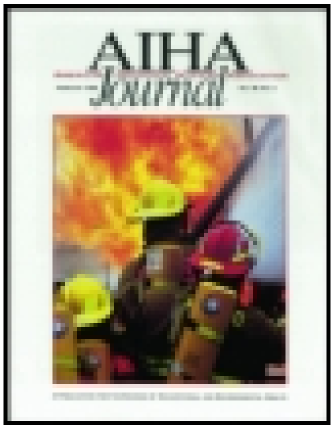

American Industrial Hygiene Association Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/aiha20

"Worst Case" Aerosol Testing Parameters: I. Sodium Chloride and Dioctyl Phthalate Aerosol Filter Efficiency as a Function of Particle Size and Flow Rate

GREGORY A. STEVENS [a] & ERNEST S. MOYER [a]

[a] U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Safety Research, Injury Prevention Research Branch, Laboratory Investigations Section, 944 Chestnut Ridge Road, Morgantown, WV 26505-2888

Published online: 04 Jun 2010.

To cite this article: GREGORY A. STEVENS & ERNEST S. MOYER (1989) "Worst Case" Aerosol Testing Parameters: I. Sodium Chloride and Dioctyl Phthalate Aerosol Filter Efficiency as a Function of Particle Size and Flow Rate, American Industrial Hygiene Association Journal, 50:5, 257-264, DOI: 10.1080/15298668991374615

To link to this article: http://dx.doi.org/10.1080/15298668991374615

Am. Ind. Hyg. Assoc. J. 50(5):257-264 (1989)

"Worst Case" Aerosol Testing Parameters: I. Sodium Chloride and Dioctyl Phthalate Aerosol Filter Efficiency as a Function of Particle Size and Flow Rate

GREGORY A. STEVENS and ERNEST S. MOYER
U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Safety Research, Injury Prevention Research Branch, Laboratory Investigations Section, 944 Chestnut Ridge Road, Morgantown, WV 26505-2888

The efficiency of filter media is dependent on the characteristics of the challenge aerosol and the filter's construction. Challenge aerosol parameters, such as particle size, density, shape, electrical charge, and flow rate, are influential in determining the filter's efficiency. In this regard, a so-called "worst case" set of conditions has been proposed for testing respirator filter efficiency in order to ensure wearer protection. Data collected on various types of filters (dust and mist; dust, fume, and mist; paint, lacquer, and enamel mist; and high efficiency) challenged with a worst case-type sodium chloride (NaCl) and dioctyl phthalate (DOP) aerosol are presented. The particle size of maximum penetration varies as a function of filter type and was < 0.25-μm count mean diameter (CMD) in all cases. The count efficiency for high efficiency filters was > 99.97% at worst case testing conditions, but the worst case count efficiencies for dust and mist; dust, fume and mist; and paint, lacquer and enamel mist filters were not nearly as efficient as existing test methods indicate. Also, as the test flow rate is increased, the count efficiency decreases. Thus, respirator filters were found to conform to the prediction of single-fiber filtration theory.

Introduction

The National Institute for Occupational Safety and Health (NIOSH), in cooperation with the Mine Safety and Health Administration (MSHA), currently is responsible for the testing and certification of respiratory protective devices. The criteria that these devices must meet in order to be certified are found in Title 30, *Code of Federal Regulations,* Part 11 (30 CFR Part 11).[1] Numerous deficiencies have been identified in this regulation[2] with regard to particulate air-purifying respirators. Therefore, a number of years ago, NIOSH undertook the task of revising 30 CFR Part 11 to incorporate updated procedures and test requirements. These revisions were recently published in the *Federal Register* as 42 CFR Part 84.[3]

Subpart V of 42 CFR Part 84 contains the requirements for particulate air-purifying respirators. Paragraph 84.273 describes the filter tests that must be met for the filters to be certified by NIOSH. Many of the requirements found in this paragraph were based on theoretical considerations of single-fiber filtration theory which predicts the existence of a most penetrating, or "worst case," size aerosol.[4-7] Little respirator filter data exists to support this theory, although some studies have been conducted on commercial filtration material which have confirmed the theory.[8-15]

The object of this study was to determine the optimum aerosol particle size for testing particulate respirator filters and to determine how this varies as a function of test flow rate. This so-called worst case challenge aerosol would be the test condition which gives the maximum filter penetration or the minimum filter efficiency. A method utilizing such an aerosol would differentiate between good, medium, and low efficiency filters of all types. The important safety issue involved is that filters tested against a worst case aerosol would protect wearers against smaller as well as larger particles. This is the only way of guaranteeing performance against virtually all size particles. The need for such methodology is evident, since data in the literature[8-15] indicate that the filter efficiencies measured using a worst case-type aerosol are significantly lower than those obtained with the current certification tests specified in 30 CFR Part 11.

Background

The efficiency of a filter medium is dependent on the challenge aerosol's characteristics and the filter's characteristics. Challenge aerosol characteristics—such as particle size, density, shape, electrical charge, and flow rate—are influential in determining the filter's efficiency. Naturally, many filter characteristics, such as packing density and fiber diameter, which are controlled by the manufacturer, are also critical. These latter characteristics (controlled by the manufacturer) are of minimal importance to NIOSH so long as the filters perform well. NIOSH's interest is with the overall performance of commercially marketed filters as a function of testing parameters.

Single-fiber filtration theory[4-7] predicts the existence of an aerosol size of minimum efficiency for fibrous filters. Stated briefly, theory predicts that an increase in particle size will cause increased filtration by the interception and inertial impaction mechanisms, whereas a decrease in particle size will enhance collection by Brownian diffusion. Thus there is an intermediate particle size region where two or more of these mechanisms are operating simultaneously. In this region, the particle penetration through the filter is a maximum, and the filter's efficiency is a minimum. This most-penetrating size aerosol is in the range between 0.1–0.4 μm (aerodynamic) for most fibrous filters. Theory also states that most mechanisms of filtration are dependent on the aerosol flow rate, where an increase in flow rate causes a downward shift in the particle size of maximum penetration. This is particularly noticeable at high filtration velocities (100–300 cm/sec) as reported by Liu and Lee.[11]

Although some experimental investigations[10,16-17] have verified these facts, little work has been done on commercially available respirator filters to determine the aerosol size at which the maximum penetration occurs. Stafford and Ettinger[9] did evaluate Whatman 41 (Whatman Inc., Clifton, N.J.) and IPC [Institute of Paper Chemistry] 1478 filter paper as a function of particle size and velocity against polystyrene latex spheres (PSL) and concluded that a reevaluation of filter testing should be considered, since a 0.3-μm aerosol does not yield minimum efficiencies for all filter media at the different velocities of concern. Also, a study[18] of the effect of charging on electret filter behavior shows the size at which maximum filter penetration occurs is aerosol charge dependent.

The present study monitored respirator filter media penetration versus particle size and flow rate. Particles in the worst case, most penetrating aerosol size range were used for testing commercially available filters of the dust and mist (DM); paint, lacquer, and enamel mist (PLEM); dust, fume, and mist (DFM); and high efficiency (HE) types. Both solid and liquid aerosols were investigated since reports in the literature[19-22] indicate that differences in filter penetration exist between them because of increased degradation, loading effects, and/or differences in charging.

Experimental Design

Air-purifying respirator filters and the filters' holders and gaskets (where separable) were tested for the initial, instantaneous filter efficiency when mounted on the holder in the manner as used on the respirator. When the filter holders were not separable, the exhalation valve was blocked to assure that valve leakage, if present, was not included in the filter efficiency results. Also, wherever possible, all filters tested were from the same lot to eliminate lot-to-lot variability.

The filters all were initially tested at a continuous airflow rate of 64 L/min. This flow rate was chosen for two reasons. First, a study by Campbell[23] predicted, and data (dioctyl phthalate [DOP] filter efficiency determinations as a function of flow rate) confirmed, that 66 L/min was the choice continuous flow rate for evaluating filters. Also, Fuchs[24] showed the existence of a flow rate of maximum penetration. Secondly, this higher flow rate should allow for easier detection of changes in the filter penetration as a function of the aerosol size. Later, this study was modified to include continuous flow rates of 16, 32, 42.5, and/or 85 L/min.

All filters were tested as received from the manufacturer without any kind of preconditioning. Filters were challenged with a solid sodium chloride (NaCl) aerosol and/or a liquid DOP aerosol. The aerosols were passed through a Kr-85 radioactive source in order to reduce the charge on the aerosol to a Boltzman charge distribution to "neutralize" the aerosol. Room temperature was employed for all the studies. Where possible, at least five filters of each type from the same lot were tested at each particle size, and the average efficiency was determined. The efficiency determined when five filters are tested should be within 0.9% of the true value. For HE filters, when three filters are tested, the measured value should be approximately 0.001% of the true value (three or more filters were actually tested). An alpha level of 0.05 was used in determining these limits.

Filters from three different manufacturers were tested against various particle sizes in the range from 0.03 to

TABLE I
List of Filters Tested

Manufacturer	Filter Type	Filter Description
A	dusts and mists	wool, felt resin
	dust, fume, and mist	wool resin
	paint, lacquer, and enamel mists, and dusts and mists	wool resin, electrostatic felt
	dusts, fumes, and mists; asbestos-containing dusts and mists; radionuclides and radon daughters	high efficiency filter paper
B	dusts and mists	—
	paint, lacquer, and enamel mists	—
	dusts, fumes, mists, and radionuclides	high efficiency filter paper
C	dusts and mists	electrostatic felt
	dusts, fumes, and mists	resin, fiberglass
	paint, lacquer, and enamel mists	wool, electrostatic felt
	dusts, fumes, mists, and radionuclides	high efficiency filter paper
D	dusts and mists	impregnated wool
	dusts, fumes, and mists	fiberglass
	pesticides, paint, lacquer, and enamel mists and dusts and mists	fiberglass

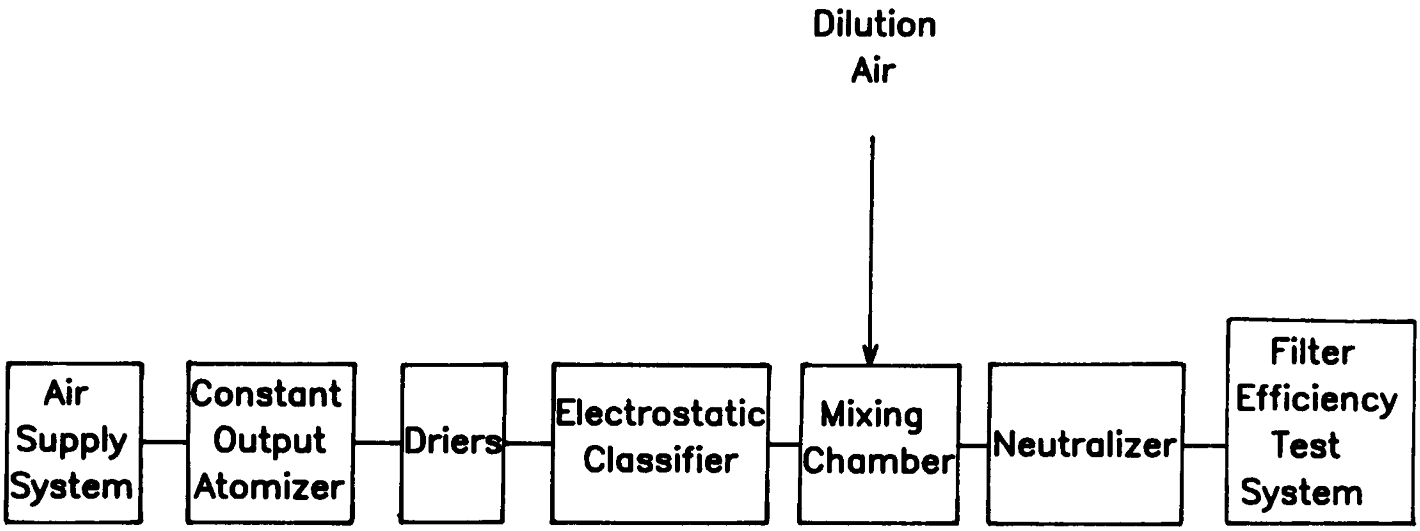

Figure 1—Schematic of aerosol generation systems

0.24-μm count mean diameter (CMD) for solid NaCl and from 0.03 to 0.30-μm CMD for DOP. Filters of the DM, DFM, PLEM, and HE types were employed in this study and are described in Table I. All filters were NIOSH certified under the current 30 CFR Part 11 regulations. In all cases the challenge concentration was maintained at less than 10^7 particles per cm^3 to avoid coagulation. The exact concentration did vary over a limited range, but by monitoring both upstream and downstream concentrations, any effect was minimized. Also, if the upstream concentration at the onset and completion of a run changed by more than approximately 3%, the tests were not considered valid runs.

Solid NaCl Aerosol Generation

The solid NaCl aerosol was generated by a TSI model 3076 constant output atomizer (TSI, Inc., St. Paul, Minn.) operating in the recirculating mode. Solutions of varying concentration of NaCl (0.001–0.1 gm/cm^3) in double distilled, deionized water were used to generate various size ranges of NaCl particles. The resulting aerosol particles were wet and highly electrostatically charged. They were passed through a series of two diffusion driers to dry the particles. The dried particles then entered an electrostatic classifier (TSI model 3071, operated with an aerosol flow rate $\simeq$ 4 L/min and a sheath and excess flow rate $\simeq$ 20 L/min, which uses the principal of electrical mobility[25-27] to select the desired particle size for testing. By this method, particles with a CMD between 0.03–0.24 μm were produced. During the initial portion of this study, there was a problem with turbulent flow inside the electrostatic classifier. This caused the geometric standard deviation (σg) to be between 1.4 and 1.6. When the turbulent flow problem was corrected, a monodisperse aerosol was obtained. The system configuration employed throughout this study is depicted in Figure 1.

DOP Liquid Aerosol Generation

The liquid DOP aerosol was produced by an evaporization/condensation technique. The system employed is basically that depicted in Figure 1, except that the drier and electrostatic classifier are replaced with an evaporation/condensation conditioner. This system has been described by Liu and Lee[28] as producing a moderately monodispersed aerosol with a geometric standard deviation of 1.3 to 1.5. The system included a TSI constant output atomizer (Model 3075) which is fed by a syringe pump (0.59 cc/min) to provide for a constant flow of liquid to the pneumatic atomizer. This results in a stable and reproducible particle-size output. A TSI Model 3072 evaporation/condensation conditioner was used for producing the DOP aerosol. By changing the DOP solution concentration, the particle size changes. Various concentrations of DOP/ethanol (5×10^{-4} to 5% by volume) were employed to generate particles with a CMD between 0.03 μm and 0.30 μm and a σg between 1.6 and 1.8 as determined with a differential mobility particle sizer (DMPS). This aerosol is not monodispersed. A plot of log particle size versus log DOP concentration showed linear correlation as per the results of Liu and Lee.[28] Also, a small amount of anthracene was added to the solutions to serve as a nucleating agent.

Aerosol Efficiency Measurements

The efficiency and penetration was monitored and recorded by means of the TSI Filter Efficiency Test System (FETS) which has been described by Remiarz et al.[29] This instrument, which was built under contract for NIOSH, contains a continuous flow, single-particle-counting condensation nucleus counter (CNC, TSI Model 3020). The CNC (Agarwal and Sem[30]) can measure concentrations as high as 10^7 particles/cm^3 when using the photometric mode and can measure concentrations down to 10^{-2} particles/cm^3 using its single-particle counting ability. When used to measure the particle concentrations both upstream and downstream of a filter, the CNC can determine count filter efficiencies as high as 99.99999+%. This instrument's sensitivity and dynamic concentration range of measurement were necessary in order to detect the differences in filter efficiency and to cover the large range of concentrations anticipated in going from upstream to downstream concentrations. This is especially true in the case of HE filters. In addition to testing efficiencies, the system measures respirator flow rates and pressure drops. The instrument is automated by means of a dedicated microcomputer system.

Aerosol Size Measurements

The aerosol size (CMD) and size distribution (σg) initially were determined with a TSI Model 3030 electrical aerosol size analyzer (EAA) according to the procedure of Liu and Pui[27] and Liu and Whitby.[31] The EAA measures the aerosol size distribution by the principle of unipolar diffusion charging and mobility analysis.[31] First, the analyzer places a unipolar charge on the aerosol and then measures the resulting mobility distribution of the charged particles by means of a mobility analyzer. All determinations of the size and σg were accomplished by hand calculations. This procedure was used until a TSI Model 3932 differential mobility particle sizer (DMPS) became available. The DMPS measures the size distribution of submicrometer aerosols by the electrical mobility detection technique. First, the aerosols are classified with an electrostatic classifier, and then their concentration is determined with a CNC. The system is automated and microprocessor controlled. The aerosol was sampled at the point of entrance into the test chamber.

When using raw EAA data to determine aerosol size and distribution by hand calculations, the resulting size will be slightly lower than the actual size.[32] This is due to the increments of the voltages applied to the collector rod in the EAA (the automated version of the EAA corrects for this shift). Therefore, a brief correlation study was performed so that the EAA data could be converted to an equivalent DMPS size. This was accomplished by determining sizes of a number of different size aerosols using both the EAA and DMPS in parallel. The data were plotted and a correlation equation determined for converting all EAA particle-size data.

Results and Discussion

The purpose of this study was to determine the worst case, most penetrating size of aerosol particulates for testing commercially available respirator filter media. The filters tested are described in Table 1. Typical results for HE filters are shown in Figure 2 and Figure 3 for NaCl and DOP, respectively. Figure 4 and Figure 5 depict results obtained for a DFM filter against NaCl and PLEM filter against DOP, respectively. It should be noted that these curves represent an average efficiency for a series of filters tested at each size, which resulted in some scatter in the data. This also is influenced by the fact that the DOP aerosol was not monodispersed. Better control of the system and uniform filters would have resulted in improved efficiency versus particle-size curves. The plots of percent filter efficiency versus challenge aerosol particle size at flow rates of 16, 42.5, 64, and 85 L/min show a minimum in the efficiency curve, as theory predicts.

In addition to the worst case penetrating particle size, the phenomenon of a shift of this region toward a smaller parti-

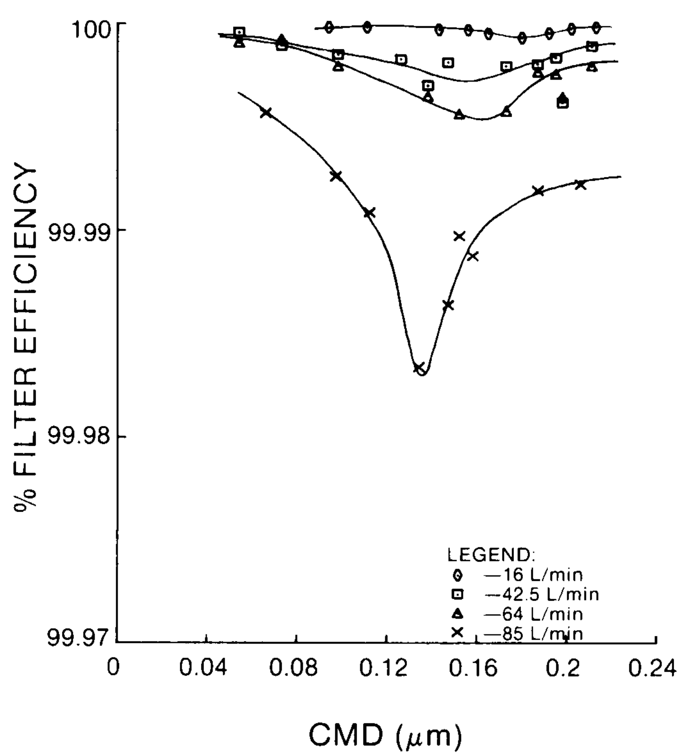

Figure 2—High efficiency filter efficiency as a function of particle size and flow rate for Manufacturer C's filters against NaCl aerosol

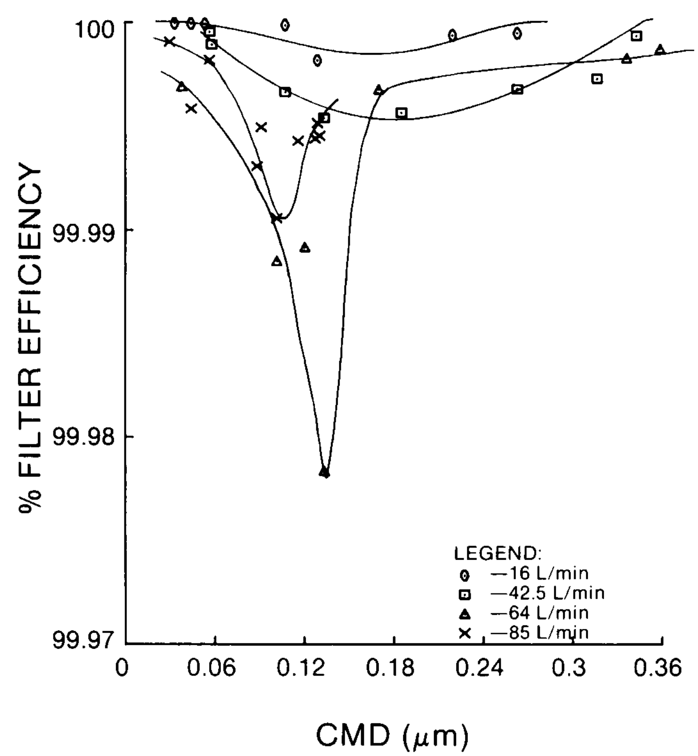

Figure 3—High efficiency filter efficiency as a function of particle size and flow rate for Manufacturer C's filters against DOP aerosol

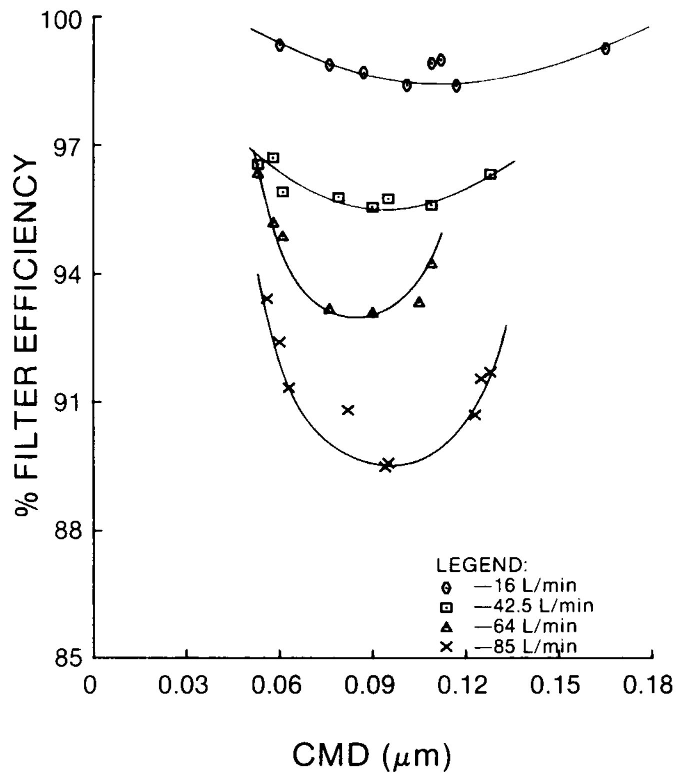

Figure 5—Paint, lacquer, and enamel mist filter efficiency as a function of particle size and flow rate for Manufacturer C's filters against DOP aerosol

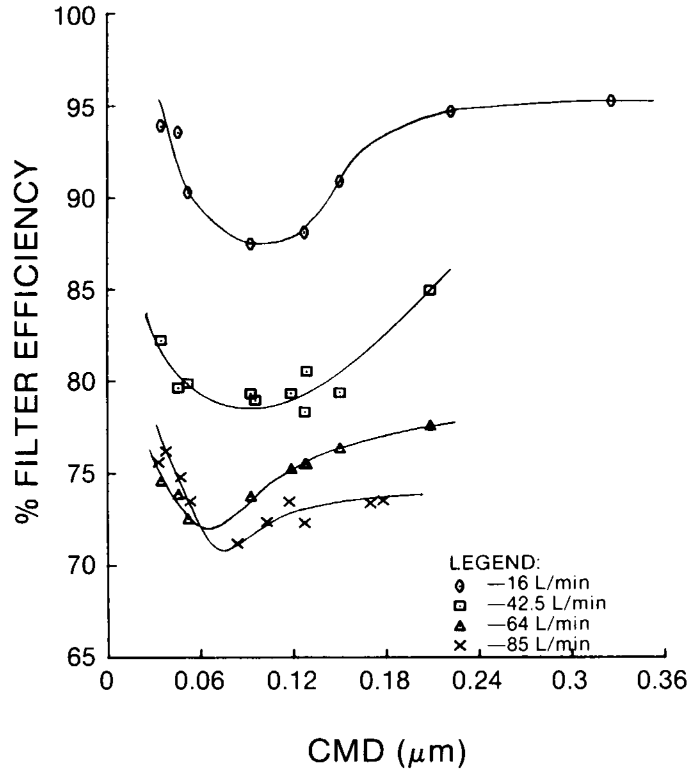

Figure 4—Dust, fume, and mist filter efficiency as a function of particle size and flow rate for Manufacturer C's filters against NaCl aerosol

cle size as the flow rate is increased is observed also and agrees with theoretical predictions. Similarly, the magnitude of penetration increases as the flow rate increases. An additional observation at a couple of particle sizes is the crossover of the efficiency curve of lower flow rates. That is, at certain points, a lower flow rate gives more penetration than a higher flow rate. This observation is in agreement with findings of Fuchs[24] and with the theory which predicts that as the velocity increases, collection by diffusion is reduced and collection by impaction is increased. Thus, there is a face velocity which should give a minimum efficiency for a given particle size and filter.

The NaCl and DOP results for all the filters listed in Table I are given in Table II and Table III, respectively. These data show that all the HE filters gave efficiencies greater than the 99.97% required by the DOP test in 30 CFR Part 11, but it must be noted that the FETS gives count efficiencies which are not equal to efficiencies determined with light photometers, as on the commercial 0.3-μm DOP instrument (Q 127). Further it should be noted that Filters A and C were tested at flow rates (64 and 85 L/min) which were higher than that presently required in 30 CFR Part 11 (42.5 L/min for single filter of pair-type respirator). Even at these higher flows, the filters gave count efficiencies > 99.97%. This basically confirms that the commercially available HE filters are indeed very good, even when tested at or near the worst case conditions.

The data in Tables II and III indicate that the other filter types (DM, DFM, and PLEM) are not as efficient when a worst case method that monitors initial efficiencies is employed. These filters gave minimum efficiencies which were significantly lower than the limits set forth for the silica dust test (>99% gravimetric TWA over 90 min)[1] or the lead fume test (>99% gravimetric TWA over 312 min).[1] It must be noted, however, that these filters were tested at a variety of flow rates, some of which were higher than those required by the present regulations (32 L/min for single filters, 16 L/min for filter pairs).

These significantly lower count efficiencies cannot be explained solely by the type of efficiency measured (count versus mass). Parameters such as particle size and charging also play an important role in determining the filter's efficiency. These results indicate that the worst case-type test is much more vigorous and is able to differentiate between good, medium, and low efficiency filters. The present tests (silica dust and lead fume) do not have the ability to discriminate between the various filter types.[33] It must be remembered, however, that the DOP and NaCl tests run in this study do not consider or evaluate any loading effects, and it is known that mechanical filters become more efficient with loading.

Table IV and Table V show the CMD particle-size range (DMPS) at which maximum filter penetration takes place for NaCl and DOP, respectively. These data show that for the HE filters, the most penetrating particle-size region is occurring at a larger particle size than for the other filter types tested. This probably is because of the increased surface area of the HE filters. These filters are pleated and have

TABLE II
Range of Minimum NaCl Initial Instantaneous Filter Efficiency[A] for Commercial Filters in the "Worst Case" Size Region

Flow Rate (L/min)	Manufacturer	Dust and Mist	Paint, Lacquer, and Enamel Mist	Dust, Fume, and Mist	High Efficiency
16	A	87–88	92–93	98–99	—
	B	88–89	92–93	—	—
	C	84–85	87–88	98–99	> 99.999
32	B	82–83	85–86	—	—
42.5	A	79–80	83–84	94–95	99.997–99.998
	C	71–72	78–79	95–96	99.996–99.997
64	A	77–78	79–80	92–93	99.991–99.992
	B	73–74	79–80	—	99.995–99.996
	C	70–71	75–76	93–94	99.995–99.996
85	A	69–70	77–78	91–92	99.977–99.980
	B	73–74	78–79	—	99.993–99.994
	C	69–70	67–68	89–90	99.986–99.987
	D	67–68	86–87	87–88	—

[A]Estimated minimum efficiency range from filter efficiency versus particle-size plots.

large surface areas, which effectively decrease the face velocity of the filters, resulting in a shift toward a large particle size of minimum efficiency.

With both NaCl and DOP aerosols, the HE filters gave a minimum efficiency at the largest particle size. For all the other filter types, the particle size of minimum efficiency was less than that observed for the HE filters. Also, the particle size at which the minimum efficiency occurred varied from one manufacturer to another within the same filter type. This suggests that the ideal method would be one which evaluates a filter versus particle size and then runs all subsequent tests at the particle size of minimum efficiency.

Conclusions

The results of this study show that respirator filters do indeed follow many of the predictions of single-fiber filtration theory. The following conclusions were noted. (1) A particle size at which a minimum efficiency occurs does exist and varies as a function of flow rate, filter type, and filter

TABLE III
Range of Minimum DOP Initial Instantaneous Filter Efficiency[A] for Commercial Filters in the "Worst Case" Size Region

Flow Rate (L/min)	Manufacturer	Dust and Mist	Paint, Lacquer, and Enamel Mist	Dust, Fume, and Mist	High Efficiency
16	A	88–89	88–89	98–99	> 99.999
	B	87–88	91–92	—	> 99.999
	C	84–85	87–88	98–99	99.998–99.999
32	B	84–85	86–87	—	99.998–99.999
42.5	A	79–80	82–83	94–95	99.997–99.998
	B	80–81	85–86	—	—
	C	72–73	78–79	95–96	99.994–99.995
64	A	73–75	77–78	92–93	99.987–99.988
	B	74–75	80–82	—	99.990–99.991
	C	67–68	72–73	91–93	99.977–99.978
85	A	74–75	76–77	87–88	99.978–99.979
	B	70–71	75–76	—	99.983–99.984
	C	69–70	70–71	86–87	99.989–99.990
	D	67–69	84–85	85–86	—

[A]Estimated minimum efficiency range from filter efficiency versus particle-size plots.

TABLE IV
Particle Size[A] Range of Minimum NaCl Initial Instantaneous Filter Efficiency for Commercial Respirator Filters

Flow Rate (L/min)	Manufacturer	Dust and Mist CMD[A] (μm)	Paint, Lacquer, and Enamel Mist CMD[A] (μm)	Dust, Fume, and Mist CMD[A] (μm)	High Efficiency CMD[A] (μm)
16	A	< 0.055	0.07–0.11	0.06–0.10	—
	B	< 0.055	ND[B]	—	—
	C	< 0.055	0.085–0.12	0.10–0.14	0.16–0.20
32	B	0.06–0.10	0.08–0.12	—	—
42.5	A	< 0.06	0.06–0.10	0.045–0.085	0.17–0.21
	C	< 0.05	0.045–0.075	0.08–0.12	0.15–0.19
64	A	< 0.06	0.06–0.095	0.05–0.08	0.16–0.20
	B	< 0.06	0.10–0.14	—	0.14–0.18
	C	< 0.05	0.05–0.09	0.07–0.11	0.14–0.18
85	A	0.06–0.10	0.065–0.10	0.05–0.08	0.16–0.21
	B	0.06–0.10	ND	—	0.14–0.19
	C	0.06–0.10	0.055–0.085	0.07–0.12	0.12–0.15
	D	0.04–0.07	0.03–0.07	0.05–0.09	—

[A]Estimated particle size of minimum filter efficiency from DMPS experimental or converted from EAA data correlation.
[B]ND = not distinguishable.

TABLE V
Particle Size[A] Range of Minimum DOP Initial Instantaneous Filter Efficiency for Commercial Respirator Filters

Flow Rate (L/min)	Manufacturer	Dust and Mist CMD[A] (μm)	Paint, Lacquer, and Enamel Mist CMD[A] (μm)	Dust, Fume, and Mist CMD[A] (μm)	High Efficiency CMD[A] (μm)
16	A	0.05–0.08	0.08–0.12	0.06–0.10	ND[B]
	B	0.06–0.10	0.09–0.13	—	ND
	C	0.04–0.08	0.085–0.125	0.11–0.15	0.125–0.165
32	B	0.055–0.095	0.09–0.13	—	0.09–0.13
42.5	A	< 0.04	0.10–0.14	0.04–0.08	0.14–0.18
	B	0.04–0.08	0.085–0.125	—	—
	C	< 0.04	0.095–0.135	0.10–0.14	0.13–0.17
64	A	< 0.04	0.08–0.12	0.05–0.09	0.11–0.15
	B	0.03–0.06	0.07–0.11	—	0.12–0.16
	C	< 0.04	0.05–0.09	0.11–0.15	0.12–0.16
85	A	< 0.04	0.06–0.09	0.07–0.10	0.095–0.135
	B	0.04–0.08	0.04–0.08	—	0.135–0.175
	C	0.03–0.07	0.06–0.10	0.08–0.12	0.09–0.13
	D	0.03–0.06	0.055–0.095	0.07–0.10	—

[A]Estimated particle size of minimum filter efficiency from DMPS experimental or converted from EAA data correlation.
[B]ND = not distinguishable.

manufacturer. (2) Minimum efficiencies for HE filters occur at larger particle sizes than for other filters. (3) HE filters showed excellent efficiencies at or near the worst case conditions. (4) DM, DFM, and PLEM filters are not nearly as efficient when tested by a worst case type aerosol as when tested with the present 30 CFR Part 11 test methods.

In relation to the changes found in 42 CFR Part 84, this study has shown that the proposals made in 42 CFR Part 84 are a step in the right direction in achieving a test regimen that is more capable of discerning a filter's ability to protect the wearer against most all sizes of particulate matter.

All of the filters, except the HE filters, tested in this study gave efficiencies that were below that currently required by 30 CFR Part 11. The HE filters, when tested at the most stringent conditions, gave efficiencies greater than 99.97%. It must be noted, however, that only filter efficiencies were evaluated in this study, and important factors, such as face seal leakage and valve leakage, were not considered. In some cases, especially with HE filters, these factors may overshadow the protection afforded by the filter itself.

References

1. "30 Mineral Resources." *Code of Federal Regulation* Title 30, Part 11. 1980. pp. 7-70.
2. **Moyer, E.S.:** Respirator Filtration Efficiency Testing. *Fluid Filtration: Gas, Volume 1.* (ASTM STP 975). edited by R.R. Raber. Philadelphia, Pa.: ASTM, 1986. pp. 167-180.
3. Part 11: "42 CFR Part 84." *Federal Register* 52:166. August 27, 1987. pp. 32402-32443.
4. **Langmuir, I., W.H. Rodebush, and V.K. Lamer:** *The Filtration of Aerosols and the Development of Filter Materials.* (Report OSRD 865). U.S. Office of Scientific Research and Development, National Defense Research Committee, 1942. p. 137.
5. **Ramskill, E.A. and W.L. Anderson:** The Inertial Mechanism in the Mechanical Filtration of Aerosols. *J. Colloid Sci. 6*:416-428 (1951).
6. **Gillespie, T.:** The Role of Electric Forces in Filtration of Aerosols by Fiber Filters. *J. Colloid Sci. 10*:299-314 (1955).
7. **Chen, C.Y.:** Filtration of Aerosols by Fibrous Media. *Chem. Rev. 55*:595-623 (1955).
8. **Lee, K.W. and B.Y.H. Liu:** On the Minimum Efficiency and the Most Penetrating Particle Size of Fibrous Filters. *J. Air. Pollut. Control Assoc. 30(4)*:377-381 (1980).
9. **Stafford, R.G. and H.J. Ettinger:** Filter Efficiency as a Function of Particle Size and Velocity. *Atmos. Environ. 6*:353-362 (1972).
10. **Thomas, J.W. and R.E. Yoder:** Aerosol Size for Maximum Penetration through Fiberglass and Sand Filters. *A.M.A. Arch. Ind. Health. 13*:545-549 (1956).
11. **Liu, B.Y.H. and K.W. Lee:** Efficiency of Membrane and Nuclepore Filters for Submicrometer Aerosols. *Environ. Sci. Technol. 10*:345-350 (1976).
12. **Moyer, E.S.:** "DOP Aerosol Particulate Filter Efficiency of Commercial Filters as a Function of Particle Size and Flow Rate." Paper presented at the American Industrial Hygiene Conference, Las Vegas, Nevada, 1985.
13. **Stevens, G.A.:** "Effect of Particle Size and Flow Rate on the Efficiency of Commercial Filters Using an NaCl Aerosol." Paper presented at the American Industrial Hygiene Conference, Las Vegas, Nevada, 1985.
14. **National Institute for Occupational Safety and Health:** *A Fundamental Study of Respirator Air Filtration Progress Report* by B.Y.H. Liu and B. Fardi. (NIOSH Grant # 1 R01 OH01485-01A1). St. Paul, Minn.: University of Minnesota, 1985. p. 38.
15. **Liu, B.Y.H. and K.L. Rubow:** Air Filtration by Fibrous Media. *Fluid Filtration: Gas, Volume 1.* (ASTM STP 975). edited by R.R. Raber. Philadelphia, Pa.: ASTM, 1986. pp. 1-12.
16. **Rimberg, D.:** Penetration of IPC-1478, Whatman 41, and Type 5G Filter Papers as a Function of Particle Size and Velocity. *Am. Ind. Hyg. Assoc. J. 30*:394-401 (1969).
17. **Lindeken, C.L., R.L. Morgin, and K.F. Petrock:** Collection Efficiency of Whatman 41 Filter Paper for Submicron Aerosols. *Health Phys. 9*:305-308 (1963).
18. **Kanaoka, C., H. Emi, Y. Otani, and T. Iiyama:** Effect of Charging State of Particles on Electret Filtration. *Aerosol Sci. Technol. 7*:1-13 (1987).
19. **Stafford, R.G. and H.J. Ettinger:** Comparison of Filter Media against Liquid and Solid Aerosols. *Am. Ind. Hyg. Assoc. J. 22*:319-326 (1971).
20. **Lockhart, L.B., Jr., R.L. Patterson, Jr., and W.I. Anderson:** *Characteristics of Air Filter Media Used for Monitoring Airborne Radioactivity.* (NRL-6054). Washington, D.C.: Naval Research Laboratory, March 1964.
21. **Posner, S.:** Air Sampling Filter Retention Studies Using Solid Particles. In *Proceedings of the Seventh AEC Air Cleaning Conference.* Long Island, N.Y.: Brookhaven National Laboratory, October 1961. p. 43.
22. **Hanford Atomic Products Operation:** *A Study of Efficiencies and Pressure Drop Characteristics of Air Filtering Media* by F.E. Adeley, R.H. Scott, and W.E. Gill (HW-28065). Richland, Wash.: Hanford Atomic Products Operation, August 1953. p. 21.
23. **Campbell, D.L.:** *NIOSH File Report: Optimum Flow Rate for Aerosol Filter Testing.* November 14, 1983. p. 11.
24. **Fuchs, N.A.:** *The Mechanics of Aerosols.* Elmsford, N.Y.: Pergamon Press, 1964.
25. **Bademosi, F.:** "Diffusion Charging and Related Transfer Processes in Knudsen Aerosols." Ph.D. thesis, University of Minnesota, Minneapolis, Minn., 1971.
26. **Knutson, E.O.:** "The Distribution of Electric Charge among the Particles of an Artificially Charged Aerosol." Ph.D. thesis, University of Minnesota, Minneapolis, Minn., 1971.
27. **Liu, B.Y.H. and D.Y.H. Pui:** A Submicron Standard and the Primary, Absolute Calibration of the Condensation Nuclei Counter. *J. Colloid Interface Sci. 47*:155-171 (1974).
28. **Liu, B.Y.H. and K.W. Lee:** An Aerosol Generator of High Stability. *Am. Ind. Hyg. Assoc. J. 36*:861-865 (1975).
29. **Remiarz, R.J., J.K. Agarwal, P.A. Nelson, and E. Moyer:** A New, Automated Method for Testing Particulate Respirators. *J. ISRP 2*:275-287 (1984).
30. **Agarwal, J.K. and G.J. Sem:** Continuous Flow, Single-Particle-Counting Condensation Nucleus Counter. *J. Aerosol Sci. 11*:343-357 (1980).
31. **Liu, B.Y.H., K.T. Whitby, and D.Y.H. Pui:** On the Performance of the Electrical Aerosol Analyzer. *J. Aerosol Sci. 6*:249-264 (1975).
32. **Knutson, E.O.:** "Operating Principles of the Electrical Aerosol Analyzer." [Private Communication] August 28, 1985. Dr. Earl Knutson, Director, Aerosol Studies Division, Environmental Measurements Lab, Department of Energy, New York, N.Y.
33. **Reed, L.D., D.L. Smith, and E.S. Moyer:** Comparison of Respirator Particulate Filter Test Methods. *J. Int. Soc. Respir. Prot. 4*:43-60 (1986).

30 March 1988; Revised 28 October 1988