Ann. occup. Hyg., Vol. 35, No. 1, pp 13–24, 1991.
Printed in Great Britain.

0003–4878/91 $3.00+0.00
Pergamon Press plc

RESPIRATOR FIT AND PROTECTION THROUGH DETERMINATION OF AIR AND PARTICLE LEAKAGE

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(*Received* 23 *October* 1989 *and in final form* 25 *September* 1990)

Abstract—A laboratory technique for determining the respirator protection factor from a test of fit is described. A dynamic pressure test quantifies the air flow through the leak. Calibration data, stored in a computer, relate the contaminant influx to this air flow, and a similar pressure test determines the flow through the respirator cartridges and, therefore, the dilution characteristics. Contaminant removal characteristics of the cartridges are stored in the computer. The contaminant penetration is calculated from these data on flow and removal efficiency. Through specification of the aerosol size distribution and the method of measurement, protection factors are calculated for specific work environments, work loads and respirator cartridges. The protection factor is shown to be highly dependent on the method of measuring the contaminant and on the cartridges used.

NOMENCLATURE

C_i	contaminant concentration inside respirator cavity
C_o	contaminant concentration in the outside air
d_a	aerodynamic particle diameter
FR	air flow ratio, $FR = Q_c/Q_l$
M	mass of air in respirator cavity
N_{ci}	amount of contaminant penetrated through cartridges into respirator cavity
N_i	total amount of contaminant inside the respirator cavity
N_{li}	amount of contaminant penetrated through leaks into respirator cavity
P	absolute pressure in respirator cavity
ΔP	pressure differential between inside and outside of the respirator
P_{atm}	atmospheric pressure
PF	protection factor, $PF = C_o/C_i$
Q	air flow rate
Q_c	air flow rate through cartridges
Q_l	air flow rate through leaks
R	gas constant
t	decay time of the pressure in respirator cavity
T	absolute temperature of the air in respirator cavity
V	volume of respirator cavity or vessel
V_c	volume of the vessel for testing cartridges
V_f	volume of air flow through cartridges
V_l	volume of air flow through leaks
V_r	respirator cavity volume
WLS_c	pressure decay slope due to air flow through cartridges, $WLS = -d(\ln \Delta P)/dt$
WLS_l	pressure decay slope due to air flow through leaks
η_c	removal efficiency of contaminants by cartridge filters
η_l	removal efficiency of contaminants by leaks
ρ	air density at pressure P and temperature T

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INTRODUCTION

TO SELECT a respirator, the fit to the wearer's face is expressed quantitatively by comparing the concentration of contaminant outside with that inside the respirator (DOUGLAS *et al.*, 1978; GRIFFIN and LONGSON, 1970; WILLEKE *et al.*, 1981) so as to minimize facial leakage by choosing a respirator shape and size that best fits the wearer's face. Since air contaminants penetrate primarily through face-seal leaks and the air purifying cartridges, the test is performed with HEPA filter cartridges so that penetration through the filters can be neglected and only the fit to the wearer's face is evaluated: any other leaks, such as through non-sealing exhalation valves or other defects, also show up. In practice the cartridges used may be of less efficient types, so that although the test reveals and quantifies the deficiencies of the respirator with respect to fit, it does not measure or predict the protection during actual use. The correlation between field measurements of the 'Workplace Protection Factor' (WPF) and the laboratory-tested Fit Factor (FF) is poor (MYERS and PEACH, 1983; MYERS *et al.*, 1984).

This study attempts to provide a test which instead of using a surrogate mask measures the protection in the workplace for the respirator actually worn. Further work is needed to perfect such methods, but the authors hope to stimulate efforts towards this goal.

Conventional methods of measuring face-seal leakage using aerosols have serious limitations. The probe can sample from only a fraction of the respirator cavity volume, so that the sample may not represent the aerosol there as a whole because during the breathing cycle there is not enough time for the air to mix thoroughly: the measured aerosol concentration is therefore strongly influenced by the relative positions of probe and site of leakage (HOLTON and WILLEKE, 1987; MYERS *et al.*, 1986, 1988).

We have avoided this problem by measuring the inflow of air by replacing the cartridges with a pressure transducer which monitors the pressure inside the respirator during breath-holding (CARPENTER and WILLEKE, 1988a,b). The pressure decay is a measure of air leakage. Since the respirator body is intact, the wearer can check the face-seal fit before and after exposure. This technique can also be used to measure the flow through the cartridges.

The flow through the cartridges depends on the cartridge type and manufacture. This will be shown to affect significantly the degree of dilution of leakage flow by cartridge flow: moreover, the efficiencies of the filter and of leakage removal will determine the average contaminant concentration inside the facepiece (CAMPBELL, 1984). However, the efficiencies can be calibrated for various industrial contaminants and stored in a computer so that only the dynamic pressure test, which is fast and simple, is needed to determine the average contaminant concentration inside the respirator relative to that outside and so obtain a true index of the protection it provides.

With aerosols, penetration through the leak can be calibrated as a function of flow rate and leak size, and through the cartridges as a function of face velocity, over a wide particle size range, and thus the computer can calculate the entire particle size distribution inside. Conventional techniques for testing fit with aerosols focus on narrow size ranges, for example, the photometric technique on particles of about 0.5 μm (HYATT *et al.*, 1972) and the particle count method (WILLEKE *et al.*, 1981) on particles of 0.1 μm or less. If the particle size distribution in the ambient air is known, the amount that gets inside the respirator can be calculated. Since the particle size distribution weighted according to number, to surface area and to mass each gives weight to a different part of the size distribution, the resulting protection factor depends on which of these is used (HOLTON *et al.*, 1987).

Actual work-place protection factors have been measured in industrial environments, and can be measured in any work environment, if cost and time are unimportant, but the concentrations of aerosols inside the respirator are low and the values obtained are likely to be fairly inaccurate (COLTON *et al.*, 1989). Approximate figures for environmental aerosol concentrations and size distributions, derived from the literature or by direct measurement, coupled with exact calibrations of leak passages, should give appropriate estimates of respirator protection.

PROTECTION FACTOR

The equation derived below expresses the protection factor in terms of the removal efficiencies and flow rates of the leak site(s) and of the cartridges. Air moves into the facepiece as shown in Fig. 1. During inhalation, a volume V_f moves at flow rate Q_c

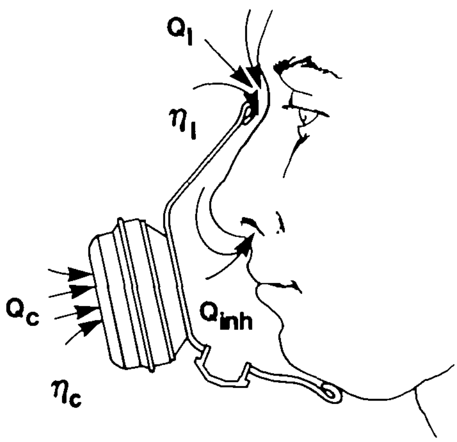

FIG. 1. Air flows and contaminant removal during respirator wear. Q = air flow rate; η = contaminant removal efficiency; c = cartridge; l = leak; inh = inhalation.

through the cartridges and volume V_l moves at flow rates Q_l through the leaks. Contaminants in the ambient air are absorbed by the cartridges with efficiency η_c, and in the leaks with efficiency η_l. If $\eta_c < 1$, the amount of contaminant penetrating through the cartridges, N_{ci}, is

$$N_{ci} = C_o V_f (1 - \eta_c), \tag{1}$$

where C_o is the contaminant concentration in the outside air. Similarly, the amount of contaminant penetrating through the leaks, N_{li}, is

$$N_{li} = C_o V_l (1 - \eta_l) \tag{2}$$

and the total amount of contaminant found inside the facepiece is

$$N_i = N_{ci} + N_{li}. \tag{3}$$

The average contaminant concentration inside the facepiece, C_i, is therefore

$$C_i = \frac{N_i}{V_f + V_l} = \frac{C_o[V_f(1-\eta_c) + V_l(1-\eta_l)]}{V_f + V_l}. \tag{4}$$

The Protection Factor, PF, is defined as C_o/C_i (MYERS *et al.*, 1983) and given by the equation

$$\mathrm{PF} = \frac{C_o}{C_i} = \frac{1 + V_f/V_l}{(V_f/V_l)(1-\eta_c) + (1-\eta_l)}. \tag{5}$$

Since $V_f/V_l = Q_c/Q_l$, Equation (5) can be rewritten as

$$\mathrm{PF} = \frac{1 + Q_c/Q_l}{(Q_c/Q_l)(1-\eta_c) + (1-\eta_l)} = \frac{1 + \mathrm{FR}}{\mathrm{FR}(1-\eta_c) + (1-\eta_l)}, \tag{6}$$

where the cartridge to leak flow ratio, FR, is defined as

$$\mathrm{FR} = Q_c/Q_l. \tag{7}$$

Equation (6) shows that PF depends on FR, which is measured for each respirator fit, and on η_c and η_l which are calibrated for each type of cartridge and leak.

In use, the exhalation valve may fail to function properly, for example, a speck of dust may create a leak. Since the pressure method used to measure Q_l is independent of leak location (CARPENTER and WILLEKE, 1988a,b), leak flow Q_l in Equations (6) and (7) indicates either face-seal or exhalation valve leakage, or both.

Equation (6) indicates that, for a given leak, increasing Q_c or η_c improves the protection provided. HEPA filters are, therefore, used whenever protection is to be optimized.

AIR FLOW PENETRATION

If a cartridge filter with $\eta_c = 1$ is used, Equation (6) reduces to

$$\mathrm{PF} = \frac{(1 + \mathrm{FR})}{(1-\eta_l)}. \tag{8}$$

If $Q_c/Q_l \gg 1$, $(1+\mathrm{FR}) \simeq \mathrm{FR}$, so that PF is linearly dependent on FR: it is, therefore, important to measure FR. Leak flow can be measured by monitoring the pressure decay with time during a few seconds of breath holding (see above). If $\Delta P = P_{atm} - P$, the slope of $\ln \Delta P$ vs time, $-\mathrm{d}(\ln \Delta P)/\mathrm{d}t$ (the Willeke Leak Slope or WLS), is constant for a constant leak (CARPENTER and WILLEKE, 1988a; WILLEKE, 1989). The leak flow is then a function of the measured WLS and ΔP during actual wear.

Q_c is also a function of the pressure differential ΔP and we have therefore now used a similar technique to measure Q_c so that the Flow Ratio can be determined independently of ΔP. The dependence of Q_l or Q_c on ΔP and WLS can be seen by considering the equation of state

$$P=\rho RT=\frac{M}{V}RT, \tag{9}$$

where ρ is the air density, R is its gas constant, T its absolute temperature and M the mass of air in constant volume V. Differentiating pressure with respect to time gives

$$\frac{\mathrm{d}P}{\mathrm{d}t}=-\frac{\mathrm{d}(\Delta P)}{\mathrm{d}t}=-\Delta P\frac{\mathrm{d}(\ln\Delta P)}{\mathrm{d}t}=\Delta P\ \mathrm{WLS}. \tag{10}$$

Differentiating mass with respect to time in Equation (9) can be related to flow rate Q for constant temperature and volume,

$$\frac{\mathrm{d}P}{\mathrm{d}t}=\frac{RT}{V}\frac{\mathrm{d}M}{\mathrm{d}t}=\frac{RT\rho}{V}Q=\frac{P}{V}Q\simeq\frac{P_{\mathrm{atm}}}{V}Q. \tag{11}$$

Combining Equations (10) and (11)

$$Q=\frac{V\ \mathrm{WLS}}{P_{\mathrm{atm}}}\Delta P. \tag{12}$$

The pressure decay test for the cartridges, described later, yields $\mathrm{WLS_c}$ for a large vessel (volume V_c), while that for the face-seal leak yields $\mathrm{WLS_l}$ for the respirator cavity (volume V_r). Hence

$$\mathrm{FR}=\frac{Q_c}{Q_l}=\frac{V_c\ \mathrm{WLS_c}}{V_r\ \mathrm{WLS_l}}, \tag{13}$$

where the leak slopes are measured by pressure decay tests.

AEROSOL PENETRATION

As shown above, contaminants may penetrate into the respirator cavity through face-seal or other leaks and also through the cartridges. The average contaminant concentration inside the respirator cavity will depend on the time average of $Q_c(1-\eta_c)+Q_l(1-\eta_l)$.

η_c depends on particle size, filtration velocity (which is a function of ΔP), filter material, filter loading and for a fibrous filter also on its solidity. The primary mechanisms of particle filtration in mechanical cartridge filters are diffusion, interception and sedimentation. For particles above 5 μm in diameter η_c is 95% or more, but may be quite low for 1 μm particles depending on cartridge type and manufacture (Tuomi, 1985).

In the face-seal leak, aerosols may be removed by the mechanisms shown in Fig. 2: larger particles may be impacted inertially onto the face of the wearer or the body of the respirator, or be intercepted as they enter the leak channel, and smaller particles may diffuse to the wall of the leak channel. When the respirator wearer is working strenuously, the pressure differential ΔP causes a relatively high velocity but laminar flow in the leak channel. This air flow enters the facepiece as a small jet which may mix

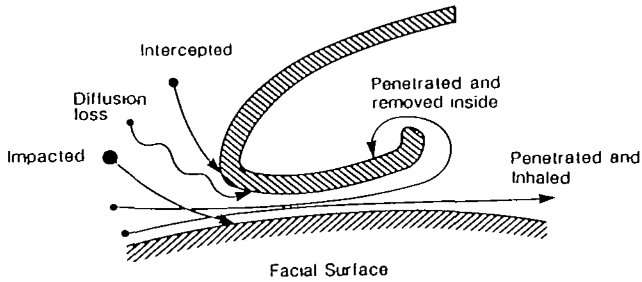

FIG. 2. Aerosol removal mechanisms in face-seal leak.

turbulently. Diffusion, gravitational settling and turbulence inside the respirator may further reduce the aerosol concentration so that only a fraction of what enters through the leak may reach the nose or mouth of the respirator wearer (MYERS *et al.*, 1986).

η_1 depends on particle size, on Q (or ΔP), on leak hole size and on the geometry of the leak(s). HOLTON *et al.* (1987) tested the aerosol leakage through a range of typical holes and found that the aerosol penetration is highest for particle sizes between 0.2 and 1.0 μm. HINDS and KRASKE (1987) also experimented with different sizes and geometries of the leaks, and found that aerosol penetration depends on particle size and pressure drop. Therefore, one should be able to develop a comprehensive equation for aerosol penetration through leaks of different sizes, but at present only limited data are available: the following equation by HINDS and BELLIN (1987) will be used for the prediction of protection from the testing of fit,

$$\eta_1(d_a) = 4.03 + 8.63\, d_a + 5 \ln \Delta P + 1.12\, d_a \ln \Delta P + 1.5(\ln \Delta P)^2 + 0.15\, d_a(\ln \Delta P)^2, \quad (14)$$

where the size-dependent efficiency of aerosol removal of the face-seal leak, $\eta_1(d_a)$, is expressed in per cent, d_a is aerodynamic particle diameter in μm, and ΔP is the pressure drop in cm w.g.

The overall aerosol removal efficiency depends on the particle size distribution which can be described in various ways, for example, by count or by mass. Relative to measurement by mass, measurement by count emphasizes the smaller particles which penetrate more efficiently. The aerosol removal efficiency depends on the particle size distribution, and therefore on the way in which this is expressed, be it by mass, surface or number (HOLTON and WILLEKE, 1987). The Protection Factor against any real aerosol is therefore an integral over the size distribution.

EXPERIMENT DESIGN

Equation (13) suggests that Flow Ratio (FR) be determined by pressure decay measurements, and CARPENTER and WILLEKE (1988a) have used it to measure the leak flow. In the present tests, three sizes of mannequin (Sierra head form, Dynatech Frontier Corp., Albuquerque, New Mexico, U.S.A.) were used on four brands of respirator. Since the negative pressure test is independent of leak location (CARPENTER and WILLEKE, 1988b), leaks were simulated by short tubes of 0.46, 0.56, 0.71 and 0.81 mm inner diameter in the attachments that replace the cartridge during the test.

The respirators were sealed in place by petroleum jelly. Each test was repeated three times. The volume of the respirator cavity was determined by water displacement.

The pressure decay test for the cartridges is schematically shown in Fig. 3. The test cartridge is attached to a large vessel (volume $V_c = 70$–120 l.), a pump reduces the pressure inside the vessel by ΔP, and when the valve between pump and vessel is closed

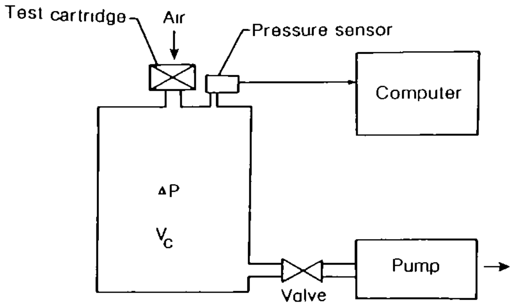

FIG. 3. Test system for cartridge flow. V_c = vessel volume for cartridge test, ΔP = pressure differential.

air continues to flow through the test cartridge: the pressure decay is monitored by a pressure sensor (model PX 164–010D 5V, 0–25 cm w.g., 1 ms response time, Omega Engineering, Stanford, Connecticut, U.S.A.). New cartridge filters were used for each test and at least two of each type were tested. The pressure decay slope is recorded by the computer. Our tests show that, as Equation (12) predicts, V WLS is constant for a given cartridge.

RESULTS

The pressure decay curves for four brands of HEPA filter and four types of organic vapour cartridge are presented in Fig. 4. Under given test conditions each type of cartridge has its characteristic WLS_c, which has a coefficient of variation less than 5%. The difference in slopes between two cartridges of a given type ranges from 1 to 10%, so that the protection factor for a given face-seal leakage depends on the type and manufacture of the cartridge. Filter loading by particulate matter will change the resistance to air flow or WLS_c in time, and therefore, also the Flow Ratio (FR).

Leakage curves for a given leak hole size are shown in Fig. 5 for respirators from four different manufacturers. The pressure decay curves, determined for the largest of the three mannequins, differ from each other because the respirator cavity volumes, V_r, are different. However, V_r WLS_l in Fig. 5 is the same ($\simeq 1450$ ml s^{-1}), since the leakage flow through a given hole is the same at a given pressure differential, irrespective of the size of the volume it enters, see also Equation (12).

Figure 6 shows, as bar graphs, the values of WLS_c (left-hand scale) and the flow ratio (right-hand scale) for the HEPA and organic vapour cartridges of Fig. 4. Here, the indicated values are twice those given in Fig. 4, since two cartridges were used on each respirator: this doubles WLS_c [see Equation (12)]. Figure 6 also shows the performance of other types of cartridge: for these, since V_c was the same in all tests, the FR values are linearly related to the WLS_c values, and V_r WLS_l is the same for the leak test. Figure 6 shows that the Flow Ratio, i.e. dilution factor, for the respirator of

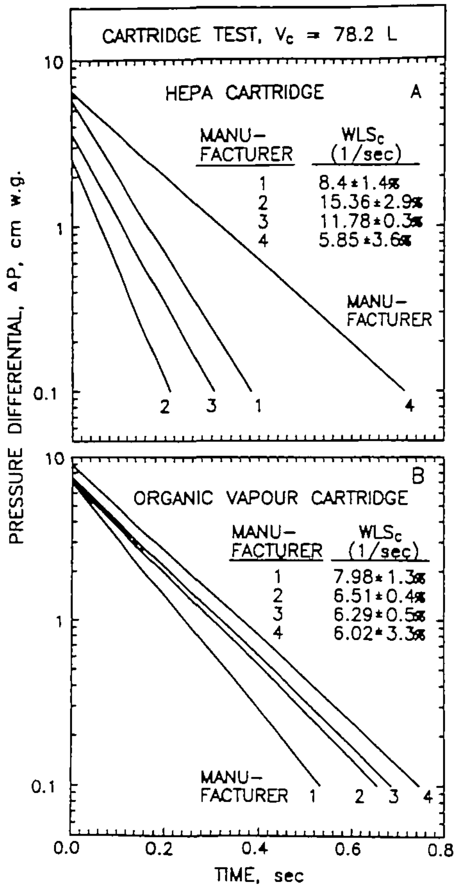

FIG. 4. Cartridge test results. Figures quoted are mean $WLS_c \pm$coefficient of variation.

manufacturer 2 is 160% higher than for the one of manufacturer 4, although the leakage, i.e. face-seal fit, is the same in both cases. Thus, cartridge resistance should be minimized to provide the maximum air flow at a given pressure differential and thereby achieve the lowest contaminant concentration inside.

We have shown that the Protection Factor (PF) depends on the Flow Ratio (FR) and on η_c and η_l. In Fig. 7, the strong particle size dependence is illustrated by assuming that the respirator is worn in an oil shale industry. A typical mass median aerodynamic diameter (MMAD) is 4.9 μm and a typical geometric standard deviation (σ_g) is 3.3 (HARGIS *et al.*, 1983). The calculated corresponding surface median aerodynamic diameter (SMAD) is 1.18 μm and the count median aerodynamic diameter (CMAD) is 0.068 μm (DRINKER and HATCH, 1954).

For this oil shale industry example, the calculated η_l for particulate mass is 49.7% for $\Delta P = 0.5$ cm w.g. (low work activity) and 21% higher for $\Delta P = 2$ cm w.g. (strenuous work). For simplicity, we have assumed that η_l, integrated over all pressure differentials during inhalation, can be represented by the removal efficiency at the average ΔP. The corresponding difference in PF, based on the above laboratory measurements and assuming 100% efficient HEPA filters, is 26%, as seen in Fig. 7(B).

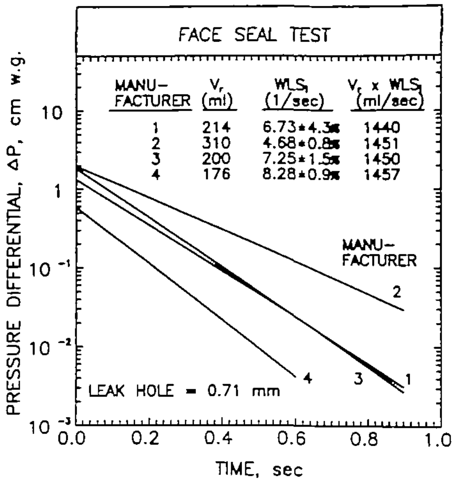

FIG. 5. Face-seal test results. Figures quoted are mean WLS_l ± coefficient of variation.

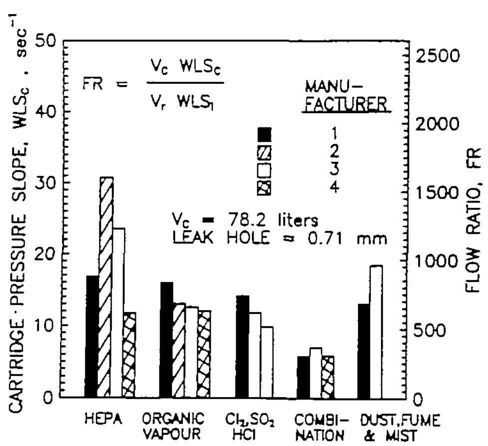

FIG. 6. Cartridge pressure slope and Flow Ratios (FR) for different cartridges on a respirator with fixed leak.

The mass measurement can be performed, for example, by sampling onto weighed filter cassettes inside and outside the respirator, and reweighing them after the test. Photometric measurements measure the scattered light and are surface related. Counting the particles on the filters or use of a condensation nuclei counter yields counts. As seen from Fig. 7(A), for low work activity η_l is 2.3% by count and 49.7% by mass. PF is 94% higher by mass than by count. By count PF for strenuous work is 7.9% higher than for low work activity and 26.4% higher by mass. A field measurement of PF by mass measurements should therefore not be expected to be equal to a Fit Factor measured photometrically in the laboratory. Nor should they be linearly related to each other, since the particle size distribution may vary considerably from

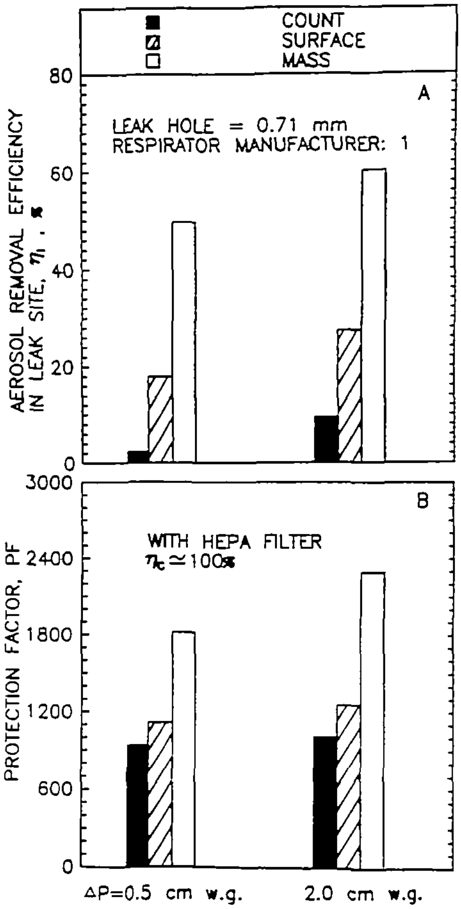

FIG. 7. Protection Factors (PF) for different work loads and aerosol measurement methods. (MMAD=4.9 μm, SMAD=1.18 μm, CMAD=0.068 μm, σ_g=3.3.)

one environment to the other. However, knowledge of the particle size distribution coupled with calibration curves for the contaminant removal efficiencies through the cartridges and the leak sites links the protection factor to the dynamic pressure tests performed in the laboratory or in the field.

While the protection factor determined by this procedure may not predict accurately the work-place protection, conventionally measured work-place protection factors are not very accurate anyhow because the air inside the respirator cavity may be incompletely mixed, or may be at or close to the detection limit. Field measurements of work-place protection are also expensive and time consuming.

Ideally, the particle concentration and size distribution should be measured in each work environment for which a protection factor for a given worker is to be determined. Alternatively, a data-base for typical work environments can be used to determine the range of work-place protection factors expected in such environments, given that a certain respirator, fitted with certain cartridges, is worn by the wearer under consideration.

CONCLUSIONS

The linkage between face-seal test and protection factor has been demonstrated for aerosols, but is equally valid for any air contaminant. The flow of air through the face-seal and other potential leaks is measured, for example, by a simple pressure test. A (portable) computer acquires the air flow data and recalls penetration efficiency data for commercially available respirators and cartridges. From these, protection factors are calculated for the specific hazardous air environment considered.

In future studies this system will be applied in the field before and after exposure to hazardous air contaminants. Work-place protection studies will be conducted at the same time so that the two methods can be compared. Since the size of the face-seal leak and, therefore, the inflow of air may vary with work activity, it is expected that stationary face-seal leak tests in a few selected head positions will be weighted to represent the specific work activity observed or considered.

These procedures for determining respirator fit and protection suggest several lines of research, including:

(1) dependence of respirator volume V_r and hence WLS_l on unobstructed air volume in the respiratory system during pressure decay testing (current research efforts here and elsewhere focus on the development of new techniques for measuring face-seal leakage that are independent of V_r and respirator pliability);

(2) face-seal leakage in different head positions and their appropriate weighting. Work activities may affect the leak size in a given head position. Vibration caused by the use of power tools may cause time variation in the size of gaps. Sweat may reduce the size of a leak channel, but may cause the respirator to slip downwards, thus potentially creating a large one;

(3) effect of leak shape. A slot-like leak channel has a larger surface to volume ratio than a circular one. At a given pressure differential less air is expected to enter through a slot than through a circular hole of equal cross-sectional area. The flow resistance of several leak channels is different from that of a single leak of equal area.

Acknowledgements—We appreciate the financial support of the U.S. National Institute for Occupational Safety and Health through Grant No. [redacted]. M. Xu, D. Han and S. Hangal were supported by stipends for graduate education, awarded by the University of Cincinnati. The authors also gratefully acknowledge the help of A. Fodor and J. Buchanan in setting up the experimental system.

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