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WILLIAM C. HINDS & PETER BELLIN

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Performance of Dust Respirators with Facial Seal Leaks: II. Predictive Model

WILLIAM C. HINDS and PETER BELLIN
University of California Southern Occupational Health Center, Division of Environmental and Occupational Health Sciences, UCLA School of Public Health, Los Angeles, CA 90024

A performance model for half-mask and single-use respirators is presented. It represents a possible alternative to field measurements of respirator performance. Experimental data on filter and leak performance given in Part I were used to develop a model that allows one to predict 1) the overall respirator penetration as a function of particle size for any work rate and 2) overall total mass penetration for any work rate and exposure aerosol-size distribution for a known respirator filter and facial seal leak condition. A simplified method based on general regression equations is presented that allows one to estimate these quantities based on QNFT (quantitative fit testing) measurements and a knowledge of the exposure aerosol-size distribution. Example calculations are given for a situation in which QNFT gives a fit factor of 50 for a half-mask with dust, fume and mist filter cartridges, but predicted protection factors for various use conditions range from 20 to 81 depending on exposure particle-size distribution and work rate of the wearer.

Introduction

In most industrial situations it is common practice to select respirators on the basis of their assigned protection factor with the presumption that the margin of safety built into the protection factor will result in adequate protection being provided. There are many situations, however, where it is desirable to go a step further and evaluate the actual exposure of a respirator wearer; that is, the concentration or amount of contaminant he or she is breathing. Examples of such situations include the following: 1) good industrial hygiene practice where it is always desirable to know the actual exposure experienced by each worker (the "evaluation" component of "recognition, evaluation, and control"); 2) epidemiological studies where accurate exposure assessment is needed to establish associations between exposure and the occurrence of symptoms or disease; 3) liability protection particularly when exposure is close to an exposure standard; 4) industrial hygiene evaluation as follow-up to observed occurrence of disease or symptoms; 5) respirator research; 6) design and development of improved respirators by respirator manufacturers; and 7) recently proposed field testing of respirators by manufacturers for certification.

Assigned protection factors have very limited usefulness for estimating a worker's actual exposure to aerosols. They represent a useful way of simply and quickly categorizing respirators in terms of minimum level of protection provided and they form the basis for selecting an appropriate type of respirator in most industrial situations, but they provide only a crude indication of the actual exposure to the wearer.

Fit factors determined by quantitative fit testing (QNFT) provide a measure of facial seal leakage that can be used to make exposure assessment in some circumstances. In the case of gases and vapors exposure assessment is straightforward: in the absence of breakthrough, exposure is equal to measured outside concentration divided by measured fit factor. This procedure requires one to assume the following: 1) perfect capture of the contaminant by the cartridges; 2) no loss of concentration as the air-gas mixture traverses a leak; 3) no difference in the percent leakage for the conditions of the QNFT test and the conditions of actual use; and 4) the measured fit factor reflects the average concentration inside the mask during inhalation.

Exposure assessment is more complicated for aerosol exposure. It requires knowing the exposure-size distribution and penetration as a function of particle size for both filter penetration and leak penetration. QNFT measurements are likely to be a poor indicator of overall respirator performance for protection against aerosols because they fail to include filter penetration (through use of high efficiency filters for testing) and do not account for losses of larger size particles in facial seal leaks. Respirator performance can be evaluated in the field but there are great practical difficulties in making measurements more sophisticated than QNFT testing, especially for aerosols.

The objective of the present study was to develop a model for selected common half-mask respirators that allows one to predict the combined penetration (filter penetration plus facial seal leak penetration) as a function of particle size for different work rates, and overall mass penetration (or protection factor) as a function of work rate and exposure-size distribution for different sizes and types of facial seal leaks. The model neglects any inward leakage through the exhalation valve or the structure of the respirator. The model utilizes data on respirator filter and facial seal leak performance given by Hinds and Kraske.[1]

No published studies have attempted to model respirator performance for aerosols in the detailed way presented here. A study by Silver *et al.*[2] described a respirator model based on an equivalent electrical circuit. Their model characterized primarily the airflow and pressure inside the mask, and did

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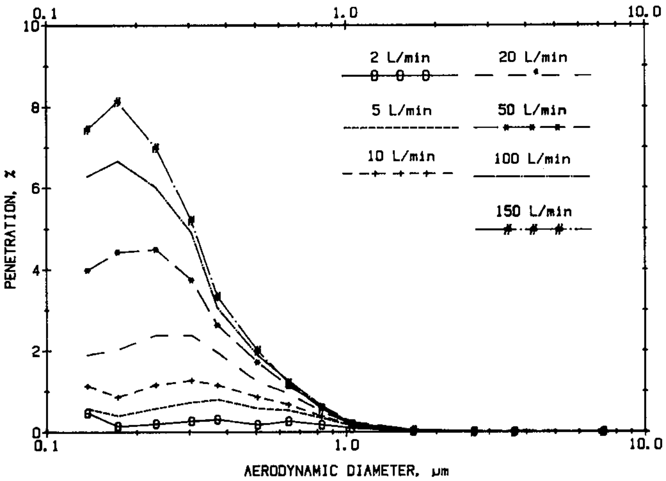

Figure 1 — Filter performance, MSA Type S dust, fume, and mist cartridge filters (2), average of three lots.

not address the issue of performance *vs.* particle size considered here. Campbell[3] gives a theoretical steady flow model based on earlier work by Williams[4] that correctly accounts for the different proportion of leak and filter flow at different flow rates but does not include the effect of particle-size dependent filter and leak penetration.

Model Development

The performance curves for filter and leak penetration as a function of particle size and flow rate (or pressure drop) (Figures 1 and 2) can be used to estimate overall performance by combining penetration due to facial seal leaks with penetration through filters. The most accurate way to do this is to combine leak and filter penetration for each particle-size and pressure-drop condition taking into account the effect of pressure drop on the proportion of leak flow. As explained in the previous paper,[1] the proportion of leak flow is different for each pressure drop. Note that Figure 2 does not characterize leakage airflow rate but rather gives the fraction of particles originally in the leakage airflow that successfully traverse the leak. A Lotus 1,2,3 spread sheet was written to combine data on penetration *vs.* aerodynamic diameter for filter and facial seal leaks at different pressure drops. It permits the setting of leak flow rate as a specified percentage of total flow rate (at any specified total flow rate) and combines the filter and leak penetration data to give combined penetration as a function of particle size and total flow. This is accomplished in three steps. The first uses only pressure drop *vs.* flow rate data and adjusts the number of leaks to give the desired percentage leak at the specified total flow rate. The second step adjusts, by linear interpolation, leak penetration data to the filter pressure drops and computes the fraction that the leak flow is of total flow rate for each pressure drop. The final step combines the leak and filter penetrations in the correct proportions for each particle size and pressure drop to give the 7 × 14 output penetration matrix.

Examples of a combined performance curves are shown in Figures 3 to 5. The conditions for Figure 3 are a MSA Comfo II with Type S dust, fume and mist cartridges having filter performance as shown in Figure 1; a 2% leak flow rate at a total flow rate of 34.3 L/min (average flow rate for a work rate of 0 kg-m/min), and leak penetration characteristics as shown in Figure 2 (1-mm diameter leak). Conditions for Figure 4 are the same except that the leak flow rate is 5% at a total flow rate of 34.3 L/min. This is equivalent to increasing the number of facial seal leaks in Figure 3 by 2.5 times. Figure 5 is for a 3M 8710 single-use respirator with a 2% leak flow rate at a total flow rate of 34.3 L/min. Leak penetration characteristics are shown in Figure 2. In Figures 3 to 5 the effect of a changing porportion of leak flow rate is evident in the size range 0.5 to 10 µm. As described in the previous paper,[1] the proportion of leak flow rate increases with decreasing total flow rate. This has the effect of increasing the separation between lines for different flow rates compared to the original leak performance curve (Figure 2). The opposite effect occurs in the filter penetration dominated region, particle size less than 0.5 µm.

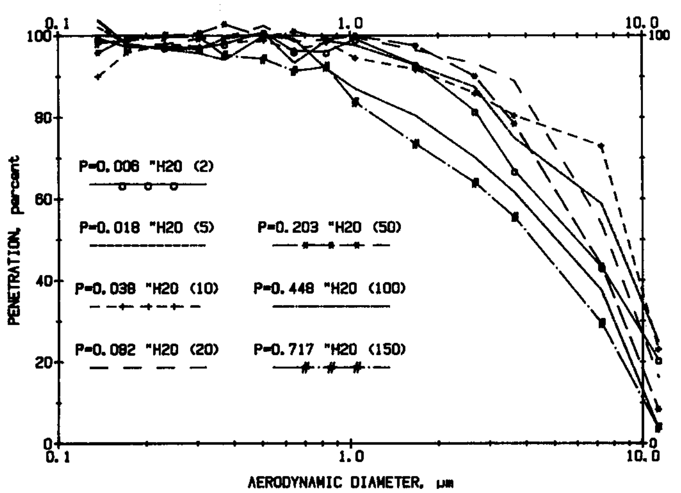

Figure 2 — Leak performance, tube leak 1.0 mm ID × 10 mm long, at six pressure drops. Parameter in parenthesis is the equivalent flow rate through a pair of MSA type S filters in L/min.

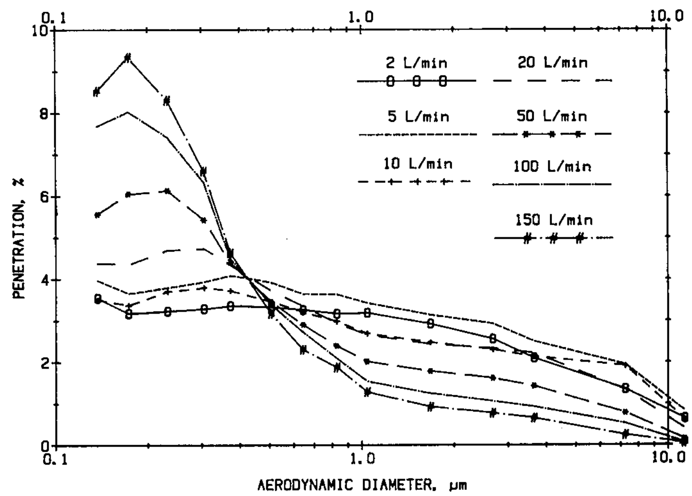

Figure 3 — Combined respirator performance, MSA Type S dust, fume, mist cartridge filters (Figure 1) with a 2% leak (Figure 2) at 34.3 L/min. Parameter is total flow.

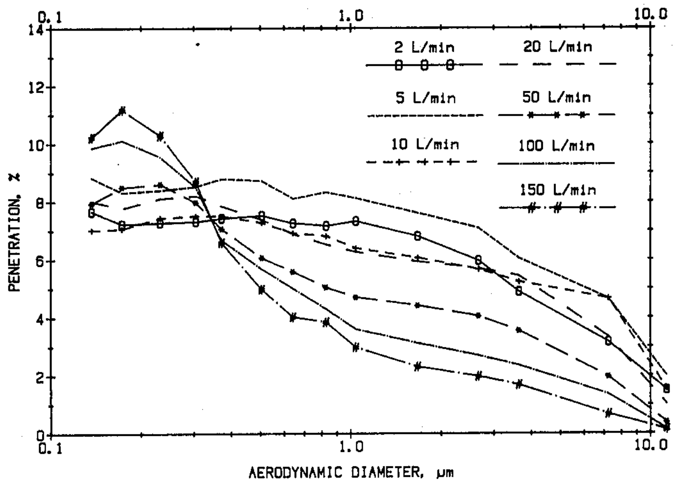

Figure 4 — Combined respirator performance, MSA Type S dust, fume, and mist cartridge filters (Figure 1) with a 5% leak (Figure 2) at 34.3 L/min. Parameter is total flow.

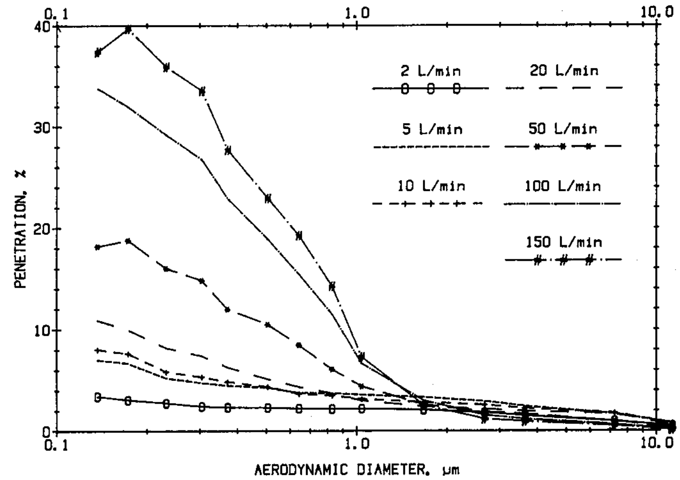

Figure 5 — Combined respirator performance, 3M 8710 single-use respirator with a 2% leak (Figure 2) at 34.3 L/min. Parameter is total flow.

The combined performance curve can be integrated over the breathing profile, inhalation flow rate *vs.* time, to obtain overall penetration as a function of particle size for selected work rates. This final step, integrating over breathing profile, also is done with a Lotus 1,2,3 spread sheet. The inhalation profiles used are those given by Silverman *et al.*[5] for six work rates from sedentary to 830 kg-m/min. The spread sheet uses linear interpolation to calculate penetration for flow rates corresponding to each of 16 time periods during inhalation and then uses Simpson rule integration to obtain overall penetration.

As an example, this has been done in Figure 6 based on the combined performance curves given in Figure 3, and in Figure 7 based on Figure 5. Once such a graph is obtained, overall performance at any particle size and work rate can be read directly from the graph. The performance curve for a given work rate can be integrated over the mass-size distribution of the aerosol the wearer is exposed to, to estimate overall penetration and protection factor under conditions of use.

The approach given above is accurate but limited to the conditions of experimental measurements. A more general and useful approach is to express these results and the data on which they are based in the form of regression equations that, within the limits of the data, predict penetration as a function of particle size, pressure drop, and leak size or filter type. The regression equations that follow were obtained using subroutines 1R and 3R of the 1984 edition of BMDPC Statistical Software for IBM PCXT.[6]

The equations given below for facial seal leaks predict only the fraction of each size particle that will enter a mask with a given leakage flow rate. The equations do not predict how much air will flow through a leak, a quantity that depends strongly on leak size, their number and shape — information not usually available. Instead, leak flow rate can be estimated by quantitative fit testing. A measured fit factor of 100 suggests that under the conditions of the test there is a 1% leak; that is, a flow, equal to 1% of the average flow through the filters, leaks through the facial seal or other leak points. The equations given below predict the fraction of a given particle size originally in the leakage airflow that gets through the leak into the wearer's mouth.

In the absence of any information about leak size or respirator pressure drop, the best single equation for predicting penetration is

$$\text{LPen} = 97 - 7.4(d_a) \qquad \text{for } 0.1 \leq d_a \leq 12\ \mu\text{m} \qquad \textbf{(1)}$$

where LPen is penetration in percent and d_a is particle aerodynamic diameter in μm. Correlation coefficient r^2 for Equation 1, based on 686 observations, is 0.821. Use of this equation is restricted to the particle size range 0.1 to 12 μm, although little overall error is obtained by assuming LPen for $d_a \leq 0.1$ μm is 100% and LPen for $d_a \geq 12$ μm is 0%.

Theoretical calculation of particle loss to leak surfaces by diffusion indicates a less than 5% loss of 0.01 μm or larger particles for the usual range of respirator use conditions. It is

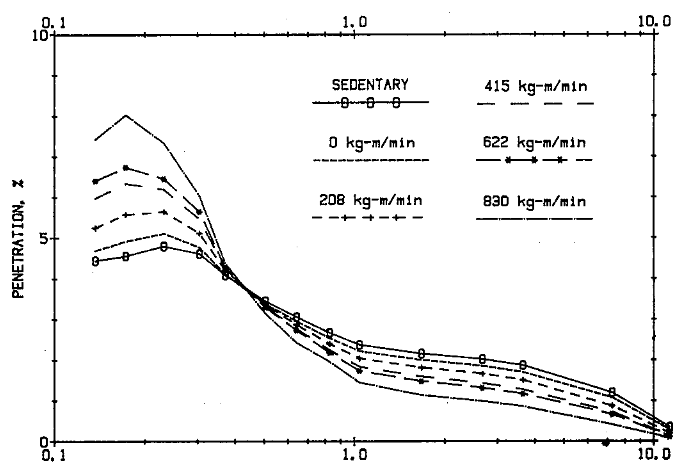

Figure 6 — Overall respirator performance at six work rates based on combined respirator performance shown in Figure 3 (MSA Type S filters with a 2% leak at 34.3 L/min).

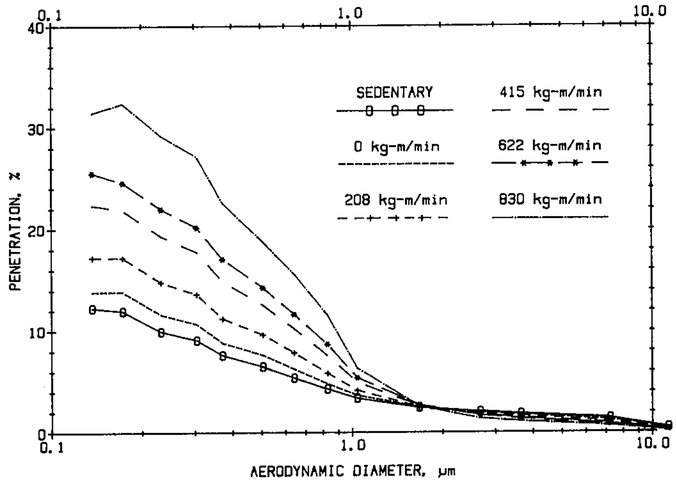

Figure 7 — Overall respirator performance at six work rates based on combined respirator performance shown in Figure 5 (3M 8710 respirator with a 2% leak at 34.3 L/min).

unlikely that particles smaller than 0.01 μm will contribute significantly to total aerosol mass. Equation 1 is based on all leak data; that is, for the 14 particle sizes, 7 pressure drops and 7 leak conditions described in Reference 1.

When pressure drop is included the best single equation for predicting penetration is

$$\text{LPen}(\%) = 90 - 9.8d_a - 7.8\ln P - 1.5(\ln P)^2 - 1.4d_a(\ln P) - 0.15d_a(\ln P)^2 \quad \textbf{(2)}$$

where P is the instantaneous pressure drop across the leak in inches of water. Correlation coefficient r^2 is 0.862. A more elaborate equation that takes into account leak size was obtained, but it gave no significant improvement in fit over Equation 2.

Similar regression equations can be developed for filters. Three brands of dust, fume and mist cartridge filters — MSA Type S, American Optical R56A, and North N7500-7, used in pairs — have an average predicted filter penetration FPen given by,

$$\text{FPEN} = (3.49 + 0.014\ \text{WR}) \exp[-d_a(3.10 + 0.00127\ \text{WR})] \quad \textbf{(3)}$$

for $0.1 < d_a \leq 1.0$ μm and,

$$\text{FPEN} = (0.2158 + 0.00025\ \text{WR}) \exp[-d_a(0.2192 + 0.000645\ \text{WR})]$$

for $d_a > 1.0$ μm. WR is work rate in kg-m/min.

Similarly, three brands of single-use dust and mist respirators (3M 8710, American Optical R 1070, and Gerson 1710) have average performance characterized by

$$\text{FPen} = (51 + 0.0367\text{WR}) \exp[-d_a(1.540 + 0.000417\text{WR})] \quad \textbf{(4)}$$

These regression equations predict the data with an rms accuracy of 15.9% and 13.8% for dust, fume and mist cartridges and 19.2% for single-use respirators. They can be used in the simplified procedure for estimating overall respirator performance given below, but they must be used with care because the range of individual filter performance is great, as much as a factor of four between the highest and lowest penetrations for a given particle size and brand of filter.

A simplified method can be used to provide a more convenient although less accurate estimate of overall respirator performance. Curves or equations giving penetration as a function of d_a and WR for filters (FPen) and as a function of d_a for leaks (LPen) are combined by,

$$\text{TPen} = (\text{CF})(\text{F})\,\text{LPen} + (1 - \text{F})\,\text{FPen} \quad \textbf{(5)}$$

where TPen is total penetration (a function of particle size and work rate), F is the average fraction that leakage flow rate is of total flow rate at 0 kg-m/min work rate as determined by QNFT test and CF is a correction factor that depends on the work rate at which the respirator will be used, see Table I. Table I was obtained by numerically averaging the ratio of leak flow at the desired work rate to that at 0 kg-m/min for each of 16 instantaneous flow rates during an inhalation cycle. Values given are for an average leak condition where leak flow rate is proportional to pressure drop raised to the 0.75 power. If accurate filter data are used, the accuracy of this method is about ± 25% of the penetration value for any particle size. Equation 5 combined with Equation 1 and 3 or 4 provides an explicit estimate of total penetration (filter and leak) for any particle size (0.1 to 12 μm) and work rate (0 to 830 kg-m/min).

Whichever way the TPen *vs.* d_a curve for the specified work rate is obtained, that curve is used to integrate over exposure-size distribution to obtain the concentration (and size distribution) to which the worker actually is exposed. For example, Table II gives overall penetration and protection factor for a respirator with a 2% leak at 34.3 Lpm and overall performance as shown in Figure 3 for four-size distributions. Values in Table II were obtained by computing mass penetration for each of 16 particle sizes and integrating over the size distribution by Simpson rule integration.

Estimated performance is given for the detailed method and the simplified method described above. Mean difference is 12.3% between the two methods. Table II shows that a dust, fume, and mist half-mask respirator that has a fit factor of 50 based on measured QNFT at a work rate of 0 kg-m/min may provide in actual use protection factors ranging from 20 to 81 (a fourfold range) depending on particle-size distribution and work rate. In general the agreement

TABLE I
Correction Factor for Use in the Simplified Method for Estimating Respirator Performance[A]

Work Rate, kg-m/min	CF
Sed	1.05
0	1.00
208	0.92
415	0.84
622	0.81
830	0.73

[A]Assumes fit factor was determined at a work rate of 0 kg-m/min. Correction factor can be approximated by, CF = 1.0 - 0.00032 (WR).

TABLE II

Comparison of Detailed and Simplified Methods of Calculating Mass Penetration and Protection Factor for a Dust, Fume, Mist Respirator with Overall Performance Characterized by Figure 6 (MSA type S Filters with a 2% Facial Seal Leak at 34.3 L/min).

Aerosol	MMD μm	GSD	WR kg-m/min	Detailed Calc. Mass Pen %(PF)	Simplified Calc[A] Mass Pen %(PF)	Difference %
Lead Fume[7]	0.32	2.25	415	4.98 (20)	6.46 (15)	+29.7%
Silica Dust, Respirable[8]	1.44	1.54	622	1.69 (59)	1.76 (57)	+4.1%
Limestone Dust, Resuspended[9]	2.1	2.1	208	1.99 (50)	1.97 (51)	-1.0%
Coal Mine Dust[10]	5.26	2.43	622	1.23 (81)	1.43 (70)	+16.3%

[A]Calculated by Equation 5; LPEN given by Equation 1 and FPEN given by Equation 3.

between the two methods is good when one considers the predictive equations used for filter penetration are for an average of three brands for the simplified method where the actual data for MSA Type S filters is used for the detailed method. The simplified method overestimates penetration for the small particle-size lead fume because of the difference between the actual and brand average filter performance described above. Penetration for the large particle-size distribution of coal dust also is overestimated by the simplified method because Equation 1 does not fully take into account the effect of pressure drop on leak performance.

Discussion

The unexplained difference between the regression equation prediction and the data is 17% for Equation 1 and 13% for Equation 2. Errors associated with interpolation and integration in the model are small and are neglected here. Based on these errors and the errors for the original data on which the model is based,[1] the expected error for combined penetration *vs.* d_a and for overall mass penetration is ± 10% of the value for the detailed method and ± 25% for the simplified method. This assumes that the work rate and particle-size distribution are accurately known and accurate performance curves for the respirator filters are used. For a single estimate for an individual, the performance curves for the actual filters used would be required; for a group or a long-term estimate for an individual the average for the type of filter used would be required.

The model predicts protection factors based on an average concentration inside the mask during inhalation. No account has been taken of the effect of mask dead space on inside concentration. In general this effect would reduce inhaled dose slightly compared to that predicted by the model.

The model presented here has not been validated by experimental measurements in the field. While in principle it is possible to do so there are great practical difficulties in such measurements. In addition to accurate measurement of external concentration and size distribution and leakage rate, it is necessary to measure mass concentration inside the mask only during inhalation without significantly modifying the flow through the mask. The latter is especially difficult in light of the sampling problems identified by Myers *et al.*[11]

The use of this approach represents a possible alternative to field measurements of worker's actual exposure while wearing a respirator. Field measurements give information that is specific and accurate for each situation but limited in the extent to which it can be generalized. While leakage can be measured with QNFT equipment (corn oil or sodium chloride), this equipment is unsuited to measuring filter performance because instrument response is sensitive to particle size, a quantity that changes as the aerosol passes through the respirator filter. The experimental difficulties described above for model validation also occur for direct measurement of a respirator wearer's actual exposure to aerosols.

Conclusion

Experimental data on filter and leak performance[1] were used to develop a model that allows one to predict the overall penetration as a function of particle size for any work rate and overall total mass penetration for any work rate and exposure aerosol-size distribution for a known mask and fit. Use of this model represents a possible alternative to difficult field measurements of performance, and the authors have demonstrated it is feasible to estimate a worker's actual exposure or actual protection factor using a simplified method based on QNFT measurement and a knowledge of the exposure aerosol-size distribution.

Acknowledgement

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