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Performance of Dust Respirators with Facial Seal Leaks: I. Experimental

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The ability of representative half-mask and single-use respirators with facial seal leaks to provide protection against aerosols was evaluated by experimental measurement. Respirators were mounted on a manikin in a test chamber and operated at seven steady flow rates over the range of 2 to 150 L/min. Samples of polydisperse and monodisperse aerosols were taken from inside and outside the respirator and analyzed by a calibrated optical particle counter over the particle-size range 0.1 to 11.3 μm. Measurements were made separately for filter performance as a function of particle size and flow rate, and simulated leak performance (penetration) as a function of particle size, pressure drop, and leak size. Flow rate *vs.* pressure drop measurements were made for all filters and leaks tested. For a given leak condition the percentage of the total flow traversing the leak varied several fold over the usual range of airflow rates through a respirator. Aerosol penetration was found to depend strongly on particle size and flow rate for filters, and to depend strongly on particle size and less strongly on pressure drop for leaks. One can conclude from these measurements that the aerosol-size distribution inside a respirator will nearly always be significantly different from that outside the respirator.

Introduction

Half-mask and single-use air purifying respirators are used widely in American industry with the largest application of these respirators being for respiratory protection against airborne particles (aerosols such as dust, fume, and mist).[1] Despite their wide use, single-use and half-mask respirators probably provide the poorest fit and have been studied least of any of the NIOSH/MSHA approved respirators.

Filter penetration and facial seal leakage represent the two primary routes of inhalation exposure for a respirator wearer. In the case of exposure to gases or vapors, it is reasonable to assume that cartridge penetration is zero in the absence of breakthrough and that the flow of contaminant through facial seal leaks is exactly equal to the airflow through the leaks. The situation is more complicated for aerosols because small particles can penetrate the filter and large particles are lost traversing facial seal leaks.

Although the most important concern is the mass concentration inside and outside the respirator and the ratio of the two, the aerosol exposure situation has the additional complication that filter and leak penetration are a strong function of particle size and as a consequence a change in particle-size distribution will occur during aerosol penetration. The size distribution change that occurs during filter penetration is different from the change that occurs during facial seal leakage. Furthermore, the penetration and leakage for each particle size and their relative contributions are strongly influenced by the flow rate through the respirator, the cyclical breathing pattern. The net effect of such a change in size distribution may increase or decrease the toxicity of a given concentration of aerosol. For example, even though the mass concentration of lead aerosol is reduced by a factor of 20 by a respirator, if the particle-size distribution inside is smaller than outside, the fraction of inhaled aerosol absorbed into the blood may be as much as four times that for the larger outside distribution yielding performance equivalent to a protection factor as low as 5.[2]

Presented here are basic data on the filter and facial seal leak performance of half-mask and single-use respirators. These data form the basis for a predictive model of respirator performance described in the following paper.[3]

Previous Work

There are few data on the performance of respirator filters as a function of aerosol particle size. Several studies have used polydisperse aerosols to evaluate the performance of respirator filters under a variety of conditions.[4-7] but these provide little insight into filter performance as a function of particle size. A study by Stafford *et al.*[8] evaluated the collection efficiency of MSA Type S and Welsh 7500-7 filter cartridges as a function of particle size, over the size range of 0.18 to 2.0 μm, for steady flow and breathing cycles associated with three work rates: 415, 622, and 830 kg-m/min. Their experimental method requires a variable dilution of the downstream sample that they correct for by means of complicated calculations involving the integration of instantaneous signals. As would be expected they found significant differences in penetration between a steady flow rate of 16 L/min and cyclical flow at average flow rates of 30 to 53 L/min. Their results, showing an increase in penetration for particles larger than 1 μm, are inconsistent with filter theory and may be an artifact of their method.

Limited data are available on the size selective characteristics of respirator facial seal leaks. Lowry *et al.*[9] evaluated the performance of six models of single-use respirators using a sodium chloride aerosol, MMAD = 0.7 μm and GSD = 2.15. They found evidence of inadequate protection for some combinations of respirators and face sizes, but one cannot distinguish between filter penetration and facial seal leakage from their measurements. Holton *et al.*[10] using human subjects found penetration through holes punched in a mask to be particle-size dependent with a decrease in penetration for particles less than 0.1 μm and greater than 2.0 μm.

Tuomi[11] evaluated the overall performance of two surgical masks and two half-mask respirators as a function of particle size. Both types of respirators were mounted on a manikin. He used a breathing machine that produced a sine wave with a mean inhalation flow rate 102 L/min. He measured penetration as a function of particle size using a corn oil aerosol and an optical particle counter (Royco Model 225) over the size range 0.35 to 9 μm. Measurements were made for two conditions, normal fitting on the manikin (unsealed) and taped to the manikin so that there was no facial seal leakage (sealed). Although not given in Tuomi's paper,[11] it is possible to estimate relative leak penetration as a function of particle size for one of the half masks tested, by comparing performance curves for sealed and unsealed conditions. Penetration is approximately constant for particle sizes below 2 μm but decreases for larger particles so that 9 μm particles have approximately one half the leak penetration of 2 μm particles.

Two studies[12,13] have evaluated filter and facial seal leakage performance under cyclic flow conditions for expedient respiratory protection, but only for one particle size.

Experimental

Overview: Experimental measurements of respirator performance were made by mounting a respirator on a manikin in an aerosol test chamber and measuring aerosol number concentration outside and inside the mask under steady flow conditions. Measurements were made for 14 particle sizes at 7 or more pressure drops. Leak penetration and filter penetration were measured separately to avoid sampling errors due to the streaming effect identified by Myers[14] and to avoid the ambiguity as to penetration source in the intermediate particle-size range. Filter inlets were blocked for leak tests and the respirator was sealed to the manikin with hot melt adhesive for the filter tests. As is explained in the following paper,[3] filter and leak penetration results can be combined to duplicate any realistic leak situation and the steady flow results integrated over breathing profiles and exposure-size distributions to obtain overall performance under realistic use conditions. Respirators were selected as being commonly used and typical of their type. No attempt was made to test all types or brands. Respirators tested include the following: MSA Comfo II with Type F, H, and S filter cartridges and Type GMA organic vapor cartridge with paint prefilter; North 7700 with N7500-7 and N7500-8 filters; American Optical R5000 with R56A and R57A filters; 3M 8710; American Optical R1070; and Gerson 1710.

Experimental measurements were made using a bench scale aerosol test chamber described in Reference 15. The 109-L chamber has a top mixing section, a honeycomb flow laminator section, a 52-L transparent plastic cylindrical aerosol test section (40-cm diameter), and a bottom exhaust plenum. Overall chamber dimensions are 0.5 × 0.5 × 1.5 m high. The vertical airflow velocity, about 4 cm/sec, is uniform within 20% of the mean throughout the test section. This air velocity is sufficiently low that it is equivalent to still air for most aerosol sampling situations. Opposed jet mixing in the mixing section produced test aerosol concentrations in the chamber that were uniform within 5% and stable within 5% for more than 1 hr. Chamber pressure can be controlled from slightly negative −1.5 mm of water (−0.06 in. of water) to slightly positive +7.6 mm of water (+0.30 in. of water) relative to ambient pressure. Standard operating conditions were a dilution air flow rate of 300 L/min and a slightly positive chamber pressure of 1.7 mm of water (0.07 in. of water).

Respirators were mounted on the face section of a fiberglass manikin (Model SM 701 manufactured by Silvestri California, Los Angeles, Calif.) having face length of 11.2 cm and face width of 13.4 cm, a facial size that is in the overlapping range for males and females.[16] The manikin was coated with a 2-mm rubber coating and modified to accommodate flow and sampling tubes and a mounting bracket. Flow through the respirator was controlled by one of five calibrated rotameters mounted on an adjacent control panel. Rotameters have full scale capacities of 100 cm^3/min to 150 L/min and are selected by a valve control system. Pressure drop, the difference between chamber pressure and the pressure inside the mask, was measured by one of three inclined manometers which together covered a range from 0 to 51 mm of water (0 to 2 in. of water).

Test aerosols were generated from oleic acid by two methods. In the range 0.1 to 4 μm a polydisperse aerosol was formed by a specially designed nebulizer that produced a low aerosol number concentration with a wide size distribution.[17] This was supplemented by two monodisperse aerosols, 7.25 and 11.34 μm aerodynamic diameter, produced by a vibrating orifice aerosol generator (TSI Inc., Model 345000, St. Paul, Minn.). With the addition of 300 L/min dilution air, all test aerosols had a number concentration in the test chamber of less than 300 particles/cm^3.

As shown in Figure 1 the inside sample is taken along the center line of the mouth tube 5 cm back from the mouth. The mouth and sampling tubes have diameters of 14 and 2.5 mm, respectively. The outside sample is taken a few cm to the left of the mask. The sample flow rate, path length, tube size and bends are the same for both inside and outside samples. Manual tubing connection was used to switch between inside and outside samples. Because of limitations of the optical particle counter the sample flow rate was held constant at 4 cm^3/sec, and as a result, sampling was not isokinetic at some respirator flow rates. Although the sample paths are identical, the sample inlet conditions are different for the inside and outside samples. The outside sample is equivalent to sampling from still air and the inside sample is taken from a moving stream. This difference between the two inlet conditions and the nonisokinetic condition gives a size dependent bias to computed penetration for high flow rates

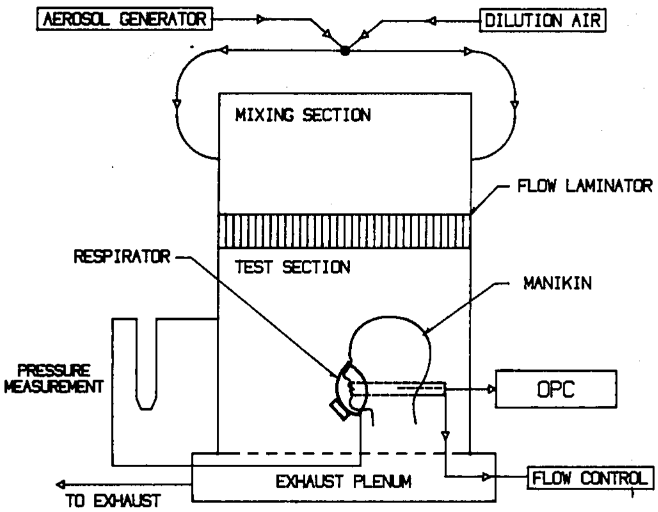

Figure 1 — Cross-sectional diagram of manikin and sampling system.

or large particle sizes. To correct for this, ten replicate samples were taken inside and outside at each flow condition without a respirator on the manikin. Correction factors were determined from the ratio of inside to outside concentration for each particle size. Correction factors were needed only for flow rates of 100 and 150 L/min and for particle sizes of 7.25 and 11.34 μm. In all cases correction factors were less than 30%.

Nebulized particles were sized and counted, and monodisperse particles were counted by a PMS Model LAS-X optical particle counter (PMS, Inc., Boulder, Colo.). This instrument was calibrated in terms of aerodynamic diameter for oleic acid.[18] Particle number concentrations of the test aerosol were well within the range for negligible coincidence error.[19] During a normal run, a series of samples were taken for 1 min each, alternating inside and outside for five replications to give a total sampling time of 5 min inside and outside at each flow rate.

Three types of facial seal leaks were used, two of which are shown in Figure 2. All were established at the facial seal of a MSA Comfo II or 3M 8710 respirator with filters blocked. The MSA half-mask filters were blocked with sealed cartridges; the 3M single-use mask filter was blocked with a flexible plastic coating. One type of leak consists of one or more metal tubes that are inserted in the facial seal and sealed in place with hot-melt adhesive. The five tube sizes used ranged from 0.5 to 3.2 mm in diameter. A second type has one or more wires inserted in the facial seal without local caulking. The facial seal was not sealed within 3 or 4 cm of the wire leak, but the remaining parts of the facial seal were sealed with high vacuum grease. Wire diameters of 0.5 and 0.9 mm were used. A third type is a natural leak that results when an unsealed half-mask is mounted on the manikin with an average strap tension of 240 g. These leak conditions are reproducible and reasonably representative of common leak types.[20] The number of leaks used was sufficient to ensure that a flow of 4 cm^3/sec was available for the optical particle counter.

For filter tests the entire mask perimeter was sealed to the manikin with hot-melt adhesive, and half-masks were checked initially for leaks with filters blocked to ensure that unintended leakage was less than 0.05% of flow through the filters. Exhalation valves were sealed with hot-melt adhesive for all tests.

Before and after each leak or filter performance test, pressure drop *vs.* flow measurements were made at 14 pressure drops, ranging up to 33.6 m of water (1.33 in. of water). These 14 points include the seven for which leak performance was measured.

For filter tests (no facial seal leaks), a plot of pressure drop *vs.* flow rate gave a straight line as would be expected for laminar flow inside a filter (Figure 3). Pressure drop *vs.* flow rate results for leaks, however, show a nonlinear relationship (also shown in Figure 3). This is a result of leak path geometry that causes flow to be intermediate between fully developed laminar flow and flow through an orifice. The shapes of the leak curves are similar for all three leak types. The relationship between leak flow Q and pressure drop P is given by,

$$Q = A\, P^b \qquad (1)$$

where A and b are constants for a given leak, For the leaks evaluated here b ranged from 0.962 for the smallest leak (0.5-mm diameter, L/D = 19.6), to 0.562 for the largest (3.2-mm diameter, L/D = 3.1). These values are in good agreement with published values for similar conditions[21] and values used in a respirator model given by Campbell.[22] The fact that leaks have a nonlinear flow *vs.* pressure drop relationship means that the proportion of leak flow relative to filter flow will be different for different flow rates. This is shown in Figure 4 where the ratio of leak to filter flow rate varies several fold over the applicable range of filter flow rates. Figure 4 is for a fixed leak geometry, and the effect is even greater for a natural leak that seals better at high pressure drops.

Flow rate is strongly influenced by leak size, being proportional to the 2.7 power of leak diameter for the leaks tested.

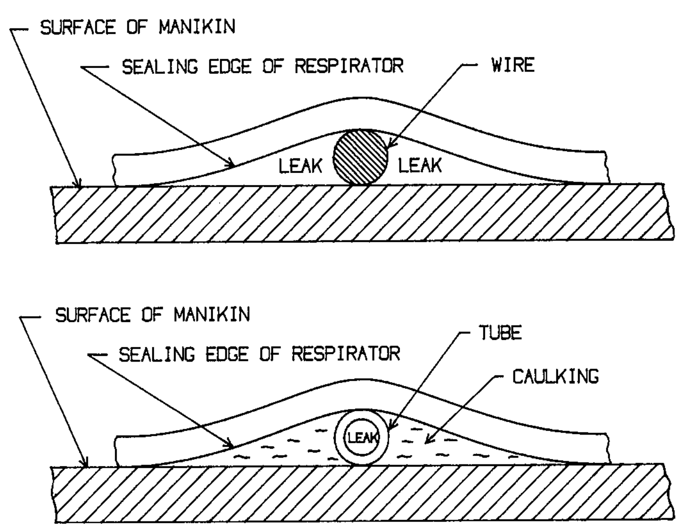

Figure 2 — Diagram of leak types used.

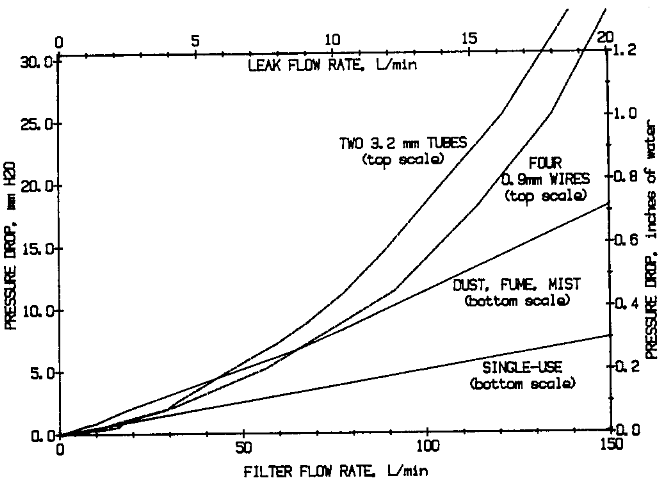

Figure 3 — Pressure drop *vs.* flow rate for filters and leaks.

As expected this dependence lies between fully developed laminar flow, exponent 4.0, and a simple orifice, exponent 2.0.

For each filter performance run, penetration was measured at seven flow rates — 2, 5, 10, 20, 50, 100, and 150 Lpm — and 14 particle-size ranges. Midpoints of particle-size ranges were 0.14, 0.17, 0.23, 0.30, 0.37, 0.51, 0.64, 0.83, 1.04, 1.68, 2.67, 3.65, 7.25 and 11.34 μm aerodynamic diameter. Sizes 0.14 to 3.65 μm were done in one run and 7.25 and 11.34 μm were done as separate runs. Five replications were made for each flow rate, alternating outside and inside. Each leak performance run was the same as a filter run except that measurements were made at seven to nine pressure drops, 0.18, 0.45, 0.94, 1.98, 5.2, 9.4, 12.7, 25.4, and 33.6 mm of water (0.007 to 1.33 in. of water), instead of seven flow rates.

Each run produced a total of about 1600 count values from the optical particle counter that are reduced to 98 penetration measurements (7 pressure drops × 14 particle sizes) by a spreadsheet. The mean and standard deviation is computed for each of the 98 values. Examples of these results for half-mask filter cartridges and a single-use respirator are shown in Figures 5 and 6. All filters tested, except high efficiency, showed a pattern similar to Figures 5 and 6 but there were large differences in the level of penetration between different filter types and brands. For example, penetration of 0.5 μm particles at 20 Lpm (through two filter cartridges) ranged from 0.25 to 1.23% for three brands of dust, fume, and mist cartridges and from 1.79 to 39.9% for three brands of single-use respirators. Figures 7 and 8 show penetration *vs.* particle size for two types of facial seal leaks. Penetration in Figures 7 and 8 represents the fraction of particles in the leaking airstream that reach the mouth. All types and sizes of leaks tested produced similar patterns.

The effect of leak size D_L on the particle size associated with 50% penetration (cut-off size) is slight. For example the range of cut-off sizes at 0.97 mm of water (0.038 in. of water) for all leak types and sizes was within ± 36% of the mean and showed no obvious trend. While this is an unexpected result, a rough estimate, based on impaction at the inlet and outlet of a leak, suggests that cut-off size should increase only as $(D_L)^{1/4}$ for a given particle size and pressure drop, except when velocity is low enough for settling losses in a leak to be important in which case it is proportional to $(D_L)^{3/4}$.[19,21]

Discussion

Conducting filter and leak tests separately gives the most general results and avoids the streaming problem identified by Myers *et al.*[14] Although the pressure drop is precisely controlled during a leak test, the flow situation inside the respirator is different from the normal situation with air flowing through the filters. A separate test was conducted using a respirator with a high efficiency filter and with a facial seal leak. Additional tests were run for the same leak in a leak-only situation. The results were equivalent for both situations although there was evidence of streaming at low flow rates.

Another pilot test was conducted with two wire leaks placed sequentially at the cheek, beside the nose, and at the chin. All three conditions showed similar leak penetration *vs.* particle-size curves and there were no systematic differences. For convenience all subsequent leaks were introduced at the left and right cheek section of the facial seal.

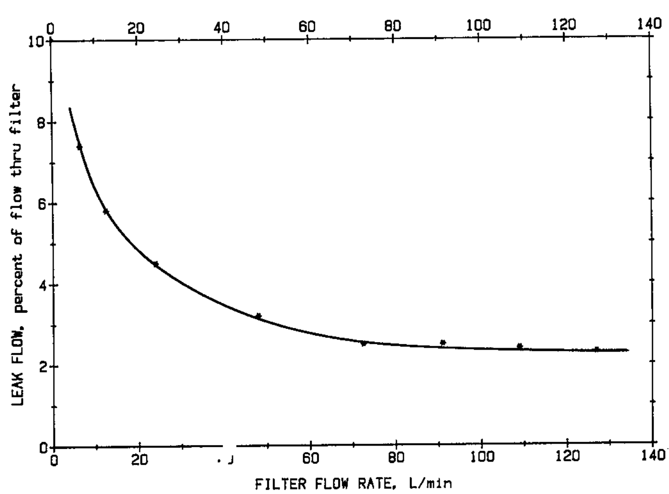

Figure 4 — Percent leakage flow rate *vs.* filter flow rate. MSA Type S filters with two 1.55-mm diameter facial seal leaks.

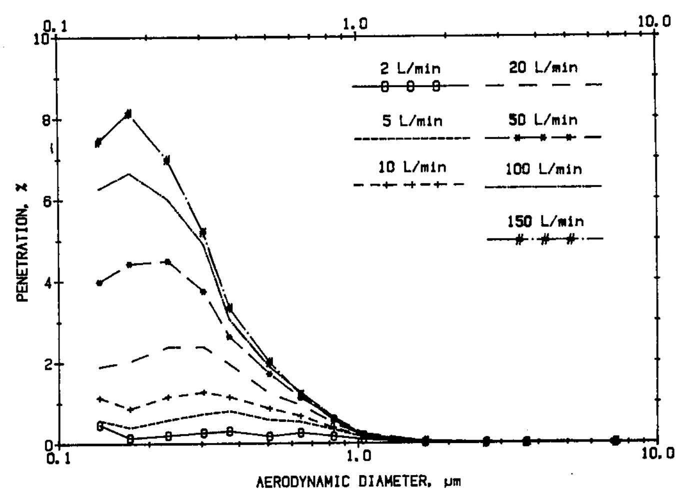

Figure 5 — Filter performance, MSA Type S dust, fume, mist cartridge filters, average of lot numbers 1184, 2583, and 3383.

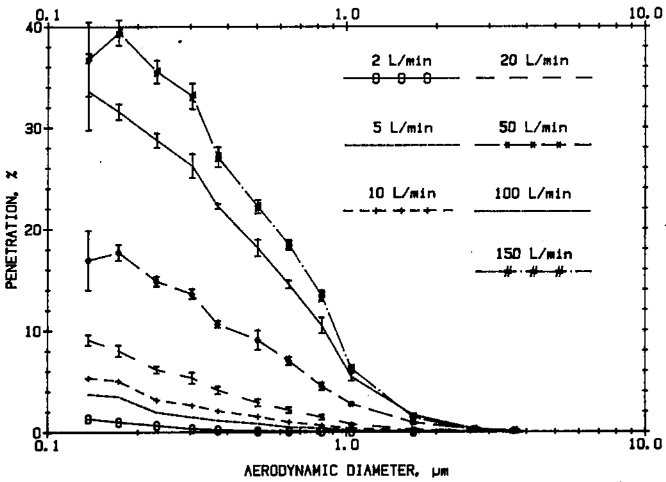

Figure 6 — Filter performance, 3M 8710 single-use respirator. Bars on 20-150 L/min lines indicate ± standard errors of the mean for each data point.

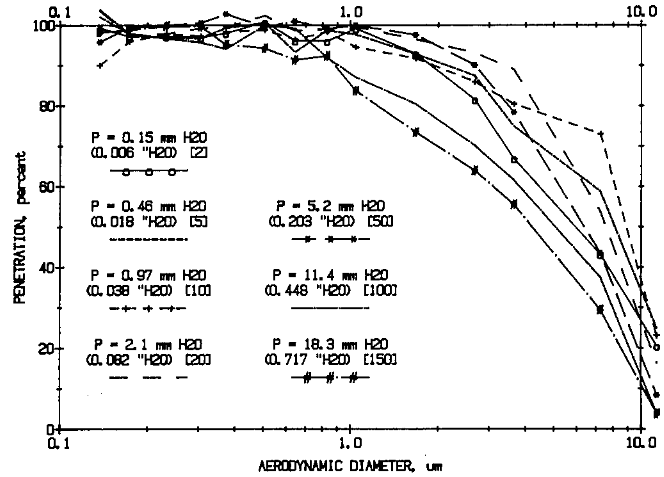

Figure 7 — Leak performance, tube leak 1.0 mm ID × 10 mm long. Numbers in brackets represent the equivalent flow rate (L/min) through a pair of MSA type S filters.

The average standard error for the leak penetration curves was 2.9%. The average standard error for the 3M 8710 filter penetration curves was 3.8% of the value for penetrations greater than 1% and 16.2% for penetrations less than 1%. The latter were less precise due to fewer counts at low penetrations. A concerted effort was made to reduce systematic errors to a minimum so they are believed to be less than ± 7%. Overall accuracy of the performance curves is estimated to be better than ± 15%.

Filter performance was found to vary significantly between types and between brands within a type. Based on three different filter brands the relative standard deviation for penetration measurements is 65% for dust, fume, and mist half-mask cartridge pairs (MSA, AO, and North) and 77% for single use respirators (3M 8710, American Optical R1070, and Gerson 1710). Three lots of MSA Type S filters (dust, fume, and mist cartridge pairs) had a relative standard deviation for penetration measurements of 57%. Note, that this relative standard deviation is of comparable magnitude to that for different brands of the same type. All filters tested showed an increase in penetration with increasing flow rate suggesting that filtration is dominated by diffusion, interception, and sedimentation mechanisms that are less effective at higher flow rates.[19] Impaction appears to play a minor role because of the low face velocities involved.

Filter results given here are essentially equivalent to those for a clean filter. A new filter was used for each run and aerosol mass loading on the filter was low, a maximum of about 170 µg for a typical run. This is in contrast to NIOSH/MSHA certification tests which test performance under adverse use conditions. The silica dust test, for example, is conducted at 2000 times the authors' test concentration and the accumulated filter load is more than 1000 times greater. This amount of loading significantly increases filter efficiency and pressure drop.

Although airflow rate through leaks depends strongly on leak size (proportional to size raised to the 2.7 power), the shape of the penetration *vs.* particle-size curve varied little with leak size or location. Penetration of aerosols through leaks was approximately 100% for particles having aerodynamic diameters of 0.1 to 1 µm regardless of leak size or pressure drop. In the size range 1-12 µm, as pressure drop increases, penetration first increases due to decreased sedimentation losses in leaks and then decreases with increasing pressure drop due to increased inlet losses and impaction losses against the face at the leak outlet. Unlike aerosol particles entering an isolated sampling inlet tube, aerosol particles entering a facial seal leak approach towards the face and experience a sharp turn in the immediate vicinity of the leak inlet. This results in impaction against the face that may be the mechanism most responsible for the shape of the leak performance curves. Application of the same facial seal leaks to half-mask and single-use respirators gave similar penetration curves when operated at the same pressure. Note, however, that the single-use respirator has a significantly lower pressure drop for the same flow rate.

The authors have evaluated the performance of representative half-mask and single-use respirators by separate meas-

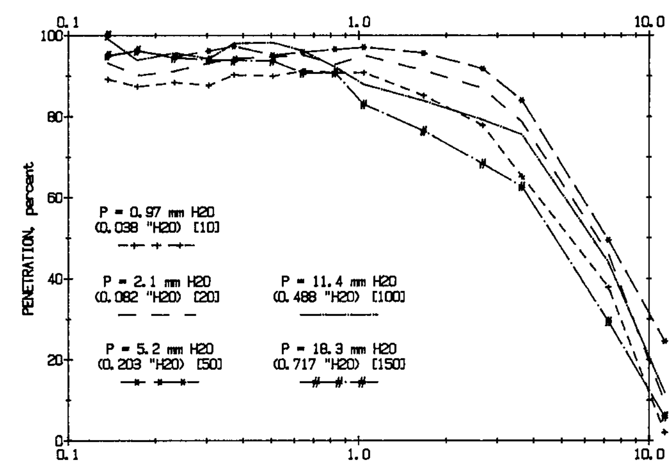

Figure 8 — Leak performance, wire leak 0.5 mm-diameter. Numbers in brackets represent the equivalent flow rate (L/min) through a pair of MSA Type S filters.

urement of filter performance as a function of particle size and flow rate and simulated leak performance (penetration) as a function of particle size, pressure drop and leak size. Respirators were mounted on a manikin in a test chamber for all measurements. Aerosol penetration was found to depend strongly on particle size and flow rate for filters and to depend strongly on particle size and less strongly on pressure drop for leaks. The percentage of the total airflow traversing the leak varied several fold over the normal range of airflows through a respirator. One can conclude from the authors' measurements that the aerosol size-distribution inside a respirator usually will be significantly different from that outside the respirator.

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