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PATRICIA M. HOLTON , DENISE LYNNE TACKETT & KLAUS WILLEKE

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Particle Size-Dependent Leakage and Losses of Aerosols in Respirators

PATRICIA M. HOLTON*, DENISE LYNNE TACKETT‡ and KLAUS WILLEKE
Department of Environmental Health, University of Cincinnati, 3223 Eden Ave., Cincinnati, OH 45267-0056

Measuring particle size-dependent leakage into and losses inside a respirator reveals the deposition mechanisms occurring at the leak site and the flow dynamics inside the respirator. This study investigated particle size-dependent leakage and deposition within the mask by examining the leakage into the mask for different hole locations, probe locations, hole shapes, hole lengths and hole sizes. The shape of the leak has an effect on particle size-dependent leakage. Probe and leak location tests indicated that not only does the total measured leakage change but also the size-dependence of the leakage changes depending on the leak and probe locations. When the leak site is in the chin area, the clean air entering through the filters at the chin helps to carry the inward leakage into the breathing zone. Particle size-dependent leakage does occur and is due to both inertial entry losses at the leak site and within the mask, and diffusional losses within the mask and leak site. Particle size-dependent curves change shape as the hole size changes with relatively more larger particles entering through the small hole size.

Introduction

Particle size determines the lung deposition, sampling efficiency and collection efficiency of aerosols.[1-3] A leak in a respirator mask during inhalation can be compared to a sampling probe and the interior of a respirator mask can be compared to the lungs that are subject to mechanisms such as particle diffusion and impaction. Therefore, some size-dependent leakage into and deposition within the respirator mask should occur.

Respirators commonly are used 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 faceseal, that surface of the mask that contacts the wearer's face. A fit test can be performed on each respirator wearer to determine which commercially available respirator fits well.

In a quantitative respirator fit test (QNFT) the concentration of an aerosol, gas or vapor in the air surrounding the respirator wearer and the concentration of that same substance inside the mask are measured and compared to determine the leakage into the mask.[4-6] A fit factor, defined as the quantitative measure of a fit of a particular respirator to a particular individual, is equal to the concentration of the test agent surrounding the respirator wearer's head divided by the concentration of that same substance inside the mask.[7] A respirator that is functioning properly may allow contaminants to enter through the faceseal or through the air-purifying elements. When high efficiency cartridges are used for filtering particulate matter, however, the leakage through the filters is assumed to be negligible and any detected leakage is assumed to have entered through the faceseal.

*Present address: Division of Environmental Hygiene and Safety, Western Michigan University, Kalamazoo, MI 49008.

‡Present address: Shell Oil Company, 1 Shell Plaza, P.O. Box 4320, Houston, TX 77210.

Presently, masks are probed along the midline of the mask in front of the nose and mouth to obtain the concentration of a test agent inside the mask. It has been reported that variables such as probe location, probe depth, leak site, breathing distribution pattern and measurement sampling rate affect the expected leakage into the mask.[8]

Several factors cause the leakage measured in a QNFT to be different from the actual leakage that occurs under working conditions. Factors such as work activity, work rate, minute volume, head and body movements, and air current velocity and direction have been suggested as possible sources of variation.[9] Design factors in the fit test such as probe location and probe depth, however, can affect the accuracy of the measured leakage.[8] In addition, a fault tree analysis of errors associated with the measured respirator leakage includes factors such as sampling error, analytical error, inaccurate collection time and inaccurate flow rate.[8,10] Particle size is a major determinant of particle behavior and for that reason this investigation examined the effect of hole location, probe location, hole shape, hole length and hole size on particle size-dependent leakage into negative-pressure half-mask respirators with a human test subject.

Test System

In order to measure the leakage into the respirator of particles with sizes between 0.07 and 4.4 μm, more than one test aerosol and measurement device were required to obtain the leakage for that range of particle sizes.[11] The leakage of particle sizes smaller than 0.07 μm was not measured because the lifetime of these particles in sufficiently high numbers in the chamber was too brief because of particle coagulation. The leakage of particle sizes larger than 4.4 μm was not recorded because of the difficulty in generating a high enough particle concentration in the test chamber resulting in a significant particle count inside the mask. The authors developed a test system with three types of test

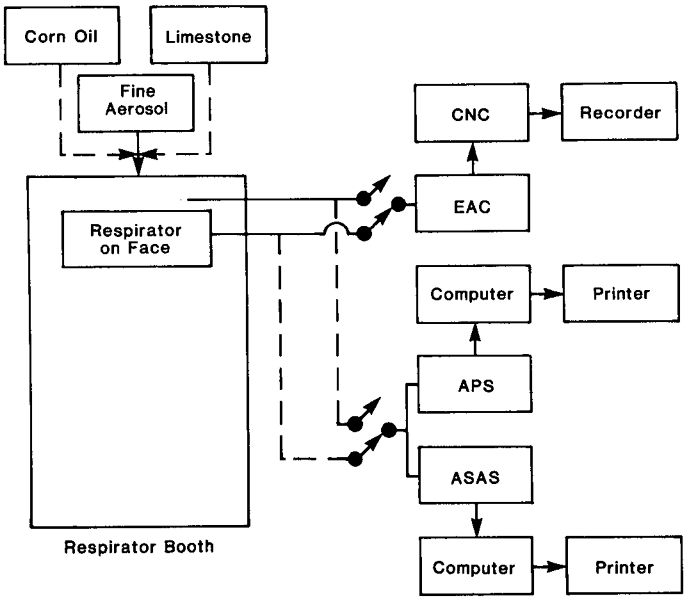

Figure 1 — Schematic of test system: EAC = electrostatic aerosol classifier; CNC = condensation nucleus counter; APS = aerodynamic particle sizer; and ASAS = active scattering aerosol spectrometer.

aerosols and two measurement systems (Figure 1). A fine aerosol test agent generated from a mixture of a smoke from burning incense and a corn oil aerosol nebulized from a Collison 6-hole nebulizer was used to measure the leakage of small particles. The measurement system for the fine aerosol test agent consisted of a TSI Model 3071 Electrostatic Aerosol Classifier (EAC) followed by a TSI Model 3020 Condensation Nucleus Counter (CNC). Upstream of the EAC was a TSI Model 3077 KR-85 Charge Neutralizer followed by a diffusion charger. When particle sizes smaller than 0.1 μm were being measured, the diffusion charger was activated to increase the number of small particles that carried a charge. For particle sizes greater than 0.1 μm the diffusion charger was turned off in order to reduce multiple charging.

The two larger particle aerosols — one a solid and one a liquid — were generated from limestone dust and corn oil: the solid limestone test aerosol was generated by a TSI Model 3400 Fluidized Bed Aerosol Generator (FBAG) and the liquid corn oil test aerosol was generated by a 1-hole Collison nebulizer. The leakage into the mask of each of these aerosols was measured simultaneously by both a PMS Model ASAS-X Active-Scattering Aerosol Spectrometer (ASAS) and a TSI Model APS 33 Aerodynamic Particle Sizer (APS). The ASAS measures optical particle sizes between 0.1 to 3.0 μm and the APS measures aerodynamic diameters between 0.5 and 16 μm. The limestone test aerosol and corn oil test aerosol were measured by the same instruments; therefore, the same size ranges were measured. The limestone aerosol, however, provided a higher concentration of large particles than the corn oil aerosol provided. The ASAS was calibrated with monodisperse polystyrene latex particles. The optical particle sizes were converted to aerodynamic particle diameters for both corn oil and limestone particles. The APS was calibrated with both monodisperse polystyrene latex particles and monodisperse oleic acid particles.

There were four comparison tests in which the leakages through two hole types or the sampling through two probe locations were examined in the same test: hole location, probe location, hole shape and hole length. In addition, the measured leakage through three hole sizes was examined in separate tests: the circular hole sizes were 0.57, 1.07 and 1.68 mm in diameter.

The negative-pressure half-mask respirator for this investigation was fitted with air-purifying cartridges that were combination high efficiency particulate and organic vapor cartridges. The mask, when worn by the test subject during one conventional corn oil quantitative fit test, gave a fit factor of 4300. Circular holes in the mask were made by inserting pieces of polyethylene tubing into a plug that was secured into a hole made in the mask. For the hole shape test, a slit was formed from two pieces of shim stock separated by two smaller pieces of shim stock. The inside diameter of the sampling probe was 0.5 cm and the depth of the probe inside the mask cavity was also 0.5 cm. The leak sites were not located at the faceseal in order to prevent deformation of the faceseal and uncontrolled leakage into the mask. Although skin and airflow effects may differ between a leak at the faceseal and a leak through the body of the mask, controlling the leak size was deemed more critical.

In the hole location comparison test the hole size was 1.07 mm in diameter and 4 mm long. Because the nose and chin areas would seem to be the most likely places for faceseal leakage to occur, one hole was located at the side of the nose and a second hole was located at the chin between the exhalation valve and the inhalation valve (Figure 2). The mask was sampled from a center probe.

In the probe location test the mask was probed at the center location in front of the nose and mouth because this is the conventional location for the sampling probe (Figure 2). The second probe was located near the leak site along the side of the nose. It was anticipated that a probe located near the leak site might provide a more accurate measurement of the size distribution of particles entering the respirator cavity. At that location, the sampled aerosol may be less affected by particle losses inside the mask and by particle deposition in the lung. The leak was a circular hole, 1.07 mm in diameter and 4 mm long.

In the hole shape test, two hole shapes were examined: a slit and a circular hole. These leak shapes were chosen because there would seem to be two types of leaks in the faceseal. One leak type would be a gap that might exist where the face is highly contoured, such as around the nose, and would be represented by the circular hole. Leakage along facial wrinkles also would be similar to leakage through circular holes. The second would be a narrow break in the seal such as a slit which might occur where the face is not highly contoured such as along the cheek. The areas of the slit and hole were within 10% of each other. The different hole shapes were located at the top leak locations on opposing sides of the nose. The circular hole was 1.07 mm in diameter, and the slit was 11 mm long and 0.076 mm wide. Both the slit and hole had identical depths into the mask of 4 mm.

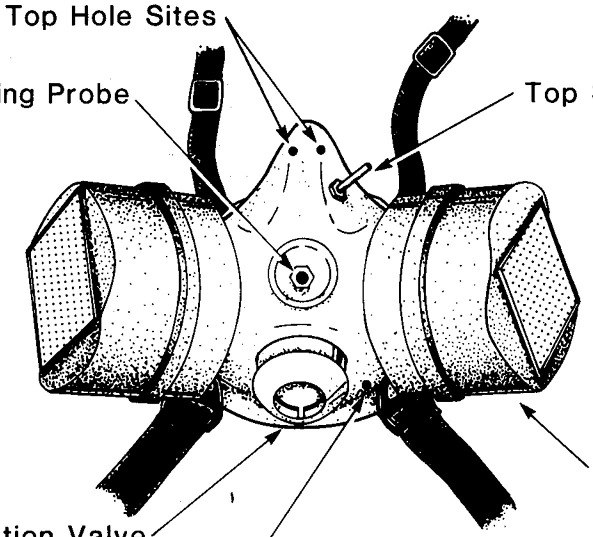

Figure 2 — Schematic of negative-pressure half-mask respirator showing the tested hole and probe locations.

Two hole lengths were examined in the hole length test. One hole was 4 mm long, which was the approximate thickness of the respirator facepiece; the second hole was 10 mm long, which was the approximate length of the seal of the respirator to the face. Each hole was 1.07 mm in diameter, and they were located on opposing sides of the nose at the top locations (Figure 2). The mask was probed at the center location along the midline of the mask between the mouth and nose.

For the hole size tests, the negative-pressure half-mask respirator was probed at the center of the mask in front of the nose and mouth. Unlike the comparison tests where the leakage through two holes or probes was measured in the same test, the leakage through each hole size was measured in separate tests. Each hole was located in the upper portion of the mask along the side of the nose (Figure 2). The length of each circular hole was 4 mm long.

Experimental Design

During testing, the test subject breathed through the nose and sat quietly inside the chamber without moving the head or changing facial expressions. Head movements were not performed to ensure that breaks in the faceseal would not occur and that all leakage would occur through the leak site. In addition, petroleum jelly was applied around the faceseal of the mask to further minimize leakage through the faceseal. The sample flow rate was 1 Lpm for the fine aerosol test and 1.09 Lpm for the limestone and corn oil tests (the APS required a sample flow rate of 1 Lpm and the ASAS required a flow rate of 0.09 Lpm) as measured by a bubble flow meter. The sample from the mask was taken during both inhalation and exhalation. In all of the testing, sampling from the mask was performed with the leak site(s) covered both at the beginning and at the conclusion of each test to determine if any inward leakage other than through the holes was occurring.

Size ranges within the limits of each instrument were chosen from which to calculate leakage measurements. Geometric midpoint diameters were calculated for each measured size range by taking the mean of the logarithm of the particles measured within each size range.[12] The midpoint diameters for the size ranges for the fine aerosol test were 0.07, 0.10 and 0.22 μm. The active scattering aerosol spectrometer measures an optical diameter, and the same optical diameters of the corn oil and limestone aerosols were measured. The aerodynamic particle sizes calculated from the optical diameters, however, were different because the density of corn oil was 0.92 g/mL and limestone was 2.7 g/mL. The aerodynamic midpoint diameters for the four size ranges for the corn oil aerosol were 0.16, 0.25, 0.55 and 1.09 μm. For the limestone aerosol the aerodynamic midpoint diameters were 0.33, 0.50, 1.00 and 1.92 μm. The APS measures aerodyamic diameters and the midpoint diameters for the four size ranges examined were 0.72, 1.11, 2.3 and 4.4 μm for both the corn oil and limestone aerosols.

Unlike the APS and ASAS, the EAC does not measure all particle sizes simultaneously or automatically. Therefore, for the fine aerosol test, the EAC was cycled manually through the three size ranges that were examined. During chamber or mask sampling, each of the three size ranges examined by the EAC were measured sequentially. The order in which the three size ranges were measured was random. Separate analyses of variances (ANOVA) at α = 0.05 were performed on the data collected from each measurement device: EAC/CNC, ASAS and APS.

For each comparison test, the fine aerosol and the corn oil tests were performed. Samples from the mask were alternated sequentially between one hole or probe site and the other hole or probe site. For the fine aerosol test a total of six measurements were taken when each hole site was open and alternated with three chamber samples. During the corn oil test, eight samples were measured with each hole open and alternated with ten chamber samples.

For each hole-size test the fine aerosol, corn oil aerosol and limestone aerosol were used as test agents. A total of 12 mask samples interspersed by five chamber samples were measured in the fine aerosol test; 16 mask samples interspersed by 10 chamber samples were measured for the limestone and corn oil aerosol tests.

Results and Discussion

The data shown in Figure 3, and subsequent figures show the mean measured percent aerosol inside the mask for each size range connected by lines that designate the measurement system. The standard deviation about the mean percent aerosol inside the mask is shown for each size range examined. In each of these figures, there were breaks that occurred between leakage measurements made with different aerosol and different detection methods. An analysis of these breaks indicated two major sources: coagulation of the fine aerosol test agent and humidity of the mask sample in the corn oil and limestone tests.

Coagulation of the fine aerosol test agent inside the chamber would cause the actual concentration at the test subject's head to be less than that measured at the chamber sampling probe, 25 cm above the subject's head. Therefore, the leakage measured in the fine aerosol test would be greater than is shown in Figure 3, and subsequent figures

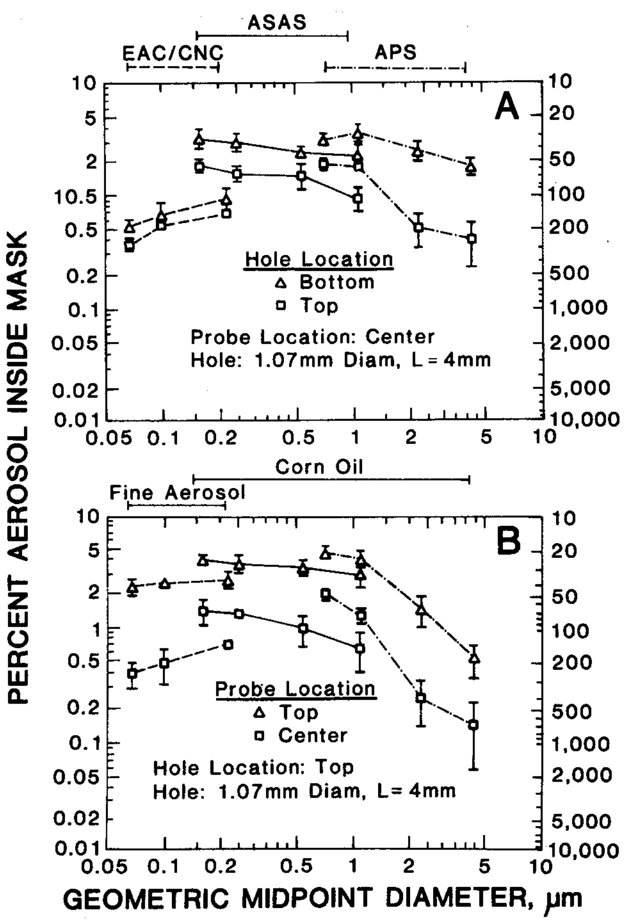

Figure 3 — Percent aerosol measured inside negative-pressure half-mask respirator during nose breathing: a) two hole locations; and b) two probe locations.

when it is corrected for coagulation and the break between the fine aerosol test data and the corn oil aerosol data measured by the ASAS would decrease.

The second break occurs between the leakages at overlapping size ranges measured by the ASAS and APS with the same aerosol test agent. This break occurred because of the humidity of the mask sample due to the humid environment inside the lungs and in the exhaled air. Droplets of moisture appeared in the mask sampling line during some of the fit testing and would indicate a saturated or supersaturated humidity condition in the lines. A threefold increase in growth has been reported for hydrophobic particles in a supersaturated atmosphere and suggests that corn oil particles also could grow because of condensation of water on their surfaces.[13] Moisture condensing on the particles inside the mask would cause them to be measured as larger particles by each instrument so that identical size ranges between the chamber and mask samples were no longer being compared. This humidity effect was not seen for the fine aerosol test because the mask sample after exiting the mask was immediately diluted by 3 Lpm of dry air in order to accommodate the airflow required by the diffusion charger. This humidity effect was more prevalent for the APS data in which the mask sample was not dried as efficiently as it was in the ASAS.[14] The break between the data from the two instruments is narrower with the limestone aerosol because moisture condensing on the surface of a limestone particle does not increase the aerodynamic size of a limestone particle significantly because of the greater density of the limestone (2.7 g/mL) compared to the corn oil (0.92 g/mL).

In the comparison tests a significant interaction of particle size and leak type or probe location would indicate that some capture mechanism either at the leak site or within the mask was occurring for one probe location or leak type and not the other. Therefore, the significant interaction would indicate a different size-dependent effect for the comparison leak or probe.

In the hole location test, the leakage measured with the bottom hole open ranged from 1.2 to 4.9 times larger than the leakage measured with the top hole open (Figure 3A). For 0.5-μm particles, this translates to fit factors of 64 for the top hole open and 41 for the bottom hole open. The volumetric leak rates were not measured for these identical hole sizes, and some variability may have existed. This effect, however, was assumed to be smaller than the effect of the hole site being located near the airflows inside the mask as described below. The greater leakage being measured with the bottom hole open may be due to the bottom hole being located such that the air entering through the filter cartridge carries the aerosol leaking through the bottom hole into the sampling area near the nose (Figure 4A). On the other hand the top hole is not close to the airflows between the filter cartridges and the nose, and aerosols leaked to the inside may not be as readily drawn past the sampling probe. These findings indicate that there is incomplete mixing of leaked aerosols inside the mask. Incomplete mixing also has been seen in a manikin study using acetone vapor as a test agent.[8]

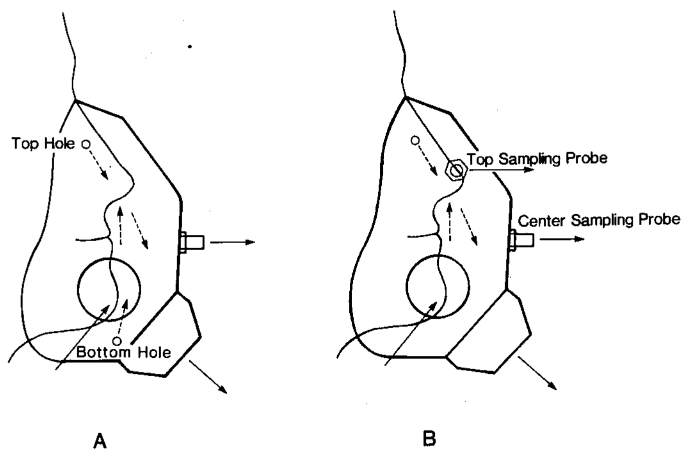

Figure 4 — Schematic showing airflows within cavity of negative-pressure half-mask respirator during nose breathing for a) two hole locations; and b) two probe locations.

The studies reported here were performed with aerosols on a human test subject. The interaction of particle size and hole location was only significant for the data measured by the APS. As seen in Figure 3A, the ratio for the bottom hole to the top hole of the percent aerosol inside the mask between 0.7 and 4.4 μm increases with particle size. The airflow through the filter cartridges that carried a greater number of all particle sizes into the sampling zone when the bottom hole was open also may be carrying more particles with sizes greater than 1.0 μm. The authors postulate that for particles greater than 1 μm entering through the top holes, more were lost inside the mask from settling and inertial impaction. Therefore, a relatively larger measured leakage at the midpoint diameters greater than 1.0 μm for the bottom hole compared to the top hole was seen.

In the probe location tests the top probe was measuring aerosol concentrations inside the mask that were from 2.3 to 6 times as high as the aerosol concentrations measured with the center probe (Figure 3B). At 0.5 μm this translates to a fit factor of 100 when measuring with the center probe and 30 when measuring with the top probe. The sample pulled by the top probe near the leak site is likely to have been less diluted by clean air than the center probe sample near the clean air supply coming through the filters. A manikin study using an acetone vapor as a test agent also showed variability in the measured concentration inside a respirator facepiece when the probe location was changed.[8] The interaction of particle size and probe location was significant for the fine aerosol test and the corn oil test with the APS as the measurement device. The center probe was measuring relatively fewer particles between 0.07 μm and 0.1 μm and between 2.3 to 4.4 μm compared to the top probe. Part of the reason may be that the center probe, which is nearer the nose, samples more exhaled air; therefore, because of increased lung losses, fewer small particles and fewer large particles are being counted. An estimate of the lung losses was made, but this correction to the data did not remove the significant interaction of particle size and probe location. Therefore, the center probe, further from the leak site, may be measuring decreasing numbers of particles smaller than 0.1 μm because of some diffusional losses within the mask cavity and measuring decreasing numbers of particles in the 2.3- to 4.4-μm size range because of settling and inertial losses within the mask cavity.

In the hole-shape test, the percent aerosol inside the mask for all of the particle sizes was smaller for the slit compared to the circular hole (Figure 5A). The percent aerosol inside the mask when the circular hole was open was from 1.4 to 2.5 higher than when the slit was open. Although the areas of the two leak sites were within 10%, there probably was an increased airflow resistance for the slit compared to the circular hole that would cause the flow into the mask and, therefore, the particle count in the mask to decrease. There was a significant interaction of hole shape and particle size for the percent aerosol measured only by the APS. This was due to higher inertial and interceptive entry losses through the slit for particle sizes larger than 2.3 μm.

Hole length made little difference in the percent aerosol measured inside the mask (Figure 5B). This would indicate that there was no essential difference in the losses because of settling or diffusion within the leak sites because of length, but that entry into the hole is the primary cause for particle losses.

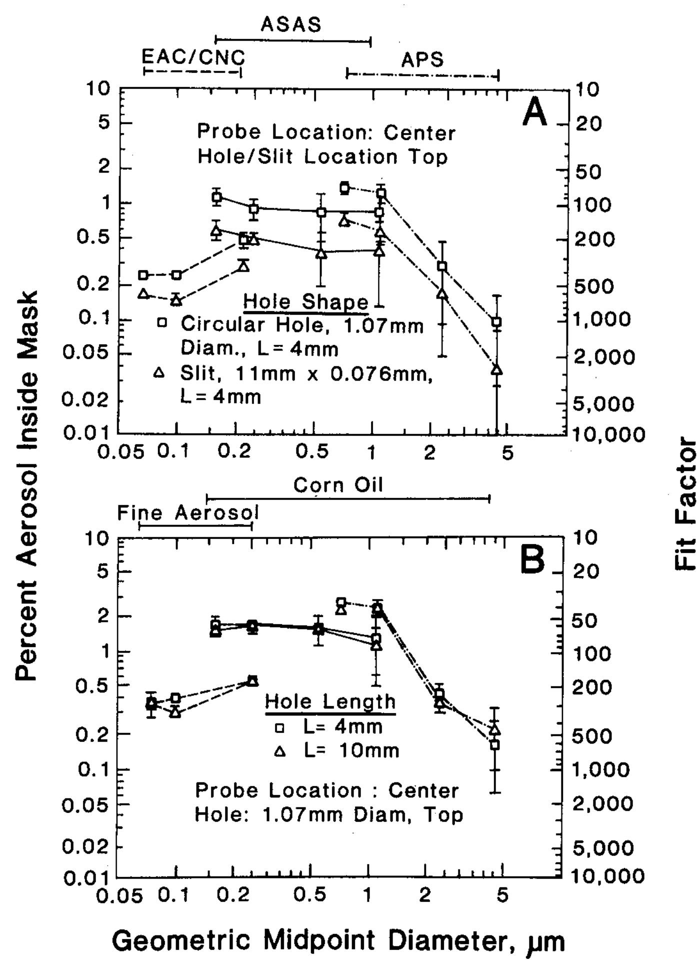

Figure 5 — Percent aerosol measured inside a negative pressure half-mask respirator during nose breathing: a) two hole shapes; and b) two hole lengths.

In the hole-size tests, the measured aerosol inside the mask increases as the hole size increases (Figure 6). As the particle size increases from 1 to 4.4 μm for all three hole sizes, the percent aerosol inside the mask decreases. Likewise, as the particle size decreases from 0.22 to 0.07 μm, the percent aerosol measured inside the mask once again decreases. Because the authors could not make a comparison between two or more hole sizes in one test, the important effect is that due to particle size on the percent aerosol measured inside the mask. For all three hole sizes, particle size had a significant effect on the leakage into the mask for the fine aerosol test. Similarly, for the corn oil and limestone aerosol tests with the APS as the measurement device, particle size had a significant effect on the aerosol concentration inside the mask. For the corn oil aerosol measured by the ASAS, only for the large hole size did particle sizes between 0.16 to 1.1 μm have a significant effect on the aerosol concentration inside the mask. For the limestone aerosol measured by the ASAS for particles between 0.33 to 1.9 μm, however, particle size had a significant effect on particle concentrations inside the mask for all three hole sizes.

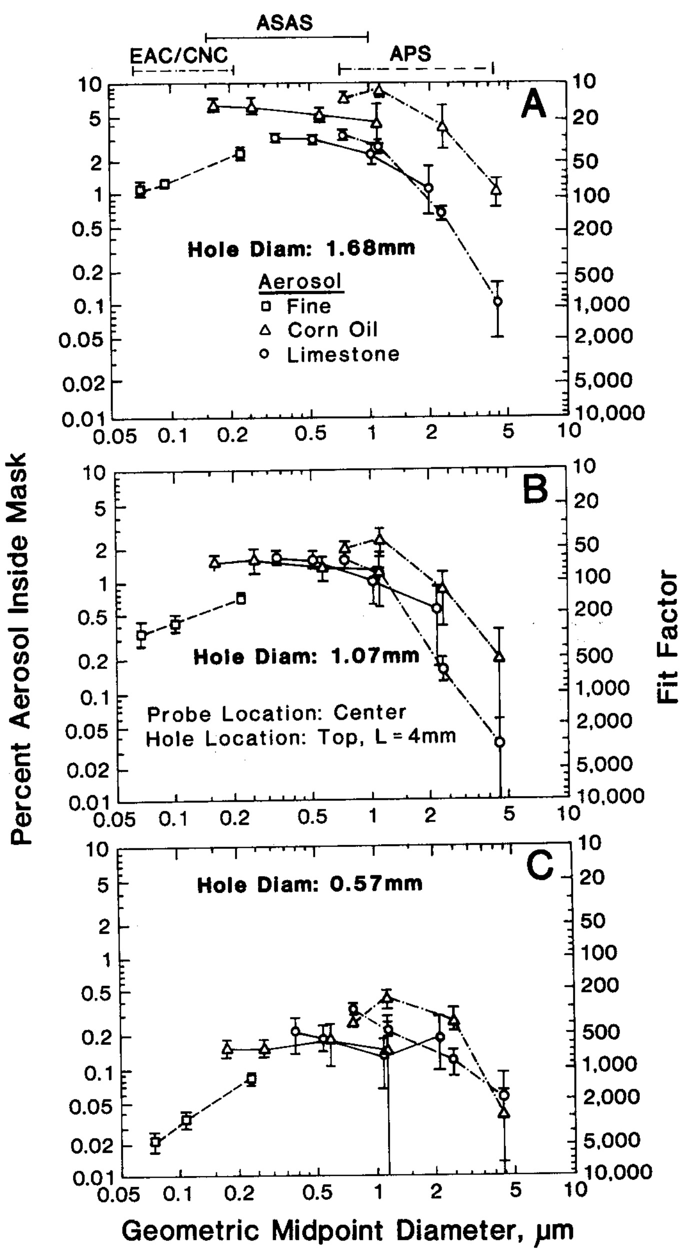

Figure 6 — Percent aerosol measured inside a negative-pressure half-mask respirator during nose breathing for three hole sizes.

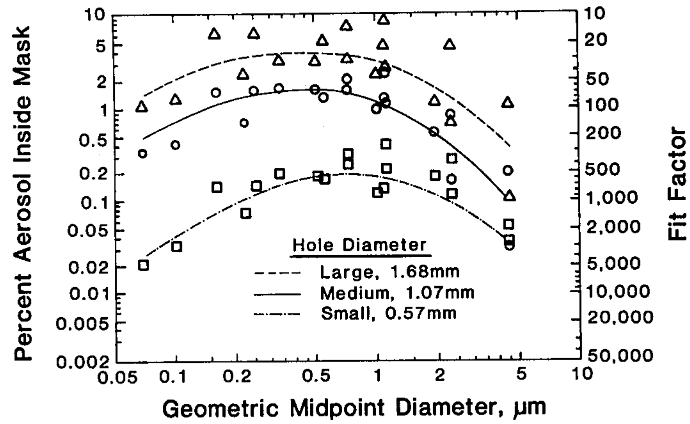

Figure 7 — Smooth curves from data showing percent aerosol inside mask for the three hole sizes.

In general, for all three hole sizes, there is little difference in the percent aerosol inside the mask for particles between 0.2 to 1.0 μm in size. For particle sizes smaller than 0.2 μm and larger than 1.0 μm, however, size-dependent leakage into the mask does appear.

Corrections for coagulation and humidity effects were made on the data and smooth curves were drawn for the corrected data for the three hole sizes (Figure 7). The equations for the curves were calculated by a multiple regression analysis. The fit factors for the small, medium and large hole sizes were 500, 63 and 21 at 0.5 μm and show the increasing leakages as the hole size increases. The shape of the curves for the medium and large hole sizes are similar to each other while the peak of the curve for the small hole size is shifted to a higher particle size. The average flow rates through the three hole sizes, measured with a bubble flow meter, decreased as the hole size decreased. Comparing the average velocities calculated from the flow rates to sampling efficiency criteria revealed that the small hole size would allow relatively more particles larger than 0.9 μm, compared to the medium and large hole sizes, because of inertial losses than would occur at the entry of the medium and large hole sizes.[2] The average velocity through the small leak hole allows relatively more particles larger than 0.9 μm to follow the flow streamlines into the leak; therefore, the shift in the peak leakage to larger particle sizes for the small hole sizes occurs.

Conclusions

This study with aerosols on a human test subject indicates that the locations of the leak and the sampling probe may have a significant effect on the measured leakage. A study that was different by measuring leakage of vapor only during inhalation from an artificial leak in the faceseal of a respirator on the head of a manikin also found that the location of the leak and the sampling probe had an effect on the leakage.[8] The further the sampling probe is from the leak site and the closer to the clean air supply, the smaller the overall leakage that is measured. The probe location test indicates that there may be some settling losses of particles larger than 1 μm and diffusional losses of particles smaller than 0.2 μm within the mask. From the authors' tests with a half-mask respirator, leak sites at the chin area seem to pose a more serious hazard than leak sites at the nose position because of the ability of the clean air entering through the filter cartridges to carry the leaked aerosols into the breathing area. It is possible, however, that the same exposure may be occurring through both holes, and the measured differences may be due to the leakage streamlines passing at different distances from the sampling probe. The hole shape does have a significant effect on the total measured leakage. The size-dependent effect indicates that a slit or narrow gap in the faceseal, compared to a circular hole, not only decreases the total aerosol leakage but also diminishes the entry of the larger particles that have the greater mass. The length of the leak site has little effect on the measured leakage into the mask.

The hole-size tests indicated that between 0.2 and 1.0 μm the measured percent aerosol inside the mask shows little size dependence. Because of inertial entry losses of particles greater than 1.0 μm and diffusional losses of particles smaller than 0.2 μm, however, size-dependent leakage does occur. As the hole size decreases, a greater percentage of larger particles enters through the leak although the total leakage decreases as the hole size decreases.

The curves shown in Figure 7 can be used to calculate the leakage into a respirator for different aerosol-size distributions and for different detection methods in a quantitative fit test. The mass leakage into a mask of an exposure aerosol with any size distribution also can be calculated. Knowing the effect of the aerosol-size distribution can become important when the respirator wearer is fit tested with a test aerosol with one size distribution but is exposed to an aerosol with a different size distribution under normal use conditions.

Acknowledgements

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References

1. **Task Group on Lung Dynamics:** Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract. *Health Physics 12*:173-207 (1966).
2. **Davies, C.N.:** The Entry of Aerosols into Sampling Tubes and Heads. *Brit. J. Appl. Phys. 1*:921-932 (1968).
3. **Lee, K.W. and B.Y.H. Liu:** On the Minimum Efficiency and Most Penetrating Particle Size for Fibrous Filters. *J. Air Poll. Control Assoc. 30*:377-381 (1980).
4. **Griffin, O.G. and D.J. Longson:** The Hazard Due to Inward Leakage of Gas into a Full Face Mask. *Ann. Occ. Hyg. 13*:147-151 (1970).
5. **Hinds, W.C., J.M. Macher and M.W. First:** Size Distribution of Aerosols Produced by the Laskin Aerosol Generator Using Substituted Materials for DOP. *Am. Ind. Hyg. Assoc. J. 44*:495-500 (1983).
6. **Clark, J.M.:** Quantitative Fit Test Methods for Respirators. *J. Int. Soc. Respir. Prot. 1*:79-94 (1983).
7. **Myers, W.R., S.W. Lenhart, D. Campbell and G. Provost:** The Forum. *Am. Ind. Hyg. Assoc. J. 44(3)*:B25-B26 (1983).
8. **Myers, W.R., J. Allender, R. Plummer and T. Stobbe:** Parameters that Bias the Measurement of Airborne Concentrations Within a Respirator. *Am. Ind. Hyg. Assoc. J. 47*:106-114 (1986).
9. **Myers, W.R., M.J. Peach, K. Cutright and W. Iskander:** Workplace Protection Factor Measurements on Powered Air-Purifying Respirators at a Secondary Lead Smelter. *Am. Ind. Hyg. Assoc. J. 45*:681-688 (1984).
10. **Myers, W.R.:** Personal interview. Morgantown, W.Va., May, 1986.
11. **Holton, P.M.:** "Particle Size-Dependent Leakage Through the Faceseal of Negative-Pressure Half-Mask Respirators." Ph.D. Dissertation, University of Cincinnati, Cincinnati, Ohio, 1986.
12. **U.S. Department of Health, Education and Welfare/National Institute for Occupational Safety and Health:** Review of Mathematics. In *The Industrial Evironment — Its Evaluation and Control.* J.L. Patteeuw. Washington, D.C.: GPO, 1973. pp. 11-18.
13. **Yosida, T., Y. Kousaka and K. Okuyama:** Growth of Aerosol Particles by Condensation. *Ind. Eng. Chem. Fundam. 15*:37-40 (1976).
14. **Knollenberg, R.G. and R. Luehr:** Open Cavity Laser "Active" Scattering Particle Spectrometry. In *Fine Particles: Aerosol Generation, Measurement, Sampling and Analysis,* edited by B.Y.H. Liu. New York: Academic Press, 1976. pp. 669-697.

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