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# The Effect of Aerosol Size Distribution and Measurement Method on Respirator Fit

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The particle size-dependent leakage into a respirator was examined by measuring the leakage of particle sizes between 0.07 to 4.4  $\mu\text{m}$  through three hole sizes in a negative-pressure half-mask respirator worn by a human subject. This investigation showed that the size distribution of an aerosol test agent and the measurement method have an effect on the leakage measured in a quantitative fit test. For instance, the ratio of percent leakage measured by light scattering between test aerosols with count median diameters of 2.2 and 0.28  $\mu\text{m}$  can be as large as 5:1. Likewise, the ratio of the percent leakage measured by a particle count method vs. a mass method of detection of the same polydisperse aerosol with a count median diameter equal to 2.2  $\mu\text{m}$  can be as high as 4:1. The mass leakage into a mask with a leak is also greater for an exposure aerosol with a count median diameter between 0.15 to 0.30  $\mu\text{m}$  compared to exposure aerosols with larger count median diameters for aerosols with the same mass concentration.

## Introduction

Respirators are commonly worn in the workplace to prevent the inhalation of toxic airborne contaminants. A respirator mask that does not adequately fit the wearer will allow penetration of airborne contaminants through the face seal. A fit test can be performed on each respirator wearer to determine which commercially available respirator fits well.

Aerosols frequently are used as respirator fit test agents. Sodium saccharin and irritant smoke are two common qualitative fit test aerosols.<sup>(1-3)</sup> Sodium saccharin is detected by taste and irritant smoke usually causes an involuntary coughing response when there is leakage into the mask. A quantitative fit test (QNFT) is necessary when a fit factor is to be determined. The fit factor is equal to the aerosol concentration outside the respirator to the aerosol concentration inside the respirator. There are a variety of QNFT methods that use different aerosols and detection methods. The conventional corn oil QNFT measures with a forward light-scattering photometer a corn oil aerosol with a CMD between 0.15 to 0.30  $\mu\text{m}$  and a GSD between 1.4 to 1.9.<sup>(4-6)</sup> Recently, a monodisperse corn oil aerosol of 2.5  $\mu\text{m}$  particles, measured by a light-scattering method, has been investigated for use with disposable masks.<sup>(7)</sup> Besides measuring an oil aerosol by a light-scattering method, a count method of detection using a condensation nucleus counter has been developed<sup>(6)</sup> and examined.<sup>(8,9)</sup> The conventional sodium chloride QNFT uses a flame photometer as a mass method of detection for a salt aerosol with a CMD equal to about 0.12  $\mu\text{m}$  and a GSD equal to about 2.1.<sup>(10)</sup> A gravimetric mass detection method<sup>(11)</sup> for a silica dust test in which the aerosol-size distribution has a CMD between 0.5  $\mu\text{m}$  to 0.6  $\mu\text{m}$  and a GSD equal to approximately two also has been investigated.

Until recently, the principal QNFT apparatus commercially available in the U.S. has consisted of three major components: the aerosol generator, generally dispersing corn oil; an exposure chamber or tent; and a photometer for aerosol detection (*e.g.*, Dynatech Frontier Corp., Albuquerque, N.M.; Air Techniques, Inc., Baltimore, Md.). In 1981, K. Willeke<sup>(6)</sup> of the University of Cincinnati discovered and proved the feasibility of using a condensation nuclei counter for aerosol detection. In this device, vapor condensation grows ultrafine particles to a size where they are optically detectable, thus eliminating the need for an aerosol generator and an exposure chamber since 10 000 to several 100 000 ultrafine particles are generally present per cubic centimeter of air space in most air environments.<sup>(12)</sup> A small portable fit test instrument that alternately samples from the respirator and the surrounding air environment recently has become commercially available ("Portacount," TSI, Inc., St. Paul, Minn.) The use of small particles for fit testing respirators prompted research on the particle-size dependence of face seal leakage presented in this and its compendium paper.<sup>(13)</sup>

A QNFT can underestimate or overestimate the face seal leakage that will occur under the actual exposure conditions in the workplace. If the QNFT underestimates the leakage that the respirator provides the wearer in the workplace, the wearer's health could be at risk because under actual work conditions the leakage is greater and may exceed safe exposure levels. A QNFT which overestimates the leakage that a respirator provides in the workplace results in additional expenses for the employer if repeated testing is required or when more expensive respirators are provided to the employees.<sup>(5)</sup>

Several factors determine the differences between the leakage measured in a QNFT and that which the worker

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actually receives. Some of these factors include the different head and facial movements and breathing rates that occur during work activities compared to those performed during a respirator fit test.<sup>(14)</sup>

The factors mentioned above affect the actual leakage into the mask. The measured leakage, however, also can be affected by lung deposition, probe location, probe depth and measurement method.<sup>(15)</sup> The particle sizes in an aerosol are known to affect the lung deposition, sampling efficiency, and collection efficiency of that aerosol.<sup>(16-18)</sup> Therefore, particle size also should have an effect on aerosol leakage into a respirator. In an ambient or industrial environment, the workers are exposed to a variety of aerosols with different size distributions, while in the laboratory fit test the same workers are exposed to a specific aerosol with generally a narrow size range. Therefore, the difference in particle sizes between the fit test aerosol and the ambient aerosol could contribute to differences in the measured and the actual respirator leakage.

This investigation examines the effect of particle size and detection method on respirator leakage that is measured in a QNFT. It also examines the effect of particle size on the leakage of aerosol mass. The present analysis is based on the particle size-dependent leakage measured for three hole sizes in the facepiece of a negative-pressure half-mask respirator.<sup>(13)</sup>

### Test System and Experimental Design

The test system required three aerosol test agents: a fine aerosol, a corn oil aerosol and a limestone aerosol.<sup>(13)</sup> The fine aerosol test agent was a mixture of smoke from burning

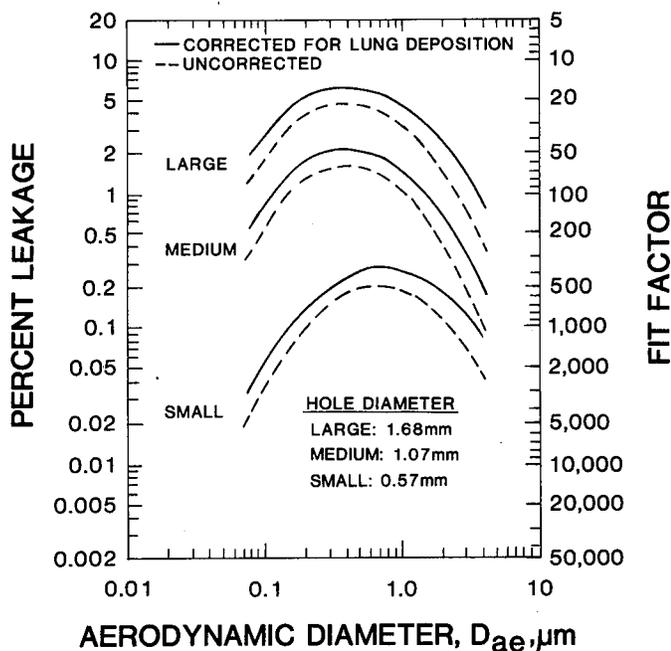


Figure 1 — Percent aerosol inside a negative-pressure half-mask respirator for three hole sizes in the facepiece (dashed curves). The same data, corrected for lung deposition, are the best estimate of the actual leakage through the three hole sizes and are designated by the solid curves.

incense and a nebulized corn oil. The measurement system for the fine aerosol test agent was composed of an electrostatic aerosol classifier (EAC) followed by a condensation nucleus counter (CNC). The corn oil aerosol was generated by a 1-hole Collison nebulizer and the limestone aerosol was generated by a fluidized bed aerosol generator. The aerosol concentration inside the mask and inside the chamber of both the corn oil and limestone test agents were measured by an active scattering aerosol spectrometer (ASAS) and an aerodynamic particle sizer (APS). With these three test aerosols and two measurement systems, the aerosol penetration through three hole sizes in a respirator facepiece was measured by particle count for each of 11 particle size ranges between 0.07 to 4.4  $\mu\text{m}$ . The testing was performed on a human subject wearing a negative-pressure half-mask respirator, and the three circular holes were 0.57, 1.07 and 1.68 mm in diameter.

The test subject breathed through the nose and sat quietly during the testing. In order that all aerosol leakage into the mask would occur through the holes placed in the mask and not through the face seal, neither head movements nor facial expressions were performed. Petroleum jelly was applied around the face seal of the mask to further minimize face seal leakage, and particle counts inside the mask were measured with the holes closed to obtain the background counts. Alternate samples were measured inside the mask and chamber to calculate the leakage into the mask.

### Results

The curves designated by the dashed lines in Figure 1 show the average percent aerosol measured inside the mask for particle sizes between 0.07 to 4.4  $\mu\text{m}$ . The aerosol inside the mask was measured during both the inhalation and exhalation phases of the breathing cycle; therefore, the measured leakage does not represent the aerosol concentration that actually is leaking through the leak site because it also reflects particle losses in the lungs. The curves designated by the solid lines show the percent aerosol inside the mask corrected for lung deposition. The curves corrected for lung deposition would more closely resemble the percent aerosol leaking into the mask and in the following discussion will be referred to as the percent leakage into the mask. The correction for lung deposition was calculated from the lung deposition model proposed by the Task Group on Lung Dynamics<sup>(16)</sup> for nose breathing at a tidal volume of 750 mL and a breathing rate of 15 breaths/min. The lung deposition curves presented by the Task Group on Lung Dynamics were used because their data covered the entire particle-size range examined in this study. The smaller tidal volume of 750 mL as opposed to 2150 mL was assumed because the test subject was a small female who sat quietly during the testing and breathed normally. When the artificial leak holes in the mask were closed, the leakage of aerosols into the respiratory cavity was very low, corresponding to very high fit factors. These maximum fit factors depend on particle size and measurement method and are 85 000 for the APS at 1.1  $\mu\text{m}$ , 67 000 for the ASAS at 0.16  $\mu\text{m}$ , and 87 000 for the EAC/CNC at 0.07  $\mu\text{m}$ .

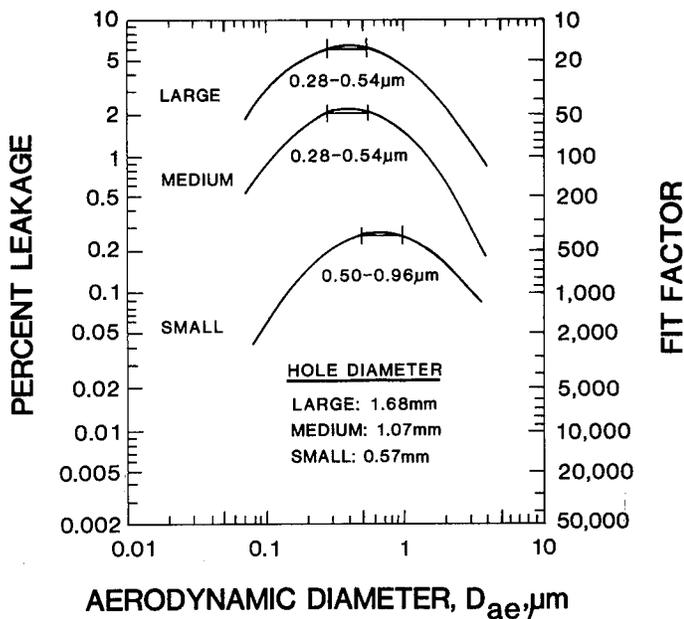


Figure 2 — Size ranges of peak leakage for the three hole sizes.

Figure 2 gives the percent leakage curves from Figure 1 and shows that the peak of the percent leakage curves for the medium and large hole sizes (0.28 to 0.54  $\mu\text{m}$ ) are similar while the peak for the small hole size (0.50 to 0.98  $\mu\text{m}$ ) is shifted to larger particle sizes. Measurements of the flow rates through the three hole sizes revealed that the air velocities through the medium and large holes were larger than through the small hole that would indicate that higher inertial entry losses may be removing more particles, larger than approximately 0.9  $\mu\text{m}$ , for the large and medium size holes.<sup>(17)</sup> These curves show that using a monodisperse fit test aerosol of 0.30 or 3.0  $\mu\text{m}$  particles to measure the leakage through a medium size hole would yield a 5:1 ratio in the measured percent leakages. For the large and small hole sizes, the percent leakage ratios would be 3.7:1 and 1.6:1, respectively.

### Discussion

From these size-dependent aerosol penetration values for the three hole sizes, the effect that the size distribution of a polydisperse test aerosol and the effect that the measurement method in a fit test have on the measured leakages can be calculated. In addition, the effect that the size distribution of an exposure aerosol has on the particle mass entering the mask can be determined.

In order to demonstrate the effect of the size distribution and the measurement method on the measured leakage, three aerosol-size distributions with count median diameters (CMD) of 0.28, 0.60 and 1.1  $\mu\text{m}$  were chosen (Figure 3a). Each of the three aerosol size distributions has a geometric standard deviation (GSD) equal to 2.0. These three count median diameters were chosen in order that the middle 97% of the particle count distribution would lie between the boundaries of the particle sizes that were tested, 0.07 to 4.4  $\mu\text{m}$ . In addition, within that middle 97% of each count distribution the number concentration was calculated to give a mass

concentration equal to 10  $\text{mg}/\text{m}^3$ . Therefore, the original count distributions were essentially lognormal but with upper and lower cutoffs. The ordinate in Figure 3a gives the differential number of particles per unit volume of air,  $\Delta N$ , in logarithmic particle size interval  $\Delta \log D_{ae}$ , where  $D_{ae}$  denotes the aerodynamic particle diameter.

The scatter and mass distributions of those same three aerosol size distributions are shown in Figures 3b and 3c to demonstrate the effect of the measurement method. The count, scatter and mass distributions of the three aerosol size distributions are the most common and currently most examined methods of measuring respirator face seal leak-

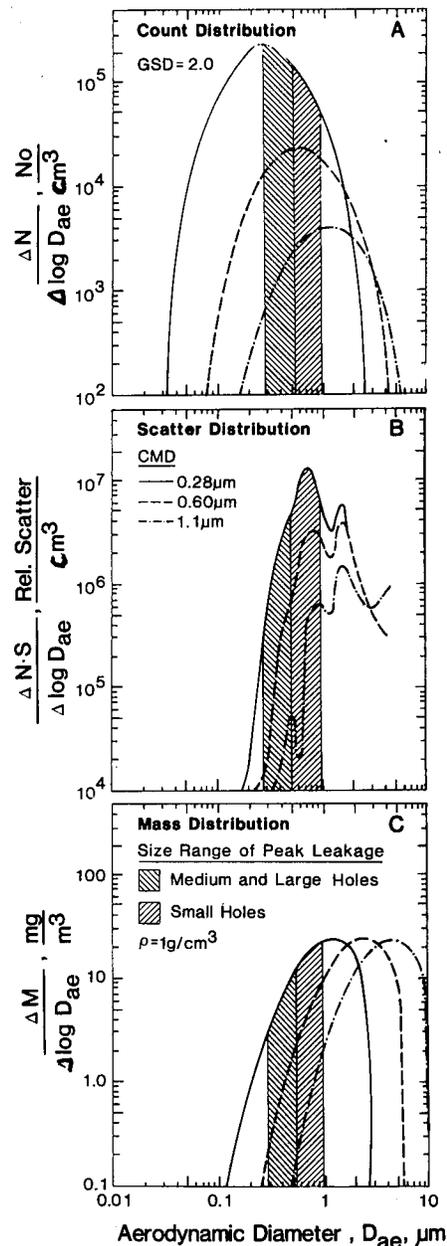


Figure 3 — Count, scatter and mass distributions of three aerosol size distributions with the size ranges of peak leakage accentuated for the three hole sizes. Each count distribution has been calculated to give a mass concentration of 10  $\text{mg}/\text{m}^3$  within the center 97% of the count distribution. The scattering intensity is designated by the letter "S".

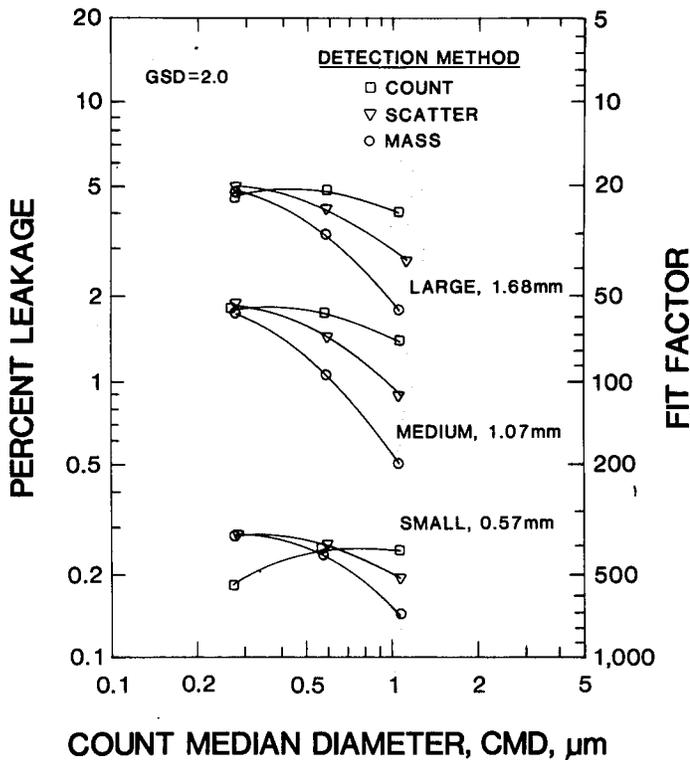


Figure 4 — Calculated percent leakage into the respirator, based on the percent leakage measured for the three hole sizes (Figure 2) for the three exposure aerosols shown in Figure 3 and for three detection methods.

age.<sup>(6-8,14)</sup> The relative scattering intensities, *S*, are for particles with a refractive index of water, 1.33, measured at a scattering angle of 30 degrees.<sup>(19)</sup> The mass distribution was calculated for an aerosol with unit density particles. The shaded areas under each distribution accentuate the size ranges of peak leakage, from Figure 2, of the particle size-dependent leakage through the three hole sizes in the mask.

The application of the percent leakage results in Figure 2 to the distributions in Figure 3 results in the leakage curves in Figure 4. Note that the percent leakage for test aerosols with CMDs increasing from 0.28 to 1.1  $\mu\text{m}$  for the scatter and mass leakage curves decreases for all three hole sizes (Figure 4). The count leakage for the small hole size, however, increases for a test aerosol with a CMD increasing from 0.28 to 1.1  $\mu\text{m}$  while for the medium and large hole sizes the count leakages for test aerosols with CMDs increasing from 0.28 to 1.1  $\mu\text{m}$  decrease. These leakage trends are explained by the overlap of the particle size ranges of peak leakage through the three hole sizes with the count, scatter and mass distributions (the shaded areas shown in Figure 3). When the range of peak leakage for a hole size overlaps that portion of the count, scatter or mass distribution where the peak particle count, scatter or mass exists, the leakage will be higher than if the overlap occurs at that part of the distribution where lesser particle counts, scatter or mass exist (Figure 3). Therefore, because the range of maximum leakage through the small hole size (0.5 to 0.98  $\mu\text{m}$ ) overlaps the center of the two count distributions with CMDs equal to 0.6 and 1.1  $\mu\text{m}$ , but is off-center for the count distribution with a CMD equal

to 0.28  $\mu\text{m}$  (Figure 3a), the leakage calculated for the CMDs that are equal to 0.60 and 1.1  $\mu\text{m}$  will be higher than when the CMD of the test aerosol is equal to 0.28  $\mu\text{m}$ . In that same manner, because the maximum leakage through the medium and large hole sizes (0.28 to 0.54  $\mu\text{m}$ ) overlaps the center of the count distribution with CMDs equal to 0.28 and 0.6  $\mu\text{m}$  and is off-center for the count distribution with a CMD equal to 1.1  $\mu\text{m}$  (Figure 3a), the leakages calculated for the CMDs that are equal to 0.28 and 0.6  $\mu\text{m}$  exceed the leakage calculated for when the test aerosol has a CMD equal to 1.1  $\mu\text{m}$ .

Some of the count median diameters of the test aerosols described in the introduction exceed the particle size boundaries of this study. Therefore, to apply this research to those test aerosols the curves in Figure 4 were extended to smaller and larger particle sizes, see Figure 5. The extended portions of the curves have been calculated from an extrapolation of the size-dependent leakage curves in Figure 2. The curves in Figure 5 show that in order to obtain the maximum leakage that occurs inside the mask with a polydisperse aerosol regardless of hole size, the fit test aerosol should have a CMD between approximately 0.15 to 0.30  $\mu\text{m}$  and use a scatter or mass method of detection. Table I lists the fit factors that would be obtained from the different quantitative respirator fit tests. The data are taken from the curves in Figure 5 for the polydisperse test aerosols and the curves in Figure 2 for the monodisperse test aerosols. The geometric standard deviation, GSD, of the test aerosol used in practice may be higher or lower than the indicated GSD = 2.0. As

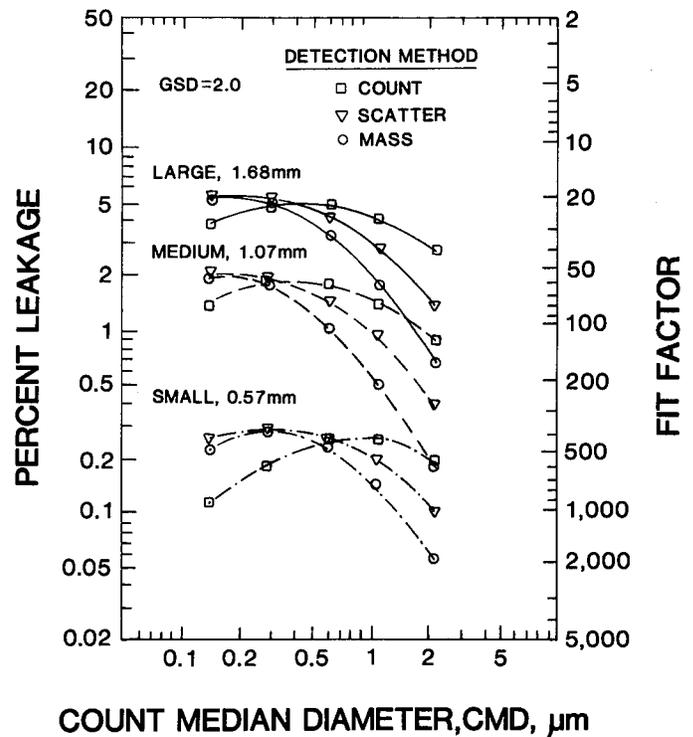


Figure 5 — Calculated percent leakage extrapolated to larger and smaller particle sizes for polydisperse aerosols with a geometric standard deviation equal to 2.0. Each count distribution has a mass concentration of 10  $\text{mg}/\text{m}^3$  within the center 97% of the count distribution.

**TABLE I**  
**Fit Factors Calculated for Each Hole Size Based on**  
**Different Detection Methods and Test Aerosols**

Test Aerosol/ Detection Method	CMD ( $\mu\text{m}$ )	GSD	Fit Factors for Hole Sizes		
			Small	Medium	Large
Corn Oil/Scatter	0.15	2.0	400	50	19
Corn Oil/Count	0.15	2.0	830	70	26
Corn Oil/Scatter	2.5	1.0	1250	250	83
Sodium Chloride/Mass	0.12	2.0	526	59	20
Silica Dust/Mass	0.55	2.0	390	83	29

seen, the difference in the measured fit factor for different test aerosols and measurement methods can be considerable. The QNFT using the 2.5  $\mu\text{m}$  monodisperse corn oil aerosol and the light-scattering detector gives the highest fit factor and is the least sensitive fit test of the tests shown, but would be a representative test when the exposure aerosol is composed of large dust particles at sizes approaching 2.5  $\mu\text{m}$ . If the respirator wearer, however, is exposed to arc welding fumes<sup>(20)</sup> that have a reported mean size of about 0.15  $\mu\text{m}$  with GSD = 1.7, the sodium chloride test that uses an aerosol with smaller particles would reflect more accurately the higher leakage or smaller fit factor.

Using a count detection method for the polydisperse corn oil test with CMD = 0.15  $\mu\text{m}$  compared to a light-scattering method causes a higher fit factor to be measured. Although mass detection of a corn oil test agent currently is not performed, the mass fit factor for the same corn oil aerosol would be 435 for the small hole, 53 for the medium-sized hole and 20 for the large hole. The mass fit factors compared to the count fit factors for the small hole size are smaller by a ratio of 2:1 but are only slightly higher than the fit factors measured by scatter. Knowing the mass leakage into the mask is more important than knowing the count leakage if one is interested in obtaining the dose exposure to the individual wearing the respirator.

A count method in which a condensation nucleus counter was used has been developed<sup>(6)</sup> and tested<sup>(7,8)</sup> to measure the aerosol to which a respirator wearer is exposed. This method registers a smaller leakage than the mass leakage when the exposure aerosol has a CMD smaller than approximately 0.3  $\mu\text{m}$  (Figure 5). The largest difference shown in this study for the effect of the detection method can be seen for larger particles in Figure 5. A count vs. mass method of detection for the same polydisperse aerosol with a CMD equal to 2.2  $\mu\text{m}$  would give a measured leakage ratio of 4:1 when the hole size is large.

From Figure 5 one can see that the mass leakage into the mask for all three hole sizes will be greatest for an aerosol with a CMD between 0.15 to 0.30  $\mu\text{m}$ . For the small hole size, the percent leakage based on mass with an exposure aerosol with a CMD equal to 0.28  $\mu\text{m}$  would be 0.27% while for an exposure aerosol with a CMD equal to 1.1  $\mu\text{m}$  the leakage would be 0.14%. The aerosol with a smaller CMD has a greater mass leakage because as the CMD increases, the proportion of larger particles in the size distribution increases, and all three hole sizes in the mask are more effective at reducing the number of particles larger than approximately 1.0  $\mu\text{m}$  from entering the mask.

Frequently, respirator wearers are exposed simultaneously to aerosols generated by a variety of sources and, therefore, a wide range of particle sizes. For instance, the exposure aerosols in a lead smelter have been measured to have particles sizes ranging from 0.7 to 17  $\mu\text{m}$  in the furnace areas.<sup>(21)</sup> If the respirator wearer is exposed to this multimodal aerosol, and if the artificial leaks induced in the mask are representative of actual leaks, the particles smaller than 1.0  $\mu\text{m}$  will affect the percent leakage more than the particles larger than 1.0  $\mu\text{m}$  because as shown in Figure 2, the larger particle sizes do not penetrate the holes in the mask as easily. A second example would be a bimodal aerosol composed of the two size distributions with CMDs equal to 0.28 and 1.1  $\mu\text{m}$  and with equal mass concentrations. Both the count and scatter fit factors for the bimodal aerosol would be closer to the fit factors for the aerosol size distribution with a CMD equal to 0.28  $\mu\text{m}$ . The reason for this is that the number of counts and amount of scatter contributed by the size distribution with a CMD equal to 0.28  $\mu\text{m}$  is greater than the number of counts and amount of scatter for the size distribution with a CMD equal to 1.1  $\mu\text{m}$  (Figure 3). The mass fit factor for this bimodal aerosol, however, is the average of the fit factors for the individual size distributions because the mass concentrations for the two size distributions were assumed to be equal to each other.

### Conclusions

This study provides a means to assess the results of quantitative fit tests with aerosols and to determine which aerosol test agent and detection method would be most appropriate for the aerosol to which the respirator wearer will be exposed. In addition, this research shows the impact that exposure aerosols with different size distributions have on the mass leakage into the mask when it is being worn by a human subject.

The results show that the maximum leakage through holes in a respirator facepiece occur approximately between 0.2 to 1.0  $\mu\text{m}$ . Larger and smaller particle sizes do not enter through the leak sites as easily. The count median diameter of a polydisperse aerosol does have an effect on the measured leakage during a quantitative fit test as does the measurement method. A 5:1 ratio in leakages can be measured by a light-scattering detection method between two test aerosols with count median diameters of 0.28 and 2.2  $\mu\text{m}$ . Likewise, a 4:1 ratio between a count and mass method of detection can be measured when measuring the same polydisperse aerosol with a CMD equal to 2.2  $\mu\text{m}$ . These large ratios indicate that the size distribution of the test aerosol and of the aerosol to which the respirator wearer is exposed in addition to the measurement method must be considered to ensure that the measured leakage will reflect the actual leakage into the respirator. The ratios of the fit factors, however, between most of the current quantitative fit test methods, shown in Table I, are smaller than 2:1. This would indicate that most of the current quantitative fit test methods have approximately the same sensitivity.

Because the holes in the mask were most effective at keeping large particles from entering the mask, the size

distribution of an exposure aerosol with a CMD between 0.15 to 0.30  $\mu\text{m}$  would give the greatest mass leakage into the mask for a constant mass concentration in the air.

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