Designation: F 1471 – 93

Standard Test Method for Air Cleaning Performance of a High-Efficiency Particulate Air Filter System[1]

This standard is issued under the fixed designation F 1471; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the procedure and equipment for measuring the penetration of test particles through high-efficiency particulate air (HEPA) filter systems using a laser aerosol spectrometer (LAS). This test method provides the capability of evaluating the overall effectiveness of HEPA filter systems consisting of one or two filter stages.

1.2 The aerosols used for testing have a heterodisperse size distribution in the submicrometer diameter range from 0.1 to 1.0 µm.

1.3 The purpose for conducting in-place filter testing by this test method is in the ability to determine penetration of multi-stage installations, without individual stage tests. Particle penetration as low as 10^{-8} can be measured by this test method. Also, the LAS provides a measure of penetration for discrete particle sizes.

1.4 Maximum penetration for an installed HEPA filter system is 5×10^{-4} for one filter stage, and 2.5×10^{-7} for two stages in series is recommended.

NOTE 1—Acceptance penetration criteria must be specified in the program, or owners specifications. The penetration criteria suggested in this test method is referenced in Ref **(1)**.[2]

1.5 The values stated in SI units are to be regarded as the standard.

1.6 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Specific precautionary statements are given in Note 2.

2. Referenced Documents

2.1 *ASTM Standards:*

F 328 Practice for Determining Counting and Sizing Accuracy of an Airborne Particle Counter Using Near-Monodisperse Spherical Particulate Materials[3]

2.2 *Military Standard:*

MIL-STD 282 Military Standard Filter Units, Protective Clothing, Gas Mask Components, and Related Products: Performance Test Method[4]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *diluter*—a device used to reduce the aerosol particle concentration to eliminate coincidence counting is in the LAS.

3.1.2 *dilution ratio*—the ratio of the undiluted aerosol particle concentration entering the diluter to the diluted portion of the particle concentration. Because diluters have inherent particle losses that may vary according to the particle size, the dilution ratio may not be constant with respect to size.

3.1.3 *laser aerosol spectrometer (LAS)*—a precision particle detector that allows single particle counting and sizing by the amount of scattered light from individual particles, where the signals can be grouped into categories corresponding to particle size.

3.1.4 *penetration*—the number of particles passing through the filter stage, to the number of particles challenging the upstream side of the filter stage. The penetration, or the challenge aerosol, may be associated for each particle size of interest.

4. Summary of Test Method

4.1 A challenge aerosol produced by Di(2-Ethylhexyl) Sebacate (DOS) or Di(2-Ethylhexyl) Phthalate (DOP) is injected upstream of the filter system and allowed to mix with the airstream. Using a LAS, samples of the aerosol are collected from the airstream through probes, both upstream and downstream of the filter system. With this test method, the penetration of the filter system can be calculated either as a function of particle size, or in a particular size of interest. Due to high particle concentrations that may be required to evaluate the performance of HEPA filter systems, it may become necessary to dilute the upstream sample to avoid errors due to coincidence counting by the LAS.

4.2 If a diluter is required, the diluter system is calibrated using lower particle counts of the same aerosol and using the LAS for the measurements (refer to Annex A1 for calibration).

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[1] This test method is under the jurisdiction of ASTM Committee D22 on Sampling and Analysis of Atmospheresand is the direct responsibility of Subcommittee D22.09on ISO TAG for ISO/TC 146.

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[2] The boldface numbers in parentheses refer to a list of references at the end of this standard.

[3] *Annual Book of ASTM Standards*, Vol 10.05.

[4] Available from Standardization Documents Order Desk, Bldg. 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

4.3 Heterodisperse submicrometer aerosols spanning the diameter range from 0.1 to 1.0 µm are used in the testing.

5. Significance and Use

5.1 This test method describes a procedure for determining the penetration of aerosols through a one- or twostage HEPA filter installation. Testing multiple filter stages as a single unit eliminates the need for: installation of auxiliary aerosol bypass ducts, installation of aerosol injection manifolds between filter stages, and entry of test personnel into contaminated areas. It provides for filter testing without interruption of plant processes and operation of ventilation systems.

5.2 The procedure is applicable for measuring penetrations requiring sensitivities to 0.1 µm.

5.3 A challenge concentration of 2.5×10^5 particles/cm^3(p/cm^3), is required for evaluation of one-filter stage, and 2×10^6 p/cm^3, or about 30 µg/L (assuming unit density), is required to properly evaluate a two-stage HEPA filter system as one unit.

5.4 This test method can determine the penetration of HEPA filters in the particle-size range from 0.1 to 0.2 µm where the greatest penetration of particles is likely to occur.

6. Apparatus

6.1 *LAS*[5]—The LAS is a particle detector for the purpose of sizing and counting single particles in a gas stream. Up to 3000 particles per second (p/s) can be counted with less than 10 % coincidence, or electronic loss at its maximum flow rate. The quantitative particle size distribution shall be a distribution by number, not mass, volume, or surface area.

6.2 The test aerosol should be in the diameter range from 0.1 to 1.0 µm.

6.3 The primary particle-size calibration of the LAS by the manufacturer shall be based on at least three sizes of monodisperse polystyrene latex spheres (PSLs), covering the dynamic range of the LAS. Calibration standards must be traceable to the National Institute of Standards and Technology (NIST).

6.4 Sample flow accuracy through the LAS of ±5 % is required, based on the manufacturer's specifications. (Refer to manufacturer's guide for altitude adjustments of the sample volume.)

6.5 The LAS must have the capability for producing a listing of the particle size distribution over the LAS range. A standard RS-232C interface signal for line printers, tape recorders, and computers is usually provided with the instrument.

6.6 For calibration aerosol having a median size two times the minimum detectable size of the LAS, the relative standard deviation of the particle size distribution indicated by the LAS, shall not be increased more than 10 % over the actual relative standard deviation of the calibration aerosol.

6.7 An aerosol diluter[6] is required to reduce the number of particles of the upstream sample to avoid significant coincidence counting losses in the LAS. The diluter must have minimum particle losses over the size range of interest and that the losses are constant with particle size. Calibration of the diluter is done with the LAS. The diluter calibration procedure is indicated in Annex A2. A schematic diagram of the diluter in calibration mode is shown in Fig. A2.1. The diluter calibration plot is presented in Fig. A2.2. A typical diluter with dimensions is illustrated in Fig. A2.3.

6.8 *Aerosol Generation*[7]—It is required that the generator produce a particle-size distribution covering the diameter range from 0.1 to 1.0 µm. It must have the capability of achieving up to 3000 p/s in gas streams when testing multiple-stage HEPA filter systems.

6.9 For streams where large volumes of aerosol are not required, an air-operated or small gas-thermal generator may be used.

6.10 Injection ports, or manifolds, must be provided for distributing the aerosol uniformly with the gas stream. Upstream and downstream probes are required to extract aerosol samples from inside the filter housing. The location of injection ports and sample collection probes or manifolds must be located in accordance with the requirements in Annex A3.

6.11 It is recommended that sample lines between the LAS, diluter, and the upstream and downstream probes be the same size and material, and the same length as practicable.

7. Reagent and Materials

7.1 *DOP or DOS*[8] is used as the liquid material to form test aerosols.

7.2 *Polystyrene Latex Spheres*. [9]

8. Calibration and Standardization

8.1 Perform the primary calibration of the LAS by the instrument manufacturer or by qualified personnel using acceptable standard methods in accordance with Ref **(2)**. Perform calibrations at regular twelve-month intervals and following any repair or modification of the instrument. Place a label showing the due date of the next calibration on the instrument.

8.2 A check calibration by the operator is recommended periodically if the instrument is used continuously or is moved to a new test location requiring vehicle transportation or rough handling. The calibration check consists of testing the LAS with at least two sizes of PSLs. The LAS must correctly size the calibration aerosols and reproduce the spectral peak to within 0.05 µm. If the instrument cannot be adjusted to within those calibration limits, then it must be returned to the manufacturer for service and calibration. Annex A1 describes a procedure for calibration of the LAS.

8.3 *Aerosol Diluter*—It is recommended that the same aerosol used in the in-place testing be used for diluter calibration. If more than one dilution stage is required, each stage

[5] Laser aerosol spectrometers are available from the following sources: Particle Measuring Systems, Inc., 1815 South 57th Court, Boulder, CO 80301, TSI Incorporated Particle Instruments Group, P.O. Box 64394, St. Paul, MN 55164, and Met One, Inc., 481 California Avenue, Grants Pass, OR 97526.

[6] Available from TSI Incorporated Particle Instrument Group, P.O. Box 64394 St. Paul, MN 55164.

[7] Aerosol generators are available from the following sources: Air Techniques Division of Hamilton Associates, Inc., Baltimore, MD 21207, Particle Measurements Systems, Inc., 1815 South 57th Court, Boulder, CO 80301 (Calibration), and Nuclear Consulting Services, Inc., P.O. Box 29151, Columbus, OH 43229.

[8] Di(2-Ethylhexyl) Phthalate (DOP) and Sebacate (DOS) are available from C.P. Hall Co., Chicago, IL 60635, and Nuclear Consulting Services, Inc., P.O. Box 29151, Columbus, OH 43229.

[9] Available from Duke Scientific Corp., Palo Alto, CA 94303.

must be calibrated independently. A procedure for calibration of the diluter using the LAS is outlined in Annex A2.

9. Procedure

9.1 An example of an in-place filter test system and sampling arrangement is illustrated in Fig. 1. Components include the gas-flow duct, filter housing with filters, the LAS, diluter, and aerosol generator.

9.2 *Aerosol Mixing Uniformity Tests*— Conduct these tests upon completion of initial installation and after any modifications or repair to the filter system. It is not required to conduct these tests each time the in-place test is performed. However, if aerosol mixing and sampling parameters are changed, then new air aerosol mixing uniformity tests are required. Refer to Annex A3 for procedure.

9.3 Measure the airflow of the test gas stream and the resistance across the filter stage following the procedure outlined in Annex A3.

9.4 Establish the arrangement of sample lines between the probes, the diluter, and LAS. Make the upstream and downstream sample lines as equal in length as practicable.

9.5 Because of expected low particle counts that can penetrate HEPA filter systems, it is necessary to measure the non-test particles in the gas stream to serve as background samples. With no aerosol generation and no sample dilution, use the LAS to sample the gas stream from the downstream sample probe only. Collect samples at this location for the same duration as will be required for the test aerosol. The background particle counts may vary depending on external leaks to the filter housing, but should not exceed 30 % of the expected test aerosol. If higher background particles are found than those suggested and if leaks in the filter housing are suspected, they must be plugged before testing can continue.

9.6 Generate the challenge aerosol at the suggested particle concentration, see 5.3.

NOTE 2—**Caution:** Avoid unnecessary loading of the filters by the test aerosols by injecting the aerosols only when ready to perform penetration measurements.

9.7 Collect samples from the upstream probe and establish the challenge particle count. This is accomplished by switching the sample line from the LAS to the diluter. Sampling periods are usually 20 s, refer to Annex A2.

9.8 Purge the sample collection system and zero the LAS before proceeding to the next step in the procedure. The purging procedure is described in A2.1.2 of Annex A2.

9.9 Accumulate two successive samples from the downstream location. Sampling time periods should be selected to yield net particle counts over background of at least 100. A10-min sampling period is usually sufficient. The difference between each set of samples shall not exceed 5 % of the larger count. If penetration of only one filter stage is being measured, shorter sampling times may be used because of higher particle counts. If significant penetration is experienced downstream of one-filter stage and coincidence counting is suspected in the LAS, then the diluter must be used in the sample line. See 6.1 and 6.7.)

10. Calculation

10.1 Calculate the penetration of the filter system for each discrete particle-size. The equation holds for each specific size particle diameter as:

$$P = \frac{C_d - C_b}{C_u D} \quad (1)$$

where:
P = penetration,
C_d = particle counts downstream,
C_b = particle counts of background,
C_u = particle counts upstream, and
D = dilution ratio.

10.2 To calculate the uncertainty of the upstream and downstream penetration measurements, a theoretical value was used in the following equation. The value is based on standard propagation-of-error techniques neglecting covariance terms and using Poisson statistics to estimate uncertainties. The equation is as follows:

$$CV_p = [(PNT_d)^{-1} + (D/(NT_u)) + CV_D{}^2]^{1/2} \quad (2)$$

where:
CV_p = coefficient of variation for penetration,

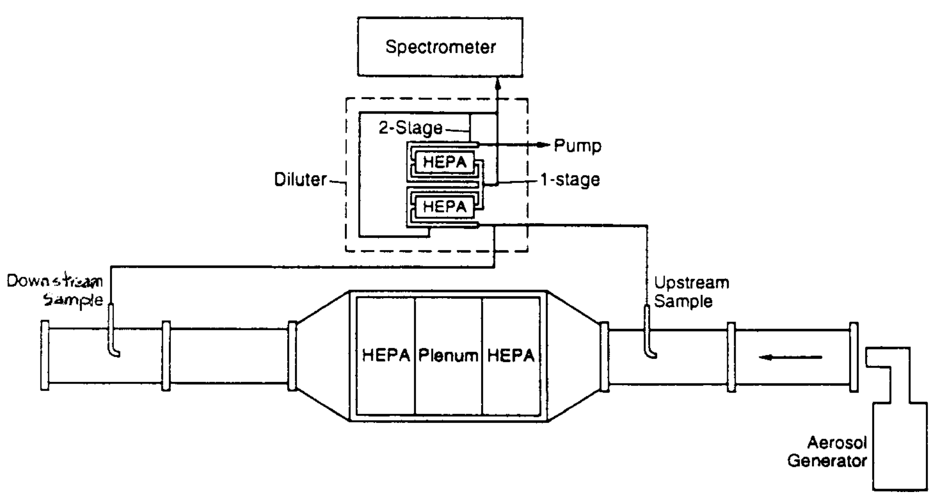

FIG. 1 Schematic Diagram of the In-Place Test Arrangement

P = aerosol number penetration,
N = undiluted upstream count rate, counts/s,
T_d = downstream counting time, s,
D = dilution ratio,
T_u = upstream counting time, s, and
CV_D = coefficient of variation for dilution ratio.

11. Report

11.1 The results of the testing shall contain, at a minimum, the following items:

11.2 Date of testing,

11.3 Identification of the filter system,

11.4 Penetration values, as a function of particle size,

11.5 The size for reporting the interval data may be either the minimum and maximum diameter for each interval or the geometric mean for the interval, and

11.6 Printed names and signatures of test personnel.

12. Precision and Bias

12.1 *Precision*—The precision of this test method for evaluating the air cleaning performance of a high efficiency particle air-filter system is being determined.

12.2 *Bias*—Since there is no reference material suitable for determining the bias for this test method, no statement on bias is being made.

13. Keywords

13.1 aerosol dilution; aerosol generator; average penetration; background particles; challenge aerosols; coincidence; compressed-air nebulizer; dilution ratio; fractional penetration; HEPA; laser aerosol spectrometer; test aerosols

ANNEXES

(Mandatory Information)

A1. LAS CALIBRATION

A1.1 The calibration procedure uses an aerosol having all particles of one size. Polystyrene latex spheres, (PSLs) are generated using a compressed-air nebulizer. The nebulizer is contained in a metal box with two chambers for diluting and drying the aerosol which contain an air-pressure regulator, dilution air control valve, and rotameter.

A1.2 A schematic view of the calibration generator is shown in Fig. A1.1. The aerosol generator must be connected to a compressed-air source that will allow the generator's pressure regulator to deliver 250 cm^3/s at standard temperature and pressure of air at 69-kPa pressure. The compressed-air source must not deliver any water droplets to the generator. If water is a concern, install a water trap before the generator. Connect the generator's output directly to sample inlet of the LAS. The nebulizer connects into a rubber stopper in the dilution chamber. The nebulizer has small internal passages for the air jet and the feed tube. These passages can become plugged if the PSL suspension is allowed to dry in the nebulizer. Upon completion of the calibration check, flush out the nebulizer with clean distilled water.

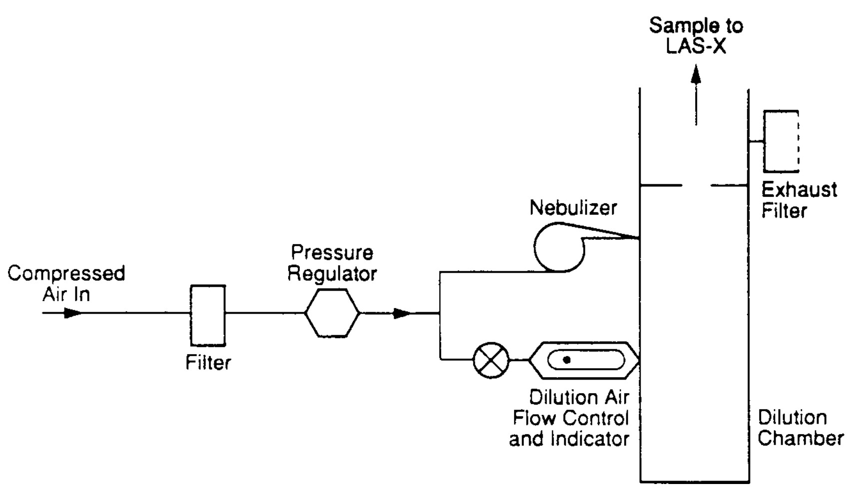

FIG. A1.1 Diagram of PSL Calibration Aerosol Generator

A2. DILUTER CALIBRATION

A2.1 The calibration of a diluter is very similar to that of the filter system penetration measurement. Refer to Fig. A2.1. However, generation of lower particle counts are required for the diluter calibration than for the actual penetration test. It is preferable, but not mandatory, to generate this aerosol in a flow system separate from the system housing of the in-place test to prevent unnecessary loading of the filters. If more than one diluter stage is required, each must be calibrated independently. An example of the diluter calibration plot is indicated in Fig. A2.2, Fig. A2.3. The diluter calibration procedure is as follows:

A2.1.1 Connect the diluter inlet to the flow system with a (HEPA-1) filter cartridge upstream of inlet duct and the diluter, and open Valves C and D. With this arrangement and no aerosol generation, accumulate a background sample with the LAS. Background particle counts are most likely due to leaks in the diluter system and must be eliminated before proceeding.

A2.1.2 Inject test aerosol upstream of the (HEPA-2) filter cartridge and allow a certain portion of the aerosol to bypass the filter by opening Valves A and B. Adjust Valve C to the desired dilution airflow in the diluter with the vacuum pump on. A typical dilution airflow of 250 cm^3/s and a ΔP across the capillary tube of 0.175 kPa are suggested for dilution ratios of 1200 to 1. Open Valve D and allow the LAS to sample the aerosol at the upstream side of the diluter to a level below which causes coincidence counting in the LAS (see 6.1). This sample arrangement establishes the challenge to the diluter. Position Valve D to purge and zero the LAS with filtered air (HEPA-3) before proceeding to the next section.

A2.1.3 Position Valve D to sample the diluted aerosol at the downstream probe of the diluter and calculate the dilution ratio. The equation holds for each specific size particle diameter as:

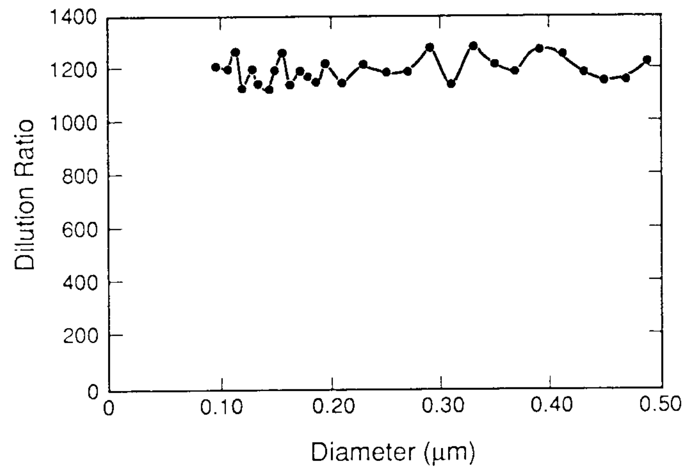

FIG. A2.2 Typical Aerosol Diluter Calibration Plot

$$D = \frac{C_u}{C_d} \quad \text{(A2.1)}$$

where:

D = dilution ratio,
C_u = upstream particle counts, and
C_d = downstream, or diluted particle counts.

A2.1.4 Only use the data for the particle size ranges where the dilution ratio remains constant and does not increase by more than 10 % for the overall distribution. Data for particles in sizes above and below that size are not to be used.

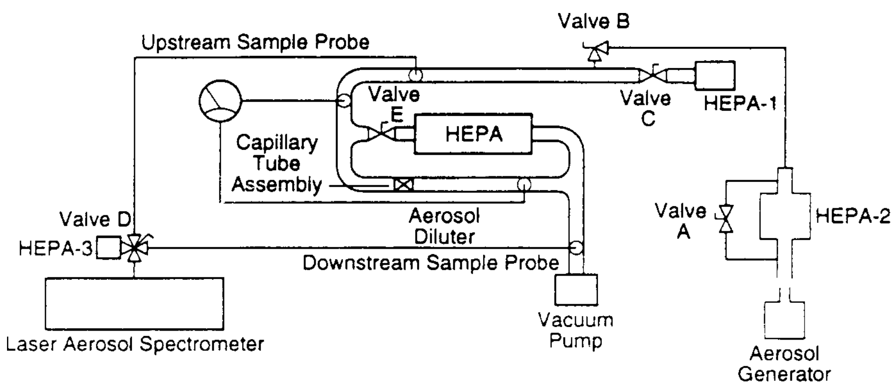

FIG. A2.1 Schematic Diagram of Aerosol Diluter in Calibration Mode

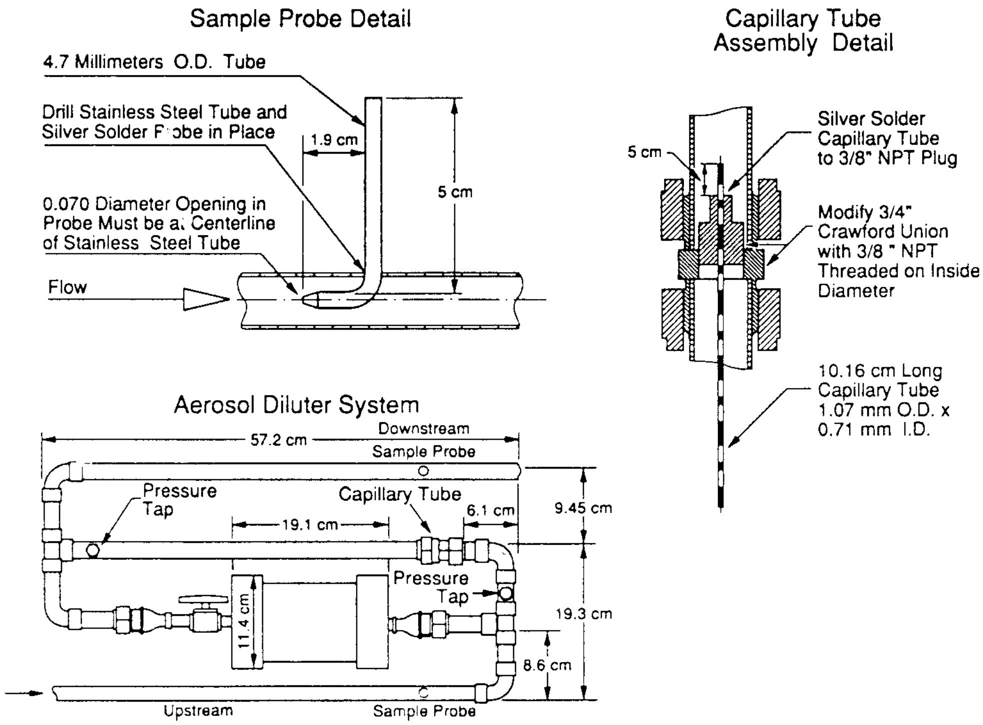

FIG. A2.3 Typical Aerosol Diluter with Dimensions

A3. AIRFLOW DISTRIBUTION AND AIR-TEST AGENT MIXING TESTS

A3.1 *Purpose*—Perform these tests to verify that the system design airflow is consistent with the fan furnished under actual field conditions at minimum and maximum filter pressure drop, and to verify that the airflow distribution across each HEPA filter stage is uniform at the design flow rates.

NOTE A3.1—These tests are to be performed only during acceptance or after extensive modification to the system, except for the airflow capacity and filter pressure drop test, that are required each time the in-place tests are performed.

A3.2 *Acceptance Criteria:*

A3.2.1 *Airflow Capacity Tests*—The system airflow shall be within ±10 % of the value specified in the test program or project specifications. Maximum housing component pressure drop airflows shall be ±10 % of the value specified in the test program or project specifications with the pressure drop greater than or equal to the maximum housing component pressure drop.

A3.2.2 *Airflow Distribution Tests*—No velocity readings shall exceed ±20 % of the calculated average. The minimum number of velocity measurements shall be one in the center of each filter. Make all measurements at equal distance away from the filters. It is recommended to conduct these measurements downstream of the filters to take advantage of the airflow distribution dampening effects of HEPA filters.

A3.2.3 *Air-Aerosol Mixing Uniformity Tests*—The purpose of this test is to verify that the challenge aerosol is introduced so as to provide uniform mixing in the airstream approaching the HEPA stage to be tested. When acceptable uniformity is achieved, an upstream sample taken in the same position that the uniformity data were obtained is defined as an acceptable single-point upstream sample. No reading shall exceed± 20 % of the calculated average reading.

APPENDIX

(Nonmandatory Information)

X1. RESULTS OF A ROUND-ROBIN TEST PROGRAM TO EVALUATE A MULTI-STAGE HEPA FILTER SYSTEM USING LASER AEROSOL SPECTROMETER (LAS)

X1.1 *Introduction:*

X1.1.1 The penetration of a two-stage high-efficiency particulate air HEPA filter system was measured by several laboratories using LASs. Single-stage HEPA filters are capable of removing 99.97 % for the particulate matter in air streams for particles having diameters greater than 0.3 µm. The purpose of this filter testing was to evaluate a new test method for determining the performance of two-stage HEPA filter systems. This test method involves challenge of the filters using an oil mist aerosol and subsequent measurements of aerosol penetration using a LAS. The current MIL-STD-282 standard applicable for single-stage filter systems measures the filter penetration at one particle size, approximately 0.3 µm in diameter, using a photometer-type detector. It requires that the challenge aerosol be 0.3 µm in diameter with a geometric standard deviation (σg) of 1.7 for testing. An existing method for in-place testing of HEPA filter systems, using a photometer for penetration measurements, specifies that 50 % of the aerosol be less than 0.7 µm with σg of 1.7. This test method places significant requirements on the test aerosol and yields little information about the dependence of penetration with particle size. The penetration measurements obtained by this test method depend on the challenge aerosol size distribution, the penetration of the filter, and the size response function of the photometer detector **(3)**.

X1.1.2 This test method presented here is an extension of the NE F3-4T **(4)** for in-place testing of HEPA filter systems for the Department of Energy nuclear industry. The main advantages of this test method are increased detection sensitivity, capability to measure the aerosol size distribution, and less required control over the challenge aerosol distribution. The increased sensitivity, achieved by the use of the LAS, allows multi-stage filter systems to be evaluated as a single unit.

X1.1.3 Penetrations as small as 4×10^{-8} can be measured. The typical photometer detector does not have the required sensitivity to measure such low penetrations. Using the LAS, both the challenge and penetrating aerosol size distributions can be measured down to 0.1 µm in diameter. More recent models extend this minimum size to 0.07 µm. With the additional size information, the filter penetration can be calculated either as a function of particle size or in a particular size of interest. This test method can determine the filter penetration of HEPA filters in the particle-size range from 0.1 to 0.2 µm where the greatest penetration is likely to occur. The only requirement on the challenge aerosol is that it lie in the range where the penetration is to be evaluated. Exact specification of its median diameter and standard deviation is not required.

X1.1.4 A major disadvantage to the LAS method is that the detection of aerosols of high concentration is subject to errors due to particle counting coincidence in the LAS. Coincidence errors are avoided by proper dilution of the challenge aerosol prior to sampling.

X1.1.5 This test method can also be used to evaluate the performance of single-stage filter systems. In these cases, lower concentrations of challenge aerosol can be used for testing than in the case of evaluations using the photometer detector.

X1.1.6 In the round-robin tests (RRT) reported here, a two-stage HEPA filter system was challenged with a heterodisperse oil mist aerosol having geometric median diameters ranging from 0.15 to 0.25 µm with a geometric standard deviation of 1.35 to 1.5. The measurements were accomplished with a LAS capable of counting and sizing particles with a 0.1 to 1.0-µm diameter. This test method describes the filtration system, the procedure used to determine penetration, and comparisons of results from the inter-laboratory evaluations.

X1.2 *Experimental Method:*

X1.2.1 The RRT filter system is illustrated in Fig. X1.1. Components included the gas stream flow duct with filters, the aerosol generator, the LAS, aerosol diluter, and pressure loss gages. Major steps associated with penetration measurements included, measuring the background downstream of the second filter stage, and particle-size distribution upstream and downstream of the filters. The test apparatus is designed to evaluate the performance of two standard 60 by 60 by 30-cm HEPA filters in series at 0.47-m^3/s airflow. For the purpose of testing by participating laboratories, upstream and downstream sample probes were each located in a removable 25-cm diameter duct. The upstream sample probe is located approximately eight duct diameters downstream of the aerosol injection position. The downstream sample probe is located eight duct diameters downstream from the second HEPA filter. These distances allow adequate mixing of the aerosol prior to sample extraction.

X1.2.2 The test aerosol was introduced into the duct at approximately eight duct diameters upstream of the sample probe. Aerosol generators used include the Air Techniques Inc., Model No. TDA-5A,[10] as well as modified Air Techniques thermal generators. All laboratories used Di(2-Ethylhexyl) Sebacate (DEHS) to produce the oil mist aerosol. The generators were capable of producing number concentrations in air of 2×10^{6} particles/cm^3(p/cm^3), or about 30 µg/L assuming unit density. High aerosol concentrations must be used so that the aerosol penetrating the dual HEPA system is greater than any background aerosol that may be leaking into the test duct after the second filter. The high concentration also allows the penetration measurements to be made in a reasonable amount

[10] Available from Air Techniques Division of Hamilton Associates, Inc., Baltimore, MD 21207.

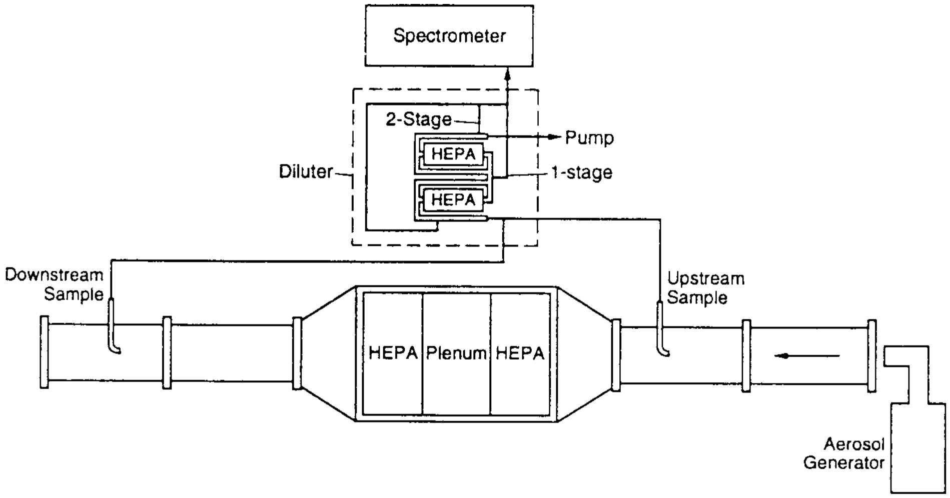

FIG. X1.1 Round-Robin Test Apparatus

of time. For example, with an upstream concentration of 2.5×10^{6} p/cm^3, a filter penetration of 4×10^{-8}, a LAS sample rate of 1.6 cm^3/s, and a downstream sample time of 600 s is required to accumulate 100 particle counts.

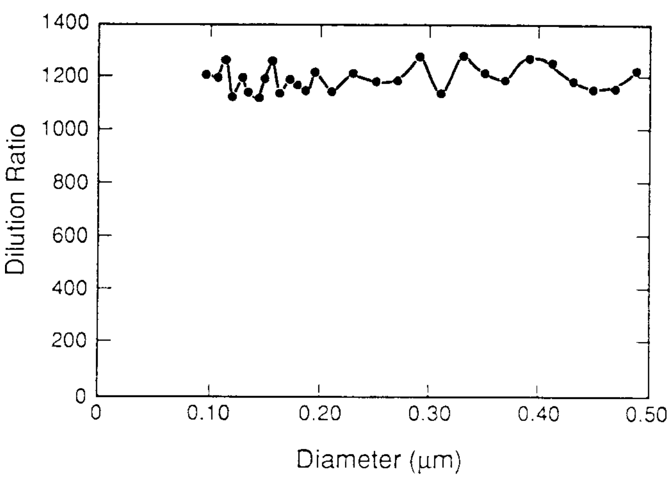

FIG. X1.2 Single-Stage Dilution Ratio, Laboratory 1

X1.2.3 Because of the high aerosol concentration used to challenge the filter system, the upstream aerosol sample must be diluted to prevent particle counting coincidence in the LAS. Particle count rates of greater than 3000 p/s must be avoided to prevent errors due to coincidence. Typically, aerosol dilution ratios of 1000 to 5000 are required. It is desirable that the diluter have minimum particle losses over the size range of interest and that those losses are constant with particle size. Calibration of the diluters can be done with the LAS using a reduced concentration of the same aerosol that is used in testing the filters. The diluter provided with the filter system allowed for either a one- or two-stage dilution. Each stage consisted of a capillary tube that allows a portion of the aerosol to pass while the rest of the air is filtered through a HEPA filter in parallel. A filtered dilution air flow of 250 cm^3/s was provided by an auxiliary pump. Dilutions of about 1000 to 1 can be achieved with a single stage. An example of a diluter calibration plot is shown in Fig. X1.2. The dilution ratio is nearly constant over the size range from 0.1 to 0.5 µm in diameter.

X1.2.4 Most of the testing was performed with the filter test apparatus under a negative pressure, that is with the air blower downstream of the filter unit. Because of this negative pressure, non-test particles can leak into the ducting from outside ambient environment. Since the concentration of test particles penetrating the filters is very low, it is necessary to ascertain the concentration of non-test particles in the system. This non-test or background concentration measurements is performed without aerosol generation and sampling with the LAS from the downstream probe. Sampling is maintained for the same time period as for the downstream aerosol test. It is desirable that the net downstream particle counts (downstream counts less background counts) be at least 100. Also, two successive sample accumulations are recommended and the difference of the two should not exceed 5 % of the larger count.

X1.2.5 The LASs used for the comparisons are capable of counting and sizing test aerosol particles from 0.1 to 1 µm in diameter. This range is adequate to determine the diameter at which maximum penetration occurs through HEPA filters at these flow conditions. The LASs used in the RRT included the Particle Measurement System 64-channel LAS-X model[5] for Laboratories 1 and 3, and a 32-channel ASASP-X for Laboratory 2. The LAS detects aerosol by the amount of scattered light from individual particles and sizes them by pulse height discrimination of the pulses. The LASs calibrated prior to the experiments, used monodisperse aerosol of polystyrene latex spheres (PSL). Minimum detectable sizes were between 0.09 to 0.11 µm in diameter. The LAS's calibrations using PSLs are presented in Fig. X1.3. The smallest sphere used during the calibration were within twice the lowest detectable size of the LAS. The LAS sampling rates ranged from 1.5 to 2 cm^3/s.

X1.2.6 In addition to slight differences in the aerosol generation and particle detection instrumentation used by each laboratory, there were some additional differences in the performance of testing by the laboratories. The dilution system provided with the filter system was inoperable at Laboratory 2 due to damage during shipment. Laboratory 2 testing was

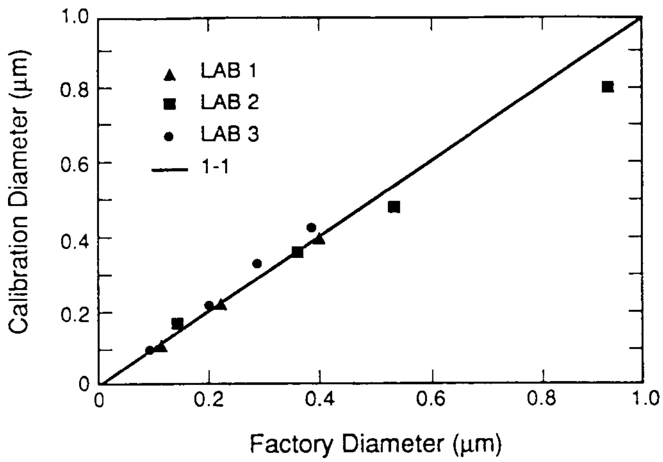

FIG. X1.3 LAS Calibration Using PSLs

accomplished with another two-stage aerosol diluter. The original filters in the system were first evaluated by Laboratories 1 and 2. When the filter system arrived at Laboratory 3, it was determined that the differential pressure across the filters was above the recommended level, therefore requiring filter replacement. The new set of filters were above the recommended change level of 0.14 kPa, therefore requiring filter replacement. The new set of filters in the RRT were tested by Laboratories 1 and 3. Laboratory 1 testing is denoted as "#1" for the first series of tests and "#2" after the filter replacement, respectively. Furthermore, some tests were performed in a pressurized operating mode by Laboratory 2 with the blower placed upstream of the system. The slight positive pressure in the system guaranteed that the penetrating particles are test particles.

X1.2.7 Calculate the penetration of the filter system for each discrete particle diameter. The equation holds for each specific particle diameter as follows:

$$P = \frac{C_d - C_b}{C_u D} \qquad \text{(X1.1)}$$

and the coefficient of variation as:

$$\frac{\Delta P}{P} = \sqrt{\frac{1}{N_u} + \frac{(C_d + C_b)}{(C_d - C_b)^2} + \left(\frac{\Delta D}{D}\right)^2} \qquad \text{(X1.2)}$$

where:
C_u = upstream concentration measured by LAS,
C_d = downstream concentration measured by LAS,
C_b = background concentration measured by LAS,
N_u = upstream particle counts,
D = dilution ratio,
ΔD = standard deviation for D, and
ΔP = standard deviation for P.

X1.2.7.1 N_u, ΔP, and ΔD are also functions of particle diameter. Error for the LAS sample volume and filter flow rate is not included in the expression for the coefficient of variation.

X1.3 *Results:*

X1.3.1 Table X1.1 lists a summary of the challenge aerosol characteristics and LAS sampling conditions for each series of tests. Four to seven penetration measurements were performed in each test series. The challenge aerosol count median diameters ranged from 0.15 to 0.25 μm and geometric standard deviation from 1.35 to 1.5. In a few tests the upstream particle concentration was somewhat less than the desired 2×10^6 p/cm^3.

X1.3.2 A comparison between Laboratory 1 and Laboratory 3 penetration results across the two-stage filter system is shown in Fig. X1.4. Penetration results presented are the average of six tests for Laboratory 1 and nine tests for Laboratory 2. The Laboratory 2 results are the average of both positive and negative pressure testing. Very good agreement in penetration values were achieved for diameters greater than 0.2 μm. The maximum penetrations are 3.7×10^{-7} and 3.1×10^{-7} for Laboratory 1 and Laboratory 2, respectively. The diameter at which the maximum penetration occurs is approximately 0.17 μm in both cases. Previous investigators have found the diameter of maximum penetration to be between 0.1 to 0.2 μm for single-stage HEPA filters **(1, 6, 7)**. The competing particle capture mechanisms, diffusion, interception and impaction, cause the maximum in the penetration-size relation. The MIL-STD 282 acceptance criteria using the dioctyl phthalate 0.3-μm diameter aerosol with photometer detection is an efficiency of at least 99.97 % for HEPA filter media. The extrapolated penetration for a two-stage filter system, 9×10^{-8}, has been indicated at a diameter of 0.3 μm. It compares favorably with the penetration results from the LAS method.

X1.3.3 In Fig. X1.5 the same data is presented with bounds of ±1 standard deviation for each of the data sets at each particle size. The average penetration of each laboratory essentially lies within these bounds for the other. Differences in penetration are not statistically significant. Standard deviations

TABLE X1.1 Summary of Challenge Aerosol Characteristics and LAS Operation

Participants	Challenge Aerosol		Concentration	Particle counts/s	Dilution Ratio
	CMD (μm)[A]	σg	(10^6 p/cm^3)		
Laboratory 1, Set 1	0.147±0.008	1.45±0.03	2.2 to 4.0	1800 to 3500	1 200
Laboratory 2 Pos[B]	0.213±0.02	1.44±0.02	0.5 to 2.3	300 to 6000	1 000 to 10 000
Laboratory 2 Neg	0.254±0.002	1.46±0.004	2.7 to 4.3	600 to 1500	5 000 to 7 000
Laboratory 3	0.190±0.008	1.50±0.02	0.5 to 4.0	800 to 1300	1 500 to 40 000
Laboratory 1, Set 2	0.164±0.005	1.37±0.04	1.0 to 1.5	600 to 2500	1 000

[A] CMD = count medium diameter as measured by the LAS based on calibrations with PSLs.
[B] This test was conducted with the fan on the upstream side of the RRT filter system.

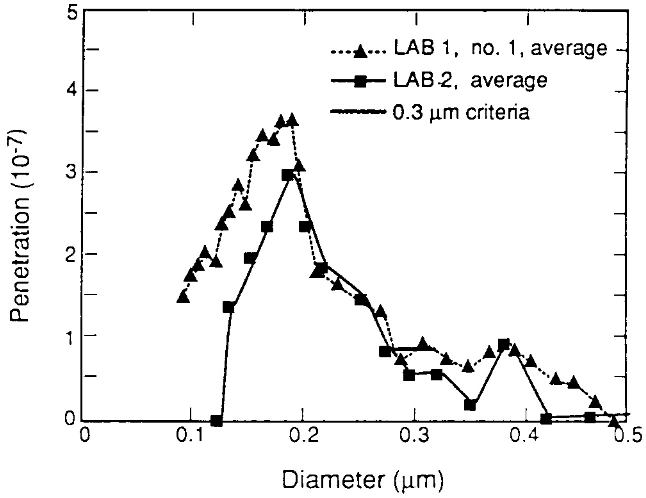

FIG. X1.4 Penetration Results, Laboratories 1 and 2, Two-Stage HEPA Filtration System

reported are about 30 to 60 % at diameter of maximum penetration. These can be explained in large part due to the low particle counts in each of the diameter ranges. Significant error in penetration can also be encountered due to errors in face velocity. An example of the magnitude of this error, as predicted by filtration theory, is presented in Fig. X1.6. At a face velocity of 2 cm/s, a variation of ±5 % in velocity can have associated errors of 30 to 40 % in penetration at the size of maximum penetration. In the current RRT, the method of flow measurements was left up to the participants.

X1.3.4 The comparison of measured penetration with the second set of filters is presented in Fig. X1.7. Higher penetrations were measured by Laboratory 3 for all particle sizes. Only the first test for Laboratory 3 is shown since the pressure drop across the single filter stage increased to 0.75 kPa as the test progressed. The penetration results for Laboratory 1 and 2 are an average of seven tests. The average results do not significantly differ from the Laboratory 3 test results.

X1.3.5 The penetration measurements made under positive and negative operating modes are compared in Fig. X1.9. The average of maximum penetrations are 2.4×10^{-7} and 4.0×10^{-7} for the positive and negative operation, respectively. However, the differences are not significant. Positive operation resulted in near zero background counts with downstream/background count ratios ranging from 30 to 300. Corresponding negative ratios range from 1.2 to 10. Even with considerable amount of background particle accumulation, credible penetration measurements can be made.

X1.3.6 In Fig. X1.8 two sets of average penetration data are compared with the single filtration theory. The theory includes the classical diffusion capture and the interception mechanisms according to Lee and Liu.

X1.4 *Discussion:*

X1.4.1 Using the LAS filter test method, filter systems having penetrations of 10^{-8} to 10^{-5} can be measured. The size of maximum penetration ranged from 0.12 to 0.18 µm in diameter. This is in agreement with both filtration theory and experimental measurements made on single-stage HEPA filter system. Penetration measurements can be achieved in a reasonable length of time and in the presence of aerosol leakage into the system from the external environment.

X1.4.2 The current RRT has indicated that it is feasible to perform penetration measurements on a 0.47-m^3/s rated airflow, two-stage HEPA filter system. It is desirable that future RRT involve a greater number of participants and a common measurement instrumentation. Possible additions to this test method should include specification of the diluter system purge times and a tolerance on the variation in the challenge concentration during testing. The LAS filter test method should continue to be pursued as a viable method for evaluating the performance of HEPA filters in-place having penetrations as low as 10^{-8}.

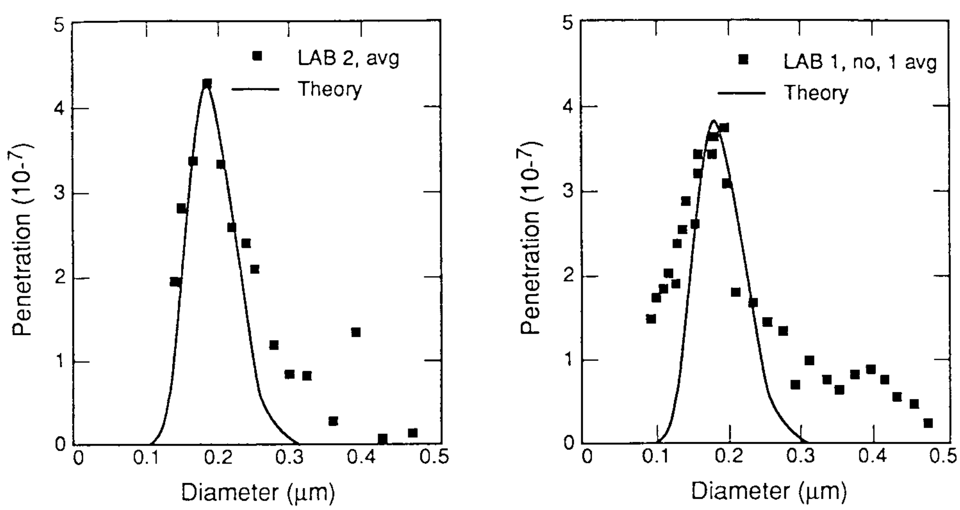

FIG. X1.8 Two Sets of Average Penetration Are Compared With the Single-Filter Filtration Theory

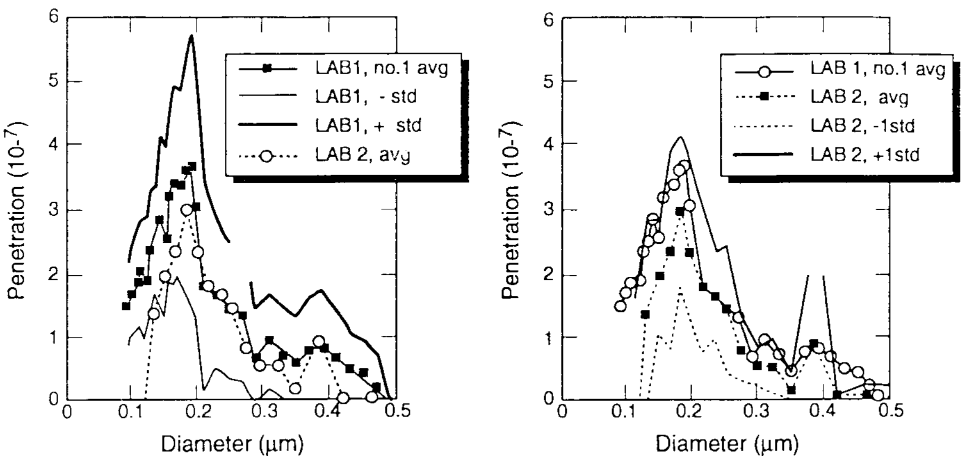

FIG. X1.5 A Plot Showing Average Penetration Measurements for Laboratories 1 and 2 Including Standard Deviation

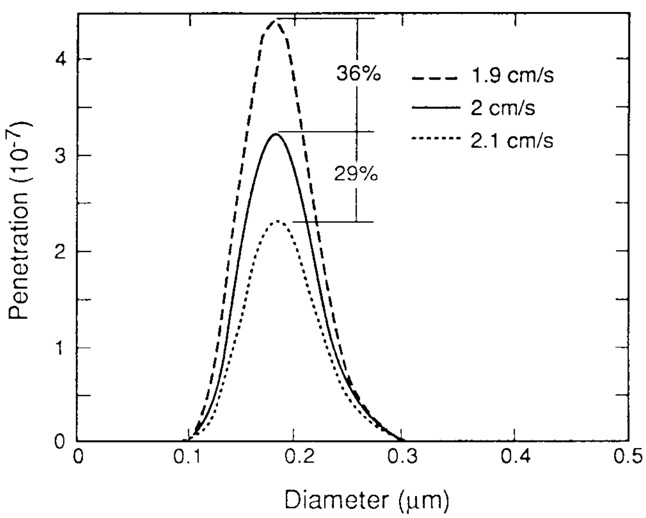

FIG. X1.6 Example of the Magnitude of This Error as Predicated by Filtration Theory

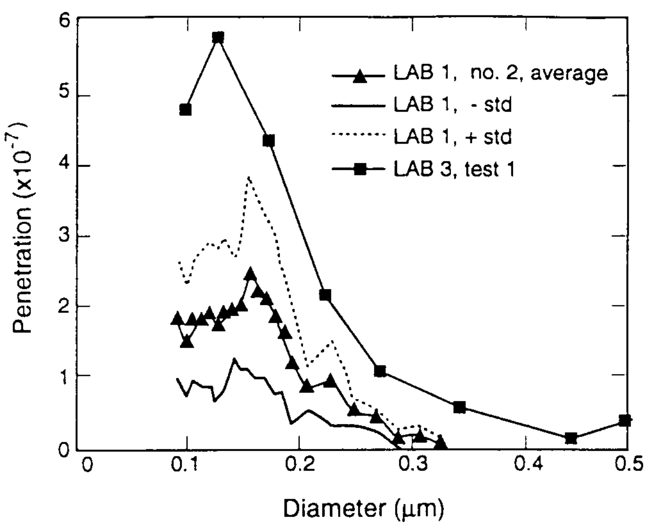

FIG. X1.7 Comparison of Measured Penetration With Second Set of Filters

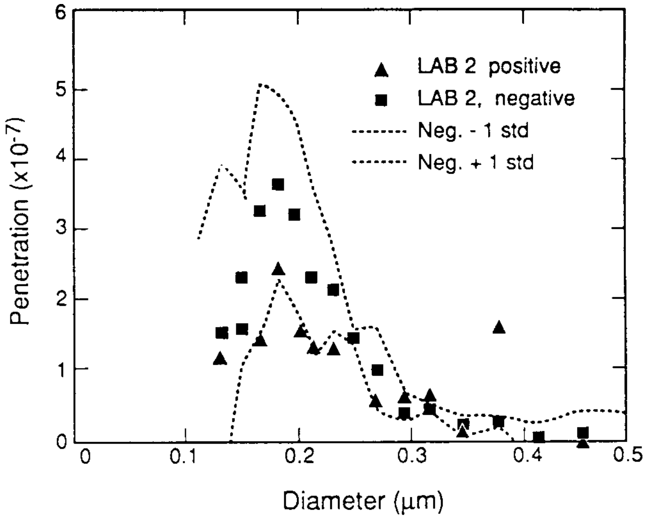

FIG. X1.9 Penetration Measurements Under Positive and Negative Operating Modes

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