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FILTER AND LEAK PENETRATION CHARACTERISTICS OF A DUST AND MIST FILTERING FACEPIECE*

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The filtering facepiece, also referred to as a disposable respirator, is an extensively used type of respirator without an officially accepted fit testing method. This study describes an aerosol generator and a sampling train, which have been developed for investigating the aerosol penetration characteristics through the filter element and the face seal. Electrostatic attraction and impaction are the two primary filtration mechanisms for micrometer- and supermicrometer-sized aerosols, respectively. Filtration and flow dynamics were found to affect aerosol penetration in distinct ways that allow for the differentiation of the face seal leakage from the filter penetration. The slope of the aerosol size-dependent penetration curve potentially may differentiate the face seal leakage from filter penetration.

Respirators are air-purifying devices commonly used in industry to protect workers from inhaling hazardous airborne aerosols. Under ideal conditions, i.e., maximum protection, respirators must completely fit and seal to the face of their users. The Occupational Safety and Health Administration (OSHA) of the Department of Labor, which regulates respirator usage, requires that respirators have a good face seal.[1] Full-face respirators, because of the size and geometry of their seal, provide the best protection; however, they are heavy, uncomfortable, and obstruct the worker's vision. Half-face respirators are more popular with workers because they obstruct less vision and are lighter, hence less burdensome. Filtering facepieces, also referred to as "disposable respirators," are the lightest, least burdensome, and therefore, the most popular types of respirators preferred by workers.

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In order for an air-purifying respirator to work, it must have a good face-to-respirator seal or fit. Several fit testing methods have been developed to determine the extent of the seal for many wearer-respirator combinations.[2–7] Some of these fit testing methods are quantitative and others are qualitative. Quantitative methods are preferred because they provide the best indication of the protection the respirator will afford its user. However, the quantitative fit testing methods accepted today apply only to half- and full-face respirators. The fitting of such respirators is performed with HEPA cartridges and is required for worker protection in specific work environments. Fit testing with low-efficiency cartridges or with disposable respirators is not legally required today, and no suitable method has been accepted. To develop a fit testing method for disposable respirators, the ultimate goal of this research, it is crucial to first fully comprehend the filter and leak penetration characteristics of filtering facepieces. The purpose of this paper is to describe the authors' recent efforts in establishing a scientific base which, it is hoped, will facilitate the development of a fit testing method for disposable respirators.

BACKGROUND

The fundamental difficulty of fit testing disposable dust and mist respirators lies in separating the aerosol that leaks through the face seal from the aerosol that penetrates the filter. In conventional quantitative fit testing with about 0.5 μm sized aerosols, the penetration of aerosols through the HEPA filter is negligible relative to the leakage of aerosols through the face seal. When fit testing a disposable respirator, where the entire respirator is made of a filtering material, the penetration of aerosol through the filtering facepiece is generally not negligible in respect to the leakage of aerosols through the face seal. If all or part of the filtering materials within the filtering facepiece are substituted with HEPA filter material, the so-called Q-respirator, the filtration efficiency will be enhanced. However, this substitution changes the face seal because the HEPA filter material is less flexible and thus invalidates the fit test. In an earlier study, it was shown that by using a monodisperse supermicrometer-sized

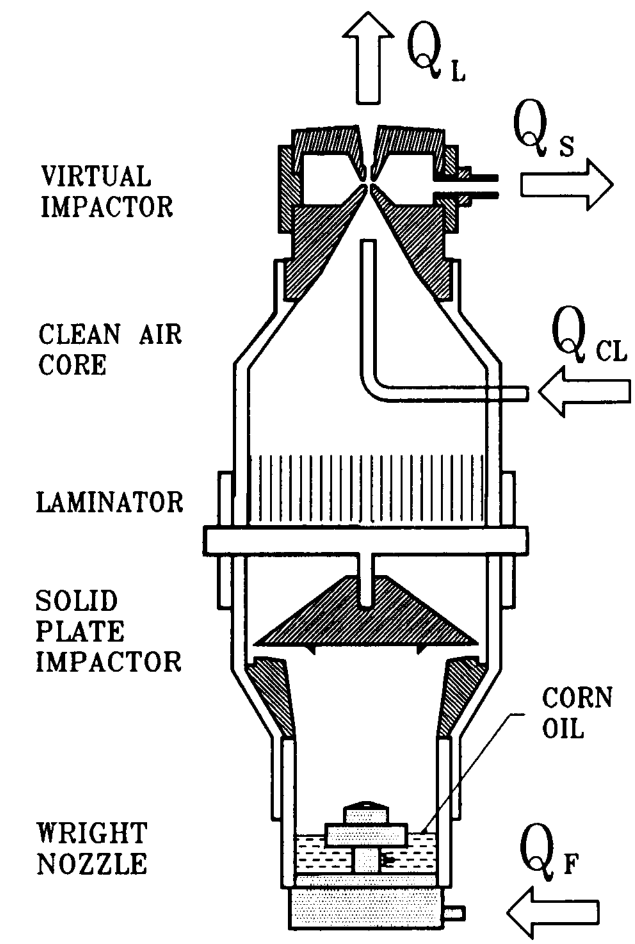

FIGURE 1. Schematic diagram of the size fractionating aerosol generator developed for studies on respirator fit and filtration. Q_{CL} = clean air core flow rate. Q_L = large aerosol exit flow rate. Q_S = small aerosol exit flow rate. Q_F = filtered, regulated airflow rate.

aerosol, the contribution of aerosols penetrating the filter material of a commercial dust and mist filtering facepiece was reduced relative to the face seal leakage.[8]

This finding suggests that the aerosol size distribution inside the respirator cavity should be measured relative to that outside the respirator over an aerosol size range of less than 1 μm to several micrometers. Two problems were encountered. First, tests showed that the aerosol generators used for quantitative respirator fit testing and any other pneumatic aerosol generator produce high concentrations of submicrometer aerosols and few supermicrometer aerosols. After removal by the filter and the face seal leak channel(s), not enough supermicrometer particles penetrate into the mask to be statistically significant. Second, if the total aerosol concentration is kept high, aerosol size spectrometers, such as optical single particle counters or aerodynamic particle sizers, do not record the true aerosol size distribution because of particle coincidence in their view volume, i.e., the simultaneous presence of more than one particle in the view volume reduces the recorded particle concentration and biases the recorded size distribution.[9]

Thus, a low-cost aerosol generator is needed with a high-output concentration of supermicrometer aerosols and a low-output concentration of submicrometer aerosols. Such a device[10] has been developed by the authors and will be described briefly.

SIZE FRACTIONATING AEROSOL GENERATOR

The new aerosol generator, schematically shown in Figure 1, combines a Wright nozzle[10] with a solid-plate impactor and a virtual impactor. The Wright nozzle has been modified to increase the large particle fraction. Very large droplets produced by this nebulizer are removed by the solid-plate impaction stage. A laminator above the impaction stage reduces the air turbulence and, thereby diminishes the deposition loss of large particles. In the virtual impactor, most of the small particles are deflected sideways and filtered out (small particle flow, Q_S). The large particles and a fraction of the submicrometer particles flow along the axis of the virtual impactor and are emitted from the device as the test aerosol (large particle flow, Q_L). Clean air core flow, Q_{CL}, about equal to the generator flow of filtered air, Q_F, has been added to decrease the fraction of small particles in Q_L.

The output from the size fractionating aerosol generator is diluted by clean air, Q_D, and introduced into a test chamber used for fit testing humans or mannequins, as shown in Figure 2. The aerosol is distributed uniformly in the approximately 2 m^3 chamber.[6,11]

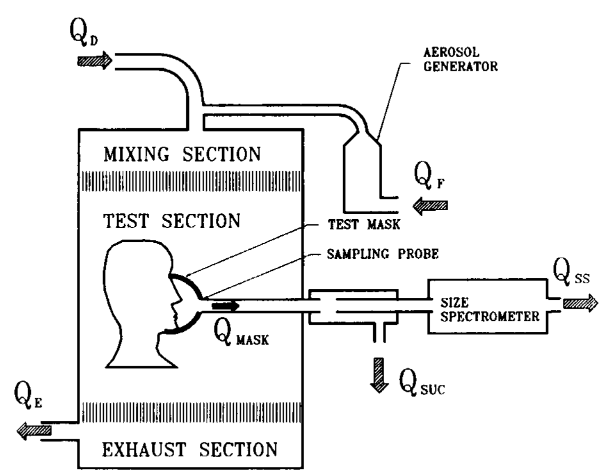

FIGURE 2. Schematic diagram of experimental set-up. Q_D = dilution airflow rate. Q_E = exhaust airflow rate. Q_F = filtered, regulated airflow rate. Q_{SUC} = suction airflow rate. Q_{SS} = sampling flow rate of aerosol size spectrometer. Q_{MASK} = airflow rate through mask.

SAMPLING PROBE AND SAMPLING TRAIN

In conventional fit testing, probe location, probe depth, and leak location may bias the data.[5,11] This is particularly true for a filtering facepiece because only the region near the probe is sampled during the inhalation phase, when a small amount of air flow (typically 1–2 L/min) is extracted through the probe. While some of the particles in the respirator cavity are sampled through the probe, most are inhaled, and a percentage of these is deposited in the lung. The fraction of exhaled particles, which is also sampled by the probe, is highly subject dependent.[12] In conventional fit testing, the respirator fit factor, which indicates the fit of the respirator to the wearer's face, also reflects the wearer's lung deposition characteristics. For a given face seal leak, i.e., fit, higher than average lung deposition, that is, higher exposure risk, results in an increased fit factor (an indication of decreased risk). For this study, the authors decided to focus on the face seal and filter penetration characteristics during inhalation. Therefore, aerosol penetration characteristics were tested for a wide range of inhalation flows.

The breathing rate at medium work load is about 32 L/min, which is also the flow recommended for the National Institute for Occupational Safety and Health (NIOSH) filter test.[13] The actual flow during inhalation is two or more times higher than that value, because the 32 L are inhaled during 30 sec or less and exhaled during 30 sec or more. The aerosol sampling train was designed to be compatible for a wide range of flow simulating different work loads and different flows during a given breathing cycle. The sampling train, shown in Figure 2, samples aerosols into the size spectrometer at 5 L/min. The suction flow rate, Q_{SUC}, is varied from 0 to 90 L/min, so that the total probe flow varies from 5 to 95 L/min in this system. The airflow through the filter and the airflow through the leak hole were extracted through the probe. Therefore, the sampling was least affected by the probe and leak locations.

The probe was designed for an average flow of 32 L/min. The dimensions, shown in Figure 3, minimize inertial and gravitational losses by selecting the inertial Stokes number to be less than 0.1 and the dimensionless gravitational settling velocity to be less than 1.0.[14,15] The inside of our inlet is rounded to further reduce entry losses. The performance of the sampling train was evaluated by generating a supermicrometer-sized aerosol and sampling it into the respirator probe without the respirator being attached to a human face or mannequin. Figure 4 shows that the measured aerosol concentration is essentially unaffected by the sampling flow for the range of 5 to 95 L/min. The bimodal size distribution of Figure 4 is tailored by the size-fractionating aerosol generator in order to clearly distinguish the removal mechanism for submicrometer-sized aerosols from that of supermicrometer-sized aerosols. The latter mode was chosen to be higher than the former so that an approximately equal number of less penetrating supermicrometer-sized aerosols reaches the aerosol size spectrometer sampling from inside the respirator.

EXPERIMENTAL MATERIALS AND METHODS

To generate stable aerosols with the desired size distribution, the input airflows to the generator, Q_F and Q_{CL}, and the effluent airflow, Q_S, were controlled and measured by mass flow meters. A dilution airflow rate, Q_D, of 1000 L/min reduced the aerosol

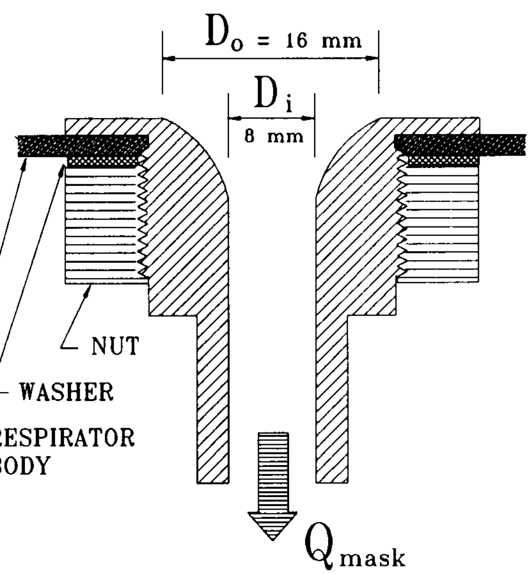

FIGURE 3. New respirator probe for sampling at 5 to 95 L/min

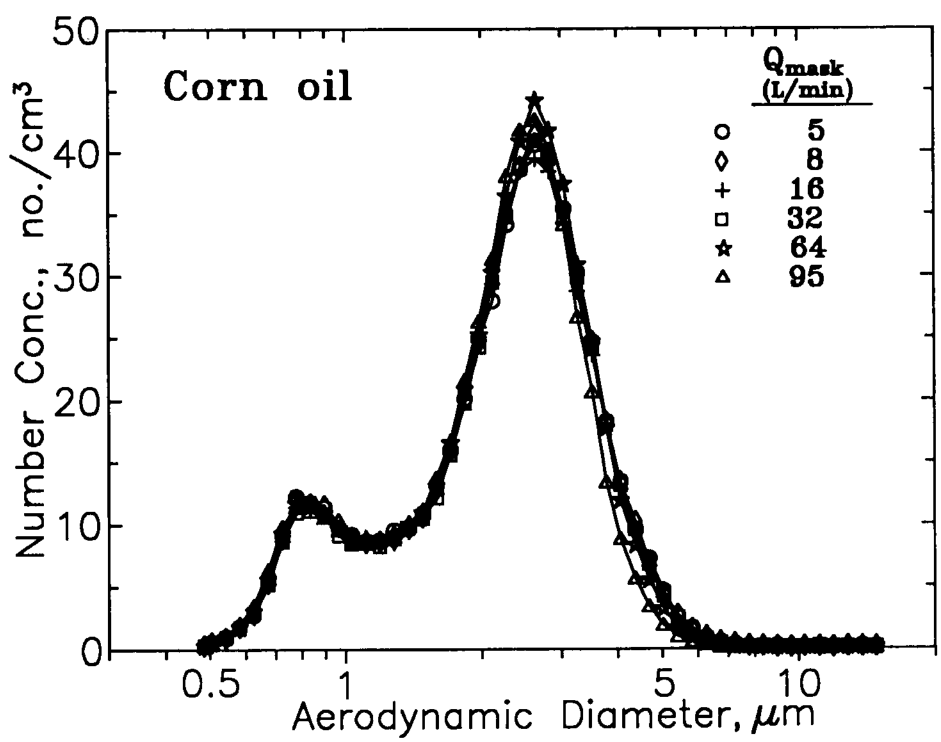

FIGURE 4. Sampling train performance for Q_{MASK} = 5 to 95 L/min

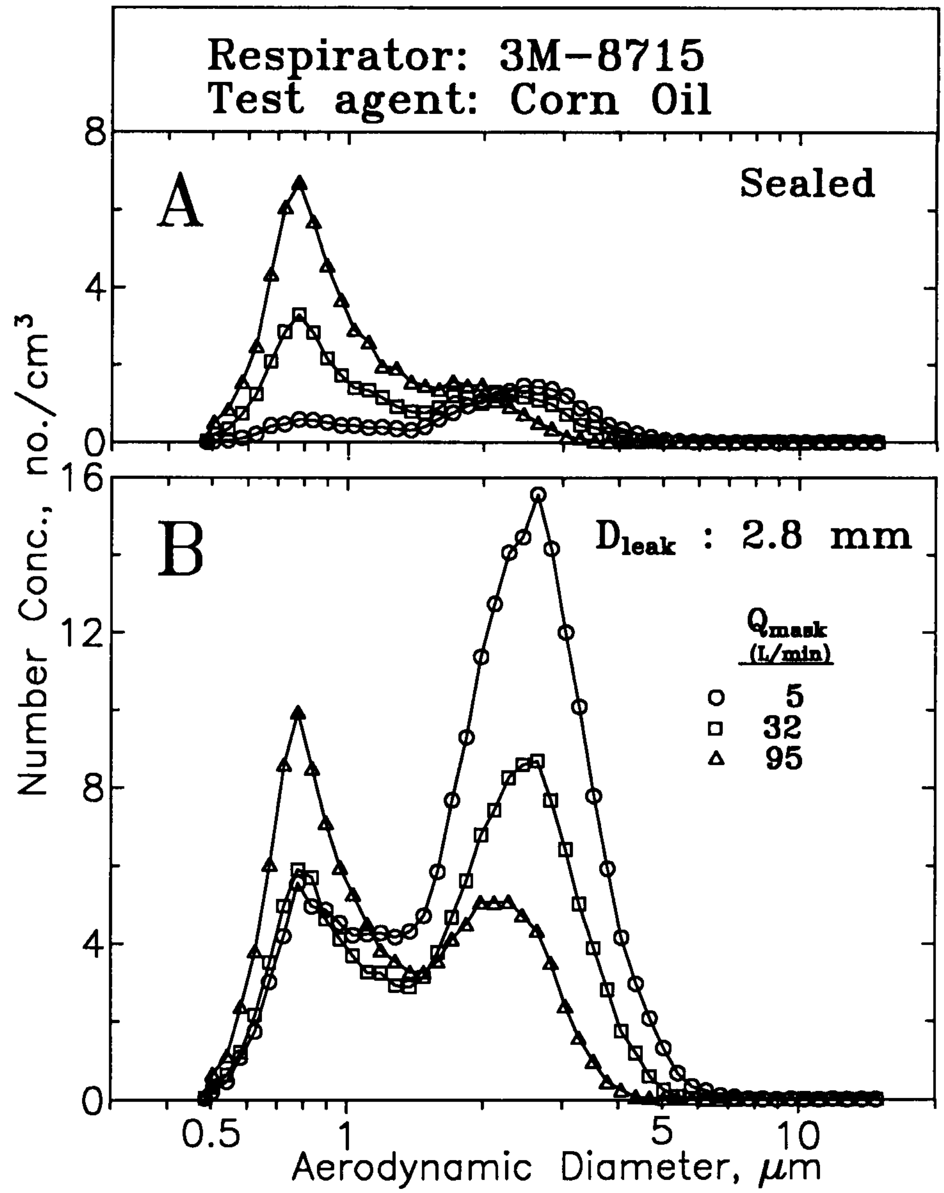

FIGURE 5. Aerosol size distributions measured inside the mask for the external aerosol of Figure 4. (A) Mask sealed to face. (B) Face seal leak hole = 2.8 mm.

concentration to a level suitable for aerosol penetration experiments in the exposure chamber, shown in Figure 2. An aerodynamic particle sizer (model APS33B, TSI Inc., St. Paul, Minn.) was used as the aerosol size spectrometer. The APS, as used, had a working range of 0.5 to 15 µm.

Aerosol penetration measurements of a typical dust and mist filtering facepiece (Model 8715, 3M Company, St. Paul, Minn.) were made by mounting the mask on a mannequin and measuring the inside and outside aerosol concentrations. To simulate the ideal face-to-face respirator seal, petroleum jelly was used to seal the respirator to the mannequin. The newly designed probe was placed in the center of the respirator. A washer was used to protect the respirator from tear by extra torque when trying to install the probe. Leaks were simulated through circular holes in a thin aluminum plate (1 cm × 2 cm), which was glued to the respirator about 6.5 cm from the probe near the right cheek. These leak diameters (2.0, 2.8, and 4.0 mm) are larger than those used in earlier studies on half masks[6,7,11,16] because the pressure drop is lower for filtering facepiece at a given inhalation flow, thus permitting less aerosol to enter through a given leak hole. For example, the pressure drops of a 3M model 8715 disposable respirator at 5, 30, and 100 L/min are 0.3, 1.9, and 6.5 mm water gauge (w.g.), respectively, while the pressure drops of a 3M half-face respirator (model 7300) with two 3M model 7255 cartridges are 1.3, 7.8, and 25 mm w.g., respectively.

The tests were performed at flows into and out of the mask, Q_{MASK}, ranging from 5 to 95 L/min. One of the six flows, 32 L/min, represents the inhalation rate at medium work load. The flows of 64, 16, and 8 L/min are twice, half, and one-fourth that value, respectively. The suction flow rate, Q_{SUC}, and size spectrometer flow rate, Q_{SS}, also were monitored by mass flow meters.

RESULTS AND DISCUSSION

The experiments were performed with corn oil as the test aerosol because the hydrophobic nature of corn oil makes it size-independent of humidity. The experiments were performed using dried and filtered air in a laboratory maintained at a relative humidity of 40–60% and a temperature of 22–28°C. The respirators had been kept in the laboratory for several days prior to testing. The penetration test was completed in less than 1 hr. Therefore, any possible bias caused by small variations in humidity and temperature was assumed to be negligible.

The flow rates in the size fractionating aerosol generator were set at $Q_F = 5.6$ L/min, $Q_{CL} = 6.5$ L/min, and $Q_S = 11$ L/min. This resulted in a challenge aerosol concentration in the test chamber of about 640 particles/cm³ with a count median diameter of 2.3 µm, which caused no coincidental effect in the size spectrometer and gave enough supermicrometer particles inside the respirator. The bimodal aerosol size distribution for these conditions is shown in Figure 4. The major advantage of this bimodal distribution is that it gave the striking clear visual illustration of how the filtration mechanism shifts from electrostatic attraction at small aerosols to inertial impaction at large aerosols, as shown in Figure 5.

From current knowledge, aerosols may deposit on the fibrous material by five basic filtration mechanisms: diffusion, electrostatic attraction, interception, impaction, and gravitational setting.[17] In theory, all these mechanisms can work simultaneously. The primary filtration mechanisms can be identified, however, through examination of the filtration performance as a function of particle size, face velocity, and other parameters.

The aerosol size distribution inside the mask is shown in Figure 5a for the filtering facepiece sealed to the mannequin and in Figure 5b for a leak hole of 2.8 mm. The aerosol size distributions clearly indicate different aerosol removal mechanisms. When the mask is sealed to the face, the aerosol concentration of the upper size mode is reduced more than that of the lower size mode. Aerosol penetration of the small particles in the lower size mode increases with airflow, which indicates that electrostatic attraction is the dominant filtration mechanism in this size range. As the airflow is increased, the time for electrostatic removal is decreased and, therefore, aerosol penetration is increased. Aerosol diffusion is similarly time dependent but is fairly insignificant for aerosols larger than about 0.5 µm.

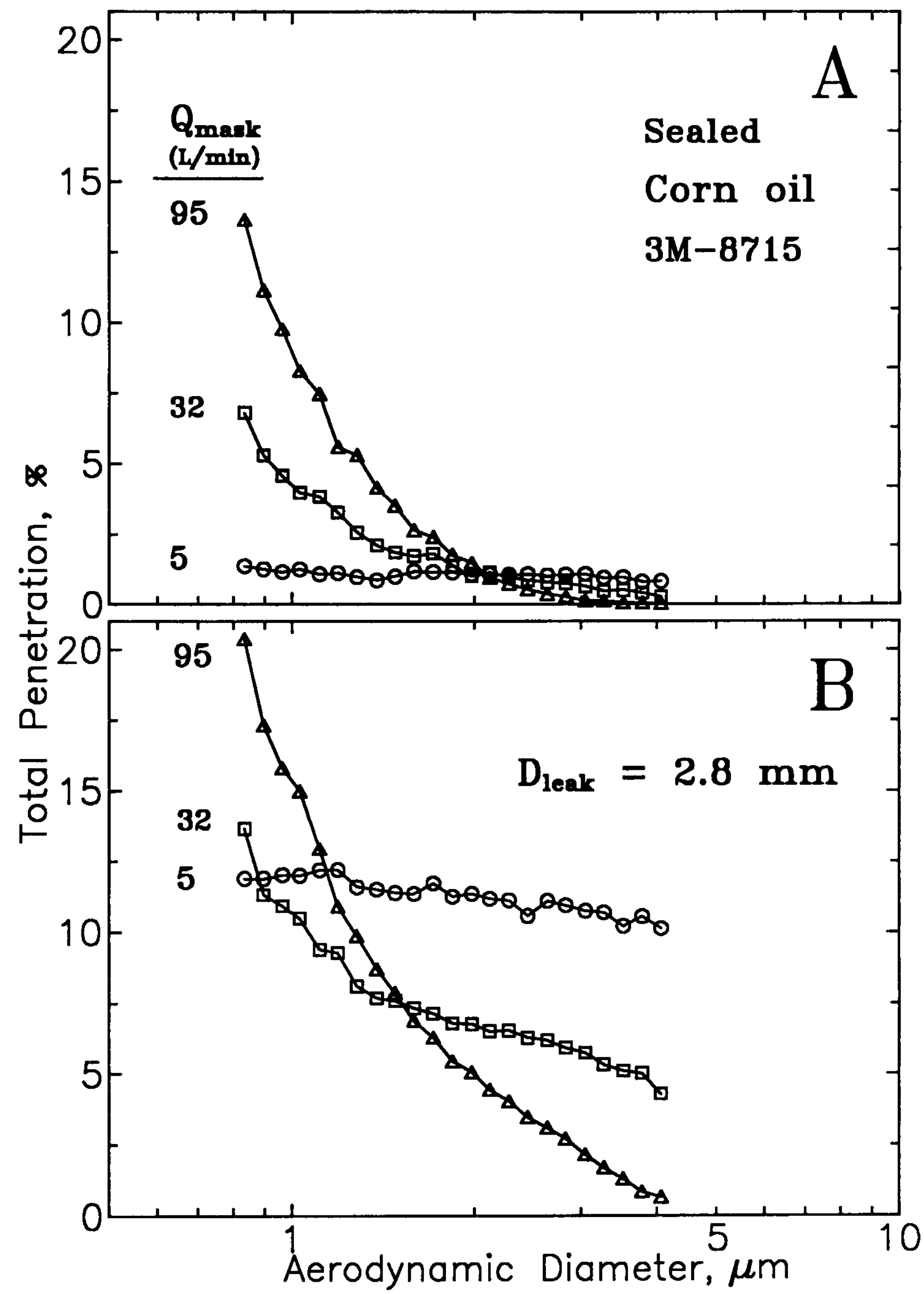

FIGURE 6. Respirator performances at different flow rates. (A) Mask sealed to face. (B) Face seal leak hole = 2.8 mm.

Conversely, the aerosol concentrations in the upper size mode vary in the opposite way. As the airflow is increased, the concentration of penetrated aerosols is reduced and the mean size of that size range is shifted to a smaller size. This indicates that impaction is the primary removal mechanism for this size range. Interception may be important for aerosol particles close to the most penetrating size,[17] which is below the working range of the instrument used. Sedimentation is almost always negligible in filters, especially when the flow is horizontal. It may contribute when the aerosol particles are large and the face velocity is low.

When a leak hole of 2.8 mm is added, additional aerosol particles enter the respirator cavity through this flow channel and increase the aerosol concentration in both size ranges (Figure 5b). The most dramatic increase in aerosol concentration occurs at the lowest flow.

The aerosol data from inside the mask (Figure 5) can be divided by the external aerosol size distribution (Figure 4) to determine the percent aerosol penetration (Figure 6). The data above 4 µm are not presented because their number counts inside the mask were too low to be statistically significant. Aerosol penetration through the filter is about 1.5% at the low flow of 5 L/min, irrespective of particle size from 0.8 to 4 µm (Figure 6a). This indicates that all aerosol particles in this size range have about the same opportunity to penetrate the filter. When a leak was added, the penetration increased about equally for all sizes (Figure 6b). This indicates that at a very low airflow, i.e., a very low pressure differential, the aerosols enter the respirator cavity through the fairly large leak channel without much removal. At higher airflows, however, the air velocity in the leak channel and in the filter is increased and removal by impaction occurs in both paths for the larger particle sizes (Figure 6).

Figure 6b also indicates that, for a given leak, the aerosol concentration inside the mask is highly flow dependent. In a fit test with a subject breathing normally, the test result would, therefore, not only depend on the face seal leakage, but also would vary according to the individual's breathing rate, which is normally not measured or controlled.

For a given leak hole, Figure 6b, the size-dependent aerosol penetration curve appears to have a unique slope for each airflow. For a fixed flow (Figure 7), each leak hole size has its own unique slope. The slope is steepest for the sealed mask. It decreases with increasing hole size. This feature of different slopes may provide a means for differentiating face seal leakage from filtration when tested at different flows.

The dependence of face seal leakage on particle size is shown in Figure 8. The indicated percentages are those of Figure 7, with the sealed mask data subtracted from the curves for different leak holes. For this calculation, it is assumed that the flow through the leak site is small compared to the flow through the filter. The three almost parallel and horizontal curves indicate that the fit factor is only slightly dependent on aerosol size. However, it should be kept in mind that the protection factor is highly dependent on particle size because large particles pene-

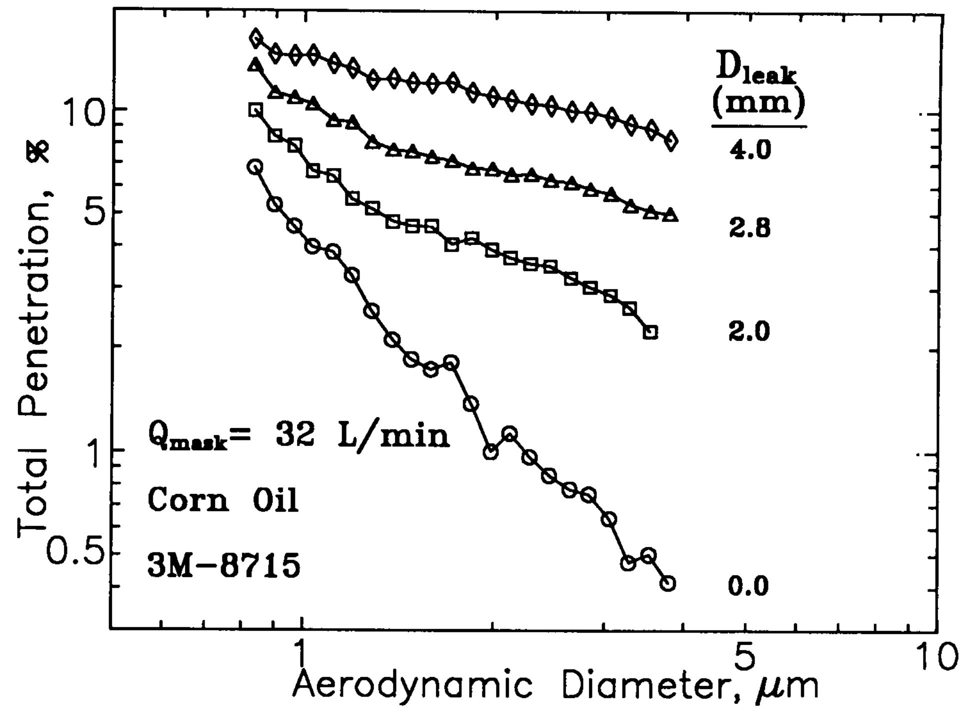

FIGURE 7. Effect of leak hole size for Q_{MASK} = 32 L/min

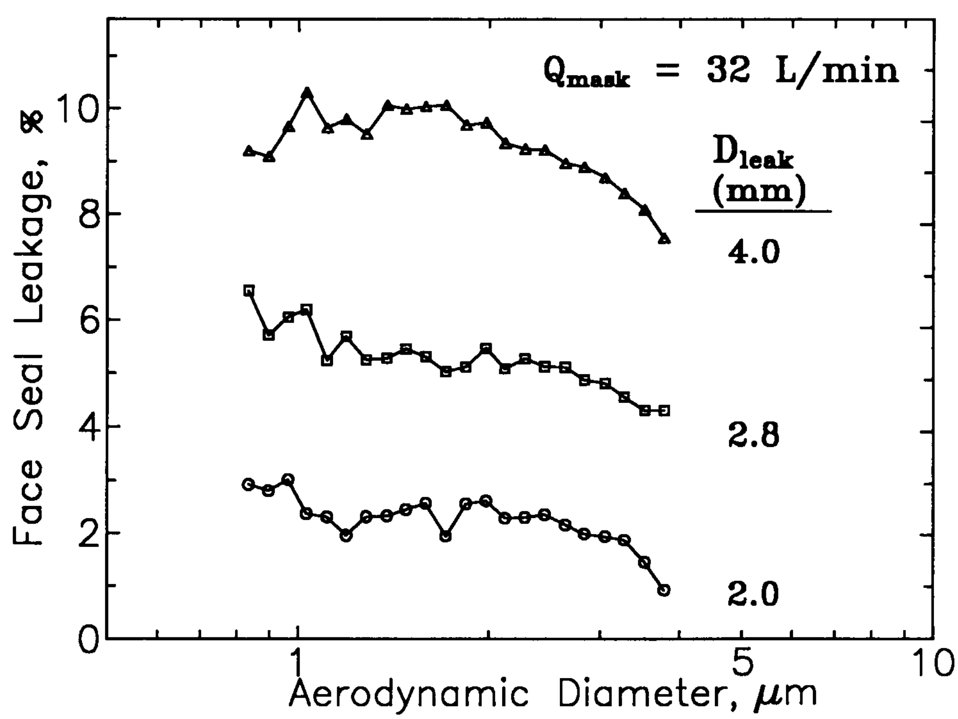

FIGURE 8. Penetration through face seal leak for Q_{MASK} = 32 L/min

trating inside the mask add considerably to the amount of particle mass present for lung inhalation.

This finding does not conflict with our previous report,[16] which showed that the fit factor is highly aerosol size dependent for half masks. In a filtering facepiece, such as the type 8715 mask by the 3M Company used in these tests, the pressure drop across the respirator is much lower than across the air-purifying cartridges of a half-mask or full-facepiece respirator. Therefore, the flow velocity through the leak site for a disposable dust and mist respirator is lower and the size of the leak is larger for a given air leakage. Decrease in flow velocity and increase in hole size, however, reduce the particle size dependence because deposition onto nearby surfaces is decreased.

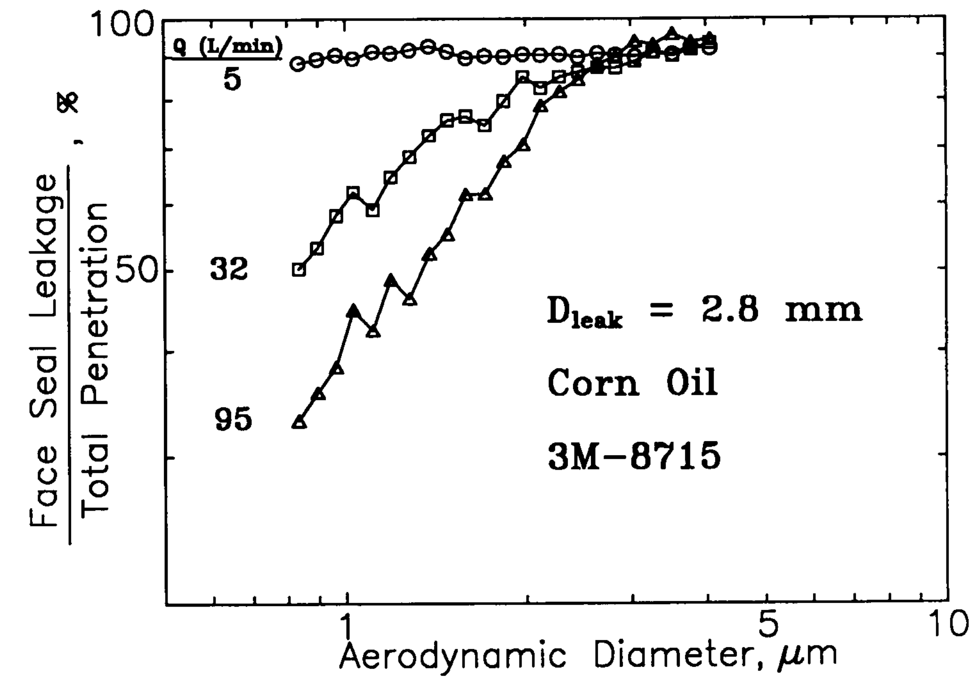

FIGURE 9. Dependence of percent aerosol leakage on particle size

The percentage of aerosols entering the respirator cavity through the face seal leak is shown in Figure 9. At the very low airflow of 5 L/min, about 95% of all aerosols enter the respirator cavity through the leak site, irrespective of particle size. At the high airflow of 95 L/min, about 95% of the 4-µm particles enter through the leak site, but only about 30% of the 0.8-µm particles. Thus, most submicrometer particles enter through the filter material even in the presence of a sizable leak hole.

CONCLUSIONS

An aerosol generator and a sampling train have been developed for the study of the filter and leak penetration characteristics of a dust and mist filtering facepiece. The aerosol generator supplies sufficient quantities of supermicrometer-sized aerosols to perform a fit test and the sampling train is essentially without particle losses for a wide range of sampling flows.

The data for aerosol penetration through the filter material indicate strong airflow and particle size dependence. Submicrometer-sized aerosols are removed by electrostatic attraction and supermicrometer-sized aerosols are removed by inertial impaction.

Aerosol penetration through the leak site for a disposable dust and mist respirator is almost independent of particle size in the measured size range of 0.8 to 4 µm. Particle size dependence of penetration increases with airflow, which is closely related to the pressure drop across the respirator.

The shapes of the aerosol penetration versus particle size curves are unique functions of airflow and leak size. These relationships will be explored further as a potential means for separating face seal leakage from filter penetration in a fit test that does not require knowledge of the filtration characteristics of the test mask.

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