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Aerosol Penetration through Filtering Facepieces and Respirator Cartridges*

C.C. Chen
M. Lehtimäki†
K. Willeke‡

Aerosol Research and Respiratory Protection Laboratory, Department of Environmental Health, University of Cincinnati, Cincinnati, OH 45267-0056

Air-purifying respirators must be certified following the National Institute for Occupational Safety and Health (NIOSH) filter test criteria (30 CFR 11). The criteria specify a range for the mean particle size and the measure of spread permissible for the test aerosol. The authors' experiments have shown that aerosol penetration as a function of particle size differs considerably among certified respirators of the same type. Filtering facepieces (disposable respirators) and cartridges of the dust-mist, dust-mist-fume, and high-efficiency particulate air type were tested. The respirators were sealed to mannequins in a test chamber. The aerosol concentrations inside and outside the respirator were measured by an aerodynamic particle sizer and a laser aerosol spectrometer over a particle size range of 0.1 to 15 μm. Five flow rates ranging from 5 to 100 L/min were used to study flow dependency. The aerosol penetration through the filters is presented as a function of particle size. Aerosol penetration and pressure drop are combined to express the performance of each filter in terms of "quality factor." Under the same test conditions, the quality factor of one respirator may be as much as 6.6 times more than that of another respirator of the same type. The filter quality factor has a greater aerosol size dependency as airflow and aerosol size increase. In general, cartridges have a larger surface area than filtering facepieces but not necessarily lower filter penetration or higher filter quality. An analysis of the data shows that the best dust-mist respirator tested may provide five times more protection than the worst dust-mist respirator tested when exposed to the aerosol size distribution specified by the NIOSH filter test criteria.

Inhalation hazards of the workplace are best minimized by substituting a less hazardous material or employing engineering controls. When this is not feasible, workers must wear respirators. The person who selects the respirator must be familiar with the specific working

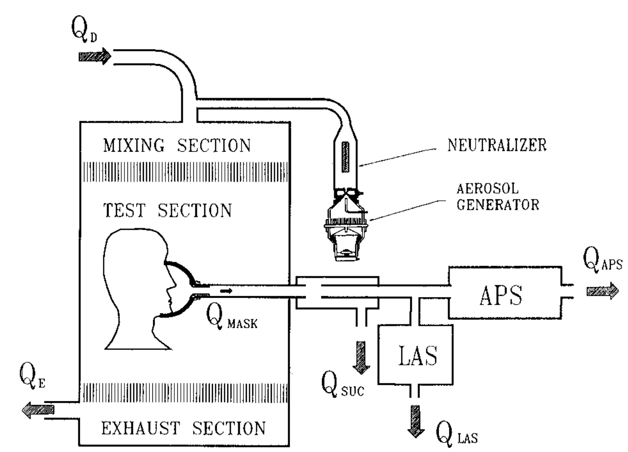

FIGURE 1. Schematic diagram of experimental setup. Q_D = dilution air, Q_{MASK} = airflow through mask, Q_E = exhaust airflow, Q_{SUC} = suction airflow, Q_{APS} = airflow of APS (0.5–30 μm), Q_{LAS} = airflow of LAS (0.1–3 μm).

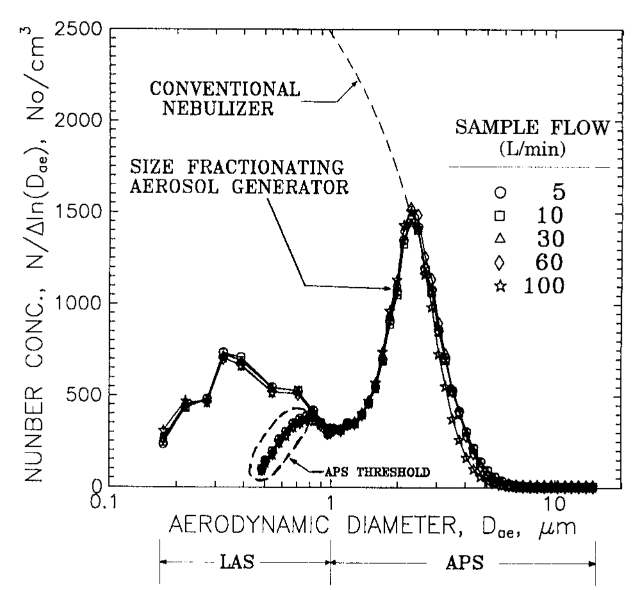

FIGURE 2. Size distribution of test aerosol, as measured by the APS and LAS

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†On leave from Technical Research Centre of Finland, P.O. Box 656, SF-33101 Tampere, Finland.

‡Author to whom correspondence should be sent.

TABLE I. Respirators of Four Categories by Four Manufacturers

Respirator Category	Respirator Code	Respirator Type[A]	Manufacturer Code	Δp[B] (mm H_2O)	P(%)[C]	q_F[D] (1/cm H_2O)
Nuisance dust	ND-A	FF	A	1.68	83.93	0.0104
	ND-B	FF	B	1.37	85.27	0.0117
Dust, mist	DM-A	FF	A	4.83	21.48	0.0318
	DM-B	FF	A	6.10	26.03	0.0221
	DM-C	FF	C	4.00	46.24	0.0193
	DM-D	FF	B	6.73	62.22	0.0070
	DM-E	CR	A	13.78	10.93	0.0161
	DM-F	CR	D	10.38	12.17	0.0203
Dust, mist, fume	DMF-A	FF	A	12.78	5.01	0.0234
	DMF-B	FF	C	16.50	23.11	0.0089
	DMF-C	CR	D	10.77	8.69	0.0227
High-efficiency particulate air filter	HEPA-A	CR	A	25.05	0.0191	0.0342
	HEPA-B	CR	A	28.42	0.0032	0.0360
	HEPA-C	FF	A	26.97	0.0089	0.0346
	HEPA-D	CR	D	23.70	0.0033	0.0436

[A]FF: filtering facepiece; CR: cartridge.

[B]Δp: pressure drop at mask flow of 100 L/min.

[C]P(%): penetration percentage of 0.3-µm aerosol.

[D]q_F: filter quality factor (0.3-µm aerosol, 100 L/min).

environment, including equipment, work situation, and human factors. In addition, an understanding of the limitations associated with each class of respirator is needed.

The National Institute for Occupational Safety and Health (NIOSH) has published criteria, the *NIOSH Respirator Decision Logic*,[1] to assist industrial hygienists in selecting the appropriate respirators for a given situation. Information on the filter quality of a given respirator would be helpful when making the selection. Filter quality is usually expressed by the "filter quality factor," which relates the aerosol removal by the filter to the pressure drop across it. Currently, the respirators available on the market are labeled for protection against certain hazardous or nuisance materials, but no information on filter quality is provided.

Certification tests of particulate respirators (dust, mist, and fume respirators) have been established.[2] In the *NIOSH Respirator Decision Logic*, the Mine Safety and Health Administration (MSHA)/NIOSH particulate respirators are divided into seven classes: dusts, fumes, mists, dusts-mists-fumes, radon daughters, asbestos-containing aerosols, and single-use dust and mist respirators.[1] The *NIOSH Certified Equipment List*[3] provides not only information on how to select a respirator but also lists all approved respirators in each category. On the basis of this list, particulate respirators are classified into four groups: single-use (SU), dusts and mists (DM), dusts, mists, and fumes (DMF) and high-efficiency particulate air filter (HEPA). In general, the first three classes are approved for respiratory protection against aerosols having an exposure limit not less than 0.05 mg/m^3 or 2×10^6 particles/ft^3, measured as a time-weighted average (TWA). The HEPA respirator is approved for radionuclides and aerosols having a TWA less than 0.05 mg/m^3. Some respirators appear in both the SU and DM lists, indicating that many of the two respirator categories have similar filter penetration characteristics. The

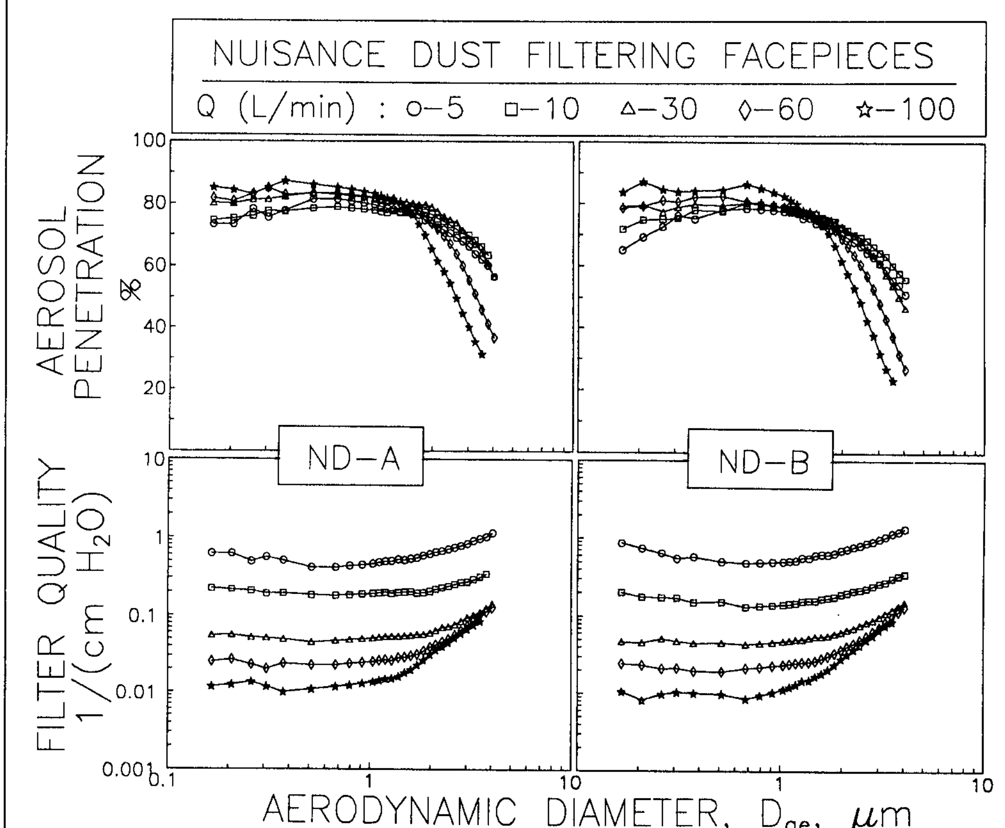

FIGURE 3. Filter penetration and filter quality of nuisance dust (ND) respirators

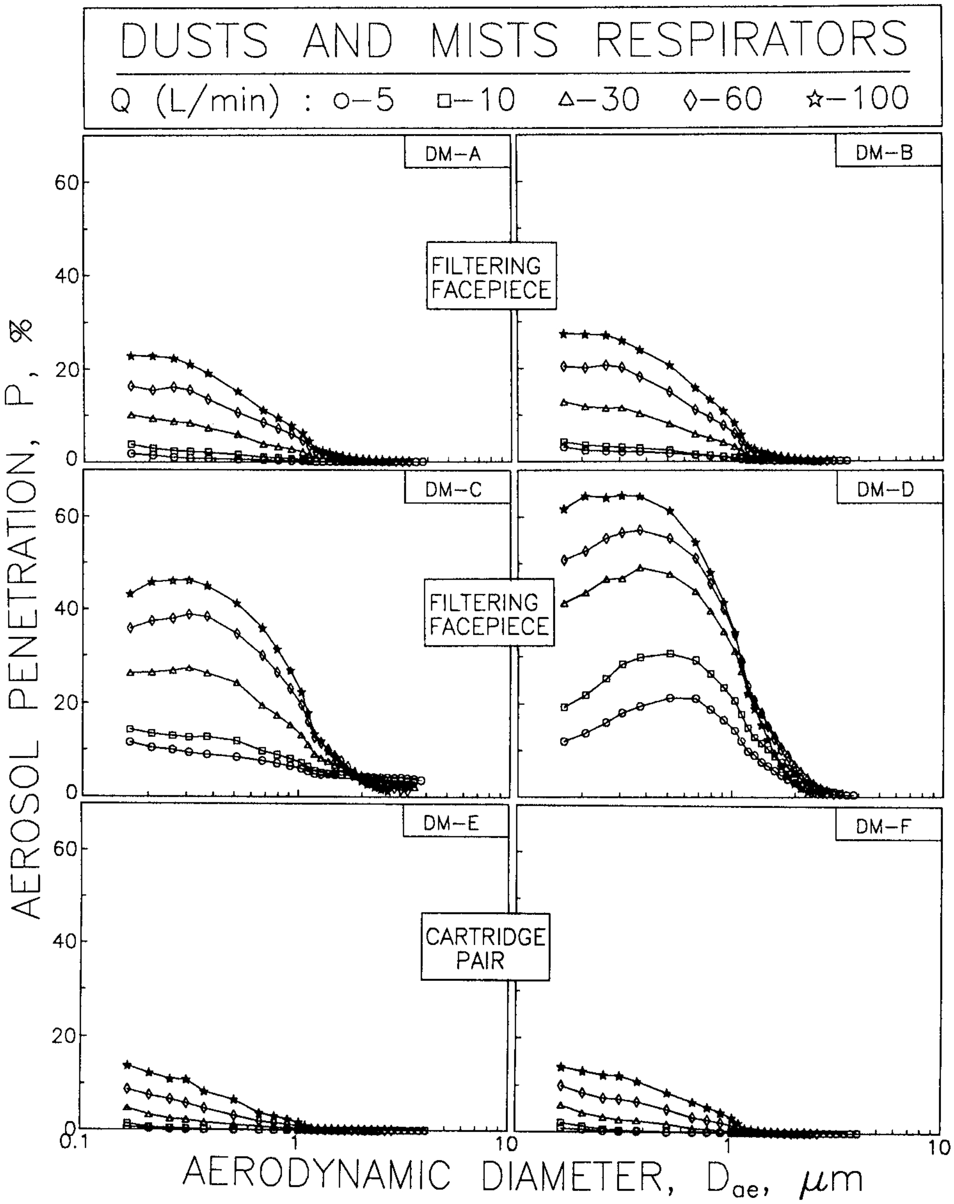

FIGURE 4. Filter penetration of six dust-mist (DM) respirators

classification system does not include nuisance dust (ND)—dusts having a threshold limit value (TLV)-TWA less than 10 mg/m^3. In this study, the SU category has been combined with the DM category, and a category for ND has been added. The respirator categories studied thus are ND, DM, DMF, and HEPA.

The objective of this study is to present basic data on the performance of particulate filtering facepieces and of cartridges used on elastomeric respirators. The performances are presented in terms of filter penetration and filter quality as a function of particle size. This study also shows that respirators of the same category—all MSHA/NIOSH approved—may perform considerably differently in terms of the mass concentration penetrated through the filter material. Face seal leakage may increase the amount of aerosol inhaled by the respirator wearer but is not considered in this study.

PREVIOUS WORK

A variety of aerosols, such as latex, silica, sodium chloride, corn oil, lead fume, dioctyl phthalate, room air aerosol, and nuisance dust (such as cement dust) have been used to evaluate respirator filter performance.[4–16] These studies have found that aerosol penetration depends on parameters such as test agent, aerosol size, aerosol charge, airflow, respirator category, filter packing density, fiber size, and fiber charge. High temperature and high humidity can deteriorate the filtration efficiency.

Cherrie et al.[11] tested the performance of seven nuisance dust respirators by using Portland cement dust. Brosseau et al.[16] used latex particles to evaluate the performance of 10 types of NIOSH-certified dust and mist respirators and found that these respirators can be statistically classified into three groups according to their penetration.

Most of these studies focused only on filter penetration. However, all certified respirators have to pass two tests: filter penetration and air resistance.[2] A respirator with perfect filtration and physiologically intolerable high air resistance is of no use. Consequently, both filter penetration and air resistance should be considered when ranking the respirators. The filter quality factor,[14] q_F, is normally used as the indicator of filter performance

$$q_F = \ln(1/P) / \Delta p \quad (1)$$

where P is the fraction of aerosol penetrated and Δp is the pressure drop. This factor should only be used to compare cartridges and filtering facepieces within the same respirator category.

A good respirator should have low filter penetration and low pressure drop. Filter thickness and packing density, aerosol loading, viscosity of the air, and filtration velocity affect the magnitude of the pressure drop. Filtration is even more complicated than pressure drop. Normally, there are five basic filtration mechanisms involved—diffusion, interception, impaction, gravitational settling, and electrostatic attraction. Each mechanism has its own governing region of aerosol size and filtration velocity.[17,18] In general, air resistances do not vary as much as filter penetrations among respirators of the same category.[18] This implies that it may be easier to improve respirator performance by enhancing filtration efficiency than by reducing air resistance. The parameters involved with optimization of filtration include fiber size, aerosol size, filtration velocity, aerosol density, air viscosity, fiber charge, aerosol charge, and permittivity of free space.

Filtering facepieces have many advantages over cartridge respirators: less maintenance, easier communication with co-workers, less burden, and less vision obstruction. They are, generally, not as pliable as the elastomeric respirators (normally having one or two cartridges), and may, therefore, incur greater face seal leakage. Some of the filtering facepieces have an extra interface rubber layer to improve the face seal fit, and thus approach the performance of elastomeric respirators. The authors have focused on the performance of filtering facepieces and have made comparisons with the performance of cartridge respirators. The respirator performances are presented as a function of aerosol size.

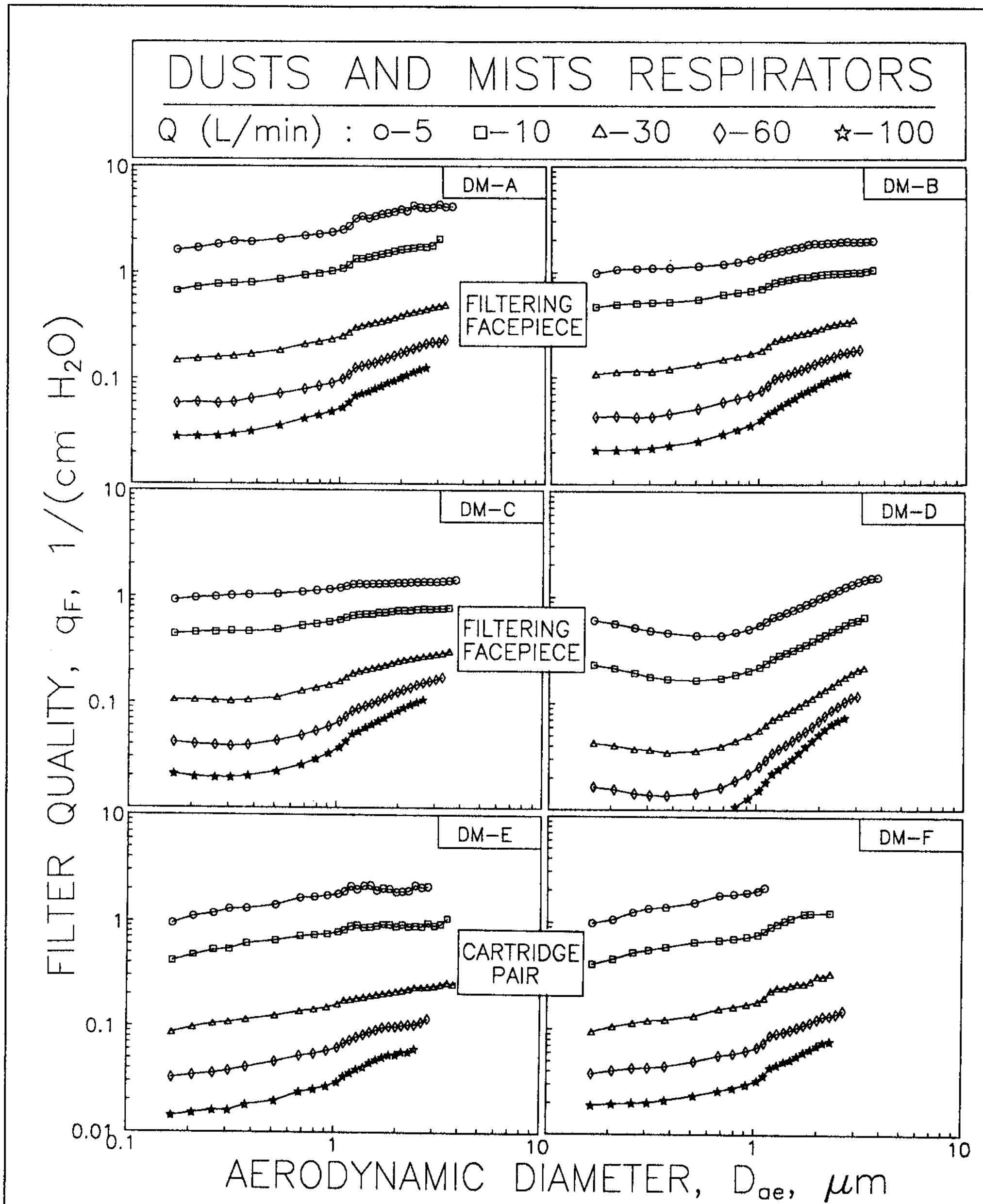

FIGURE 5. Filter quality (q_F) of six dust-mist (DM) respirators

EXPERIMENTAL MATERIALS AND METHODS

The design and characterization of the aerosol generation and sampling system used in this study, schematically shown in Figure 1, were upgraded from a previous study on a dust-mist filtering facepiece.[19] The preceding system used an aerodynamic particle sizer (Model APS33B, TSI Inc., St. Paul, Minn.) to measure aerosol size from 0.8 to 15 µm. It has been modified to measure over a wider size range by adding a laser aerosol spectrometer (Model LAS-X CRT, PMS Inc., Boulder, Colo.), which has a working range of 0.1 to 3 µm. This was done to include the most penetrating aerosol size (the particle size with the highest filter penetration), normally ranging from 0.2 to 0.3 µm.

Corn oil aerosol was used as the test agent. A newly developed size-fractionating aerosol generator[20,21] produced aerosols with selected size distributions. The size-fractionating aerosol generator tailors the size distribution in order to reduce the coincidence effect caused by the high concentration of small aerosols and to improve the particle statistics by increasing the number of large aerosols being collected inside the respirator. A 10 mCi Kr-85 radioactive source was used to neutralize the aerosol to Boltzmann charge equilibrium. The aerosol was mixed with clean air and entered the test chamber used for fit testing mannequins. Suction flow, Q_{suc}, and all the flows involved with aerosol generation were controlled by mass flow controllers (Model 247C, MKS Instruments, Andover, Mass.), to ensure stable chamber concentrations. The pressure drop inside the respirator was measured with an inclined manometer.

Nine different products of filtering facepieces and six different products of cartridges (listed in Table I) were sealed to a mannequin by using petroleum jelly. The filter penetration was determined by measuring at least three respirators of each product. Most samples deviated by 1% to 10% from the mean.

The aerosols inside and outside the respirator were sized by the aerodynamic particle sizer (APS) and the laser aerosol spectrometer (LAS). The sampling flows of the APS and the LAS were fixed at 5 L/min and 0.06 L/min, respectively. By adjusting the suction flow, the respirator performances were tested at mask

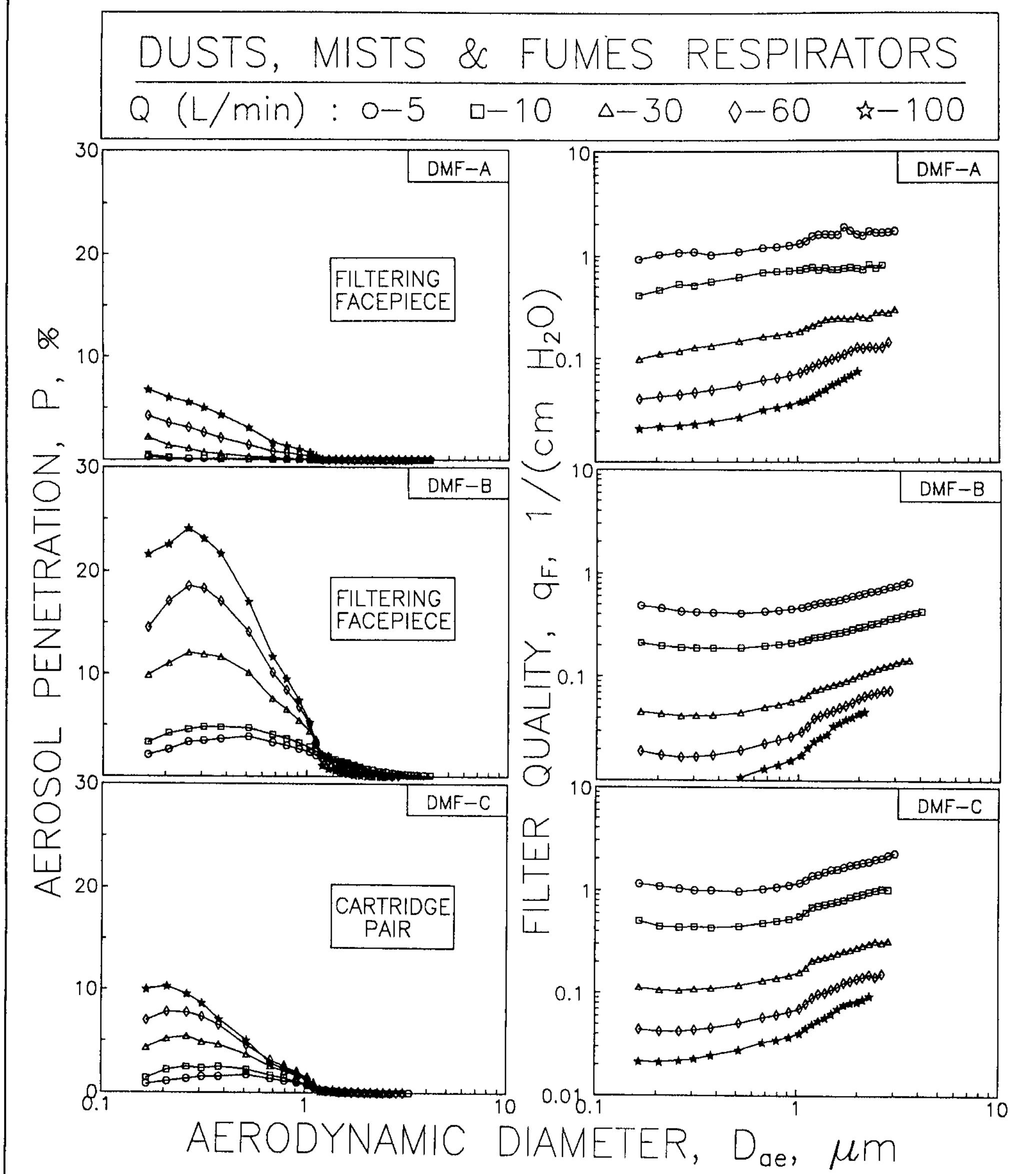

FIGURE 6. Filter penetration and filter quality (q_F) of three dust-mist-fume (DMF) respirators

flows, Q_{mask}, ranging from 5 to 100 L/min. A specially designed sampling probe was used to facilitate the mask flow and minimize aerosol deposition in the sampling system.[19]

The APS and the LAS are both real-time optical particle counters, but they size aerosols by different principles.[22,23] The APS displays the size distribution data as a function of aerodynamic particle diameter; the LAS displays them as a function of optical particle diameter. From an industrial hygiene viewpoint, the aerodynamic size is more directly related to the aerosol deposition in the human respiratory system than the optical size. Accordingly, an electrostatic aerosol classifier (Model 3071, TSI Inc.) was used to calibrate the LAS. This allows the LAS to display aerosol size distributions in terms of physical diameter. These have been converted to aerodynamic diameter because the density of corn oil is known (0.95 g/cm^3).

Figure 2 shows that the combined use of the APS and LAS instruments is appropriate. The LAS has a working range from 0.1 to 3 μm and the APS has a working range from 0.5 to 30 μm. After normalization, the size distributions of the LAS and the APS overlap well from 0.8 to 1.0 μm. The low end of the APS size distribution was not used because of the decrease in sensor sensitivity below about 0.8 μm.[23] In this study, the LAS was used to provide data on submicrometer-sized aerosols, and the APS provided data on supermicrometer-sized aerosols. Figure 2 also confirms that the performance of the sampling train is not affected by mask flows ranging from 5 to 100 L/min.[19] Normally, the aerosol output from a nebulizer has a count median diameter (CMD) of about 0.4 to 0.6 μm. Figure 2 shows that the size-fractionating aerosol generator used reduces this peak in the submicrometer size range (to avoid particle coincidence in the instrument's view volume) and adds a peak in the supermicrometer size range (to ensure a statistically sufficient number of large particles penetrated through the filter material).

The sampling time of these two size spectrometers was normally set for 3 min. When testing HEPA respirators, a longer sampling time (3 to 5 hr) was used to collect a sufficient number of aerosol particles from inside the respirator. The HEPA respirator tests were conducted only at the 100-L/min mask flow because the particle count was not sufficient at the lower flow rates. The 0.3-μm channel of the LAS was used as the indicator. If the 0.3-μm channel collected less than 100 aerosols, sampling was continued until the count reached 100. This increased the statistical quality of the filter penetration data.

RESULTS AND DISCUSSION

The performances of nuisance dust (ND) respirators from two different manufacturers are shown in Figure 3. ND-A and ND-B have similar penetration patterns. Both of them pass about 80% of the submicrometer-sized aerosol when tested for mask flows of 5 to 100 L/min (collection efficiency = 1 – penetration

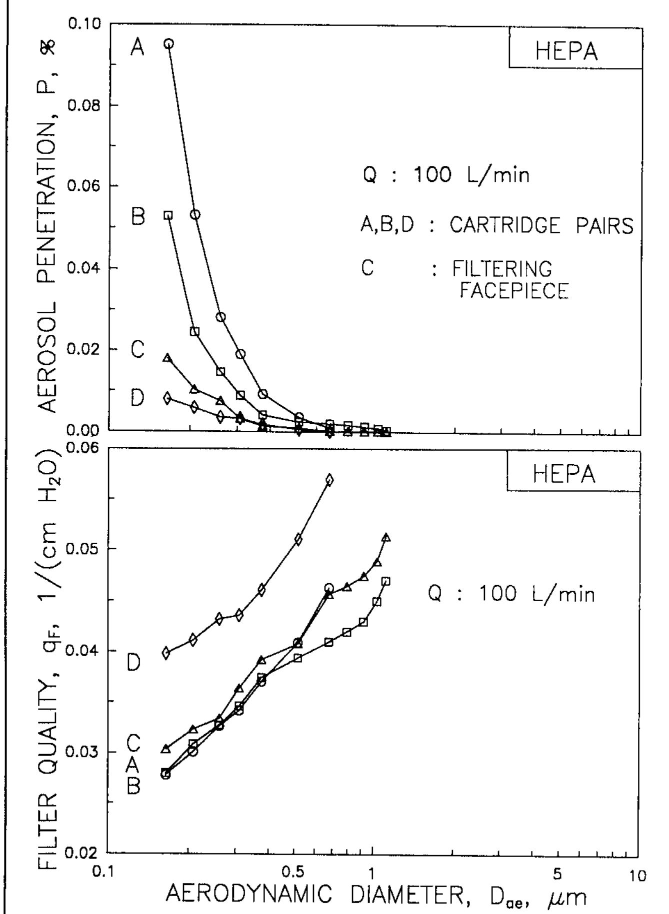

FIGURE 7. Aerosol penetration and filter quality (q_F) of four high-efficiency particulate air filter (HEPA) respirators

percentage = about 20% in this case). The penetrations of supermicrometer-sized aerosol particles clearly decrease with mask flow, indicating that the nuisance dust respirators remove large aerosol particles by impaction.[17,19] The filter quality also has strong aerosol size dependency, especially in the supermicrometer size range. The filter quality, shown on a logarithmic scale, increases as the aerosol becomes larger than the most penetrating size. It is lowest for the highest flow rate. The filter quality values increase with increasing aerosol size and merge at infinity because the aerosol penetration through all of the respirators approaches zero.

Figure 4 shows the filter penetration of four dust-mist filtering facepieces (DM-A,B,C,D) and two dust-mist cartridges (DM-E,F). The surface area of each filtering facepiece is about 165 cm^2. Each DM cartridge contains an 8-cm diameter fibrous filter mat. Thus, a cartridge pair has a total surface area of about 100 cm^2. In the submicrometer size range, the penetration curves for each DM respirator are more clearly separated than those of nuisance dust respirators. This indicates that the dust-mist respirators remove the small aerosols more efficiently and have a stronger flow dependency than nuisance dust respirators. The increase in aerosol penetration with increasing mask flow is explained by the fact that the primary removal mechanisms are diffusion and electrostatic attraction.[17,19] The great variability in penetration can be easily noticed. For example, the penetration of 0.3-μm aerosol particles ranges from 11% for DM-E to 64% for DM-D when tested at an equivalent inhalation flow rate of 100 L/min (corresponding to a high work load at a breathing rate of 50 L/min or less).

As indicated above, aerosol penetration alone is not enough to rank respirator filters. Evaluation of the total performance should include both the filter penetration and the air resistance, which may be indicated by "filter quality" (Equation 1). The respirator with the lowest filter penetration is not necessarily the best respirator from a filter quality standpoint. This is illustrated in Figure 5, where DM-A has the highest filter quality, although DM-E and DM-F have lower filter penetration than DM-A. This implies that DM-A is best engineered to facilitate the air passing through and at the same time effectively remove aerosol particles in the airflow. The variability in filter quality among filtering facepieces of different manufacturers is high. For example, the filter quality for 0.7-μm aerosol particles at a flow of 5 L/min through DM-A is 2.05 and that through DM-D is 0.31; i.e., they differ by a factor of 6.6.

Figure 6 displays the filter penetration and the filter quality of two dust-mist-fume filtering facepieces (DMF-A and DMF-B) and one dust-mist-fume cartridge pair (DMF-C). The DMF filtering facepieces tested have about the same surface area as the DM filtering facepieces tested. The DMF cartridge pair, which is made up of pleated filter material in the cartridge holder, has a total surface area of about 200 cm^2. Normally, dusts and mists are referred to as supermicrometer-sized aerosols and fumes as submicrometer-sized aerosols. Therefore, the dust-mist-fume respirators are expected to allow less aerosol penetration of submicrometer-sized aerosol particles than the dust-mist respirators. DMF-A and DMF-C follow this expectation. DMF-B, however, has exceptionally high filter penetration, even higher than some of the dust-mist respirators. Conversely, DMF-C, a cartridge filter, has the best filter quality although it does not have the lowest filter penetration. Manufacturers can decrease the aerosol penetration of a given filter material by increasing its thickness. However, this does not change the filter quality because the pressure drop is increased correspondingly.[24]

The performance data of four HEPA respirators are shown in Figure 7. Among them, C is the only filtering facepiece. MSHA and NIOSH certify respirators as HEPA respirators if they filter at least 99.97% of 0.3-μm dioctyl phthalate aerosol at flow rates of 32 and 85 L/min.[1] These four HEPA respirators all meet this requirement because the penetrations at 100 L/min are less than 0.03% and the penetrations at 85 and 32 L/min should be lower than at 100 L/min. HEPA-D has the lowest filter penetration and an outstanding filter quality. The aerosol penetration data for the other three HEPA respirators differ, but their filter quality data are similar.

All of the data shown are for new, unused filtering facepieces and cartridges. For filters in which only the mechanical forces of diffusion, interception, impaction, and gravitational settling remove particles, aerosol loading increases the filtration efficiency with time.[24] If the filter material is electrically charged, the coating of the fibers by particles reduces the electrostatic effect and the removal efficiency decreases with

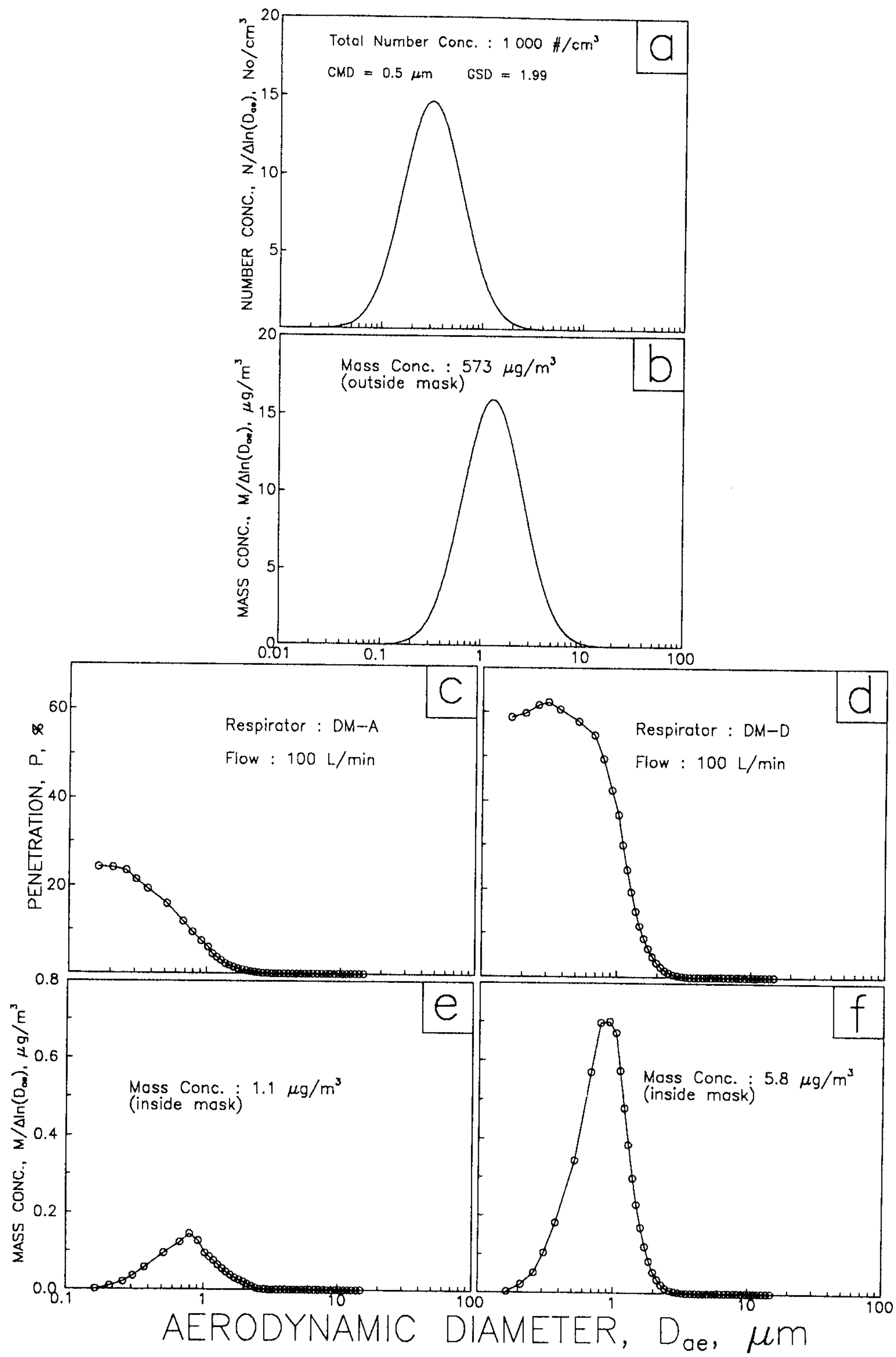

FIGURE 8. Test aerosol penetrating through the best and the worst dust-mist filtering facepieces tested

time. When enough loading has occurred, the blocking of the interstitial spaces again increases the collection efficiency.[24]

The results of this study obtained with corn oil aerosol are used to evaluate the current filter test protocol. The NIOSH-regulated filter test specifies a range of mean particle sizes and measures of spread permissible for the test aerosol.[2] Dust and mist respirators are required to retain 99% of silica aerosol with a count median diameter (CMD) of 0.4 to 0.6 μm and a geometric standard deviation (GSD) not greater than 2. The variability among respirators is shown in Figure 8, where the CMD is 0.5 μm and the GSD is 1.99. The aerosol number concentration is assumed to be 1000 particles/cm^3. This corresponds to a mass concentration of 573 μg/m^3 outside the respirator, as shown in Figure 8b. The filtering facepieces that performed best and worst were chosen to make the contrast (Figure 8c and 8d, see also Figure 4). The penetration data varied by a factor of three (60% versus 20%) at the most-penetrating size (normally referred to 0.3 μm). The mass concentration inside the respirator varied by a factor of 5.5 (5.8 versus 1.1 μg/m^3), as shown in Figure 8e and 8f. Upon loading the filter with aerosol particles, the penetration of aerosolized silica dust will differ from that of the corn oil test aerosol. However, the indicated data are for previously unused respirators prior to loading.

The aerosols used in the filter test are intended to classify the respirators. The required mean size and spread are not necessarily best for differentiating by filter quality. The effect of variation in CMD is shown in Figure 9a for a mask flow of 100 L/min and a GSD of 1.99. The ordinate represents the ratio of the mass concentration inside the DM-D respirator to that inside the DM-A respirator. This ratio increases with CMD, reaches a maximum at a CMD of about 1 μm, and then decreases with increasing CMD. In this case, a CMD of about 1 μm has the highest sensitivity for differentiating the dust-mist filtering facepieces tested.

Figure 9b shows the effect of variations in GSD for a fixed CMD of 0.5 μm. The performance ratio increases with increasing GSD and approaches 5.5 above a GSD of 2. At a high GSD, there are more large and small aerosols present than at a small GSD.

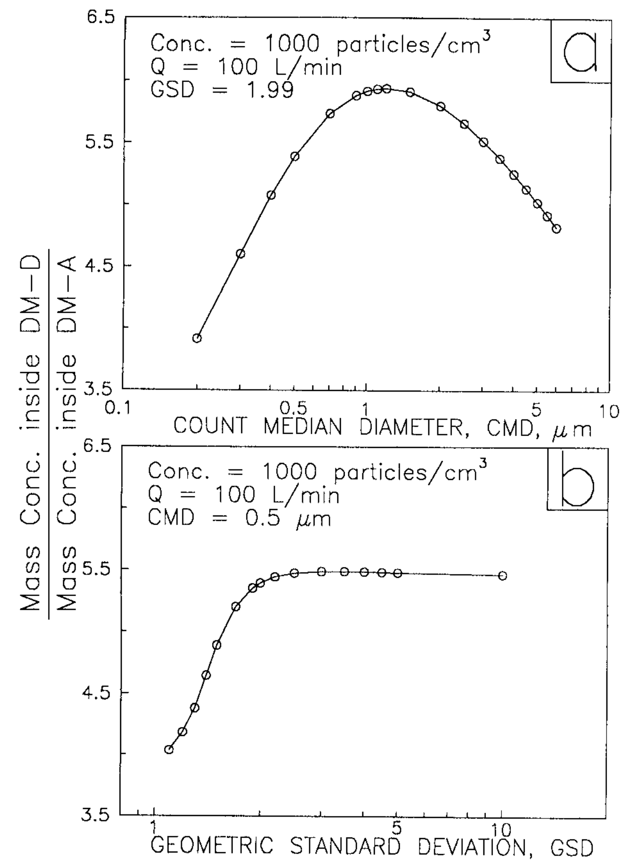

FIGURE 9. The effect of count median diameter (CMD) and geometric standard deviation (GSD) of the test aerosol on the ratio of the performance of the best to the worst dust-mist filtering facepiece tested

The large aerosols cannot penetrate the filter; the small aerosols do not contribute significantly to the mass concentration. Therefore, the ratio remains constant at a GSD larger than 2. When a monodisperse aerosol (GSD ≃ 1) is used, the filter test reveals the filtration efficiency at a certain aerosol size, in this case 0.5 µm. If the purpose is to determine the best dust-mist filtering facepieces, a GSD of 2 or higher reveals the performance over a wide size range. However, the use of a high GSD can make the filter test less sensitive because the large aerosol particles retained by the filter material dominate the mass.

A new filter test protocol[25] proposed by NIOSH adopts test aerosols with a smaller mean size of 0.2–0.3 µm and a smaller GSD of ≤1.6. This new method also advocates the use of a suitable light-scattering photometer or equivalent instrumentation. These changes will make respirator certification a more rigorous process because a 0.25-µm aerosol normally has higher filter penetration than a 0.5-µm aerosol, especially at high mask flows, and because photometric instruments are most sensitive to submicrometer-sized aerosols. However, the authors' data show that the filter penetration of submicrometer-sized aerosols cannot be used to predict the filter penetration of supermicrometer-sized aerosols, which is responsible for most of the exposure in terms of mass concentration.

CONCLUSIONS AND RECOMMENDATIONS

The APS and the LAS instruments have been used successfully to measure aerosol penetration over a wide size range, from about 0.1 to about 15 µm. The variability in filter penetration has been shown to be high by use of these instruments. Dust-mist respirators have the widest range of filter penetration among the ones tested. The filter penetration at a specific particle size may differ by over five times for the DM respirators tested. For a typical polydisperse test aerosol, this difference may be as much as a factor of 5.5 when the aerosol mass concentrations are considered.

One of the DMF respirators tested had exceptionally high filter penetration, higher than some of the DM respirators. This raises the question of whether the current filter test protocol is appropriate, or whether quality control during respirator manufacturing is adequate. Because respirators are used to protect wearers over a wide particle size range, the choice of mean size and spread in the size distribution of the test aerosol is closely linked to the success in predicting the protection received. Comparisons of DM respirator performance indicate that the performance of a respirator in the 0.2 to 0.6 µm size range does not predict the performance of the respirator in the supermicrometer size range. Therefore, testing at one submicrometer and one supermicrometer particle size appears to be the minimum necessity for measuring and differentiating the filtration performances of respirators.

The mask flow used in this study is constant. The results, theoretically, should correlate well with cyclic flow. Further study is needed to find the constant flow that is representative of cyclic flow.

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