American Industrial Hygiene Association Journal

ISSN: 0002-8894 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/aiha20

CHARACTERISTICS OF FACE SEAL LEAKAGE IN FILTERING FACEPIECES

C.C. Chen & K. Willeke

To cite this article: C.C. Chen & K. Willeke (1992) CHARACTERISTICS OF FACE SEAL LEAKAGE IN FILTERING FACEPIECES, American Industrial Hygiene Association Journal, 53:9, 533-539, DOI: 10.1080/15298669291360120

To link to this article: https://doi.org/10.1080/15298669291360120

AIHA JOURNAL Advances in Industrial & Environmental Hygiene

AM. IND. HYG. ASSOC. J. 53(9):533–539 (1992) 4475

CHARACTERISTICS OF FACE SEAL LEAKAGE IN FILTERING FACEPIECES*

C.C. Chen
K. Willeke†

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

Several studies have found that aerosol size, testing method, leak size, leak position, sampling probe location, and the mixing condition inside the respirator affect the results of fit factor measurements. This study focuses on the effect of leak shape and filter resistance because leaks have been reported to vary in shape from circular to slit-like. Four leaks of different shape but the same cross-sectional area were used to study their effect on aerosol penetration. Dust-mist and high-efficiency particulate air filtering facepieces provided different filter resistances. An aerodynamic particle sizer and a laser aerosol spectrometer were used to measure the particle size–dependent aerosol concentrations inside and outside the respirators. The filtering facepieces were sealed to a mannequin and artificial leaks were inserted near the right cheek. Aerosol penetration was measured for five flow rates ranging from 5 to 100 L/min. The pressure drop across the mask was monitored with an inclined manometer. At a given pressure differential, a slit-like leak and multiple circular leaks have been found to pass less aerosols than a single circular leak of equal cross-sectional area because the leak flow decreases with an increase in leak shape complexity. If there is substantial lack of face seal fit and the breathing rate is low, a HEPA respirator may provide less protection than a dust-mist respirator because the pressure drop is considerably higher for a HEPA respirator, resulting in more aerosol flow through the leak.

Respirators are commonly used to protect workers from inhaling hazardous substances in the workplace. The logic for selecting an appropriate respirator is well documented.(1) Prior to using a respirator in the workplace, the worker has to pass a fit test to ensure that the contaminant entering the respirator cavity is below the regulated limit.(2)

Two factors, the fit factor (FF) and the assigned protection factor (APF), are normally used to quantify respirator performance. The FF measures the degree of the fit to the wearer's face and is defined as the ratio of the challenge aerosol concentration to the aerosol concentration inside the respirator cavity. The regulated minimum FFs for air-purifying half-face and full-face respirators are 100 and 1000, respectively.(1) If the test subject cannot find an appropriate respirator to meet this minimum requirement, he or she must use a positive-pressure respirator. APF is a measure of the minimum anticipated workplace level of respiratory protection that would be provided by a properly functioning respirator or class of respirators to a percentage of properly fitted and trained users. An APF of 10 has been assigned to air-purifying half-mask respirators, including disposable particulate respirators, if they have been properly fitted by using a quantitative fit test.(2)

Several fit test methods have been reported for selecting an appropriate respirator.(3–12) Several parameters have been found to affect the FF.(13–20) The following may contribute to its variability: design and size of the sampling probe, location and depth of the sampling probe,(14) leak site,(13,15,16,19,20) breathing pattern,(14) sampling flow rate,(13,14) aerosol size,(15,16) type of respirator, and the mixing condition inside the respirator.(13–16)

Photographic recordings of the aerosol deposition patterns on the wearer's face have shown that the leaks may be circular or rectangular in shape.(19,20) There may also be more than one leak. Circular or near-circular leak channels may occur because of wrinkles in the wearer's face; rectangular or slit-shaped leak channels may occur when the respirator does not fit snugly to the face or when the perimeter of the respirator deviates from the facial contour, e.g., near the nose and the chin.

In order to deal with the different shapes in a uniform manner, the effective diameter,(21) D_e, will be used to index the shape effect.

$$D_e = 4\frac{\text{cross-sectional area}}{\text{perimeter}} \qquad (1)$$

---

*The authors appreciate the financial support of the National Institute for Occupational Safety and Health through Grant No. R01-OH-01301. C.C. Chen was supported by a stipend for graduate education awarded by the University of Cincinnati during part of his Ph.D. study.

†Author to whom correspondence should be addressed.

For a circular leak channel, the effective diameter equals the hole diameter. For any other shape, the effective diameter, also referred to as the hydraulic diameter, is less than the diameter of a circular hole of equal cross-sectional area. In the present study, the effects of leak size, shape and length, and filter resistance on FF have been examined for filtering facepieces (also referred to as disposable respirators). Filtering facepieces are becoming very popular among workers because in comparison with re-usable respirators they are lightweight, less burdensome, obstruct vision less, and allow easy communication with co-workers. Because aerosol penetration through a leak site depends on pressure difference and the shape and size of the leak, many of the conclusions from this study are relevant for elastomeric respirators with air-purifying filter cartridges as well.

EXPERIMENTAL MATERIAL AND METHODS

One brand of a dust-mist (DM) and one brand of a high-efficiency particulate air (HEPA) filtering facepiece were chosen to represent low and high pressure drops, respectively, across the filter material at a given flow rate. In order to have a statistically high number count of aerosol particles inside the respirator cavity, particularly of supermicrometer-sized particles, a circular hole diameter of 3.18 mm (4/32 in.) with a cross-sectional area of 7.92 mm^2 was chosen as the reference hole size for several leak tests. Leakage through leak channels of the same cross-sectional area, but of a smaller effective diameter, was tested by use of 4 holes of 1.59 mm (2/32 in.) diameter, 16 holes of 0.79 mm (1/32 in.) diameter, and a long slit of 0.50 mm × 15.84 mm, as shown in Figure 1. The leak channels were 15 mm long. The effect of leak length was tested at leak lengths, L_{leak}, of 1, 15, and 30 mm.

The leaks were studied by inserting and gluing circular and rectangular tubes into the filtering facepieces about 6.5 cm from the centered sampling probe. Each filtering facepiece was sealed to a mannequin by use of petroleum jelly. Aerosol penetration was measured for five constant sampling flow rates ranging from 5 to 100 L/min, i.e., for each test the entire flow through the filter material and the leak(s) was sampled by the probe inserted in the facepiece halfway between nose and mouth.(22) The airflow was controlled by a mass flow controller. Thus, the effects of probe and leak locations and the associated dependence on mixing in the respirator cavity were avoided. The pressure drop across the filter was measured with an inclined manometer.

The design and characterization for the challenge aerosol generation and sampling system used in this study have been detailed elsewhere(22) and are outlined here. Selected corn oil aerosols were generated by use of a size-fractionating aerosol generator that was developed for filter and respirator fit testing.(23) A 10-mCi Kr-85 radioactive source neutralized these aerosols to Boltzmann charge equilibrium. The aerosols were then diluted by filtered air and introduced into the test chamber. The aerosol concentrations inside and outside the filtering facepieces were measured by an aerodynamic particle sizer (Model APS33B, TSI Inc., St. Paul, Minn.) over a size range of about 0.8 to 5 µm, and a laser aerosol spectrometer (Model LAS-X CRT, PMS Inc., Boulder, Colo.) over a size range of about 0.1 to 3 µm. The optical equivalent diameter reported by the latter instrument was converted to its physical diameter through calibration with an electrostatic aerosol classifier (Model 3071, TSI Inc.). The aerodynamic diameter was then calculated through knowledge of the particle density. The challenge aerosol concentration was about 650 particles/cm^3 (measured by the APS) with a count median diameter of 2.3 µm, which caused no coincidence effects in the size spectrometers and resulted in a sufficient number of supermicrometer-sized particles inside the respirator.

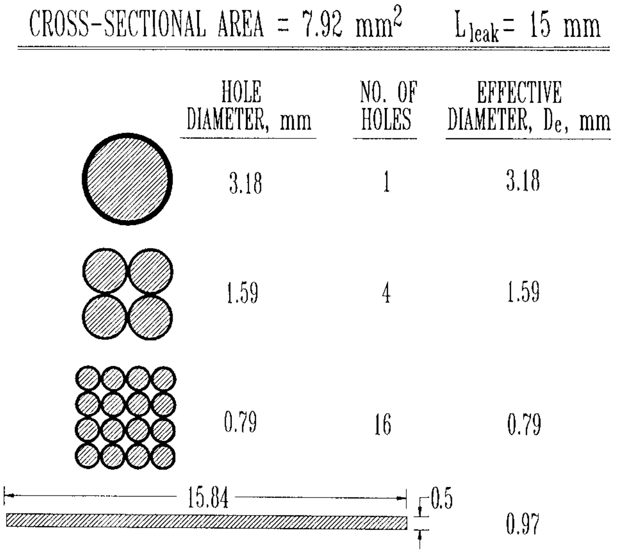

FIGURE 1. Leak sizes used in study

RESULTS AND DISCUSSION

Figure 2 shows the aerosol penetration characteristics as a function of particle size for the two filtering facepieces with two different leaks added, each being a single, 15-mm long, circular hole. The corresponding FFs are shown as well. The value of an FF is the inverse of the fractional penetration value. The aerosol penetration data for the HEPA respirator are approximately those for the leak because aerosol penetration through the HEPA filter is of the order of 0.01% to 0.1% or less at the indicated flow rates. The percentage of aerosol penetration is highest for the lowest flow rate and lowest for the highest flow rate, i.e., the amount of aerosol penetration through the leak relative to the aerosol penetration through the filter material is lowest for the highest flow rate, given a leak of fixed dimensions. At a low pressure differential, the flows through both leak and filter material are laminar. At a high pressure differential, the flow through the filter material is still laminar, but the flow through the leak hole is in the transition regime between laminar and turbulent flow. In general, leak

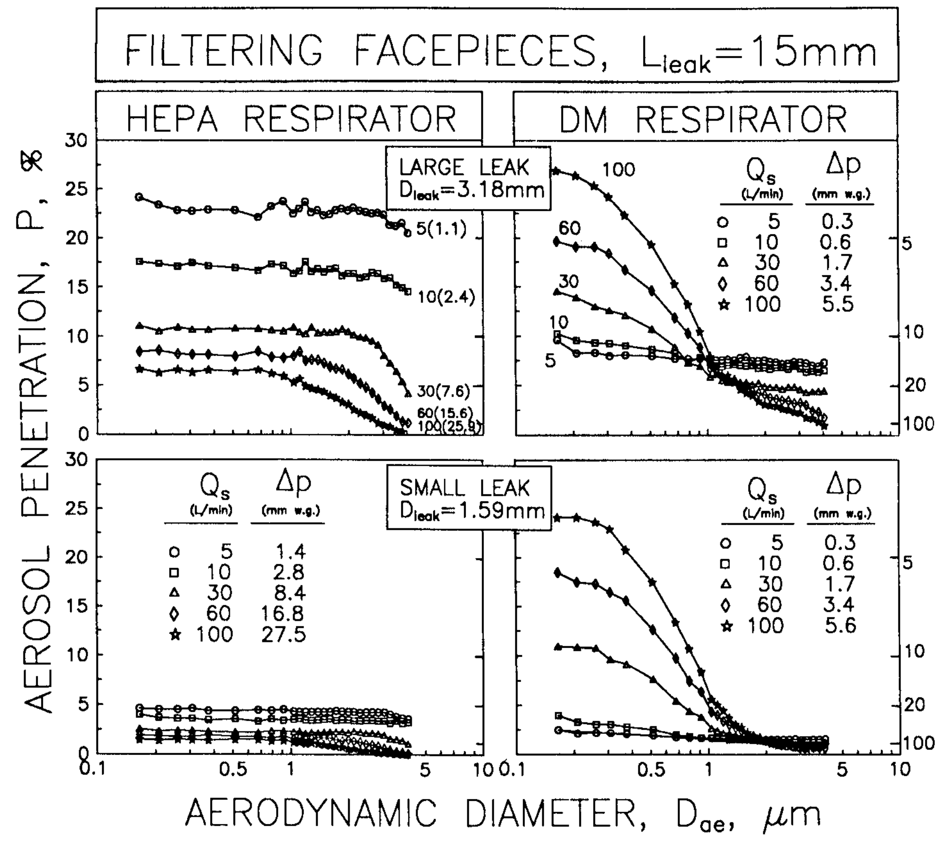

FIGURE 2. Combined filter and leak aerosol penetration data for typical high-efficiency particulate air (HEPA) and dust-mist (DM) filtering facepieces

flow Q_l relates to pressure differential Δp through exponent n and proportionality factor K.

$$Q_l = K \Delta p^n \qquad (2)$$

For viscous laminar flow $n = 1$; for turbulent flow $n = 0.5$. In the transition region $0.5 < n < 1$. Therefore, the fraction of leak flow at a higher pressure differential is less than expected for laminar flow.(9,10)

All the filtering facepieces have about the same surface area, but a DM respirator is made of considerably less filter material than a HEPA respirator. Accordingly, the particles reside for less time in the filter layer of a DM filtering facepiece than a HEPA one, given that the DM and HEPA filtering facepieces are made of the same material and same packing density. Therefore, aerosol penetration through the DM respirator is significant, particularly in the submicrometer-size range.(24) The pressure differential, Δp, is correspondingly less, as shown by comparing the pressure data for the DM respirator to those for the HEPA respirator in Figure 2. In the submicrometer-size range, aerosol penetration for the DM respirator is highest for the highest flow rate that reflects its filtration characteristics and is the opposite of the leak characteristics seen for the HEPA respirator. In the submicrometer-size range, most of the filtration removal in a DM respirator is by electrostatic attraction.(25) Mechanical removal mechanisms, such as interception and impaction, dominate in the supermicrometer size range for filtration and leak flow, which results in the crossover of the curves near 1 μm for the DM respirator, as shown in Figure 2.

Because a HEPA filter is close to 100% efficient, the test data with the HEPA filter reflect the aerosol penetration through the leak. As seen, only a low particle size–dependence exists over the measured particle size range when the leak rate is 5 to 10 L/min. At these flow rates, representing the initial and final phases of the inhalation cycle, the pressure differential is low and a relatively high proportion of the total flow enters the leak ($n = 1$ in Equation 2). The curves are fairly flat in the supermicrometer-size range because the particle motion in the inlet portion of the leak is gentle and passage through the relatively large leak channel is nonturbulent. At higher flow rates, reflecting average and high inhalation rates, strong particle size dependency exists in the supermicrometer-size range, as previously observed.(15) These are attributed to impaction losses in the inlet portion of the leak and increased losses in the leak itself where the flow is now in the transition or turbulent regime, as indicated above.

For the large leak hole in the DM respirator, the aerosol penetration curve for the highest flow rate is about the same as for the small leak hole, suggesting that the high flow rate curves for the DM respirator reflect primarily its filtration characteristics. Only for the low flow rates is the percentage of aerosol penetration significantly different for different leak sizes. At low flow rates, small particles passing through the filter material are effectively removed by electrostatic attraction and the percentage of flow through the leak is increased, as also seen for the HEPA filter. Examination of the 5-L/min curves for the large leak indicates that the DM respirator may—at moderate flow rates—provide more protection than a HEPA filter when there is substantial leakage because the high pressure drop across the HEPA filter at a given flow rate pulls in more aerosols through a leak of a given size.

The effect of leak size is shown in Figure 3 for singular circular holes of 0- to 3.18-mm diameter. A HEPA filtering facepiece was chosen for this test because the percentage of aerosol penetration, P, is essentially zero for all particle sizes, as shown by the lowest curve in Figure 3. The other curves, therefore, represent aerosol penetration through the leak of the indicated sizes. As seen, P increases with leak size, as

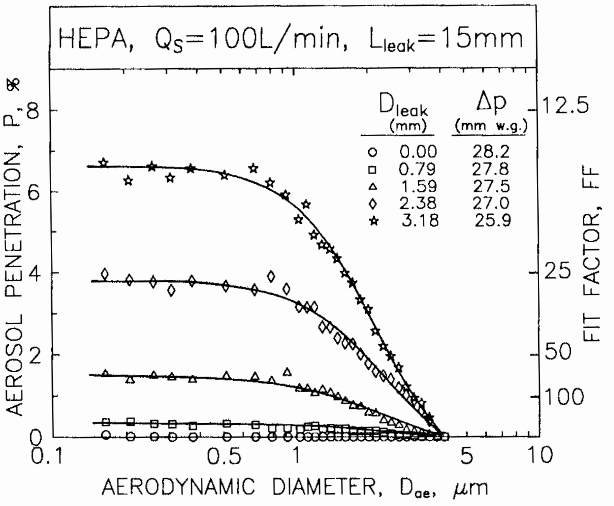

FIGURE 3. Aerosol penetration dependence on leak size

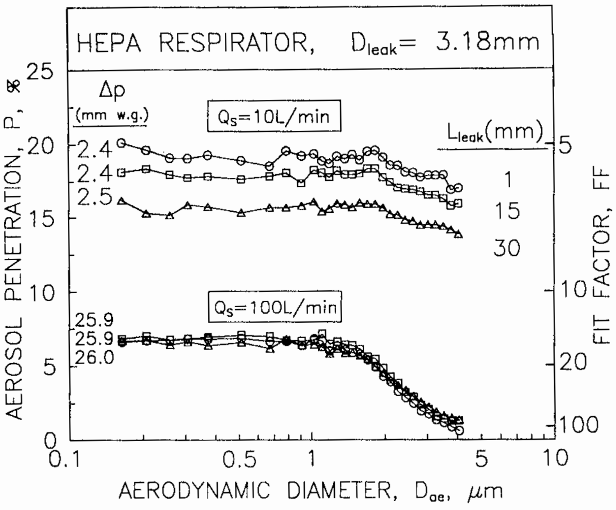

FIGURE 4. Effect of leak length on aerosol penetration

expected. Pressure drop, Δp, decreases with increasing leak size, as flow through the leak channel offers less flow resistance. The percentage penetration of submicrometer-sized aerosols is 0.4% for a leak diameter of 0.79 mm and 6.6% for a leak diameter of 3.18 mm; i.e., the large leak passes about 16 times more aerosol than the small leak, corresponding to the area ratio of the large to small hole. With little or no aerosol particle removal in the submicrometer-size range, small particles move through leaks of the same shape approximately in proportion to the flow rate.

The large leak hole allows more flow to pass through than the small leak; therefore, it induces a lower pressure drop, as indicated in Figure 3. However, the difference in pressure drop caused by the leaks is small. Thus, aerosol penetration through the HEPA filter material is approximately the same, and the measured increase in aerosol penetration is primarily caused by the increased amount of aerosol penetration through the larger holes, which leads to the conclusion that aerosol penetration of submicrometer-sized particles is approximately proportional to the cross-sectional area ratio of the leaks, if the leaks have the same shape. Very small leaks, however, do incur increased particle losses in the submicrometer-size range.(15,16) In the supermicrometer-size range, Figure 3 shows a significant reduction in aerosol penetration, which is caused by mechanical removal mechanisms.(22) The aerosol penetration of supermicrometer-sized particles falls off rapidly as the flow increases; this decrease is attributed to particle impaction.

Figure 4 shows the effect of leak length. The percentage of aerosol penetration at low flow rates is higher than at high flow rates because the fraction of leak flow decreases with increasing sampling flow,(9) as also shown in Figure 2. An increase in leak length results in higher pressure drop and less aerosol penetration percentage. The difference in aerosol penetration between long and short leaks is more pronounced at a low flow rate than at a high flow rate. At a low flow rate through a leak of given size, the Reynolds number is lower and, therefore, the flow is more viscous than at a high flow rate. Thus, the leak flow rate is more affected by the length of the leak channel at the low sampling flow rate of 10 L/min than at the high flow rate of 100 L/min, as seen in Figure 4. Aerosol penetration at the high flow rate drops off more rapidly with an increase in supermicrometer particle size than at the low flow rate, as seen in the discussion of Figure 2. Some of the new commercially available filtering facepieces have larger sealing surfaces, which provide not only a better face seal but may also lower the aerosol penetration because of the increase in leak length.

Figure 5 shows that the pressure drop across a HEPA filtering facepiece, sealed to a mannequin, increases linearly with flow rate through the respirator. This test indicates that the flow through the filter material is laminar over the entire range of inhalation and exhalation flow rates. When the circular 3.18-mm reference leak is added, some of the flow goes through the leak, thus reducing the flow through the filter material and with it the pressure drop. The difference in flow rate between the curves with and without a leak at a given pressure, therefore, equals the flow through the leak. At a total flow rate of 100 L/min, Figure 5 indicates that about 7 to 8 L/min (determined from the curves) pass through the 3.18-mm diameter hole; the remaining 92 to 93 L/min pass through the filter material. The difference in pressure drop between sealed and leaking respirators at a given total flow rate is, thus, a measure of leak flow rate. Because this change is small relative to the total pressure drop, it may be difficult to use as a basis for fit testing.

Figure 6 shows that the difference in pressure drop from the sealed case becomes less as the effective diameter of the leak decreases from that of a circular hole. As the leak area is divided into several holes or a long slit of the same total cross-sectional area, the air molecules are in contact with more inner wall surface area, which increases the flow resistance and, therefore, reduces the magnitude of the leak flow. The HEPA filtering facepiece used for the tests shown in

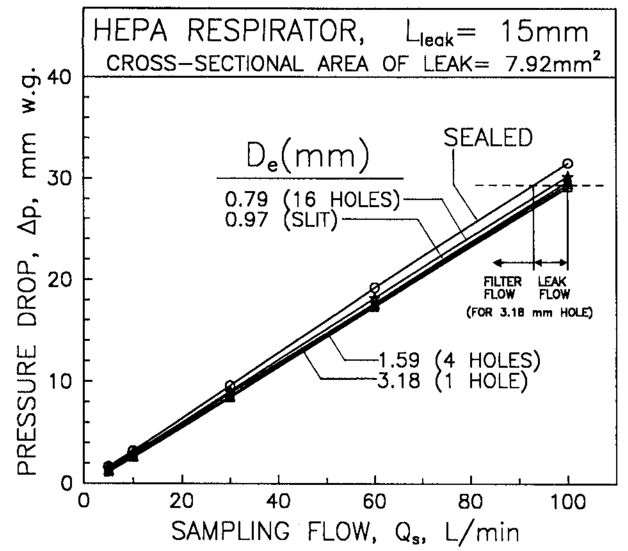

FIGURE 5. Effect of leak shape and sampling flow rate on pressure drop. The lowest curve is for D_e = 3.18 mm.

Figures 5 and 6 had the artificial leaks attached, resulting in a smaller filtration area and a slightly higher pressure drop than in the previous tests.

Figure 7 shows the aerosol penetrations through respirators with leaks of four different effective diameters. Aerosol penetration increases with the effective diameter of a leak of given cross-sectional area because air resistance and aerosol deposition decrease with increasing effective diameter. The percentage of aerosol penetration and the range of penetration values for the indicated flows decrease with a decrease in effective diameter.

The influence of effective leak diameter on aerosol penetration is shown for one fixed sampling flow rate in Figure 8. Aerosol penetration is only moderately dependent on particle size in the submicrometer size range but is strongly dependent on particle size for particles larger than about 1 µm. The curves for the different effective diameters converge at about 5 µm for the indicated flow rate. The aerosol penetrations of submicrometer-sized aerosol particles through the circular leak hole and the long slit of equal cross-sectional area are about 7% and 5%, respectively, a difference of 40%.

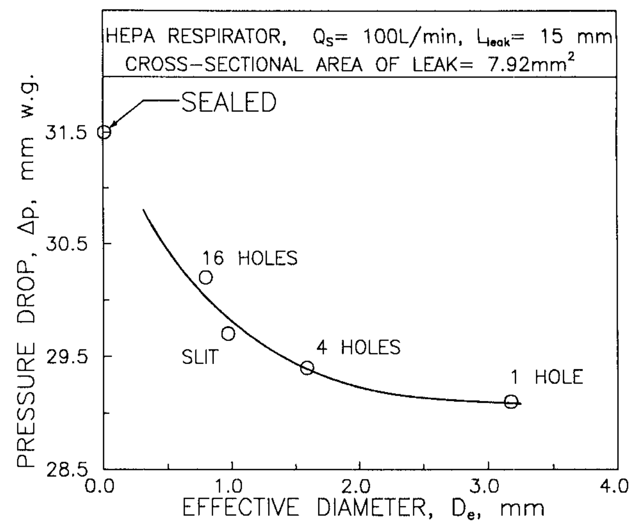

FIGURE 6. Effect of effective diameter on pressure drop

The authors conclude from this that the shape of a leak of given cross-sectional area affects the leak flow and, therefore, the penetration of aerosols.

Figure 9 shows aerosol penetration as a function of effective leak diameter for 2-µm particles. This particle size was chosen for this illustration because it reflects the transition region between sub- and supermicrometer particle-size behavior. The leak penetration data theoretically approach zero

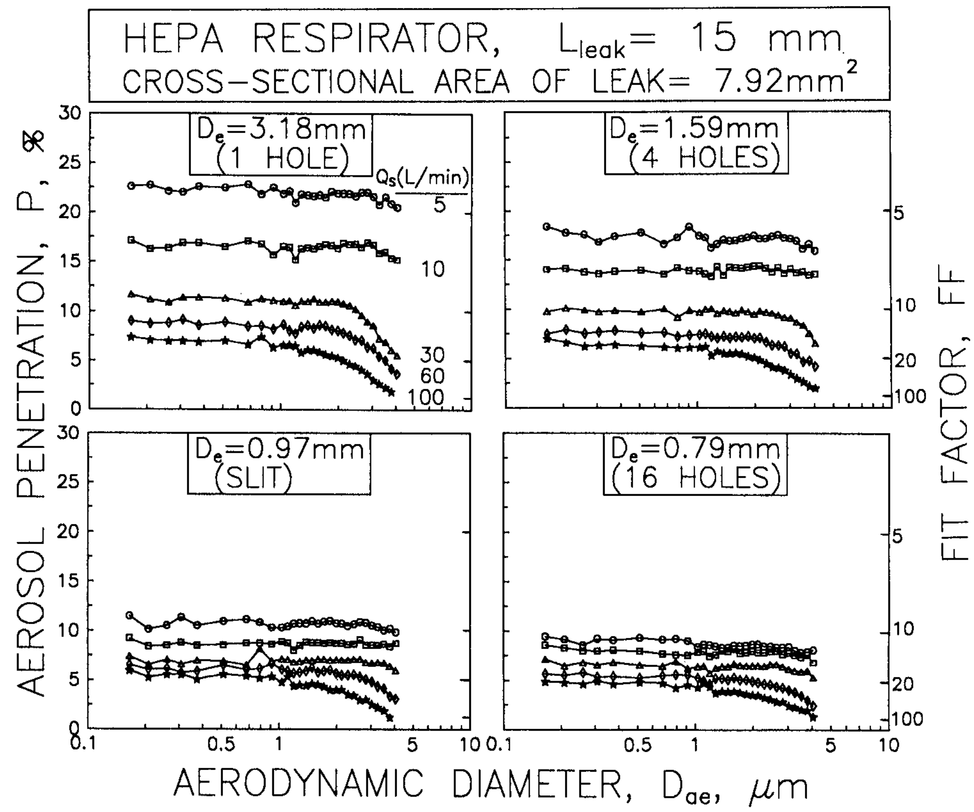

FIGURE 7. Effect of leak shape on aerosol penetration

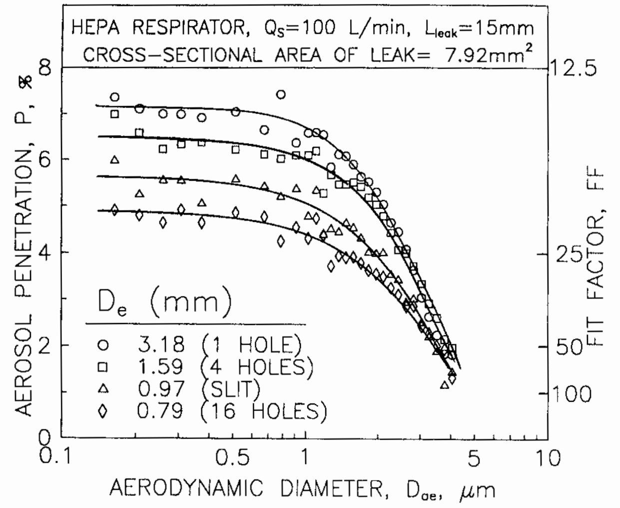

FIGURE 8. Aerosol penetration dependence on effective leak diameter

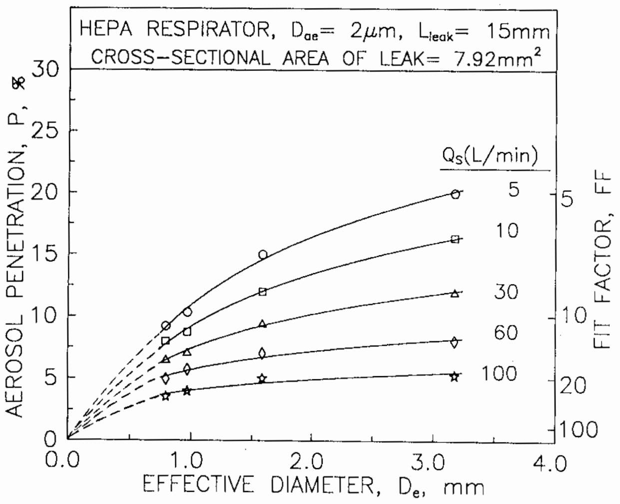

FIGURE 9. Effect of leak shape on the penetration of 2-μm aerosol particles

as the effective diameter approaches zero. The effective diameter dependency is stronger for low sampling flows than for high sampling flows because the leak flow fraction is higher at low sampling flows (see also Figure 2).

CONCLUSIONS

If there is substantial lack of face seal fit and the wearer performs a light workload (low breathing rate), a HEPA respirator may provide less protection than a DM respirator. This may occur because the high pressure drop across the HEPA filter pulls a greater amount of aerosols through a leak of given size than the much lower pressure drop across the dust-mist respirator. Thus, the sum of aerosol particles penetrating the filter material and leak may be lower for the dust-mist respirator than for the HEPA respirator. If the leak size is small, the HEPA respirator always performs better than the dust-mist respirator, as intended.

Aerosol penetration through leaks of the same cross-sectional area decreases with an increase in leak shape complexity. Increasing leak length may decrease aerosol penetration significantly at very low flow rates. Large sealing surfaces, therefore, may increase the seal and, in addition, decrease the aerosol penetration for a given leak size.

REFERENCES

1. "29 Labor," *Code of Federal Regulations* Title 29, Pt. 1910. 1988. pp. 726–734.
2. **National Institute for Occupational Safety and Health:** *NIOSH Guide to Industrial Respiratory Protection,* by N.J. Bollinger and R. Schutz (DHHS/NIOSH Pub. No. 87-116). Washington, D.C.: Government Printing Office, 1987. pp. 191–253.
3. **Burgess, W.A., L. Silverman, and F. Stein:** A New Technique for Evaluating Respirator Performance. *Am. Ind. Hyg. Assoc. J. 22(6)*:422–429 (1961).
4. **Hyatt, E.C., J.A. Pritchard, and C.P. Richards:** Respirator Efficiency Measurement Using Quantitative DOP Man Tests. *Am. Ind. Hyg. Assoc. J. 33(10)*:635–643 (1972).
5. **Hack, A.L., O.D. Gradley, and A. Trujillo:** Respirator Protection Factors: Part II—Protection Factors of Supplied-Air Respirators. *Am. Ind. Hyg. Assoc. J. 41(5)*:376–381 (1980).
6. **Willeke, K., H.E. Ayer, and J.D. Blanchard:** New Methods for Quantitative Respirator Fit Testing with Aerosols. *Am. Ind. Hyg. Assoc. J. 42(2)*:121–125 (1981).
7. **Hinds, W.C., J.M. Macher, and M.W. First:** Size Distribution of Aerosols Produced by the Laskin Aerosol Generator Using Substitute Materials for DOP. *Am. Ind. Hyg. Assoc. J. 44(7)*:495–500 (1983).
8. **Hardis, K.E., C.A. Cadena, G.J. Carison, R.A. da Roza, and B.J. Held:** Correlation of Qualitative and Quantitative Results from Testing Respirator Fit. *Am. Ind. Hyg. Assoc. J. 44(2)*:78–87 (1983).
9. **Hinds, W.C. and C. Kraske:** Performance of Dust Respirators with Facial Seal Leaks: I. Experimental. *Am. Ind. Hyg. Assoc. J. 48(10)*:836–841 (1987).
10. **Carpenter, D.R. and K. Willeke:** Quantitative Respirator Fit Testing: Dynamic Pressure versus Aerosol Measurement. *Am. Ind. Hyg. Assoc. J. 49(10)*:492–496 (1988).
11. **Xu, M., D. Han, S. Hangal, and K. Willeke:** Respirator Fit and Protection through Determination of Air and Particle Leakage. *Ann. Occup. Hyg. 35*:13–24 (1991).
12. **Crutchfield, C.D., M.P. Eroh, and M.D. Van Ert:** A Feasibility Study of Quantitative Respirator Fit Testing by Controlled Negative Pressure. *Am. Ind. Hyg. Assoc. J. 52(4)*:172–176 (1991).
13. **Liu, B.Y.U., K. Sega, K.L. Rubow, S.W. Lenhart, and W.R. Myers:** In-Mask Aerosol Sampling for Powered Air Purifying Respirators. *Am. Ind. Hyg. Assoc. J. 45(4)*:278–283 (1984).
14. **Myers, W.R., J. Allender, R. Plummer, and T. Stobbe:** Parameters that Bias the Measurement of Airborne Concentration within a Respirator. *Am. Ind. Hyg. Assoc. J. 47(2)*:106–114 (1986).
15. **Holton, P.M., D.L. Tackett, and K. Willeke:** Particle Size-Dependent Leakage and Losses of Aerosols in Respirators. *Am. Ind. Hyg. Assoc. J. 48(10)*:848–854 (1987).

16. **Holton, P.M. and K. Willeke:** The Effect of Aerosol Size Distribution and Measurement Method on Respirator Fit. *Am. Ind. Hyg. Assoc. J. 48(10)*:855–860 (1987).
17. **Myers, W.R., J.R. Allender, W. Iskander, and C. Stanley:** Causes of In-Facepieces Sampling Bias—I. Half-Facepiece Respirators. *Ann. Occup. Hyg. 32*:345–359 (1988).
18. **Myers, W.R. and J.R. Allender:** Causes of In-Facepiece Sampling Bias—I. Full-Facepiece Respirators. *Ann. Occup. Hyg. 32*:361–372 (1988).
19. **Oestenstad, R.K., J.L. Perkins, and V.E. Rose:** Identification of Faceseal Leak Sites on a Half-Mask Respirator. *Am. Ind. Hyg. Assoc. J. 51(5)*:280–284 (1990).
20. **Oestenstad, R.K., H.K. Dillon, and L.L. Perkins:** Distribution of Faceseal Leak Sites on a Half-Mask Respirator and Their Association with Facial Dimensions. *Am. Ind. Hyg. Assoc. J. 51(5)*:285–290 (1990).
21. **Sabersky, R.H., A.J. Acosta, and E.G. Hauptmann:** *Fluid Flow: A First Course in Fluid Mechanics.* New York: MacMillan Publishing Co., 1971. pp. 142–172.
22. **Chen, C.C., J. Ruuskanen, W. Pilacinski, and K. Willeke:** Filter and Leak Penetration of a Dust and Mist Filtering Facepiece. *Am. Ind. Hyg. Assoc. J. 51(12)*:632–639 (1990).
23. **Pilacinski, W., C.C. Chen, and K. Willeke:** Size-Fractionating Aerosol Generator. *Aerosol Sci. Technol. 13*:450–458 (1990).
24. **Chen, C.C., M. Lehtimäki, and K. Willeke:** Aerosol Penetration through Filtering Facepieces and Cartridges. *Am. Ind. Hyg. Assoc. J. 53(9)*:566–574 (1992).
25. **Chen, C.C., M. Lehtimäki, and K. Willeke:** Loading and Filtration Characteristics of Filtering Facepieces. Submitted to *Am. Ind. Hyg. Assoc. J.* (1991).