inefficient filters.

4.2. New Filters for ORNL Stores Stock

Essentially all filters for stores stock have been tested with Sinclair-Phoenix photometers (Fig. 5). Since the instruments were calibrated against Naval Research Laboratory type photometers (Fig. 6), errors in efficiency determinations reflect, in some complex way, the composite errors of both instruments.

In October 1962, 100 high efficiency filters were checked by the

quality assurance station at Edgewood, Md., and the same filters were later checked at ORNL prior to stocking. For comparison it was assumed that the values reported by Edgewood were correct and that all differences were due to errors in ORNL's measurements. The comparison showed the average deviation between the efficiencies measured by ORNL and those reported by the quality assurance station to be $\pm 0.003\%$ and the standard deviation (σ) to be 0.005%. In addition, 95% of ORNL's values were within $\pm 0.010\%$ of the reported values, or, statistically, 2σ equalled 0.010%.

Figure 13 shows representative data used for the above comparison. The efficiencies reported by the filter manufacturer are included, but the data were not used in the analysis.

An identical analysis was made on data representing a shipment of 98 filters of a different manufacturer. The filters were tested using a Sinclair-Phoenix photometer, and the efficiencies of 95% of the filters were checked within $\pm 0.012\%$ of the values reported by the Edgewood Arsenal quality assurance station. Since the results include the composite errors of two instruments (the Sinclair-Phoenix was calibrated against an NRL type photometer), smaller 2σ values would probably have been found if the filters had been tested at ORNL with an NRL type photometer.

4.3. Statistical Control Test

A carefully designed statistical control test was conducted in the filter test rig to permit estimating confidence limits. Efficiencies were measured using an NIL photometer (NRL type instrument) since this instrument is now in general use at ORNL and since AEC quality assurance stations use a similar photometer.

A series of efficiency measurements were made on each of two 24 X 24 X $11\frac{1}{2}$ in. high-efficiency filters. A new filter and a visibly damaged one were selected for the tests.

Test 1-A (New Filter)

1. A high-efficiency filter was installed in the rig (Fig. 3) in the conventional manner.

2. The air pressure on the aerosol generator was set to give a nominal upstream concentration of 90 concentration units. (One concentration

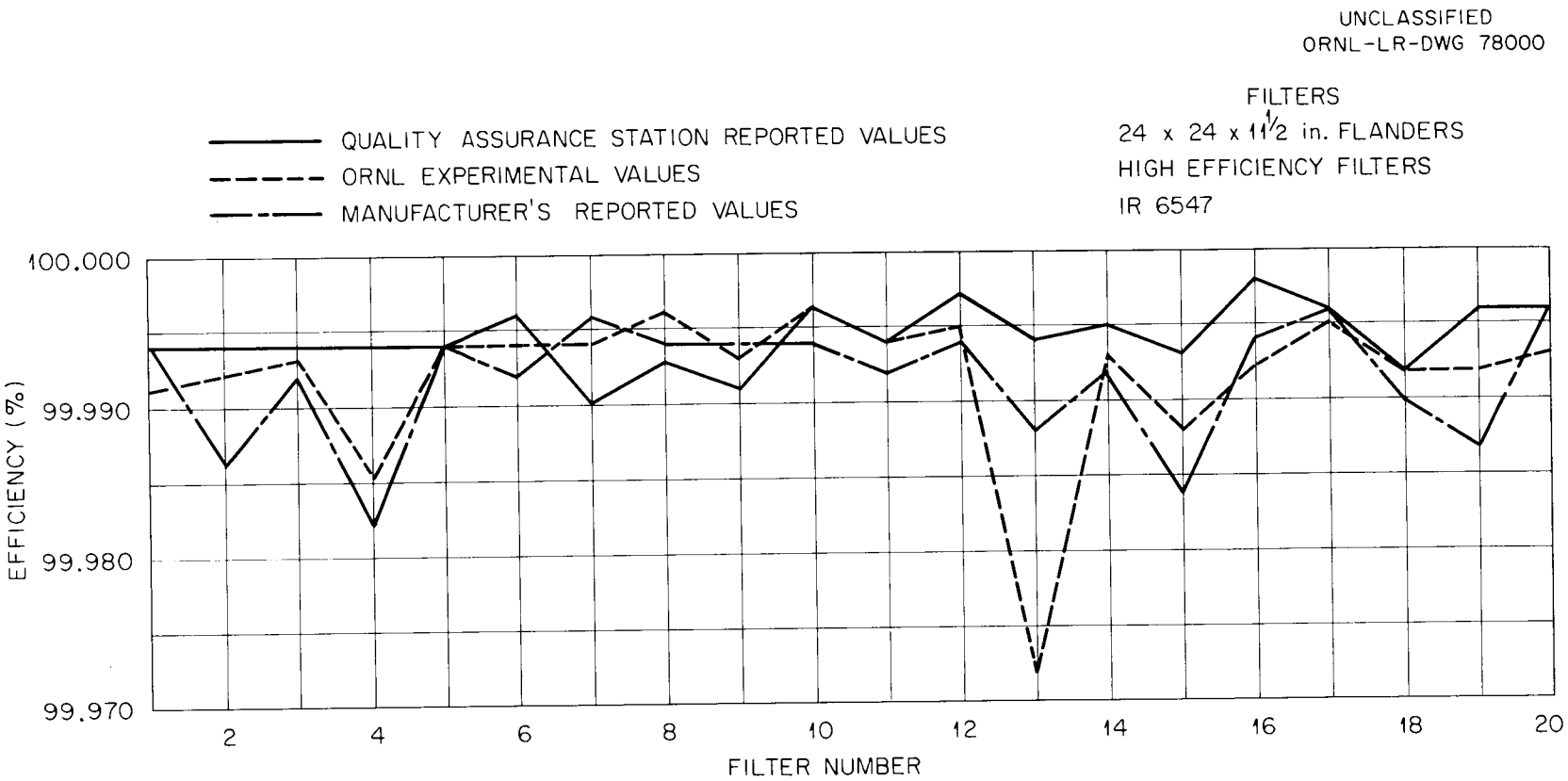

Fig. 13. Comparison of Efficiency Measurements by Filter Manufacturer, Quality Assurance Station, and ORNL

unit is approximately 0.8 μg of dioctyl-phthalate (DOP) per liter of air.)

3. Five technicians, A through E, read the photometer, first on the upstream sample and then on the downstream sample. The calculated efficiencies are recorded in column 1 of Table 4.3.1.

4. The upstream concentration was changed slightly, so the absolute values did not change significantly, but enough that a technician would not be influenced by his previous reading.

5. The photometer was again read and the data are tabulated in column 2.

6. Steps 4 and 5 were repeated three more time, and the data are shown in columns 3,4, and 5.

Test 1-B (New Filter)

Test 1-B was run with the same filter as used for Test 1-A. A nominal upstream concentration of 50 concentration units was used; otherwise the test was a duplicate of 1-A.

Tests 2-A and 2-B (Visibly Damaged Filter)

Tests 2-A and 2-B duplicated 1-A and 1-B, except that a visibly damaged filter was used; the data are given in Table 4.3.2. A statistical analysis of the data from Tests 1-A, 1-B, 2-A and 2-B was made by the Statistics Section, ORNL Mathematics Panel. The analysis indicates that for sound filters (represented by Tests 1-A and 1-B), the 95% confidence limit is ±0.0037% with the precision estimate carrying about three degrees of freedom. The 95% confidence limit applies to a <u>single</u> test by <u>any one</u> of the five participants in the experiment when the concentration of the aerosol upstream of the filter is above about 50 concentration units. It is anticipated that the 95% confidence limit of ±0.0037% will decrease as more statistical control tests are run. Since filters are usually purchased with an efficiency of 99.97% minimum (two digits after the decimal point), a 95% confidence limit of ±0.0037% is better than actually required.

Instrument fluctuation is usually experienced when inefficient filters or systems are tested. Since the amount of fluctuation depends on several factors, a statistical analysis of the data from Tests 2-A and 2-B cannot be considered representative of tests of relatively inefficient

Table 4.3.1. Results of Statistical Control Tests of 1-A and 1-B

Test 1-A

Technician	1	2	3	4	5
	Nominal Upstream Concentration of Aerosol In Concentration Units				
	92	88	96	92	88
	Efficiency (%)				
A	99.9934	99.9933	99.9940	99.9945	99.9952
B	99.9936	99.9933	99.9943	99.9946	99.9950
C	99.9935	99.9938	99.9944	99.9945	99.9954
D	99.9935	99.9933	99.9943	99.9946	99.9953
E	99.9935	99.9932	99.9945	99.9946	99.9954

Test 1-B

Technician	1	2	3	4	5
	Nominal Upstream Concentration of Aerosol In Concentration Units				
	51	46	50	47	54
	Efficiency (%)				
A	99.9952	99.9946	99.9956	99.9955	99.9961
B	99.9945	99.9940	99.9955	99.9951	99.9960
C	99.9952	99.9948	99.9959	99.9954	99.9963
D	99.9948	99.9944	99.9954	99.9953	99.9959
E	99.9952	99.9950	99.9958	99.9954	99.9959

Table 4.3.2. Results of Statistical Control Tests 2-A and 2-B

Test 2-A

	1	2	3	4	5
	Nominal Upstream Concentration of Aerosol In Concentration Units				
	83	82	78	80	80
Technician	Efficiency (%)				
A	99.899	99.899	99.896	99.897	99.895
B	99.901	99.896	99.899	99.895	99.898
C	99.900	99.897	99.897	99.899	99.897
D	99.902	99.898	99.897	99.900	99.897
E	99.902	99.898	99.898	99.899	99.898

Test 2-B

	1	2	3	4	5
	Nominal Upstream Concentration of Aerosol In Concentration Units				
	52	47	51	49	50
Technician	Efficiency (%)				
A	99.899	99.895	99.898	99.899	99.895
B	99.900	99.897	99.899	99.900	99.895
C					
D	99.900	99.898	99.898	99.900	99.896
E	99.900	99.899	99.898	99.895	99.897

filters or systems. Nevertheless, Table 4.3.2 shows an unexpected degree of consistency between technicians, and, in addition, there appears to be little difference between the results of Tests 2-A and 2-B, even though one should expect higher precision at the higher aerosol concentrations. Additional control tests are required before general conclusions may be made concerning confidence limits on tests of relatively inefficient filters or systems.

5. MISCELLANEOUS TESTS AT ORNL

5.1. Introduction

Concurrent with the program of testing new filters for stores stock and in situ testing of systems, some investigation has been carried out on parameters which appeared to influence filter efficiency determinations. Instead of conducting an exhaustive study of each influencing factor, preliminary tests were made to obtain the maximum amount of data in a minimum amount of time. It was anticipated that a general study of potential problems would indicate those areas requiring additional attention. The preliminary tests completed to date were designed to indicate: (1) linearity relation of the NRL type photometers; (2) the effect of airflow on the efficiency of a filter or filter system; and (3) the effect of prolonged exposure to aerosol (DOP) on filtration efficiency and resistance to airflow.

5.2. Linearity of the NRL Type Photometer

Even though the NRL type photometer shown in Fig. 6 is considered a standard for aerosol testing of high-efficiency filters, a check was made to determine its linearity as a function of aerosol concentration.

A 24 X 24 X $11\frac{1}{2}$ in. high-efficiency filter was installed in the test rig, and the blower was adjusted to give an airflow of 740 cfm. The output of aerosol was maintained constant by means of a pressure regulator in the air supply to the generator. A bypass line with a 0 to 10 scfh flowmeter was installed around the filter, and measured amounts of unfiltered air were discharged into the filtered air stream. The concentration of aerosol in the mixed stream was then measured as a function of the bypass flow. The data, which are plotted in Fig. 14, show that the photometer is linear with concentration at the low concentration end of the scale. The concentration at 0 scfh bypass flow is due to the fact that the filter is not 100% efficient.

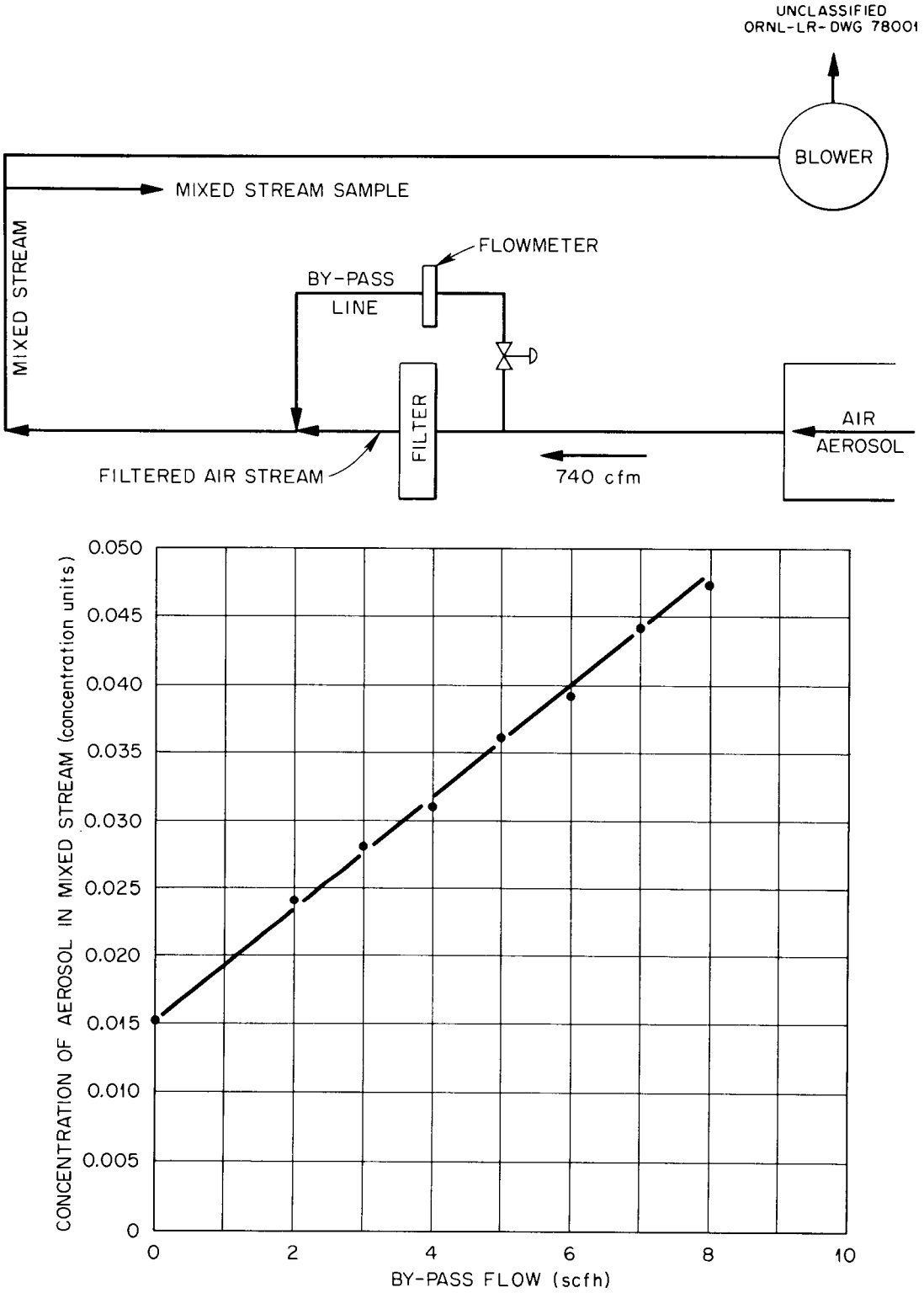

Fig. 14. Linearity of NRL Type Photometer at Low Concentrations of Aerosol.

The linearity of the photometer was also checked in the higher concentration range. An aerosol generator was arranged to produce a constant amount of smoke, and the concentration was varied by changing the airflow through the test rig. The concentration of the aerosol was measured at several flow rates between 470 and 1080 cfm. The data are shown in Fig. 15. If the measured concentration is inversely proportional to the airflow, the instrument may be assumed to be linear over the range of concentrations used. At the low airflows the concentration measurements are likely to be more precise, but the airflow measurements would contain the largest errors; at high airflows the reverse should be true. Near the midpoint of the curve a reasonable precision of measurement can be expected for both airflow and aerosol concentration. The inverse proportionality criterion is thus applied to the concentration measured at 780 cfm, and this curve is compared with the experimental curve of Fig. 15. Excellent agreement exists between the experimental curve and the predicted curve. The curves differ in the low flow range; however, the difference amounts to only 30 of 470 cfm, thus the NRL type photometer exhibits good linearity over a wide range of aerosol concentrations.

5.3. Effect of Airflow on Filter Efficiency

Airflow has little effect on the efficiency of a new (or undamaged) filter over the normal operating range. Aerosol tests on 24 X 24 X $11\frac{1}{2}$ in. filters, at airflows between 400 and 1100 cfm, showed a slight decrease in efficiency with increasing flow, but the trend was barely discernible as a result of the normal scatter of the test points. On the other hand, airflow has a significant effect in the case of filters containing defects due to the "pinhole" effect.[8]

A single 1/8-in.-diam. hole was made in the filter medium of a 24 X 24 X $11\frac{1}{2}$ in. high-efficiency filter. The efficiency of the filter was then measured as a function of airflow rate. The results are shown in Fig. 16; a significant improvement in efficiency is observed at the higher airflows. The scatter in the test results was believed to be due to a "pulsing" of the hole in the filter. In an attempt to overcome this, a synthetic defect was made by drilling a 1/8-in.-diam. hole in a piece of sheet metal and this, in parallel with a sound filter, was placed in the path of the air in the test rig. The test was repeated, and the results are shown in Fig. 17. While the use of a synthetic defect did not reduce the amount of scatter, the filter showed a significant improvement in efficiency with increasing airflow as in the previous test.

The trend shown in Figs. 16 and 17 is known as the "pinhole" effect.

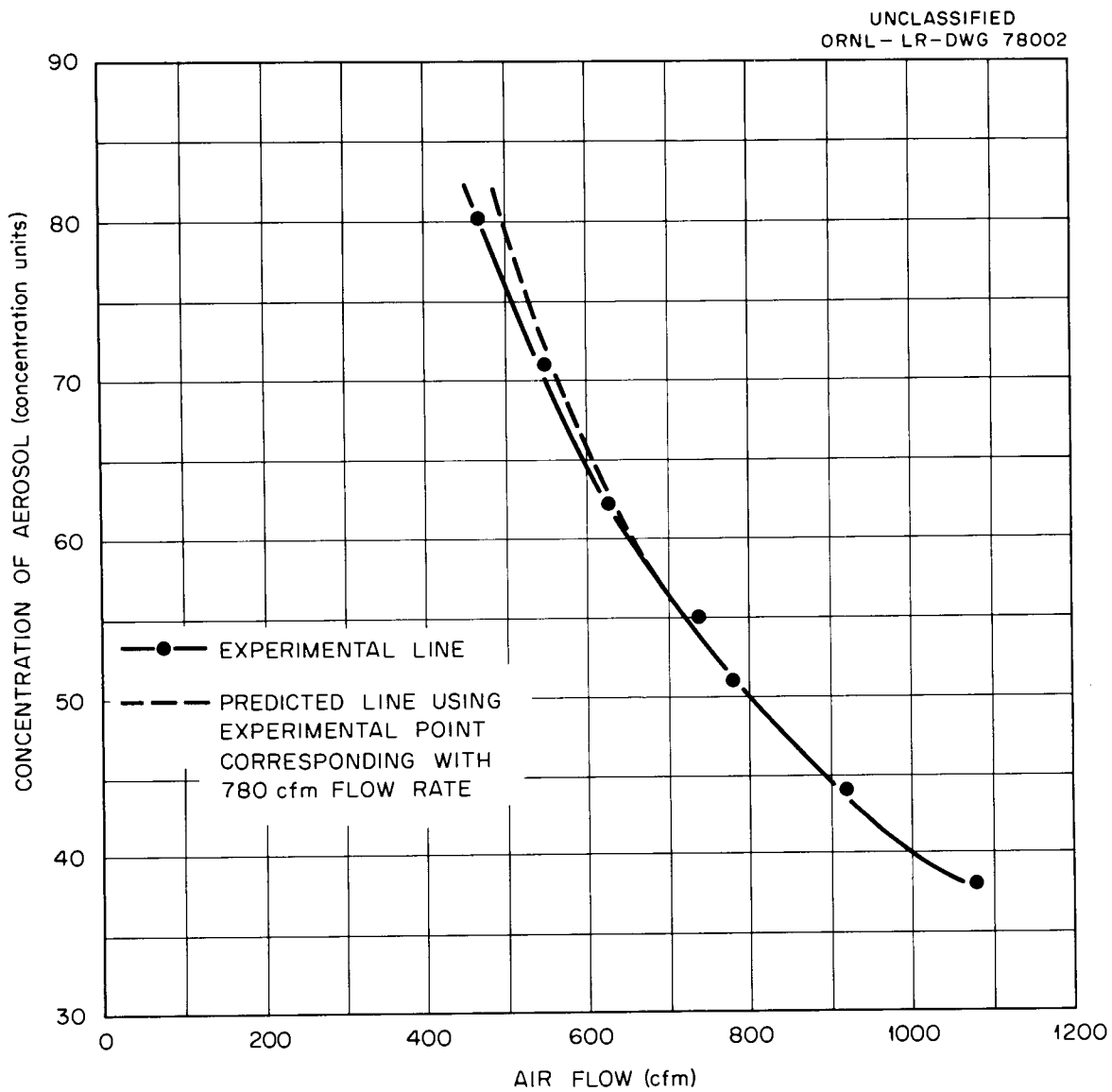

Fig. 15. Linearity of NRL Photometer Over a Wide Range of Aerosol Concentrations.

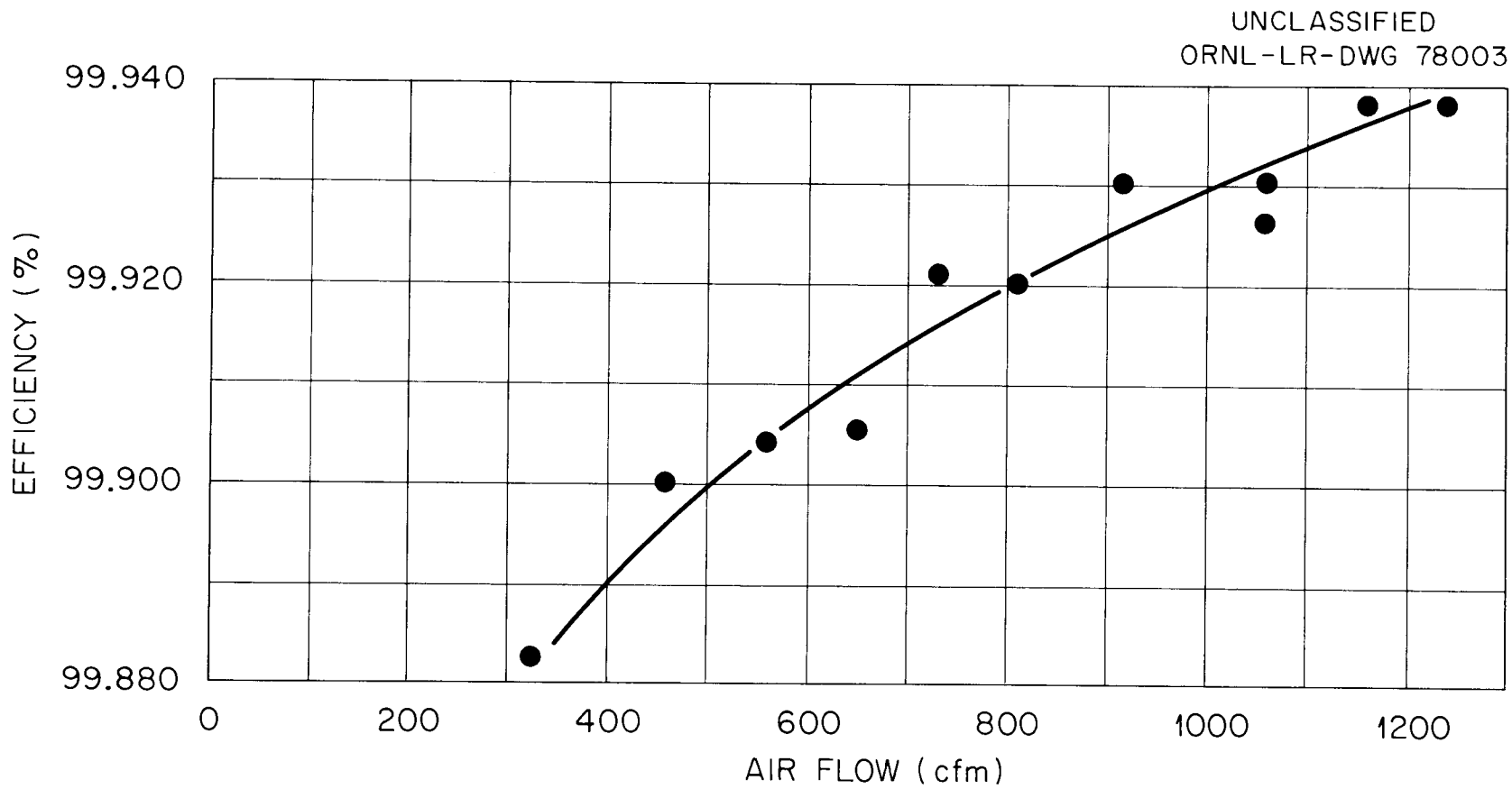

Fig. 16. Effect of Flow Rate on the Efficiency of a Damaged Filter.

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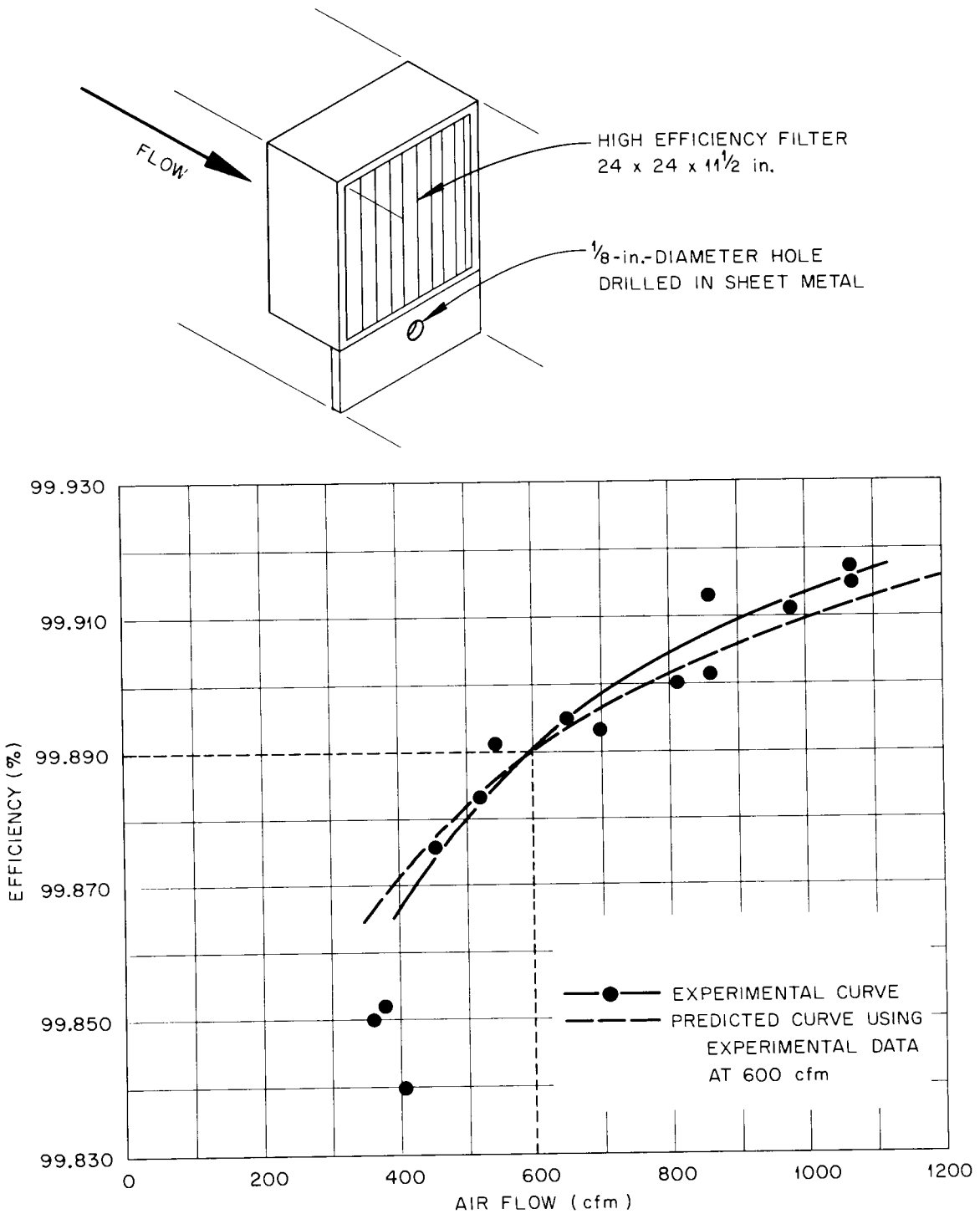

Fig. 17. Effect of Flow Rate on the Efficiency of a Filter with a Synthetic Defect.

The air penetrating the filter medium has laminar or streamline flow characteristics, whereas the air flowing through the hole or defect is turbulent. In turbulent flow, pressure drop is proportional to the square of the flow rate, whereas in laminar flow, direct proportionality exists. Since the pressure drop across the hole (defect) must equal the pressure drop across the filter medium, a lesser increase in flow through the hole is required to balance an increase in flow through the filter medium. In other words, proportionately less unfiltered smoke passes through the filter-hole combination with increasing flow in the system, and thus an improvement in the system efficiency is observed.

The "pinhole" effect may be expressed mathematically as follows:

$$\Delta p_f = A(Q - Q_h) \approx AQ, \tag{1}$$

$$\Delta p_h = B Q_h^2, \tag{2}$$

$$\Delta p_f = \Delta p_h, \tag{3}$$

$$AQ = B Q_h^2 \text{ or } Q_h = \sqrt{\frac{AQ}{B}}, \tag{4}$$

where

Q = total airflow

Q_h = airflow through the defect

Δp_f = pressure drop across filter

Δp_h = pressure drop across defect

k = aerosol concentration before filter

A, B = proportionality constants

E' = efficiency of filter medium without defects ($E' = 1$ for a perfect filter)

The percentage of the total amount of smoke which passes through the filter and hole is

$$\% \text{ penetration} = \left[(1 - E')Qk + k\sqrt{\frac{AQ}{B}}\right]\frac{100}{Qk} = \left[1 - E' + \sqrt{\frac{A}{BQ}}\right]100, \quad (5)$$

and the overall efficiency of the system is

$$\% \text{ system efficiency} = (100 - \% \text{ penetration}) = \left[E' - \sqrt{\frac{A}{BQ}}\right]100. \quad (6)$$

Equation 6 is thus a general equation which permits one to make a prediction of filter (or system) efficiency as a function of flow from a single determination. The filter used for the test represented by Fig. 17 had an efficiency of 99.976%; thus E', according to the above nomenclature, is 0.99976. The faired curve shows an efficiency of 99.890% at 600 cfm. These data substituted into Eq. 6 permits the calculation of A/B as follows:

$$99.890 = \left[0.99976 - \sqrt{\frac{A}{600\,B}}\right]100, \quad (7)$$

or

$$\frac{A}{B} = 0.000444. \quad (8)$$

If Eq. 8 is substituted into Eq. 6, the resulting formula expresses the efficiency of the particular system as a function of flow, or

$$\% \text{ system efficiency} = \left[0.99976 - \sqrt{\frac{0.000444}{Q}}\right]100. \quad (9)$$

The predicted curve based on Eq. 9 is shown in Fig. 17 with the experimentally determined curve.

The method of predicting efficiency vs flow rate from a single measurement applies only when the size of the leakage path remains constant. In some instances filters are installed in a manner such that the pressure drop across the bank tends to unseat them, in which case the unseating force is approximately proportional to the airflow. In these cases, Eq. 6 would not be applicable if the size of the leakage path at the gasket changes with variations in the airflow rate.

In MIL-STD-282, Method 502.1.1, "DOP-Smoke Penetration of Gas-Masks", it is specified that M 11 canisters are to be tested with an aerosol flow rate of 32 liters/min. This is below the 85-liter/min flow, which corresponds roughly with the peak breathing rate of a man doing moderate exercise however, the value was selected because of the "pinhole" effect. If a canister passes the efficiency test at 32 liters/min, it will almost always pass at 85 liters/min, but the converse is not necessarily true.

5.4. Effect of Prolonged Exposure to DOP Aerosol on Efficiency

The cause of leakage in systems with an unsatisfactory efficiency is often found by probing the downstream side of the filter bank with aerosol flowing through the system. The probe is connected to the photometer, and leakage paths are found by observing the erratic behavior of the pointer on the amplifier. The probing operation may require a few minutes to a few hours, depending on the size of the filter bank. Therefore, it is important to know the effect of prolonged aerosol injection on the efficiency of the filters.

A few tests have been made using standard 24- by 24-in. high-efficiency filters in the test rig shown in Fig. 3. The results of the tests are shown in Fig. 18.

Test A. A filter was subjected to a continuous flow of aerosol at a concentration which approximates that which is frequently used for measuring filter efficiency. Figure 18 shows that the efficiency decreased from 99.995% to 99.955% in 7 hr, and the pressure drop across the filter increased from a 0.95-in. water column to a 1.43-in. water column in the same period.

Test B. Test A was duplicated, except that the aerosol concentration upstream of the filter was reduced by a factor of 2. A comparison of the curves for Tests A and B (Fig. 18) shows that the effective life of the filter was extended by the use of the lower aerosol concentration. Upon completion of the test, clean air was passed through the filter for 9 hr at a flow rate of 1040 cfm. No improvement in efficiency was observed, in fact, the efficiency decreased from 99.955% to 99.943% during the 9-hr period.

Test C. Test A was duplicated in all respects, except that the method of introducing the aerosol was altered. Aerosol, of the same concentration as used in Test A, was injected for 5 min, and then the flow of aerosol was discontinued for 25 min while clean air was swept through the system.

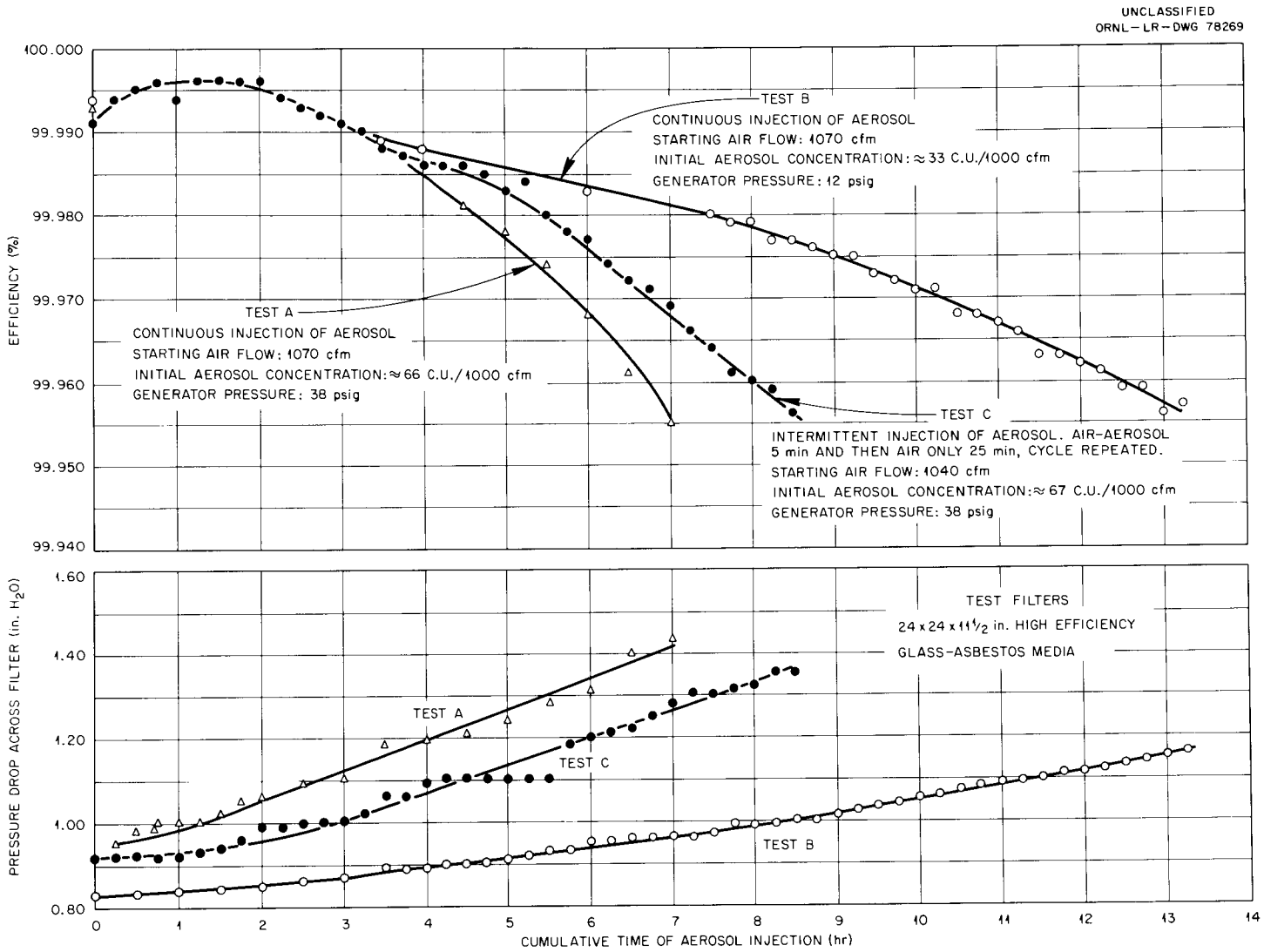

Fig. 18. Effect of Prolonged Exposure to DOP on Filter Efficiency.

The cycle was continued until a pronounced decrease in efficiency was observed. The abscissa of Fig. 18 is the cumulative time of aerosol injection (the total testing time would be about six times the value shown on the abscissa).

The data indicate that the intermittent periods of airflow without aerosol injection allowed the filter to maintain its high efficiency for a longer period of time. Time is computed as the cumulative time of aerosol injection so that different tests may be compared on a consistent basis.

6. FILTER SYSTEM DESIGN CONSIDERATIONS

6.1. General

The prime function of a high-efficiency filter installation is to remove micron and submicron particulate matter from an air stream before the air is discharged to the atmosphere. In some instances the procedure is reversed, that is, particulate matter is removed from atmospheric air before the air is used. Air supply to a "clean" room is an example of the latter case. In either case, experience has shown that (1) the greatest design effort is directed toward providing a system of adequate capacity, (2) a lesser or comparable amount of attention is given to the structural and functional adequacy of the filter bank plus enclosure, and (3) little or no consideration is given to providing means for initially and periodically verifying the filtration adequacy of the installation. Gradually there has been an increasing awareness by the many participants in the atomic energy program of the importance of in situ checking "high"-efficiency filter systems. While most existing installations can be tested in situ, sometimes at considerable expense and effort, in situ testing of future installations can be simplified by careful planning during the conceptual stage.

6.2. Specific Considerations

The standard in situ test consists in injecting an aerosol into the system ahead of the filters, and calculating a "system" efficiency from the measured concentration of the filtered and unfiltered smoke. Section 3.2 discusses means of accomplishing the test when a representative sample of the unfiltered smoke cannot be obtained in the conventional manner. Other problems may exist; however, many of them can be avoided in future systems as a result of careful preplanning. Figure 19, which is intended to represent a typical high-efficiency filter system,

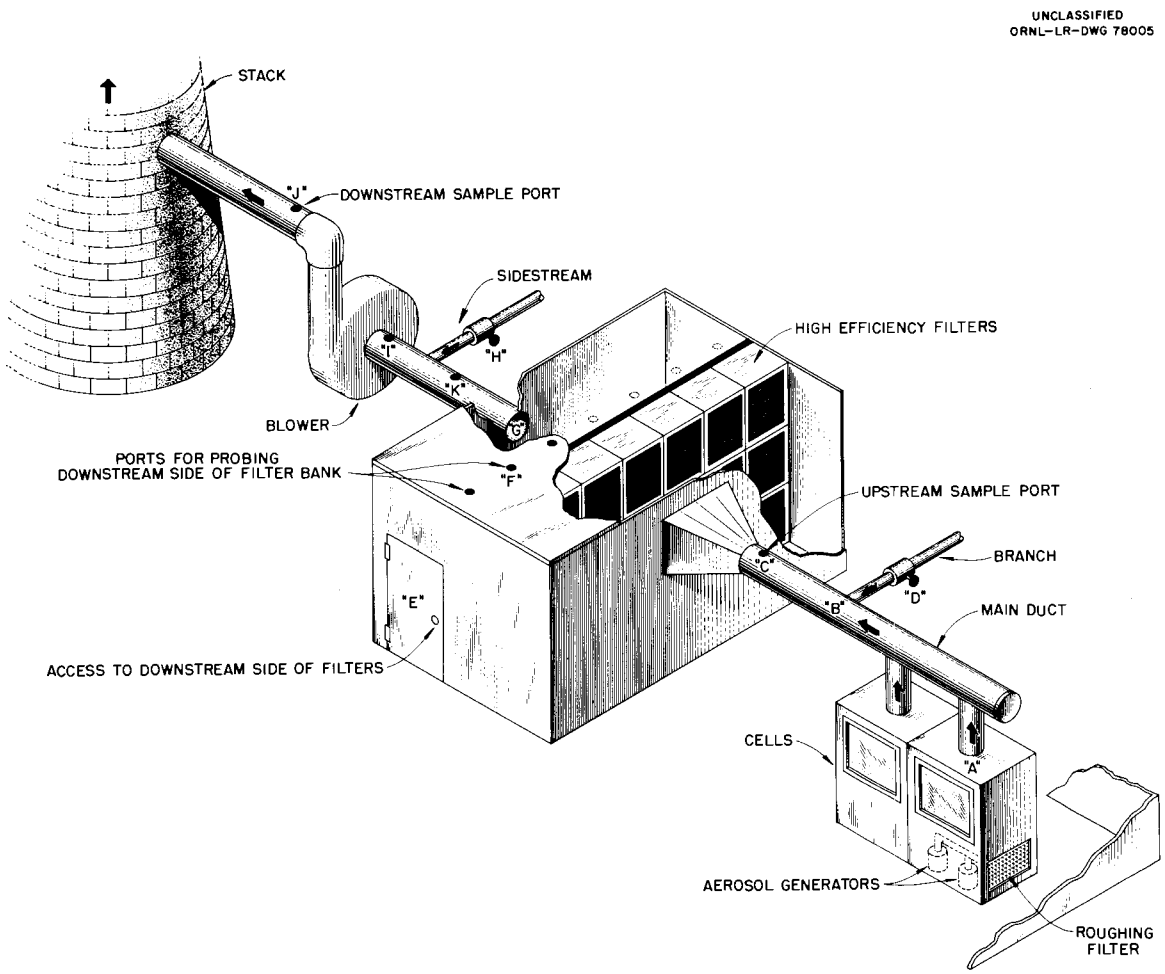

Fig. 19. Items Which Deserve Consideration When Designing a New Installation.

illustrates some of the points which should receive attention during the design stage to facilitate in situ efficiency testing.

Items to consider are:

1. In this case the aerosol generators can be installed in a cell, and the incoming air is used to sweep the smoke into the system.

2. Since a side stream enters the main duct ahead of the filters at "B" the length of duct between "B" and the upstream sample point "C" should be sufficient to induce thorough mixing of the two streams. If valve "D" can be closed during an in situ test, then the distance between "A" and "C" should be sufficiently long that a mixed sample will exist at "C". If these conditions cannot be attained because of physical limitations, then provisions should be made for using one of the alternate test procedures discussed in Sec 3.2.

3. A designer should always assume that the system will not have a satisfactory efficiency on the first test or subsequent tests; thus means for locating the sources of leakage should be provided. This is particularly true for large multifilter installations. Ports may be provided in the filter housing, just downstream of the filters, so that probing of the entire downstream side of the bank can be accomplished. The ports shown as "F" should be $\frac{1}{2}$ in. in diameter (minimum) but sized and spaced to permit full coverage of the filter bank.

   If the size of the filter house permits, an access door "E" to the downstream side of the filter bank would allow probing by the method shown in Fig. 12.

4. If valve "H" can be closed during an in situ test, the filtered air sample may be removed at sample port "J." A downstream sample port at "I" would also be satisfactory if the duct between "G" and "I" is long enough to induce thorough mixing.

   If valve "H" must remain open, then the filtered air sample must be taken at "K," and the duct between "G" and "K" should be sufficiently long so that a homogeneous sample is available at "K."

Most systems can be tested in situ; however, the task is easier and more economical and the results are usually more reliable when installations are designed to facilitate such tests.

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