

Review: Protection Factors of Respirators with Special Reference to Dust Respirators

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Abstract

The review starts with a brief account of the problems associated with both the definition and the measurement of protection factors in respiratory protection. Some specimen measurements of filtration efficiency are given, followed by a description of leakage and definitions of the various parameters that depend on it. An account is given of the problems of sampling, followed by the results of such exercises, carried out on both mannequins and human subjects, under laboratory conditions. The importance of respirator fit emerges from these measurements, and this is supported by a substantial amount of work done on qualitative tests of fit. Measurements of protection factor carried out in the workplace are described. It is generally, though not universally, the case that values of protection factor measured at the workplace are considerably lower than those measured in the laboratory. The review ends with the author's opinions on the direction that future work should take.

Introduction

Respirators purify atmospheric air by filtration, in contrast with breathing apparatus, which supply air to the wearer from a source separate from the surrounding atmosphere. (In North American vocabulary the former are termed "air purifying" respirators. The term "respirator" is common to both). Contaminants may enter the breathing zone of a respirator wearer by penetrating through the filter or by leaking through the face seal, exhalation valve, or elsewhere. Contaminants in the surrounding atmosphere may enter breathing apparatus only by leakage.

Respirator filters may be composed of sorbent material such as activated charcoal, which filters

out gaseous contaminants, fibrous material that captures **particulates**, or composites consisting of the two materials in series and effective against both types of contaminant. There are features of behavior common to the different types of respirator, but the behaviour of **particulate-filtering** respirators is more complicated because the physical properties of different dust particles in a cloud may differ widely, whereas the different molecules of any chemical species are virtually identical. Most of this review is devoted to respirators incorporating particulate filters, but many of the conclusions reached are equally applicable to gas-filtering respirators, and some to breathing apparatus.

The most important performance parameter of any type of respiratory protective equipment gives a quantitative measure of the protection afforded by the equipment: the protection factor. The protection factor of a respirator against a contaminant is usually defined as the quotient of the concentration of that contaminant in the ambient atmosphere and its concentration in the air breathed by the wearer, and it can be defined either as an instantaneous value or as an average over time. From the point of view of scientific understanding, the more useful value is the instantaneous protection factor, whereas from the point of view of hygiene studies, the average of the parameter over a working period is more important. This average should be defined in such a way as to give the quotient of the total amount of contaminant that would be breathed by an unprotected worker and the amount that would be breathed, under the same conditions, by the same worker with the protection of the respirator.

Many factors can affect the value of the instantaneous protection factor, but an attempt to include all of them would lead to impossible

complications. For example, a filter is a very effective flow straightener, which means that the air breathed by the wearer of a respirator will originate in a different place from the air breathed by an unprotected worker. Likely differences between the concentration of contaminants in these two regions should, strictly speaking, be accounted for in the definition of protection factor; and if the filter is remote from the wearer's face, as in powered respirators or helmets, this difference may be substantial.

Even if effects such as these are neglected, the number of variables that will influence the protection factor is considerable. The filtration efficiency depends critically on the physical properties of the particles challenging the filter. Their size and shape is important in all filters, as is their electric charge, particularly if the filter is made from electrically charged material. The size-selectivity of any leakage path is also important, as are intrinsic properties of the challenging particles, such as density and dielectric constant. The experimental study and the theoretical analysis of protection are difficult, but much progress has been made.

Leakage of Aerosols into Respirators

Definitions

The vocabulary relating to leakage is imprecise, and a large number of terms, some of which are ambiguous, have been in use. Terminologies have been offered by Hack et al. (1982), Myers et al. (1983), and Guy (1985). The terms defined below are not given as a prescriptive list, but as a descriptive list reflecting what is found in the literature.

Total Inward Leakage—the fraction of aerosol in the air challenging the respirator that enters it during wear; or the quotient of the average aerosol concentrations in the air breathed by the wearer and in the ambient air. Total inward leakage, in general, consists of components due to filter penetration, faceseal leakage, and exhalation valve leakage. The total inward leakage is usually defined with respect to the aerosol mass and is normally expressed as a percentage; zero corresponds to a perfect respirator, and 100% to an absence of any protection. The term can be defined with respect to an industrial aerosol or a test aerosol.

Protection Factor—the reciprocal of the total inward leakage when the latter is expressed as a fraction. Infinity corresponds to a perfect respirator, and unity to the absence of any protection.

Workplace Protection Factor—protection factor defined with respect to an industrial aerosol in real conditions, during periods when the respirator is actually worn, as opposed to *Effective Protection Factor*, which includes periods when it is left off, giving no protection (Myers et al., 1983). Both of these are also referred to as *Real Protection Factor*. There is good reason for preferring workplace or effective protection factor to real protection factor because the former are unambiguous; the latter is not.

Program Protection Factor—a protection factor achieved over an extended period by a specified work program. The concept goes one step beyond Effective Protection Factor and its value depends on a wide range of variables, including workplace environment, worker activity and motivation, training, administration, and monitoring.

Laboratory Protection Factor—a protection factor measured on a human subject using a test aerosol.

Assigned Protection Factor—a value of protection factor assigned to a device or to a type of device, to indicate the protection factor that could be achieved when it is properly fitted on trained users. It has been suggested that "properly fitted" should be taken to imply that a successful fit test (vid. inf.) has been carried out. (Both this parameter and the laboratory protection factor are sometimes called the *Nominal Protection Factor*. Because of this ambiguity, the expression Nominal Protection Factor will not be used in this article.)

Values of assigned protection factors for different types of respirator are quoted by Hyatt (1976) and by Barraclough (1977), from maximum permitted leakages in standard tests. Hyatt assigned a value of 10 and Barraclough 7–10 to half-mask dust respirators, and both assigned a value of 1000 to positive-pressure powered dust respirators with high-efficiency filters. They assigned values of 50 and 1000 respectively to negative-pressure **full-facepieces**, the latter author emphasizing the limitations inherent in Assigned Protection Factors as originally defined. The difference highlighted the enormous effect that a small amount of inward leakage can have on the protection factor, especially when the latter is high. The problems of assigning a protection factor to a respirator on the basis of laboratory tests will become apparent later in this review, when on-site measurements of protection factor are discussed.

Fit Factor—the reciprocal of the fraction of the total air entering a respirator that does so through leaks. Perfect fit, which eliminates leaks, gives a fit factor of infinity; the worst possible case gives a fit factor of unity. If a test aerosol penetrates through leaks with negligible loss, and if very few particles penetrate through the filter, the measured protection factor (sometimes called the *Quantitative Fit Factor*) will be close to the fit factor as defined above. The results of such measurements on aerosols will be referred to in this review as "fit factors."

Fit factor is one of the most fundamental and important parameters describing the performance of respiratory protective equipment, since it does not depend on the properties of any challenge aerosol.

Like the workplace protection factor, the laboratory protection factor can equal the fit factor when the air intended to enter the device (the air supply of breathing apparatus or the filtered air of a respirator) is perfectly clean and when, on the other hand, the air leaking in has the same concentration of contaminant as the ambient air. This is the case for breathing apparatus used against gaseous contaminants, and nearly so for respirators used against them, provided that breakthrough of the vapor through the sorbent medium has not occurred. This simplification has encouraged the use of gaseous tracers in respirator measurements, as will be seen below. In the case of measurements with aerosols, the finite filtration efficiency and the size-dependence of both this and the leakage path will complicate the measurement.

The usefulness of the fit factor, and indeed any protection factor defined as an instantaneous value, is limited by the fact that it is not constant throughout the breathing cycle, since leakage flow has an inertial component that is more marked at high flow rates. The effect of this is to make leakage more significant at lower flow rates, as illustrated by Hinds and Kraske (1987). In spite of these limitations, fit factor has the special property of being the only parameter that can be defined without reference to any specific aerosol.

Mean Values of Leakage or Protection Factor

All of the parameters mentioned above will vary during the period that the respirator is being worn and from one period to another, and so calculation of the protection achieved over extended periods requires average values to be taken. Which average should be used is illustrated by the following example:

Suppose a respirator is worn for two identical periods of time in which the dust concentration is constant, but in which the inward leakage is 50% for one period and 0.1% for the other. The arithmetic mean of total inward leakage is approximately 25% and this is a useful average. Any given respirator with this total inward leakage would have allowed the same quantity of contaminant to be breathed as would the respirator with the varying leakage.

If, however, the arithmetic mean of the protection factors (2 and 1000) were taken, the result would be a protection factor of 501, which is

equivalent to total inward leakage of approximately 0.2%.

This is quite meaningless, since a total inward leakage of 25% was calculated in the example. If protection factors are averaged, the harmonic mean (the reciprocal of the arithmetic mean of the reciprocals) must be used which, in the case above, is approximately 4, equivalent to the total inward leakage of 25%, used in the example. If the protection factors apply for different periods of time, or if the ambient concentration of contaminant varies, the appropriate mean must be time-weighted and concentration-weighted.

This reasoning can be applied to the situation in which a respirator is worn for only part of a working shift. The respirator has a total inward leakage of 100% for the period during which it is not worn; and the **effective** protection factor must be calculated by means of an appropriate average. Figure 1, based on calculations of harmonic mean, illustrates the very rapid drop in **effective** protection factor resulting from short periods without protection, especially when the workplace protection factor is high.

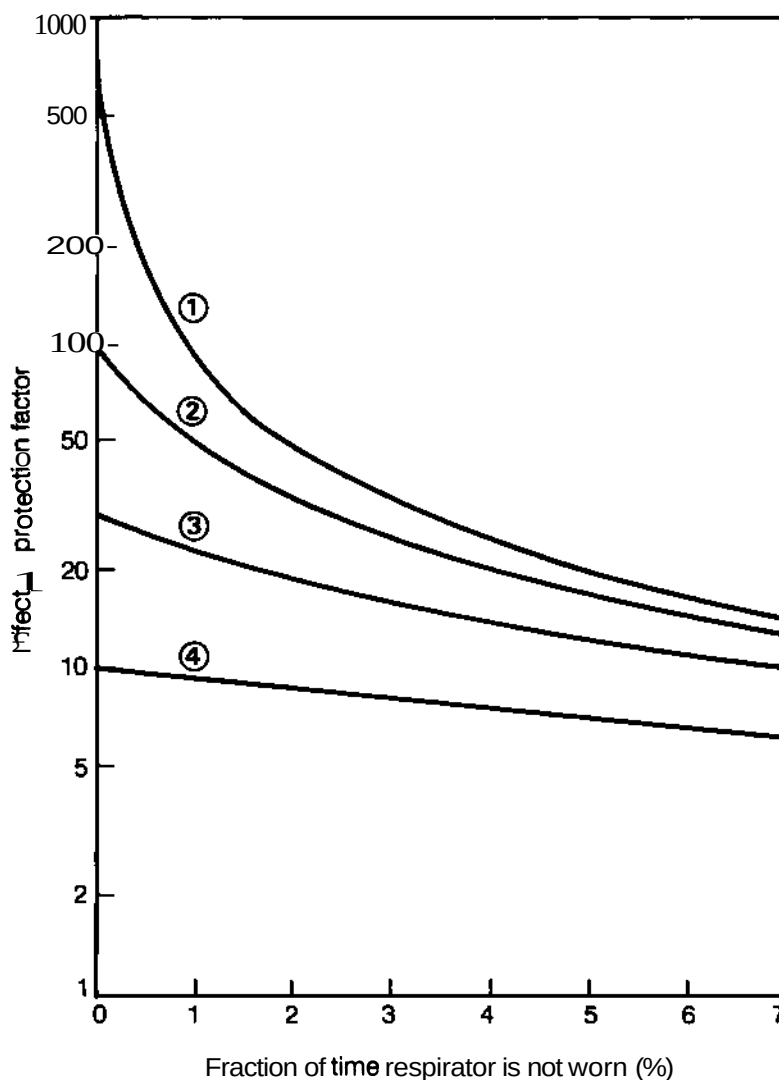


Figure 1. Variation of effective protection factor of respirators as a function of the fraction of time they are not worn.

- (1) Workplace protection factor (Myers, 1983) of 1000.
- (2) Workplace protection factor of 100.
- (3) Workplace protection factor of 30.
- (4) Workplace protection factor of 10.

Measurements of Filtration Efficiency

Filtration efficiency is the most easily measured of the variables relevant to protection. Filters tend to straighten and make uniform the airflow through them, and the aerosol concentration downstream of an undamaged filter is usually fairly homogeneous.

Measurements of filtration efficiency using polydisperse aerosols of standard particle-size distribution have a long history, but progress in the ability to characterize filters has been rapid since the development of easy methods of production of monodisperse aerosols and methods of real-time sizing of aerosols. Measurements with monodisperse urea aerosols have been carried out by Wake (1985, 1987a); and Figure 2 shows typical penetration curves for two respirators of widely different efficiency, the general features of which are commented on by Wake and Brown (1988).

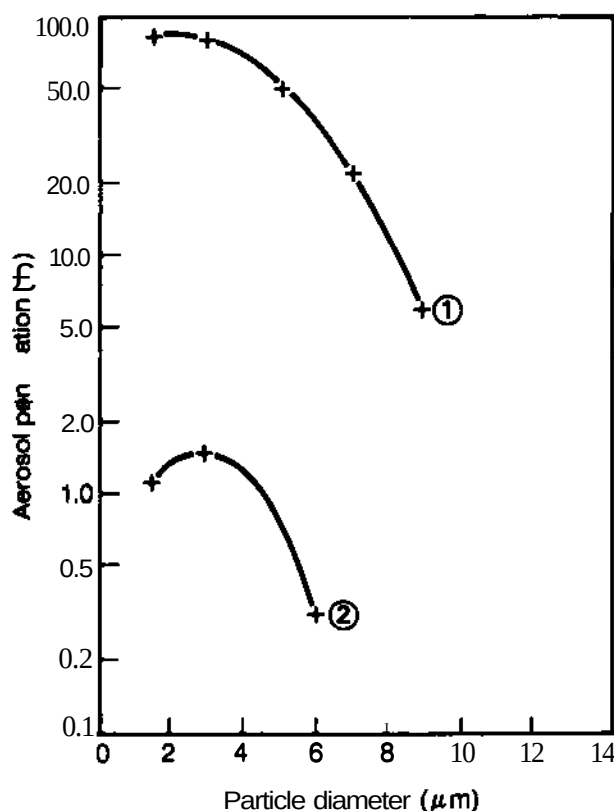


Figure 2. Penetration of monodisperse aerosols through disposable face masks, taken from Brown (1989): (1) Purely mechanical respirator for use against dusts of low toxicity; (2) electrically charged approved respirator.

Measurements with monodisperse aerosols give the penetration of particles as a function of particle size, and this penetration varies exponentially with the thickness, t , area weight or pressure drop of a filter. For example

$$\text{Penetration} = e^{-\alpha t} \quad (1)$$

where α in Eq. (1) is known as the layer efficiency, and it enables aerosol penetration through a filter of any thickness to be predicted on the basis of a single measurement. Values of layer efficiency for a range of particle sizes can be used to estimate the likely penetration of polydisperse aerosols, including industrial aerosols. Measurements made with polydisperse aerosols and a size-selective detector are less accurate; and non size-selective measurements are of less value still, because in such cases no relationship like Eq. (1) applies, and the total aerosol penetration can be related to the filter thickness only by an empirical model (Brown et al., 1987).

Brosseau et al. (1989) measured the penetration of monodisperse latex aerosols in the size range 0.1 to 2.0 μm through electrically charged respirator filter material. They measured aerosol concentration with a laser photometer, and observed penetrations of the order of 10% for the smallest particles studied, decreasing with increasing size to about 0.5% for the largest particles. The results of other tests allowed them to classify filters into basic quality categories.

Ruuskanen et al. (1988) measured the penetration of polydisperse corn oil aerosols through a type of electrically charged disposable mask, sizing the particles with an optical particle counter and an aerodynamic particle sizer; they found that as particle size increased from less than 1 μm to about 4 μm penetration decreased monotonically, their results being in general agreement with those of Wake and Brown (1987). At larger particle sizes, results corrupted by instrument error were obtained (Wake and Brown 1987; Wake, 1989) but these were outside the range quoted by the other workers.

If penetration values at much larger particle sizes are needed, real-time measurements are no longer feasible, and dust collection with subsequent analysis is necessary. Such measurements have been carried out by Wake (1987b) and by

Wake and Brown (1988) on masks for protection against **low-toxicity** dusts using coal dust as the test aerosol and Coulter analysis as the detection method. Relatively high penetrations of large particles were observed, which were attributable to particle bounce.

All of the above authors found that aerosol penetration through filters of medium or high efficiency tended to increase with face velocity. **Stafford et al.** (1973) measured the time-integrated penetration of polystyrene latex spheres under cyclic airflow conditions, corresponding to the breathing pattern characteristic of moderate exercise. They found that the penetration of aerosol through the filters was then generally greater than that of dioctyl phthalate (DOP)

aerosol under the steady flow conditions specified in standard tests. However, the average face velocity during the cyclic tests was higher than that under the steady flow conditions.

Brosseau et al. (1990) measured the penetration of a silica aerosol through three filters spread through the quality range they had previously specified (Brosseau et al., 1989), using a steady airflow of 32 litres/min and a sinusoidal flow with a maximum at 100 litres/min, and they found that the aerosol penetration in the latter situations were consistently about 1.5 times higher than in the former. They carried out similar tests with amosite asbestos but found no simple pattern, and poor correlation with the results obtained using silica.

Measurement of Total Inward Leakage— Fundamental Experimental Problems

The problems associated with the measurement of total inward leakage are of two kinds: those common to all types of sampling and those specific to the behaviour of respirators *and* not encountered elsewhere.

General Sampling Problems

The general problems of sampling aerosols are well known and have been investigated widely with reference to the behaviour of dusts sampling devices. **Iso-kinetic** sampling is the ideal technique for sampling from moving air, but this is not possible within a respirator because of the complicated time-dependent nature of the air movement inside. An account of the manner in which general sampling problems apply to sampling within respirators is given by Liu et al. (1984), who show that particles with an aerodynamic diameter of up to 5 μm can be sampled there with almost 100% efficiency, but that the sampling rate and the sampling tube diameter are critical for larger particles. Particle loss is high at low entry velocities because of gravitational settling and at higher velocities because of **inertial** losses. There is a range of intermediate values for any system at which losses are minimized. Since in-mask turbulence makes a simple theoretical approach impossible, the range of sampling rates for minimum loss must be found experimentally. A funnel-shaped inlet is efficient for a wide range of particle sizes and flow rates, but the efficiencies vary

among respirators because airflow patterns within them differ.

If the test agent is a gas, these sampling errors do not occur, but there remains the possibility that the gas will be adsorbed by the component material of parts of the respirator other than the filter, or by parts of the experimental apparatus. Schwabe (1980) carried out a comparison exercise using penthrane, methane, sodium chloride, and oil mist as test agents on a human subject wearing a respirator, a mannequin with a respirator, and a breathing machine connected to a system of filters and capillaries in parallel, simulating a leaky filter. The test agents behaved in broadly similar ways, much of any variation being hidden by experimental error. **Meunier** (1987) has reviewed a number of comparison exercises. Most of his work was, like Schwabe's, applied to military respirators and was particularly relevant, therefore, to low total inward leakages.

Measurement Problems Specific to Respirators

In addition to sampling problems, there is a problem specific to respirators and common to both types of test agent: that of imperfect mixing of leaked and filtered air. This imperfect mixing is well-illustrated by the computer calculations of Liao and **Beale** (1988), who calculated and plotted concentration contours within a model leaky half-

mask disposable respirator. Their calculations are based on the "Sheffieldhead" but it is clear that the conclusions have more general application. Myers et al. (1986a) demonstrated imperfect mixing by means of smoke leaking into a full facepiece respirator and visible through the visor, as shown in Figure 3. More recently Oestenstad et al. (1990a) have carried out tests on human subjects exposed to fluorescent aerosols. The subjects were photographed under UV light after removing their respirators; and in some instances the leakage paths were vividly illustrated by the deposited aerosol.

Alternative Methods of Sampling

If a sample is taken for analysis from inside a mask during a normal period of respirator wear, the sample size must be small relative to the total volume of air breathed; otherwise the normal conditions inside the respirator would be disrupted. Owing to the heterogeneity of test agent concentration, however, a small sample may be unrepresentative of the average concentration. This problem may be circumvented by the use of methods other than in-mask sampling. For example, all the air passing into the breathing tube of a mannequin may be sampled, a procedure not possible with a human subject. Alternatively, the air exhaled by a subject may be sampled, which is

a straightforward procedure if the respirator worn has an exhalation valve, because this provides a well-defined route for the exhaled air.

However, mannequin experiments are not completely realistic, although they have played an important part in respirator studies, and will be dealt with at length in a later section. Neither is sampling of exhaled air ideal, for it is complicated by the normal deposition or absorption losses within the subject's respiratory system. The extent of deposition or absorption depends on the test agent used, but it is of the order of 80% for the sodium chloride aerosol used in many tests (Walkenhorst and Dautrebande 1961) the high value being caused by the **hygroscopicity** of the particles, which swell in the humid air within the lungs. If particle size effects are neglected, a correction can be made by measuring the aerosol concentration in the exhaled breath of subjects breathing **unfiltered** test aerosol under the same conditions (British Standards Institution, 1969).

The problem of imperfect mixing applies only to the **inspiratory** part of the breathing cycle. When in-mask sampling is continuous rather than confined to inspiration, its effect is reduced, but particle retention in the respiratory system then needs to be measured separately and taken into account.



Figure 3. Imperfect mixing of leaked and filtered air in a full facepiece respirator made visible by smoke. (Reprinted with permission of *AIHA*, Vol. 47(2) 111 (1986) and Warren R Myers).

Bias During In-Mask Sampling

An account of bias (i.e., systematic error in the form of a tendency consistently to oversample or to **undersample**) during in-mask sampling from half-mask respirators on a dummy head connected to a breathing machine has been given by Myers et al. (1986a, 1988). They sampled air at a constant rate during inhalation only, and throughout the breathing cycle, using acetone as the test agent and infrared **spectrophotometry** as the analysis method. Their equipment was designed so they were able to take an unbiased sample of the mixed air "**breathed**" by the dummy head for comparison with the measurements made with their probes. They created artificial leaks between the **half-mask** and the dummy head by inserting tubes at the region of contact, and they were able to demonstrate leakage directly, using a bubble flowmeter. Cohen (1984) previously used simple photographic techniques, shining light through face seal leaks, to demonstrate that leaks could be reasonably well approximated either by circular holes or by slits and that these occurred in about equal numbers. Myers et al. (1986a, 1988) used tubes of circular cross-section and flattened tubes to simulate leaks of these shapes. Considerable bias was observed, ranging from oversampling by a factor of almost 2 to undersampling by a factor of almost 6. The position of the sampling tube and the leak path were varied, and it seemed that the most severe under-sampling took place when the sampling tube and the leak lay on opposite sides of nose and mouth.

During the study the authors were able to vary a large number of experimental parameters. The most important conclusion of their work was that there was a wide variation of sampling bias amongst **different** models of respirator, which appeared to be influenced by the relative positions of the inhalation valve and the sampling probe; and the authors pointed out the danger of using such tests to identify the best-fitting among a number of models of respirator. No consistent pattern of variation of bias with probe position on the mask surface emerged, but bias decreased consistently as the probe was positioned more deeply within the mask. Altering the sampling rate did not appreciably **affect** bias, but at high sampling rates, the leakage itself increased slightly. Bias was significantly **affected** by neither the shape of the leak path nor the number of leak paths. The authors commented that bias was lower during mouth breathing than during nose breathing; and they also remarked that unless

specifically instructed, human subjects wearing respirators tended to breathe through the nose during laboratory tests, but through the mouth during normal work.

Myers and Allender (1988) studied sampling bias with respect to **full-facepiece** respirators, using mannequins along with the same test agent and detection method as described above. Some of the respirators tested were designed so that the filtered air was directed toward the wearer's face; others were not. This had such a large effect on the observed sampling bias as to make comparisons among different models of respirator impossible. The "clean air wash" in some respirators caused very serious undersampling. Other bias errors were similar for halfmasks and **full-facepieces**.

An account of the **effect** of probe position and of dead-space volume on the measured values of face seal leakage during in-mask sampling was given by Bostock (1988), who used sodium chloride aerosol, detected by flame photometry. The tests were carried out on the Sheffield dummy head connected to a breathing machine, using a filter in the lines to produce a simulation of 100% lung retention of the test aerosol. A simple theoretical model predicted that the dead space could introduce errors, the fractional magnitude of which was comparable with the quotient of the dead space and the tidal volume; experiments gave some support to this. The possible error in measurement associated with the effect of probe position was, however, considerably greater than dead-space errors, and values of total inward leakage differing by a factor of four were observed on the same respirator.

Bostock was able to get improved results by substituting for the standard sampling probe a special probe in the form of a 20 mm diameter sphere perforated by a series of holes on the equator perpendicular to the sampling tube. Such a probe reduces errors caused by the directional nature of a normal sampling probe, though errors associated with its position remain. Holton et al. (1987) investigated the **effects** of varying the position of both the leaks and the sampling probe, when measuring leakage of a test aerosol into respirators worn by human subjects.

Their results were basically similar to those of Myers et al. (1986a) with gaseous tracers, and they found that varying the position of either leak or probe altered the measured leakages. They also found that measured leakage tended to be higher if the probe was situated near the likely leak path.

Measurement of Total Inward Leakage into Respirators Worn by Mannequins

Measurements made on a mannequin have the advantage that all the air breathed can be sampled, which averages out any bias; but they have the drawback of lacking realism, since the properties of a dummy differ considerably from those of the human face. However, experiments on mannequins are very valuable in the study of parameters that do not depend critically on these properties.

Hinds and Kraske (1987) reported some measurements made on a range of half masks and filtering facepiece respirators, many of which are approved for factory use in the United Kingdom. Both polydisperse and monodisperse aerosols of oleic acid were used as test aerosols. The authors, using an optical particle counter, measured the penetration of these aerosols through the filters whilst ensuring that the seal against the face of the mannequin was perfect. They then measured facesal leakage in a separate experiment, in which no air was allowed to pass through the filter, deliberate leaks being introduced by inserting wires or narrow tubes between the perimeter of the respirator and the surface of the mannequin. During this part of the experiment, the filter cartridge in cartridge-type respirators was replaced by a sealed cartridge, and the filter area of filtering facepieces was sealed with plastic film. The two sets of results, for filtration and facesal leakage, could be combined by making the assumption that the pressure drop across the filter equaled the pressure drop across the facesal leaks.

In their work, the authors measured the air flow through the filter and through the facesal leak paths separately as a function of the pressure drop, and they observed the following relationship between flow rate, Q , and pressure drop, P .

$$Q = AP^b \quad (2)$$

Similar relationships were used by Williams (1983) and Campbell (1984) in purely theoretical analyses, with $b=1$ for the flow through the filter, consistent with theoretical models of purely viscous flow (Davies, 1973). Flow through facesal leaks would be expected to have an inertial component, which would be greater for large leaks, and such inertial effects would reduce the value of b .

The authors found $b = 0.56-0.96$ for facesal leakage flow, and they observed that the fraction of air flow through the leak paths decreased as the total flow increased, as shown in Figure 4. Fahrback (1970) observed a similar variation during a study of pinhole leaks in high efficiency filters, finding that for flow through very small leaks, $b = 1$, which is consistent with purely viscous flow.

Hinds and Kraske's results showed that aerosol penetrations through the filters were less than 0.5% for particles larger than $1.0 \mu\text{m}$. For particles smaller than about $1.0 \mu\text{m}$ penetration through the filter increased with decreasing particle size and with increasing flow rate. The authors attributed the latter effect to a reduction in capture efficiency by diffusion and gravitational settling, though this sort of velocity dependence is also characteristic of particle capture by electrostatic effects, which are highly significant in many respirator filters (Brown and Wake, 1985).

Of particular interest in this work are the measurements of particle-size dependence of face seal leakage. Specimen results for this parameter are shown in Figure 5. The size-dependence is quite different from that of the filter penetration, and the velocity-dependence is much weaker. Particles smaller than $1 \mu\text{m}$ in diameter have

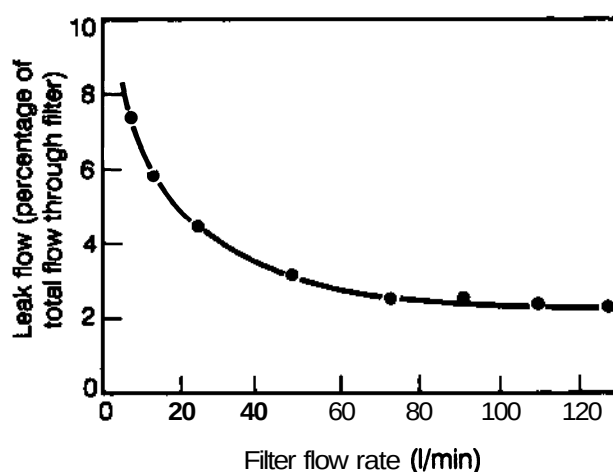


Figure 4. Leakage airflow as a fraction of total airflow into a respirator. (Reprinted with permission of *AIHJ*, Vol. 47(2): 839 (1987) and W C Hinds).

penetrations of almost 100%; and the particle size at which penetration is 50% varies only little, lying between 3 μm and 8 μm . The authors drew attention to the important fact that the particle-size distribution of the aerosol within a respirator will be different from that of the ambient aerosol. When particle toxicity is size-dependent (e.g., silica, coal dust), quoted protection factors based on gravimetric estimation or on any method that neglects particle size should be treated with caution. However, uncertainty about the stability of leak size, position, and geometry during actual wearing limits the applicability of these results.

Basically similar measurements had been made by Tuomi (1985) using a corn oil aerosol and a light-scattering meter. Tuomi used a Sheffield head and a breathing machine to test four masks: a good quality respirator, a respirator of poorer quality, and two surgical masks that would be expected to behave rather like masks for use

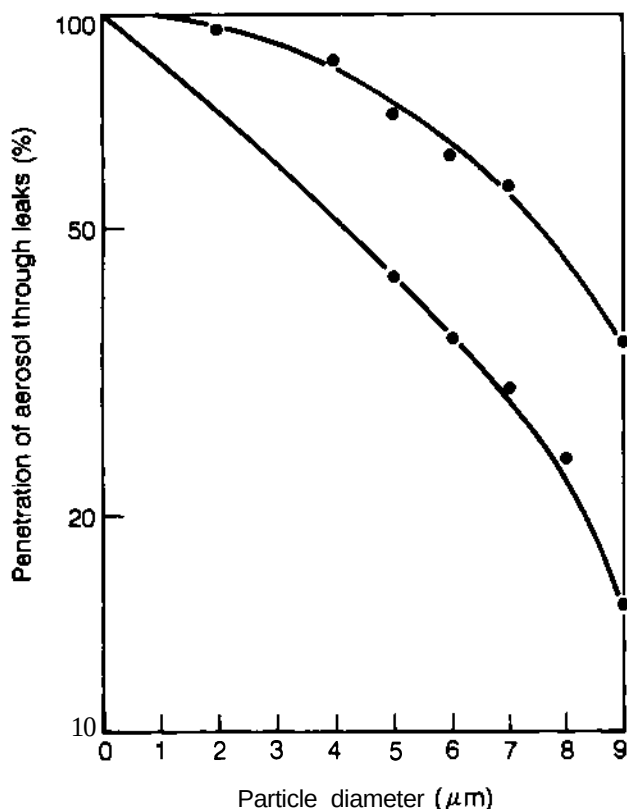


Figure 5. Particle size dependence limits of aerosol leakage into a respirator. Penetration is defined as the quotient of the aerosol concentration in the leaked air and that in the ambient air. The two curves are the limiting curves observed experimentally. (With permission of *AIHAJ*, Vol. 48(10); 843 (1987) and W C Hinds).

against dusts of low toxicity. The total inward leakage through the devices was measured when they were fitted so as to be leaky, and the measurements were repeated with the masks taped to the dummy head. Tuomi, like Ruuskanen et al. (1988), did not measure face seal leakage alone; their results are, therefore rather more difficult to interpret than those obtained by Hinds and Kraske (1987), but the two sets of results were basically consistent. The respirators performed very differently from the surgical masks, and the consistently poorer performance of the untaped masks gave a clear indication of face seal leakage.

Chen et al. (1990) used polydisperse corn oil aerosols produced from a generator of their own design and measured with an aerodynamic particle sizer for leakage tests on filtering facepieces. Their results are in basic agreement with those of Hinds and Kraske (1987) in that they found a high bias towards small particles in the filtered aerosol but not in the leaked, and that the size selection of the two methods of entry were velocity-dependent in a way that suggested electrostatic capture during filtration and inertial impaction during leakage. They considered that size measurements of the in-mask aerosol might be used as a means of identifying its method of entry.

The special problem of exhalation valve leakage was studied by Burgess and Anderson (1967), who found that flap-type valves usually allowed less than 0.1% of a challenge aerosol to leak, and valves of a more complicated construction less than 0.02%. Hinds and Bellin (1988b) studied valve leakage using mannequins, specifically separating leakage into two components: the slight ingress of contaminated air as the valve shuts between expiration and inspiration and the general leakage during inspiration itself. Small particles were found to be more penetrating than large, and the variation was greater than that of the face seal leakage but less than that of filter penetration.

Bellin and Hinds (1990) found that aerosol penetration through properly functioning valves ranged from 0.001% at low flow rates to 0.01% at flow rates corresponding to heavy breathing. Observed performance was better under cyclic flow than under steady, because of the same dead-space effects that cause a valve cover to improve the performance of the valve. The authors simulated leaks by placing copper wire across the valve seat, and found that leakage increased with wire thickness, being typically 1% with 0.25 mm copper wire.

Deposited material sufficient to cause 1% leakage was found to be clearly visible under good illumination. The authors advised against a negative-pressure method for testing valve leakage because reduced pressure can cause an artificial improvement in valve seating.

Deposits of dried saliva can cause valves to become stuck in the open position (private communication, R A Bentley), and in these circumstances leakage can be much greater than the values quoted above. Valves that are wet from condensation, on the other hand, may perform better than dry ones. The improved seating of wet valves is reported by Burgess and Anderson (1967) who found that the opening pressure of wet valves was consistently higher than that of dry ones. Brosseau et al. (1990) remarked that valves may improve with use for a time because limited wear or deformation may improve their seating, but that eventually deterioration will occur, because of warping or perishing of the valve material.

Predictive Model of Workplace Protection Factors Based on Mannequin Measurements

Hinds and Bellin (1987) used the previous results (Hinds and Kraske, 1987) to predict workplace protection factors by means of a simple model which assumed that the quality of respirator fit was not altered by workplace conditions. Such an assumption is clearly an oversimplification, limiting the practical use of the model. However, it is useful in illustrations of the effect of variables like particle size on respirator performance. With this simple model the approximate total inward leakage can be calculated easily. In further work Hinds and Bellin (1988a) extended the model to calculate, within its limitations, the workplace protection factor of respirators against dusts with various size distributions.

Xu et al. (1991) supplemented a model of this sort with measurements of air leakage into respirators, and therefore fit factors, using the method (vid. inf.) of Carpenter and Willeke (1988a; 1988b).

Measurement of Total Inward Leakage on Human Subjects

Measurements carried out on human subjects have a realism that measurements on mannequins lack, but they have the problem of sample bias as described above. Separate measurements of the two components of total inward leakage (filter penetrations and **face seal/exhalation** valve leakage) were made by Balieu (1980), using a paraffin oil test aerosol measured by light-scattering photometry. His subjects were placed in a tent, which could be filled with the test aerosol, making it possible to take samples of the ambient test aerosol and of the aerosol within each respirator, believed to be of the **ori-nasal** half mask type. Additional experiments were carried out in which clean air could be supplied either to the filter or to the **face seal/valve** region. These gave estimates of **face seal/valve** leakage and of filter penetration respectively.

If experiments had been completely **repeatable** and free from random error, the two types of leakage would have been additive. In general the total inward leakage measured was approximately the sum of the partial leakages but there were discrepancies. Face seal leakage in general made a significantly larger contribution to total inward leakage than did filter penetration.

Oil mist and sodium chloride are probably the most popular aerosols used in tests involving human subjects. DOP is sometimes used in filter testing, but uncertainties about its effect on health make substitutes preferable for human subjects. Willeke et al. (1981) compared the behaviour of DOP aerosol, measured both by a photometer and by a condensation nucleus counter, and that of condensation nuclei generated by a variety of means, including that of running an electric motor and using the very fine carbon aerosol issuing from the brushes, and detected by a condensation nucleus counter. The actual leakage of DOP measured using the photometer was slightly higher, but there was a simple, almost linear relationship between the measurements made by the two methods.

Similar measurements were carried out by Ernstberger et al. (1988), except that they used both corn oil aerosol and ambient aerosols, which they measured with an optical particle counter, sensitive only to particles with diameters greater than 0.5 μm . They made measurements on a large number of wearers, using half-masks and **full-facepieces** in the normal way, and respirators that had been deliberately made leaky. There was a

strong correlation between the results using the two aerosols, and when they differed the penetration observed with ambient aerosol tended to be higher. For values of total inward leakage close to that at which a choice between acceptance and rejection of the respirator would be made, there was no statistically significant difference between the two sets of results, though there was at lower levels of leakage. The ambient aerosol method is now used in a commercially available fit-testing device, which has been found by Rose et al. (1990) to give results in good agreement with those obtained with a polydisperse oil aerosol and a photometer.

In general, measurements of total inward leakage on respirators worn by human subjects have been applied to a study of the effects of specific variables. Some studies have involved deliberate and well-defined leaks, others have considered the effects of specific human characteristics or activities.

Effect of Well-Defined and Deliberately Induced Faceseal Leaks

An investigation of the effect of physical characteristics of leaks in a half-mask respirator worn by a still, nose-breathing human subject, has been described by Holton et al. (1987) and further by Holton and Willeke (1987). These authors measured the penetration of combustion aerosols, and aerosols of nebulised corn oil and dispersed limestone, through deliberately constructed leaks. Aerosol concentrations in samples taken from inside the respirator were measured using a condensation nucleus counter, an aerosol spectrometer and an aerodynamic particle sizer. Leaks in the bottom edge of the mask gave higher measured values of leakage than geometrically similar leaks in the top. It would be expected that the airflow through a leak would depend strongly only on the geometry of the path and the pressure drop across it, suggesting that the variations observed here are caused by the persistent problem of imperfect mixing.

The size-selectivity of leaks was basically consistent with that observed by Hinds and Kraske (1987) in their mannequin experiments. Holton et al. (1987) and Holton and Willeke (1987) observed a broad maximum penetration in the size range $0.1\text{--}1.0\text{ }\mu\text{m}$. Both smaller and larger particles penetrated less, the smaller probably because of diffusion, and the larger probably

because of either impaction or settling or both. The leakage of $0.1\text{--}1.0\text{ }\mu\text{m}$ particles was probably indicative of the actual air leakage into the respirator. This leakage increased with the size of the leakage hole, being about 0.2% for a 0.57 mm diameter hole, 1.5% for a 1.07 mm hole, and 5% for a 1.68 mm hole. Correction for lung retention of the aerosol increased these fractions by a factor of about 1.5. There was greater leakage through a circular hole than through a slit of the same cross-sectional area, which is consistent with the fact that the resistance of the slit would be greater; but leakage varied only little with the length of the circular hole, which might point to the importance of fluid entry effects in leak resistance.

Effect of Facial Movements on Respirator Fit

Measurements of total inward leakage, as defined above, have been carried out by Longson (1982) using in-mask sampling on a total of twenty human subjects wearing power-assisted respirators or powered helmets, with both sodium chloride and sulphur hexafluoride as tracers, the former being measured by flame photometry, the latter by electron capture analysis. A subject wearing a respirator was required to walk on a treadmill within a test chamber whilst reciting a standard text and performing a series of head movements; a procedure designed to simulate the range of head and facial movements likely to occur in normal conditions of respirator use. The test using SF_6 is sufficiently sensitive to detect 10 ppm of leakage.

No measurements were carried out on wearers who kept still, but measured fit factors during head-moving and talking respectively were: for the full facepieces, 50,000–80,000 and 1600–37,000; for the half-masks 20,000–80,000 and 3000–6000; and for the powered helmet 300 and 40.

Bentley et al. (1983) carried out similar experiments, monitoring the pressure inside the respirators during the tests. They found both inward leakage and an occasional negative pressure spike, but no striking correlation between the two. They did observe that inward leakage was considerably greater during talking than during the other activities and that this applied to air-fed helmets as well as to powered respirators. Further work by these authors and their colleagues (Bentley et al., 1984) involving about 80 tests each on four models of full-facepiece respirator, showed fit factors measured with sodium chloride aerosol and SF_6

gas of between 120 and 200,000 for positive-pressure respirators with the power switched on, and 30–200,000 for the same devices without power.

Murata et al. (1979, 1980) used sodium chloride aerosols to measure the fit factor of half-masks and full facepieces. They carried out tests on eight masks worn by 44 experienced test subjects, measuring total inward leakage during normal breathing, smiling, talking, and head-moving. They found that smiling caused a greater increase in leakage than talking, and that in general mouth movement was worse in this respect than head movement, a fact also observed by Manninen et al. (1988) using ethanol vapour as a tracer. The geometric mean fit factors for a single half-mask respirator worn by a range of subjects during normal breathing were between 300 and 600 with geometric standard deviations of between 2 and 3. For the full facepieces during normal breathing, geometric mean protection factors were between 2000 and 3000, and geometric standard deviations between about 2 and 3. The lowest values of protection factor observed during the exercise were in single figures for the half masks, and of the order of 100 for the full facepieces.

Lowry et al. (1977) also used sodium chloride aerosol in measuring fit factors for six disposable respirators, worn by a panel of ten subjects specially chosen to represent the range of facial types encountered in the population. Total inward leakage was measured during normal breathing, heavy breathing, head-moving, and talking, and an average was taken. All of the respirators gave a fit factor of at least 5 when worn by eight of the test subjects, but only two gave this measure of fit for all ten subjects.

Lowry et al. (1979) described a method for measuring the leakage of powered respirators, using DOP test aerosol, in-mask sampling, and scattered light photometry. The members of their specially chosen test panel carried out a set of facial movements designed to reveal inadequacies of fit. All of the powered respirators that they tested gave fit factors greater than 1000, provided that power was maintained.

Ikezawa et al. (1976) found that total inward leakage, measured by sampling sodium chloride aerosol through the exhalation valves of a series of respirators, was 1–5% for most half-mask respirators and 0.1–1% for full-facepiece respirators,

though leakages of more than 20% were observed in some instances both for half-masks and for full facepieces.

Whether or not speaking should form part of the test procedure is open to doubt (private communication, C D Crutchfield), since while speaking, the subject is normally exhaling, and so the pressure inside the facepiece would be positive and leakage would be outward.

Effect of Seal Type and Strap Tension on Respirator Fit

Burgess et al. (1970) investigated the effect of seal type on the leakage of full-facepiece respirators, using uranine aerosols collected on membrane filters and estimated by fluorimetry. They found that flat or inner flap seals were more efficient than pneumatic seals, though the opposite was observed by Griffin and Longson (1972), and good results were observed at that time with pneumatic seals in "approval" testing (private communication, R N J Barraclough).

Burgess et al. also investigated the effect of varying the tightness of the respirator harness by placing an inflatable pillow between it and the back of the test subject's head and using the pressure within the pillow as an estimate of the seating force between the mask and the wearer's face. The variation of leakage with pressure was complicated by statistical variation, but typically about 0.75 psi (5 kilopascals) ensured an adequate seal, and further tightening of the straps beyond this level caused little improvement. Hyatt et al. (1972) measured the strap tension in respirators by monitoring their elongation and then calibrating them by measuring the extension caused by known weights. Typically the head strap of a respirator adjusted by the wearer to give subjective good fit had a tension of 1.0 lb wt (4.5 Newtons) and the neck strap 0.7 lb wt (3 Newtons). Ikezawa et al. (1976) studied the effect of adjusting the seating pressure of the respirators on the quality of fit, and they found that it tended to reduce the incidence of really poor fit, but that it had little effect on fit in the normal range.

Effect of Human Variables on Respirator Fit

The most widely investigated human variable is probably that of facial hair. Griffin and Longson

(1972) measured total inward leakage into full-facepiece breathing apparatus worn by a number of subjects who had beards or sideburns, and by the same subjects after shaving. On average the observed total inward leakage was about 30 times greater when facial hair interfered with the seal than when the subjects were clean shaven.

A combination of a qualitative iso amyl acetate (banana oil) test (*vid. inf.*) and a quantitative test, in which DOP aerosol was measured by forward light-scattering photometry, was used by Skretvedt and Loschiavo (1984) to investigate the effect of beards on the fit factor of respirators. They observed median fit factors of 3000 and more than 10,000 for half-masks and full facepieces, respectively, for a sample of 303 clean-shaven wearers. The median fit factors were reduced to 12 and 30 respectively for a sample of 67 bearded wearers. Although the parameter "median fit factor" does not give a good indication of average protection, the change in it does illustrate well the effect of facial hair on respirator fit. In addition, about 98% of the clean-shaven wearers, but none of the bearded wearers, passed the qualitative test wearing a half-mask respirator.

Balieu (1980) carried out tests on seven subjects, including bearded men, with a range of twelve different respirator/filter combinations. All of his respirators are believed to have been of the **ori-nasal half-mask** type. Observed fit factors against paraffin oil test aerosol varied between 6.4 and 56,000, nearly four orders of magnitude of variation. No bearded subject achieved a fit factor higher than 51, though the lowest value, 6.4, was for a clean-shaven subject.

Hyatt et al. (1973) measured the effect of facial hair growth on the fit factor of both half-masks and **full-facepiece** respirators, using DOP test aerosols. They found that fit became worse with time over a 12-day period in which stubble was allowed to grow. The effect of established facial hair depended on its length, texture, and density. Hounam et al. (1964) in earlier work, found that up to about seven days stubble had less effect on pneumatic-type seals than on other types. After this, all types were equally affected.

Longson (1982), as part of the exercise described in the section on facial movement measured the effect of facial stubble on the observed protection factors of powered respirators. He found that the effect was small, though a signifi-

cant effect was found on the performance of powered breathing apparatus tested as part of the same exercise.

Stobbe et al. (1988) reviewed work on the effect of facial hair on **face** seal leakage, bringing together experimental results obtained with a range of respirators and a variety of test agents. Facial hair increased leakage of negative-pressure respirators by a factor of between 20 and 1000. No significant difference attributable to facial hair was observed in the case of powered positive-pressure respirators, but the relatively small amount of data available on these led the authors to consider the results inconclusive. Rajhans and Brown (1988) discussed the implications of facial hair on respirator leakage with reference to **employers'** legal obligations to provide respiratory protective equipment.

Fundamental to the quality of fit is facial shape. Hyatt et al. (1972), using a DOP aerosol measured by light scattering, did more than 1500 tests on 150 subjects, having a range of different facial shapes. Total inward leakage for half masks varied between less than 0.1% and more than 10%, and for full facepieces between less than 0.01% and more than 1%. The leakage depended on facial dimensions and on whether or not the subject was used to wearing a respirator. One of their conclusions was that respirators needed to be produced in more than one size. Gross and Horstmann (1990) reiterated this, and wrote that it was particularly necessary for a workforce comprising both men and women.

Hack and McConville (1978) measured 21 facial parameters with a view to specifying an **anthropometric** test panel. Typically, the coefficients of variation of the various lengths they measured were about 6%, though of course a complete knowledge of correlations among the variables is necessary for a complete specification of variation. The panel for full facepiece testing was specified on the basis of **face** length (the distance between the chin and the nasal root depression between the eyes) and face width (the distance between the bony part of the cheeks at its widest point), and a panel of 25 members with the appropriate distribution of these parameters was chosen, without regard to sex or race. The panel for **half-mask** testing was chosen on the basis of face length and lip width.

Liau et al. (1982) have analysed previous statistics of fit factor and facial measurements to

find the **effect** of facial dimensions on respirator fit. They used four dimensionless variables, each of which was the quotient of an **anthropometric** variable and a corresponding characteristic length on the respirator. The variables studied were the quotient of facial length and respirator length, the quotient of facial width and respirator width, the quotient of mouth width and respirator width, and the quotient of nasal root width and respirator nose-cup width. The authors did not report experimental details of the protection factor measurements, and their study was limited to clean-shaven white male subjects. The fit correlated with the normalized facial width and the normalized mouth width, but not with the other variables. Where correlation did occur it was not striking, and the authors attributed this to the influence of other variables such as tightness of the harness straps.

Packard et al. (1978) made some measurements on the leakage of a mouthpiece type of respirator designed for emergency use in atmospheres containing chlorine, and similar in construction to the emergency respirator, known as a "**self-rescuer**," which is supplied to British miners for protection against carbon monoxide during escape in the event of underground fire. They used a refrigerant as a test agent, and they found that the mouthpiece device compared favourably with a half-mask respirator, since its fit was affected neither by variations in facial shape nor by the presence of facial hair, though problems were experienced by workers who wore dentures. Discomfort during wear would limit its use to emergency conditions.

Effect of Respirator Use on Respirator Performance

Lowry et al. (1977) measured the protection factors of six disposable respirators after they had been worn for seven hours, the length of a working shift. For about a quarter of this period the respirators were exposed to 15 mg/m^3 of sodium chloride aerosol, and for the rest of the time to clean air. Two of the masks showed deterioration during this exercise, though it is not clear whether this was in the form of an increase in filter penetration or a reduction in the quality of fit.

Measurements of the performance of respirators after they had been used against foundry aerosol and returned to the laboratory were carried out by Bostock (1980) using sodium chloride aerosol. He measured the aerosol penetration

through the filters, and the total inward leakage into the respirator cavity, using a probe that passed through a modified exhalation valve. In most instances the increase in the aerosol penetration through the filters was small, though two filters tested showed extremely high penetration, probably as a result of electric charge loss due to aerosol loading (Brown et al., 1988) or because the filters were of the wrong type. Of more significance was the great variation in total inward leakage amongst respirators with low filter penetration. This varied between 0.2% and 40%, and in many cases it could be attributed to poor wearer practice or to poor maintenance of the exhalation valves of the respirators.

Identification of Leakage Sites

Detection methods that use in-mask sampling measure the extent of leakage but they do not identify where it occurs, which may be very important if modifications in respirator design or specification are to be considered. A short review of previous methods of identifying sites is given by Oestenstad et al. (1990a), including the visual identification of deposits of coal dust, used as a test dust, finding leaked freon test gas with a halide detector, and shining light through the leaks to expose photographic paper held within the mask. In a promising method, the same authors used a fluorescent tracer aerosol of 4-methyl-7-diamino **coumarin** (MDC) with a mass median diameter of $0.55 \mu\text{m}$ and concentration between 18 and 50 mg m^{-3} . The aerosol was breathed both by mannequins and by human subjects, and the results, in some instances exhibiting marked streaming, were in the form of photographs taken in UV light.

Oestenstad et al. (1990b) applied this method to evaluate a single half-mask respirator, worn by 73 subjects of both sexes and of several ethnic types. The most consistent features shown by the photographs was that the nose and chin were the most frequent leakage sites, and leaks here were usually associated with a lower fit factor than leaks elsewhere.

Functional Form of Variation of Protection Factor or Fit Factor

In many instances a person required to wear a respirator in the course of his work will do so at regular intervals. The quality of fit and, therefore, the value of the protection factor achieved, will vary and the appropriate average of the latter (the

harmonic mean) will depend on the form of this variation. Murata et al. (1979, 1980) observed that the distribution of protection factors measured for a single model of respirator worn by a range of subjects could be reasonably approximated by a log-normal distribution, but that the distribution parameters were altered by head or mouth movement. Da Roza et al. (1983) measured the leakage of DOP aerosols through various respirators worn by various subjects and found that the distribution of the protection factor for a single wearer and a single respirator tested on a number of occasions followed a log-normal distribution, but that the mean and variance both varied with subject and respirator. Bentley et al. (1984) found that pooled results for respirator/subject sets sometimes followed a log-normal distribution and sometimes did not.

It will be seen later in the article that measurements of workplace protection factor and effective protection factor can be approximated reasonably well by a log-normal distribution, though there is as yet no theoretical justification for its use. The distribution has the interesting property that if protection factors follow this form, their reciprocals—the total inward leakages—will do so as well. It does not, however, appear to be possible to predict anything concerning the distribution parameters; they must be obtained from experiment. The fact that protection factors vary means that more than one fitting is necessary before a sound estimate of likely protection can be made, but if enough measurements are made for the distribution parameters to be calculated, estimates of likely protection can be made with some confidence.

A log-normal distribution is usually specified in terms of its geometric mean (or median) and its

geometric standard deviation. It has been shown above that the harmonic mean is the appropriate average to use for protection factors over several periods of wear, and the same reasoning might be applied to pooled data. Just as the geometric mean of any distribution is lower than the arithmetical mean, it is higher than the harmonic mean. In the case of the log-normal distribution there is a simple relationship between the parameters (Aitchison and Brown, 1963): if the geometric mean protection factor is m and the geometric standard deviation is s , the harmonic mean is

$$m \exp - s^2 / 2 \quad (3)$$

The difference between these two values is illustrated on specimen experimental data shown in Figure 6.

Lenhart and Campbell (1984) calculated an assigned protection factor on the basis of the log-normal distribution, using data from workplace trials. They considered that the protection factor likely to be achieved by 95% of the respirators is the correct value to use, which, in the above notation, is $m \exp - 1.64s$. The reasoning used is similar to that of Myers et al. (1983) except that the former authors used the measured values of m and s , whereas the latter authors used more conservative estimates, accounting for the fact that the measured values are uncertain estimates of the true values.

The fifth percentile value can be read directly from Figure 6, and it may be greater or less than the harmonic mean. A British Standards technical committee (British Standards Institution, 1985), following similar reasoning, recommended using the 15th percentile obtained from laboratory trials, which would be given by $m \exp - 1.04s$.

Qualitative Tests of Fit

The importance of using quantitative tests to obtain assessments of respirator fit is stressed by a number of workers, (see for example, Miller, 1980), though qualitative tests on a respirator are of definite value because they can be carried out quickly at the workplace. Hardis et al. (1983) compared quantitative and qualitative methods of assessing the leakage into half-mask and full-facepiece respirators worn by human subjects. The quantitative test involved the use of DOP as a test

aerosol, which was measured by light scattering; criteria of acceptability were set at 10% leakage for the half-masks and 1% for the full facepieces. No measurements of leakage as a function of particle size were carried out, but the DOP aerosol had a mass median diameter of 1 μm .

One of the qualitative tests was a negative-pressure test, in which the respirator cartridges were sealed off, and the subject, creating a negative

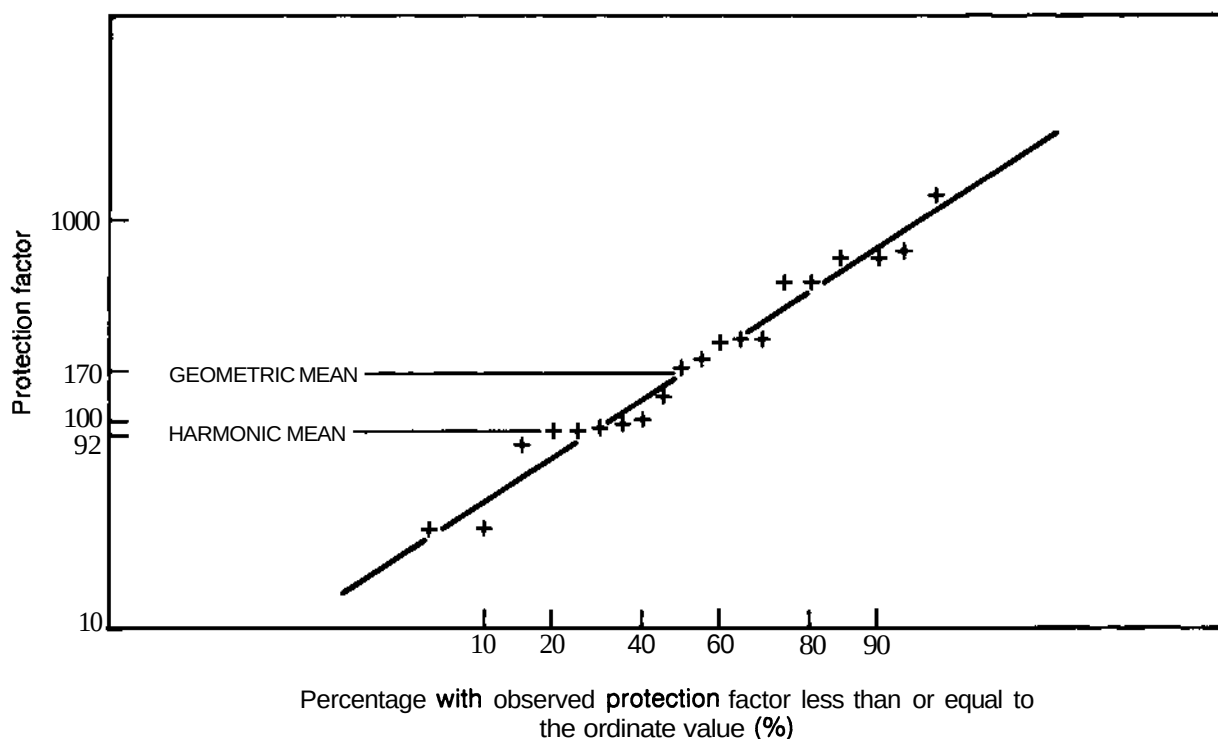


Figure 6. Log-normal probability distribution fitted, by-eye, to specimen experimental protection factor data taken from Bentley et al. (1984). The geometric mean and the harmonic mean of the data are shown. The fifth percentile is the assigned protection factor according to Myers et al. (1983).

pressure within the respirator, attempted to make it hold to his face. A successful outcome was counted as a pass.

A second qualitative test involved fitting gas filters to the respirator and subjecting the wearer to an atmosphere containing iso-amyl acetate vapour produced from a soaked swab. Detection, by the wearer, of the characteristic smell of the substance was counted as a fail.

A third test was basically similar to the above except that it involved irritant smoke; and for the purpose of the test the respirator was fitted with high-efficiency particulate filters. Leakage of smoke into the respirator causes a reflex cough, which indicates a fail.

Qualitative tests using vapours and aerosols have the drawback that their ambient concentrations are uncertain; moreover, subjective odour thresholds vary considerably. The authors quote that the thresholds for iso-amyl acetate vary by two orders of magnitude among subjects, and they came across one subject who could not smell it at

all. The irritant smoke test does not have this drawback, and it has an advantage in that the test subject cannot fake a pass, because of the involuntary nature of the response. The conclusions of the authors were that none of the subjective tests was satisfactory for full face-masks, because correlation with quantitative measurements was too poor, and that for half-masks the irritant smoke test was best and the iso-amyl acetate test second.

Marsh (1984a) assessed the irritant smoke fit test for respirators by comparing it with an oil mist quantitative fit test. He found that the smoke test would identify 92% of both half-mask and full-facepiece respirators with fit factors of less than 10 or less than 100, with a 95% confidence limit. In another paper, the same author (Marsh, 1984b) assessed an aerosol of saccharin, generated by nebulising an aqueous solution, as an agent for qualitative tests. If the subject is conscious of the sweetness of the test agent, a fail is registered. The results were that the test would identify 95% of respirators with fit factors less than 10 and 92% of those with fit factors less than 100, with a 95% confidence limit.

Both Hardis et al. (1983) and Marsh (1984 a and b) discuss the types of error that can occur in qualitative fit testing. The more serious error, termed a P-error, is that of passing a respirator that has an inadequate fit factor. The other type of error, termed an α -error, is that of failing a respirator that gives adequate protection. The authors mention the economic drawbacks to the latter type of error, but the error also has an associated health hazard; for if a sound respirator is discarded, there is a finite probability that a substitute will show the p-error.

Calculation of the probability that a subject will receive an inadequate respirator is straightforward. If a fraction 0 of the respirators give inadequate fit, however this is defined, if the probability that an inadequate respirator will pass the qualitative test is p, if the probability that a satisfactory respirator will fail is a, and if a test failure is followed by the selection of new respirator with the same characteristic probabilities, the final probability, p, that a test subject will receive an inadequate respirator depends explicitly on a

$$p = ep / 1 - [a(1 - \theta) + 0(1 - \beta)] \quad (4)$$

It is clear from Eq. (4) that p depends more weakly on a than on p. In particular if P is zero, so is p, irrespective of the value of a. The a error is, therefore, less of a health hazard than the P error but not negligible.

Extension of Qualitative Fit Tests to Semi-Quantitative Methods

Carpenter and Willeke (1988a) have extended the negative pressure fit test to a semi-quantitative level. Like its forerunner, the test can be applied only to cartridge-type respirators, and it is carried out whilst the cartridge or cartridges are blanked off. The blank cartridge used in the test contains a small, built-in pressure transducer. The wearer of the mask creates a slight negative

pressure, and then holds his breath. The pressure is then monitored as it approaches ambient pressure by air leakage. The rate of change of pressure is governed by the extent of the leaks and the volume of the cavity between the respirator and the wearer's face, and this volume can be measured by repeating the experiment with a leak path of known size. A complication is that rate of change of pressure depends also on the compliance of the mask material.

The same authors (Carpenter and Willeke, 1988b) compared measurements made on masks with artificial leaks (in the form of tubes inserted into the masks) using this system and conventional leakage measurements with corn oil aerosol detected by light-scattering photometry. Measurements involving the sampling of aerosols inside a respirator depend upon the position of the probe, as described above, whereas the pressure rapidly becomes uniform and so the siting of a pressure transducer is not critical. The authors show that their method gives consistent results.

However, the problem of variable mask compliance makes the pressure decay curves **different** for different masks, and causes them to be non-linear. As a result (private communication, Journal referee) the device has been withdrawn from the US market.

Recently Crutchfield et al. (1991) have used a method rather similar in form but **different** in interpretation, to measure the leakage of air into respirators. A test subject, wearing a respirator with a **blanked-off** cartridge, holds his breath whilst air is withdrawn from the respirator using a sampling tube, the rate at which air was withdrawn and the in-mask pressure both being monitored. Provided that the fit does not alter, such measurements can quantify the extent of leakage that would occur at a particular in-mask pressure during normal wear.

Measurement of Workplace Protection Factors and Effective Protection Factors

The most directly relevant measurements from the point of view of occupational hygiene are those of protection factor made at the workplace. In the summaries that follow, some researchers have measured workplace protection factor, as defined above, in which some means are used to

ensure that sampling is carried out only when the respirator is being worn. Other workers measure effective protection factor by sampling throughout the working period, even when the respirator is not being worn.

Harris et al. (1974) as part of a general assessment of the **effectiveness** of dust respirators in coal mines, measured the effective protection factors of five models of respirator, all approved by the appropriate authority, worn by 37 miners, representing 11 job classifications in four coal mines. The authors measured the dust concentrations both inside and outside the respirators, by sampling on membrane filters preceded by size-selecting cyclones. They found that the measured protection factors were greater than 10 in about 15% of cases, and occasionally less than 1. Values below 1 were clearly the result of experimental error, and certain very high values of measured protection factor almost certainly were. The authors correlated the data with a number of variables, finding that the effective protection factor was larger in one mine (by a factor of two) than in the others. The fraction of time that the respirators were actually worn was measured, by means of a thermistor placed inside the mask, and was typically about 50%. The significance of this figure for effective respiratory protection, and the way that this is affected by wearer acceptability, should not be overlooked. It was also observed that the miners would put on and remove the respirator 30 or more times during a shift.

Revoir (1974) measured what appeared to be the workplace protection factors of three types of disposable mask against cotton dust at the workplace. The results of laboratory measurements of filtration efficiency against silica dust, carried out as part of the same general exercise, indicated that one of the three was a type of mask designed to protect against dusts of low **toxicity**, whereas the filtration efficiency of the other two would, in the **UK**, probably qualify them for approval against toxic dusts. The first wearer measurement was of total inward leakage of coal dust with the masks being worn in a laboratory test chamber. **In-mask** membrane filter sampling was used, and the wearers were required to carry out prescribed head and mouth movements during the tests. The masks were then tested by in-mask sampling in normal working conditions at a cotton mill. A lightweight sampling tube pierced the mask, and was connected to a filter/pump unit which, to ensure that its weight did not affect the fit of the respirator, was suspended from a hat worn by the subject. The sampler outside the mask contained an extension tube acting as an **elutriator**. The average total inward leakages of coal dust measured in the laboratory were 6.0% and 1.7% for the two types of mask, and those for cotton dust in the workplace were 8.2% and 3.1%, respectively.

Moore and Smith (1976) measured the protection factors of three types of half-mask respirator against the gaseous pollutant sulphur dioxide in the atmosphere at a copper smelter. They collected external and in-mask samples using microimpingers containing acidified hydrogen peroxide, finding median workplace protection factors of 22, 18, and 13 for the three types of mask; and they remarked that a subjective assessment of comfort was not a good indicator of the effectiveness of a respirator.

Smith et al. (1980) measured the effective protection factors of half-mask respirators used against cadmium. The in-mask sample was taken on a filter attached to the respirator. Tubes from this filter holder and from a second on the **wearer's** lapel ran to a plenum chamber connected to a single pump. Pressure changes inside the respirator due to breathing caused a 10% reduction in the average in-mask sample flow rate. The cadmium on the filters was measured by atomic absorption **spectrophotometry**. A single high value of 103 was observed in the case of one man, who was known to take a great deal of care in fitting his respirator, behaviour not typical of the workforce, but the rest of the protection factors observed, averaged for each individual, had geometric means between 1.5 and 15.4 and geometric standard deviations between 1.6 and 6.8, respectively.

Myers and Peach (1983) measured the protection factor for a powered respirator on a dummy head connected to a breathing machine, against silica dust generated in the laboratory, and for respirators either connected to specially constructed dummies or worn by people at work in a silica bagging plant. The dust was sampled inside and outside the mask, using membrane filters without size-selectors; in-mask sampling was temporarily halted if the wearer removed the mask. The samples were analysed both **gravimetrically** and by x-ray diffraction. The in-mask silica concentration in the laboratory tests was too low to be measured, indicating a very high protection factor. Protection factors observed in the on-site tests on free-standing respirators varied between 300 and 2000, whereas workplace protection factors observed varied between 16 and 215 according to x-ray analysis for silica, and between 8 and 161 according to gravimetric analysis.

Dixon and Nelson (1984) measured the workplace protection factors of negative pressure respirators against lead-bearing aerosol, applying a correction for the effect of lung deposition on the

aerosol concentration in the mask during exhalation. They estimated the error to be about 20%, and comparable with errors caused by deposition in the sampling tubes. They measured the lead content of the samples by proton induced x-ray emission (**PIXE**) analysis. As part of the same exercise they measured respirator fit factor both before and after the work period using a commercial instrument that measures ambient aerosol concentration. They found no significant correlation between fit factor and workplace protection factor. The geometric mean workplace protection factor observed was 3400 and the geometric standard deviation 3.8. Removing the respirator in order to talk altered these values to 2400 and 5.1, respectively, still indicating higher protection than that observed by other workers.

Lenhart and Campbell (1984) measured the workplace protection factors of half-mask negative-pressure respirators and positive-pressure respirators at a primary lead smelter, using membrane filter sampling without size selection, and measuring the lead content by atomic absorption spectroscopy. In both cases the observed protection factors were approximately log-normally distributed like those of Dixon and Nelson, but the geometric mean and geometric standard deviation were 180 and 4.1 for the negative pressure respirators, and 380 and 2.6 for the powered devices. The latter gave, in general, significantly higher protection, but the protection factors observed were well below the values normally assigned, even though a fit test had been carried out on the half-masks before workplace use, and only those with a fit factor greater than 250 were selected.

Methods of measuring workplace protection factors of air-filtering helmet respirators have been described by Myers et al. (1984a), who agreed with other authors that the best site for an in-mask probe is between the nose and the mouth, and who recommended atomic absorption spectroscopy as an analysis method. Protection factors of two **different** models of air-fed helmets were measured at a secondary lead smelter using this procedure, with the sampling filters sited between the nose and the mouth and fixed to the inside and outside of the helmet visor. The actual sampling exercise was described by Myers et al. (1984b), who found that the performances of the two models of helmet did not differ greatly, the geometric mean workplace protection factor being 182 and the geometric standard deviation 3.3. Laboratory measurements of fit factor, using corn

oil, carried out as part of the same exercise, resulted in a geometric mean of 6200 and a geometric standard deviation of 2.5 and not only were there large **differences** between individual pairs of values, but also a very poor correlation.

The workplace protection factors observed by Myers et al. (1984b) are considerably greater than the effective protection factors measured by Que Hee and Lawrence (1983), in a study of the wearers of powered helmets exposed to lead at a brass foundry. Nine out of a total of 13 measured protection factors were single figures, and three were <2. The very low values were caused by bad working practice, such as the frequent lifting of the helmet visor; though low values were caused by the use of side shields of the incorrect size. The authors considered that previously specified test movements used in qualitative fit testing did not accurately simulate movements carried out at work.

Measurements of workplace protection factors of negative-pressure **full-facepiece** respirators used against lead fumes produced by the burning of lead paint were made by Shackleton et al. (1985). The sampling method involved membrane filter samples taken both outside and inside the respirators, the samples being analysed by atomic absorption spectroscopy. Adequate protection against the concentration of lead they measured would have required protection factors of about 200, but the **observed** protection factors varied approximately log-normally with a geometric mean of 23.6 and a **geo-metric** standard deviation of 3.5. The authors **at-tributed** these values in part to imperfect mixing during in-mask sampling, but principally to the leakage of the respirators when used in real industrial situations.

Myers et al. (1986b) measured the workplace protection factors of powered helmets at a lead battery assembly plant, using their own test protocol (Myers et al., 1984a). In this study the authors specified that the test subjects should be clean shaven. As in the **authors'** previous study (Myers et al., 1984b) the observed performances of the two designs of helmet were sufficiently similar for pooled data to be analysed, and the result was that the measured protection factors closely followed a log-normal distribution, with a geometric mean of 127 and a geometric standard deviation of 2.28.

Grauvogel (1986) carried out measurements of effective protection factor at a lead-acid battery plant, finding values for wearers with **different** jobs ranged from 2 to 74, with a geometric mean of 15.6.

Fergin (1984) measured the workplace protection factor of three types of disposable mask used at an aluminium smelting works, and found geometric mean protection factors of 16, 20, and 161 for the three types on clean-shaven workers; and 22, 16, and 183 on bearded workers. In contrast with measurements of laboratory protection factor (*vid sup*), **Fergin's** measurements showed no significant differences between the protection factors for the two categories of worker.

Reed et al. (1987) used in-mask filter sampling without size selection, followed by weighing, to measure the workplace protection factors of a filtering facepiece type of mask, used against dust from the ingredients of a concrete patching compound. The observed protection factors approximated reasonably well to a log-normal distribution, with a geometric mean of 18 and a geometric standard deviation of 3.1.

Tannahill et al. (1990) measured the protection afforded by three types of negative-pressure full-facepiece respirators against asbestos during stripping operations. They measured the workplace protection factors by counting asbestos fibres on membrane filter samples taken inside and

outside the respirators and found geometric mean values of 200, 580, and 120, and geometric standard deviations of 4.3, 5.2, and 4.4 for the three models, in contrast with the protection factor of 900 assigned to this type of device.

Galvin et al. (1990) measured the protection factors of half-mask respirators against styrene vapour, limiting their observations to trained workers who did not have troublesome facial hair. Irritant smoke fit tests were carried out beforehand, and a correction for pulmonary retention of styrene was employed. The pooled results for all of their tests gave a geometric mean protection factor of 79 and geometric standard deviation of 3.5.

Tannahill et al. (1990) observed a positive correlation between the measured workplace protection factor and the external concentration of pollutant, as did **Shackleton et al.** (1985) and **Moore and Smith** (1976), though this pattern does not seem to be universally followed. A possible explanation is that a wearer will be more meticulous in fitting the mask to his face when the high concentration of pollutant makes him aware of an increased hazard.

Summary and Conclusions

If only two points emerge from this review, they are that a considerable amount of work has been done, and that none of this has yet provided a complete answer to the problem of measuring and understanding the protection given by respirators in actual working conditions.

Aerosol filtration has been the subject of considerable study, much more than the few examples directly specific to respirator filters quoted in this review. The reason is that filter parameters can be defined rigorously and measured **repeatably**. Leakage is much more variable and poorly defined. Filters are highly size-selective, and so any filter may have widely different filtration efficiencies against different challenge aerosols. Leakage paths will also be size-selective, but the form of their size-selection curve will be different.

Breathing takes place at a range of volume flow rates throughout the resting breathing cycle, and hard physical work increases this range. A

given volume flow rate corresponds with a particular filter face velocity, depending on the area of the filter, and this will affect the filtration efficiency. The probability of particle capture is likely to increase with velocity for masks suitable only for low **toxicity** dusts, since their filters are purely mechanical in action; but it will decrease with velocity for filters that act by electrostatic forces, a category that includes most respirator filters and filtering facepieces used against toxic dusts. The velocity-dependence of size-selection of leak paths is **different** from those of filters.

The nature of the air flow through a filter is fundamentally different from that through a leak. Air flow through a filter is dominated by viscosity, whereas that through a leak may have a significant inertial component. These two types of flow differ in their pressure-flow rate characteristics, which means that the fraction of the air going through each path will vary with the total air flow, even if the geometry of the face-filter system were to be fixed. In practice it is likely that geometric

changes take place as the air flow alters, which is a further complication.

The extent of face seal leakage varies among respirators, depending on how well they are designed and constructed. A single mask has different face seal leakages on different faces. Faces can be broadly classified according to age, sex, and ethnic type, but within these categories they will vary individually. Skin texture, or wetness, and the presence of a beard or of stubble are important, and spectacles may interfere with fit unless they are specially designed. A mask may have been donned with care, or without, and the importance of training respirator wearers to achieve correct fit must be stressed. The wear and tear experienced during a shift may alter the quality of the filter and the fit of a disposable respirator in particular, and filtration efficiency may be reduced as a result of dust loading.

Most of the measurements of whole respirator performance reported here have been carried out using test aerosols rather than industrial aerosols, which are harder to control and to measure. Furthermore, the capture of aerosols by various mechanisms depends critically on their physical properties such as particle size, shape and density, and only indirectly on their chemical composition. However, the size distribution of test aerosols is usually quite different from that of many industrial aerosols, and it is difficult to correlate results obtained using the one with those obtained using the other. The value of protection factor measurements made with test aerosols must, therefore, be questioned; but if it is assumed that the test aerosols are completely captured by the filters and that they penetrate through the leaks without losses, total inward leakage measurements made with them give an approximation to the fit factor; and it is likely that many of the measurements made with test aerosols approximate to this condition. The real usefulness of the fit factor is that, being a ratio of airflow rates, it is an intrinsic property of the respirator/wearer system, which does not depend on the properties of any particular aerosol. Moreover, if any improvements are to be made to respirator design, these must involve either increased filtration efficiency or improved fit factor, and there is more scope for the latter.

The relationship between fit factor and protection factor against an aerosol that has significant but not complete penetration both through the filter and through the leaks is not

simple. Calculations based on measurements of size dependence of penetration through both leaks and filters are illuminating in this respect, and a reappraisal of the relative importance of aerosol penetration through leak paths and through filters could lead to a revision of respirator specification. More work is needed on this subject, particularly using monodisperse aerosols and involving human wearers.

Nevertheless, it is unlikely that such studies could resolve the observed striking difference between the results of laboratory measurements and those carried out in industry. Not only may the laboratory protection factor be an order of magnitude or more larger, but there may also be poor correlation where both parameters are measured on a number of different models of respirator worn by a single subject, or a number of specimens of the same model worn by several subjects. The likely reason for this is not that the two parameters are fundamentally unrelated, but that the conditions in which the measurements are made are completely different. The measurement of fit factor carried out in the laboratory, or at least in controlled conditions, is inapplicable to situations in which a large number of variables such as atmospheric conditions, immediate work tasks and individual behaviour can have significant effect.

The discrepancy might be resolved by real-time measurements of fit factor, on-site, whilst a subject is working in a normal way; such measurements would certainly be very informative, though no experimental technique exists as yet for carrying them out.

Most measurements of protection factor or related quantities carried out so far suffer from the familiar problem that the leaked air and the filtered air are not mixed. This effect is widely observed and extensively described, but in the end observers have the choice of sampling from inside a mask worn by a human subject, with the problem of imperfect mixing, or of sampling exhaled air, with the problem of uncertain lung deposition, in either of which cases the result will be a biased measurement; or, thirdly, of sampling all of the air breathed by a mannequin, resulting in an unbiased measurement on an artificial system. A solution to this problem would be most valuable, but the way ahead is not clear.

Data obtained so far from several fittings of a single mask to the same wearer, or from a number of specimens of the same model of mask fitted to a

number of wearers, often conform reasonably well to a log-normal distribution, but no other distributions have been seriously considered, and a theoretical study of this might increase the confidence one could have in data interpretation.

On-site measurements of workplace or effective protection factor have been relatively few. One problem is that a considerable amount of time is needed in order to obtain very few results, which are themselves representative of a parameter that is highly variable.

A further problem is that apparatus used in the measurements can be highly disruptive of the system it is designed to study. Real-time dust-sampling instruments can be used to measure industrial aerosol concentrations, but they require a sampling tube to run between the respirator and the instrument. Membrane filter systems are smaller, but it is difficult to accommodate the sampling head in or close to a mask. Cumbersome sampling apparatus could convert a lightweight disposable mask into an unwieldy piece of equipment, which would discourage potential wearers, and affect the results obtained when measurements are made. This is an obvious place where improvements would help the progress of the study.

A final question concerns the actual value of the concept of protection factor. Explicit reference to protection factor can be avoided, but the concept is implicit in any recommendation for respirator use. Specification of respirator types as acceptable or unacceptable, or as high, medium, or low efficiency is a qualitative use of the concept, and an attempt to apply this to actual usage has all of the problems associated with a quantitative protection factor, without the benefit of making as much use as possible of available knowledge.

A purely qualitative approach makes error more likely. The mistake of allowing an inadequate respirator to be used is self-evident, and it is very likely that in order to avoid this, a respirator of an unnecessarily high specification will be recommended. This causes an economic burden, but a more serious problem is that confidence that this will improve effective wearer protection is misplaced. Respirators achieve high protection factors in part by special design features, and these may impose a burden of discomfort on the wearer, with the likelihood that the respirator will be removed for at least part of the working period. The drastic reduction in effective protection factor caused by this has been discussed in the review. The optimal solution to respirator selection is possible only when both the hazard and the protection employed against it are quantified.

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