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Collection of Silica and Asbestos Aerosols by Respirators at Steady and Cyclic Flow*

L.M. BROSSEAU[a†], M.J. ELLENBECKER[b], AND J.S. EVANS[a]
[a]*Harvard School of Public Health, Department of Environmental Science and Physiology, Boston, MA 02115;* [b]*University of Lowell, Department of Work Environment, Lowell, MA 01854*

Air purifying dust/mist respirators are presently tested using a silica aerosol under conditions of steady flow. In experiments, the predictive validity of such tests was evaluated by testing respirators using silica and asbestos aerosols under conditions of both steady and cyclic flow. Silica penetration at steady flow was reasonably predictive of silica penetration under cyclic flow. However, asbestos penetration under cyclic flow was not predicted well by penetration of either silica or asbestos at steady flow. Furthermore, the potential for exhalation valve failure under cyclic flow was identified. Current NIOSH protocols for evaluating respirator performance should be reconsidered in light of these findings.

Tests used by the National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA) to certify respiratory protective equipment were originally developed by the Bureau of Mines in the early 1900s.(1) The test procedures have changed little, but equipment design has advanced rapidly. There is general agreement among respirator users and manufacturers that the current certification tests are, in many cases, inappropriate for modern respirator designs.(2)

NIOSH has recognized the need for updating respiratory protection certification tests, and the research reported here was designed to address certain aspects of the certification program for particle-filtering respirators.(2-4) Such tests now employ a limited number of aerosols—none of which is fibrous in nature. Air purifying respirators equipped with dust/mist filters are tested using continuous flow, while only disposable respirators (those which until recently had no exhalation valve) are tested under more characteristic cyclic flow conditions.

Even though respirators using dust/mist filters were previously certified for use in asbestos conditions,(1) NIOSH has recommended that they not be used in such environments(5) and the Occupational Safety and Health Administration (OSHA) asbestos standard prohibits use of these respirators in asbestos-containing atmospheres.(6) These actions were taken with little or no knowledge of the asbestos collection efficiency of dust/mist filters.

The particular issues addressed by this research are as follows.

1. What is the penetration of silica and asbestos aerosols through electrostatically charged dust/mist respirator filters when challenged with silica and asbestos under conditions similar to those of NIOSH approval tests, i.e., continuous flow of 0.032 m^3/min?
2. What is the relationship between penetration measured at continuous flow and that measured using a more representative cyclic flow?
3. Is it possible to predict, within acceptable limits of error, the observed performance by either purely theoretical models or by semi-empirical models based on measured performance with monodisperse aerosols?

The first two points are addressed in this paper; the third point is discussed elsewhere.(7) The answers to these questions will help to determine if the NIOSH certification results can be used to predict the behavior of a respirator under actual use conditions (i.e., cyclic flow with a significantly different aerosol from that used in the approval tests).

METHODS AND MATERIALS

Three manufacturers' dust/mist filters were tested. These were chosen to represent the range of filter performance observed in a previous experiment in which collection of monodisperse aerosols was measured.(8) Four combinations of aerosol and flow were tested (in the order listed below).

1. Silica aerosol at steady flow.
2. Asbestos aerosol at steady flow.
3. Asbestos aerosol at cyclic flow.
4. Silica aerosol at cyclic flow.

Preliminary calculations suggested that ten replicate tests would give sufficient statistical power for data analysis. Thus, ten

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†Correspondence should be addressed to this author at: New York University Medical Center, Institute of Environmental Medicine, A.J. Lanza Laboratories, Long Meadow Road, Tuxedo, NY 10987.

replications of each respirator of three manufacturers at each of the four aerosol/flow conditions (a total of 120 filter pairs) was tested. Filter/facepiece combinations were randomized within each of the four sets of experiments.

All respirators and parts were purchased through normal distribution channels. The filter pairs were drawn from two lots for two of the manufacturers and from a single lot for the third. Two half-mask silicone/rubber facepieces were included in each set of tests; thus, eight facepieces per manufacturer and a total of 24 facepieces were included in the entire set of experiments. The filter pairs were randomly assigned to a facepiece; where two separate lots of filters were included care was taken to ensure that each received an approximately equal number of filter pairs from each lot. Filters, facepieces, and facepiece elements were only tested in their approved configurations for these experiments, i.e., within manufacturers' specifications.

Exhalation and inhalation valves were not replaced during the steady flow experiments. Preliminary tests showed that the exhalation valves of at least one manufacturer (#2) were unfavorably influenced by the 90-min breathing pattern of the cyclic tests; therefore, all valves were replaced before each cyclic flow test. The valves were drawn from one lot for each manufacturer, and were matched to the appropriate manufacturer's facepiece.

Variables critical to the design of these experiments included

1. Relative humidity and temperature within the test chamber
2. Generation of test aerosol within the chamber
3. Sampling from the chamber
4. Creation of cyclic flow similar to the human breathing pattern
5. Mounting and sealing of the experimental filters/facepiece
6. Safety of personnel during the course of the experiments.

The approach used to minimize problems associated with each of these factors is described below.

The experimental apparatus (Figure 1) was designed to produce conditions similar to the NIOSH certification tests for dust/mist (steady flow) and disposable (cyclic flow) respirators.(9,10) The NIOSH approval protocols require that disposable respirators be tested with a cyclic flow breathing pattern, because they usually lack exhalation valves. The filters of disposable respirators experience both inward and outward airflow during normal use, while the filters attached to a half-mask air purifying respirator will normally experience only an inhalation flow.

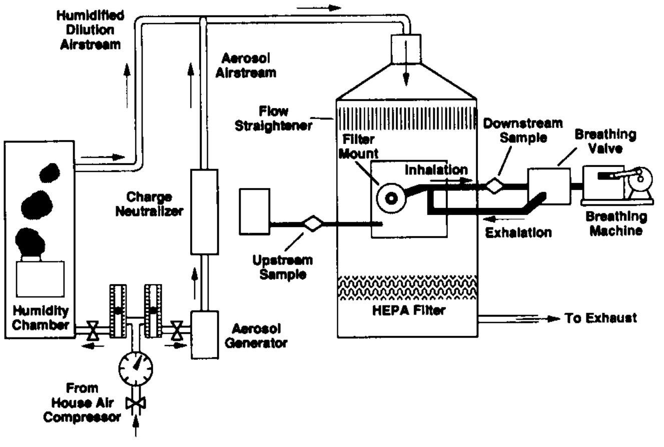

Figure 1—Respirator filter/facepiece test system.

A 0.3-m^3 exposure chamber constructed of galvanized steel was placed on and sealed to a high efficiency particulate air (HEPA) filter. The test aerosol entered the top of the chamber, passed through an air distributor into the body of the chamber, and was drawn through the HEPA filter into an exhaust duct connected to a general exhaust system. A small axial fan located below the air distributor and directed upward ensured complete aerosol mixing within the chamber. Previous work showed that this combination of air distributor and mixing fan produced a homogeneous aerosol concentration within the chamber.

Air for dilution and aerosol generation was obtained from a house compressor, passed through a drying filter, and divided into two separate airstreams adjusted with valved rotameters. One airstream was directed through an aerosol generator (discussed below) into a Kr-85 charge neutralizer (TSI, Inc., St. Paul, Minn.); the other was directed into a 4.4-m^3 plastic cylindrical chamber in which an ultrasonic humidifier was located. The humidifier output was adjusted by voltage regulator for an average relative humidity (rh) of 50% in the test chamber, chosen to meet NIOSH certification test requirements of 20-80% rh. Humidified dilution air was then combined with the aerosol as it entered a 7.6-cm diameter duct connected to the top of the exposure chamber.

A Vaisala capacitive thin film humidity sensor (Woburn, Mass.) and a thermistor (Gulton Industries, Inc., East Greenwich, Conn.) were placed immediately after the HEPA filter (previous work confirmed that relative humidity measured at this location was similar to that within the chamber). The output from these probes, attached to a Rustrak Ranger digital readout data logger (Gulton Industries, Inc.), was monitored continuously. Manual adjustments to the dilution air humidifier were made as necessary to maintain 50% rh within the test chamber. A record of humidity and temperature during each test run was obtained by transferring stored data from the data logger to an IBM-compatible personal computer and analyzing the results with a Pronto software program (Gulton Industries, Inc.) to determine mean relative humidity and temperature for each experimental run.

A manometer attached to a static pressure tap measured pressure within the chamber, which was kept slightly negative by adjusting a blast gate located in the exhaust duct immediately after the HEPA filter. Prior to the experiments, the collection efficiency of the HEPA filter was tested with mineral oil and a light-scattering photometer (Air Techniques, Inc., Baltimore, Md.) and found to be >99.99%.

The silica aerosol was generated with a Wright dust feeder.(11) The aerosol, #28 silica (200-mesh) from Whittaker, Clark and Daniels, Inc. (South Plainfield, N.J.), consisted of >99% free silica. The asbestos aerosol, using UICC (Union Internationale Contre le Cancer) amosite obtained from R.E.G. Rendall of the Pneumoconiosis Research Group (Johannesburg, South Africa), was produced with a modified Timbrell generator.(12) Amosite was chosen because it is the straightest fiber of all forms of asbestos and thus represents a "worst case" fibrous aerosol.‡

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‡Chrysotile, the asbestos used most extensively in the United States, should be filtered more efficiently than amosite because of its "curlier" morphology.

A sample of the silica aerosol was collected and analyzed by scanning electron microscope and found to have a count median diameter (CMD) of 0.46 μm and a geometric standard deviation (GSD) of 2.5. Impactor samples (Andersen 2000) of the aerosol taken before and after the experiments gave similar estimates of the count median aerodynamic diameter and somewhat smaller estimates of the GSD (2.0 to 2.3). Transmission electron microscope measurements of the length and width of fibers on two samples of the asbestos aerosol yielded a pooled distribution of lengths with a CMD of 4.5 μm (GSD of 2.7) and of widths with a CMD of 0.2 μm (GSD of 2.5).

Samples of the silica and asbestos aerosol concentrations within the chamber were obtained by drawing air through 1.36- and 0.72-cm diameter probes, respectively, with inlets located near the respirator facepiece. Probe diameters were selected to meet the still-air sampling criteria of Davies.(13) In the silica experiments, the aerosol was sampled for three consecutive 30-min periods onto preweighed 47-mm diameter Whatman (Maidstone, England) GF/A glass fiber filters at 0.01 m^3/min through a calibrated critical orifice attached to a rotary vane pump. Pressure downstream of the orifice was continuously monitored with a pressure gauge to verify that filter loading did not affect the sample airflow. The silica concentration in the chamber was maintained at 50–60 mg/m^3, as required by the NIOSH certification test methods. Downstream silica samples were collected on preweighed 50-mm diameter filters for one 90-min period at 0.032 m^3/min, as specified by the NIOSH test protocol for these respirators. Total mass collected on the upstream and downstream filters was determined gravimetrically. Mass penetration was calculated by dividing the downstream concentration by an average of three 30-min samples of the upstream concentration.

The asbestos aerosol was sampled upstream by three consecutive 30-min tests onto a 47-mm diameter 0.8-μm pore size mixed cellulose ester filter (Millipore, Bedford, Mass., or Gelman Sciences, Inc., Ann Arbor, Mich.) using a DuPont Alpha-1 personal sampling pump at a flow of 100 cm^3/min. Downstream asbestos samples were collected on either 25- or 47-mm diameter filters at a flow rate of 0.032 m^3/min for 90 min. A portion of the filter was prepared and counted by phase contract microscopy according to the NIOSH 7400 method.(14) Asbestos concentrations within the chamber ranged from 800–1200 f/cm^3.

Each respirator facepiece was sealed to a filter mount (Figure 2) designed to direct the movement of inhalation and exhalation air through the facepiece and was attached by a compression fitting to the rear wall of the exposure chamber. During steady flow experiments the exhalation portion of the filter holder was closed off, and a downstream sample was taken at a continuous rate of 0.032 cm^3/min through the respirator filters onto a filter mounted on the outside of the chamber. A rotary vane pump fitted with a calibrated critical orifice and a pressure gauge regulated flow through the downstream sampling train.

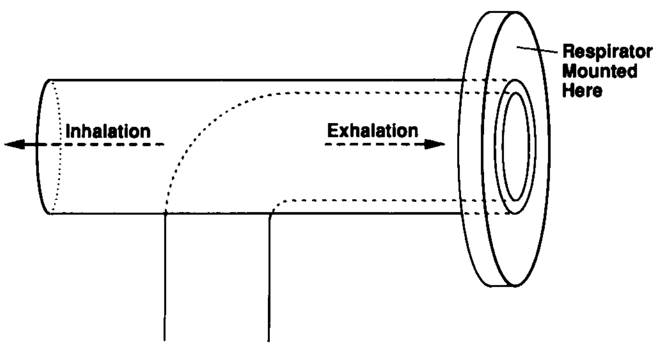

Figure 2—Respirator test mount.

A cyclic flow pattern representative of human breathing at a medium work rate was created through the use of a breathing machine fitted with a 622 kg-m/min cam, as described by Silverman(15) and Wilson and Harrod.(16) The flow was sinusoidal, with a peak value of 0.1 m^3/min, a period of 2.55 sec, a mean flow rate of 0.076 m^3/min, and a minute volume of 0.037 m^3. The airflow was divided into separate exhalation and inhalation air currents by a valve placed at the outlet of the breathing machine. Heating and humidification of the exhalation air were accomplished by a method described by Nelson.(17) Exhalation air from the breathing valve was directed into a 500-mL flask seated in a metal-jacketed heating mantle, the temperature of which was controlled with a voltage regulator, bubbled through 50 mL heated water, and then directed through a glass condensor tube, which removed most of the large water droplets. This highly humidified air passed through a section of brass pipe wrapped with heat tape, also controlled by a voltage regulator.

A temperature probe was placed in the air stream immediately ahead of the entry point into the test chamber. Before and after each experiment a humidity probe was also placed in the exhalation air stream at the same point. Appropriate adjustments to the heating mantle and heat tape voltage regulators were made to maintain 94 ± 3% rh and 35 ± 2°C temperature in the exhalation air, as outlined in the NIOSH certification tests.(10) These data were stored using a digital data logger.

Each of the test facepieces was first sealed with clear silicone adhesive to a fiberglass mold, which was fashioned to fit the facepiece contour and sealed to a lucite disc. Each mount was then screwed to a gasketed filter holder at the start of an experiment. The integrity of the facepiece seal was tested for leaks by mounting the entire setup on the filter holder, closing the respirator filter and exhalation openings, and drawing air through the inhalation portion of the filter mount for several seconds. If the facepiece collapsed slightly it was assumed that the facepiece was well-sealed. This evaluation was repeated at the end of each experimental set.

A 50 x 102 cm lucite window placed over a gasketed opening at the front of the test chamber and held in place with four clamps was designed to allow access to the apparatus within. Exhaust was adjusted with the use of a blast gate when the chamber was open to create a minimum face velocity of 30 m/min at the opening. Personal and area air samples were collected periodically and analyzed for asbestos to ensure that aerosol was not being released to the room during filter changing.

Safety precautions were taken to minimize personal exposure to the asbestos aerosol; these included loading the dust generator in a glove box and wearing a respirator equipped with high efficiency filters each time the chamber was opened to mount a new test filter. At the end of each test, the respirator facepiece was wiped with wet towels before removal from the chamber and the entire filter mount was immersed in water before applying a new respirator/filter combination. The entire area around the chamber was regularly cleaned with a HEPA-equipped asbestos vacuum.

Although these experiments were similar in many ways to those of NIOSH certification tests, they were not intended to exactly replicate NIOSH test results. One notable difference was that the authors chose to neutralize the silica and asbestos aerosols for analogy to previous latex aerosol experiments.[8] Because neither the nature nor degree of aerosol charge were determined, it is not possible to predict how the authors' results might differ from those of NIOSH.

RESULTS

Mass penetration of silica (Figure 3) under continuous flow conditions was typically less than 0.1%. The average penetration was 0.1% for Manufacturer #1, 0.2% for Manufacturer #2, and 0.8% for Manufacturer #3. Mass penetration of silica at cyclic flow averaged 0.2% for Manufacturer #1, 0.4% for Manufacturer #2, and 1.1% for Manufacturer #3. Under both flow conditions, the results for Manufacturer #3 exhibited greater variability than those for the other manufacturers.

Generally, the penetration of silica under conditions of cyclic flow was about one and a half times as great as that measured under steady flow conditions. Thus, for silica, within the experimental errors of the system, the steady flow results were reasonable predictors of the cyclic flow results.

Count penetration of asbestos (Figure 4) under conditions of continuous flow was almost always less than 0.5%. The average count penetration was 0.01% for Manufacturer #1, 0.1% for Manufacturer #2, and 0.01% for Manufacturer #3. Under cyclic flow conditions penetration was consistently less than 0.1% for Manufacturers #1 and #2; but for Manufacturer #3 average penetration was about 0.6% and results were variable, with some tests showing penetration greater than 2%.

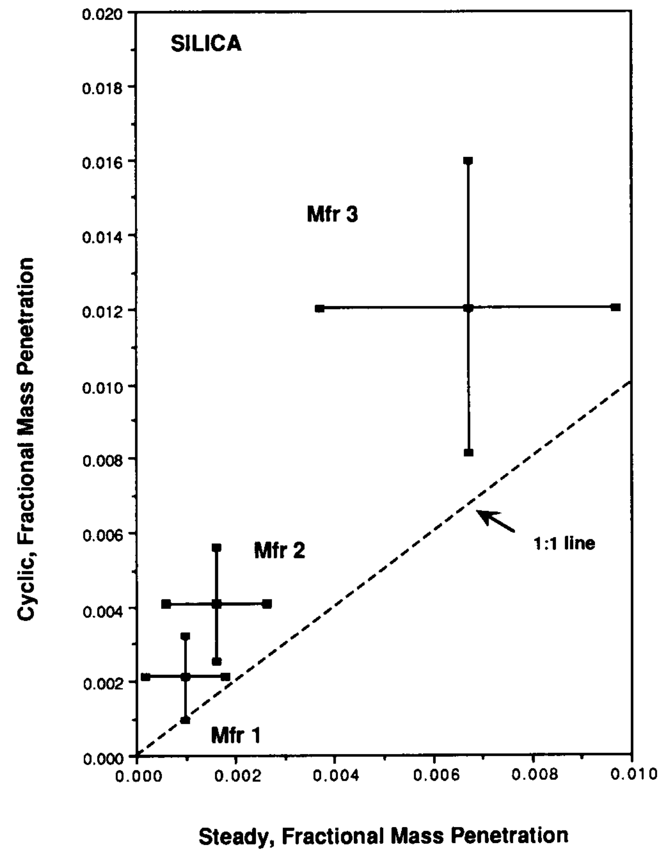

Figure 3—Steady versus cyclic flow, silica (mean ± 2 standard errors of the mean).

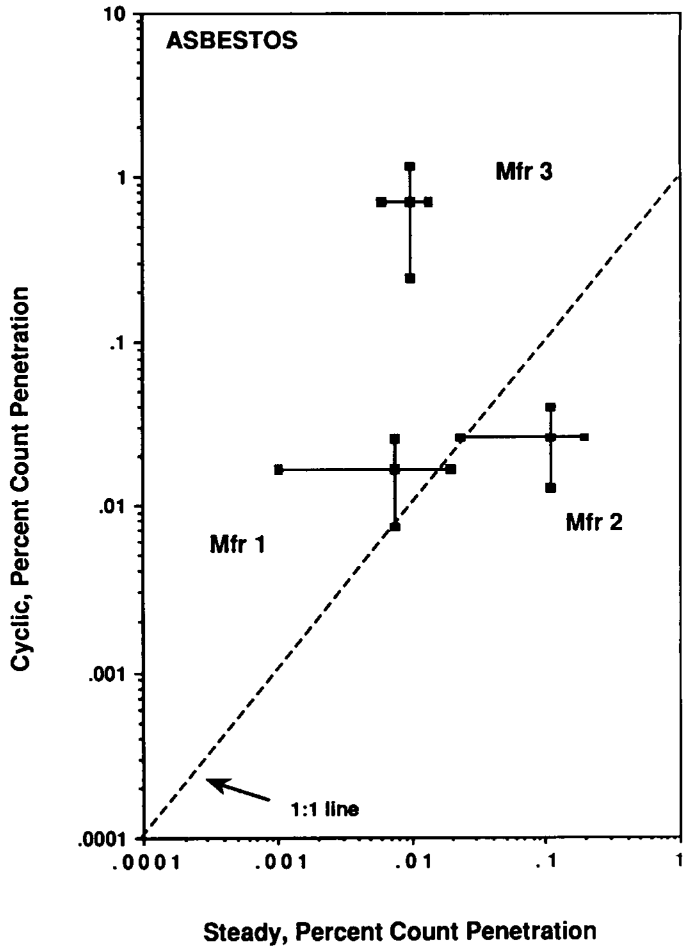

Figure 4—Steady versus cyclic flow, asbestos (mean ± 2 standard errors of the mean).

For asbestos, therefore, the results were not as simple to interpret. Within the error of these experiments, the switch from steady to cyclic flow did not affect the performance of two manufacturers' filters (#1 and #2). But the performance of the third manufacturer's filters was 60 times worse under cyclic flow than under continuous flow.

DISCUSSION

Analysis of Penetration Data

The results obtained for the steady flow silica experiments might be expected to characterize a particular filter's performance when challenged with other aerosols and under more realistic conditions of flow, because this is the test prescribed by the NIOSH certification procedure for dust/mist filters. The results of these experiments with a silica aerosol were consistent with this view. Although silica penetration under cyclic flow was somewhat greater than under steady flow, the performance of a dust/mist filter under steady flow appears to be predictive of its performance under cyclic flow.

The authors' studies are consistent with those of Stafford et al.[18] Using monodisperse latex aerosol ranging in size from 0.2 to 2.0 μm, Stafford found that cyclic flow penetration was higher than that under steady flow; for some particle sizes, penetration under cyclic flow was five times greater than under steady flow.

Although steady flow silica experiments are useful in estimating the penetration of silica aerosols under cyclic flow, they do not appear to be predictive of the penetration of an asbestos aerosol under steady flow. As Figure 5 indicates, the authors' data suggest no simple relationship between mass penetration of silica and count penetration of asbestos.

Comparison of silica and asbestos penetration at cyclic flow was not attempted, because the authors' asbestos cyclic flow data (Figure 6) suggested two modes of performance for Manufacturer #3. The single lowest data point is comparable to performance of the other two respirator models, and might be indicative of "normal" penetration for this respirator. The remaining data points indicate a much higher penetration, and might represent a failure mode for this respirator. To evaluate this possibility, an additional set of experiments was performed, using asbestos under cyclic flow. In these experiments, the filters and facepieces of Manufacturers #2 and #3 were switched, such that Manufacturer #2's filters were combined with facepieces from Manufacturer #3, and vice versa. Five replicate tests of each of the two new filter/facepiece combinations were performed. The results of the additional experiments (Figure 7) indicated that the facepiece and not the filter was responsible for the atypical performance of Manufacturer #3's respirators.

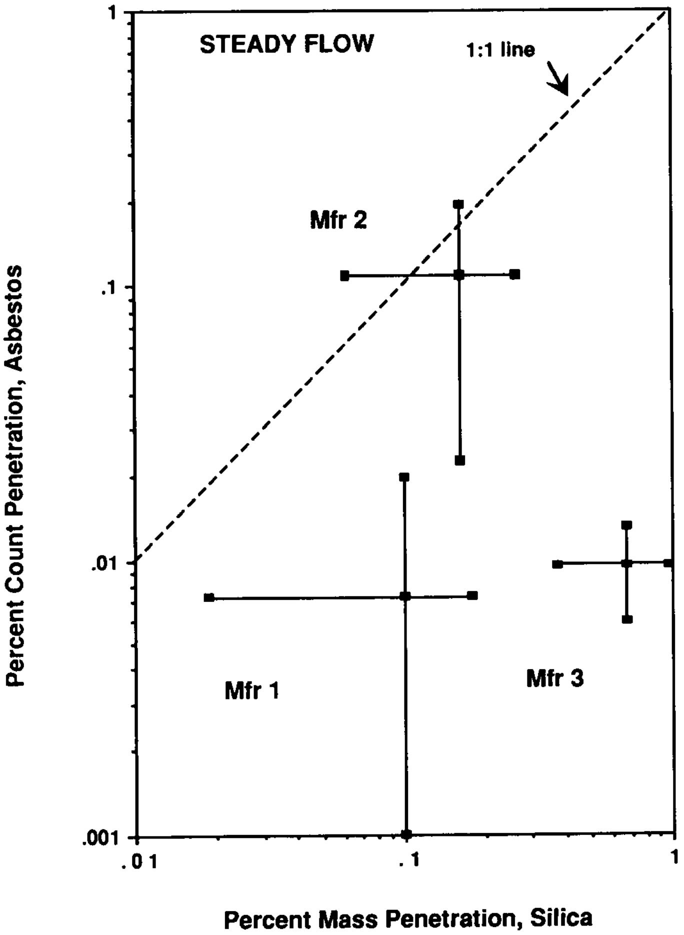

Figure 5—Steady flow, silica versus asbestos.

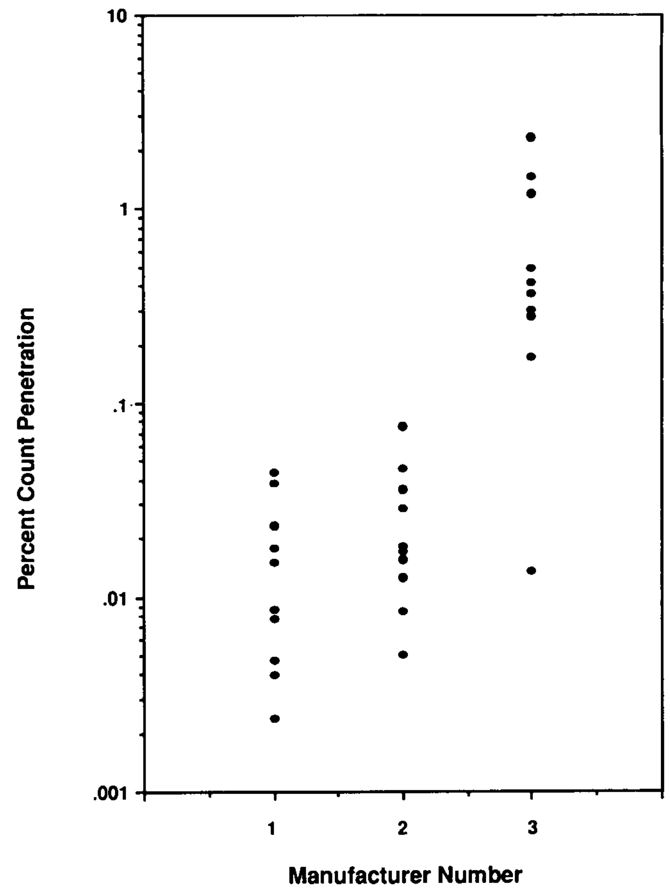

Figure 6—Penetration of asbestos at cyclic flow.

Exhalation Valve Failure

Although it is possible that the poor performance of Manufacturer #3's respirators under cyclic flow may have been caused by facepiece leakage, visual inspection of the respirator suggested that leakage was probably caused by faulty exhalation valves. Scrutiny of Manufacturer #3's used valves revealed that the cyclic flow pattern caused the valves to deform, becoming convex rather than concave; this change in form apparently affected the valve's ability to close during the inhalation cycle.

One initially puzzling aspect of this explanation of the asbestos data is that similar degradation of Manufacturer #3's valve performance was not evident from results of the silica cyclic flow experiments. This apparent discrepancy may be related to size-dependent penetration of the leaky valve and valve seat. Because smaller particles have less inertia, they may follow more easily the tortuous airflow paths around a valve and through the valve seat openings. Relatively large changes in the penetration of small particles are necessary to produce noticeable changes in mass penetration; however, these same changes are readily observed using measurements of count penetration. Thus, it is possible that degradation of Manufacturer #3's valve performance also occurred in the silica cyclic flow experiments, but that it was not detectable.

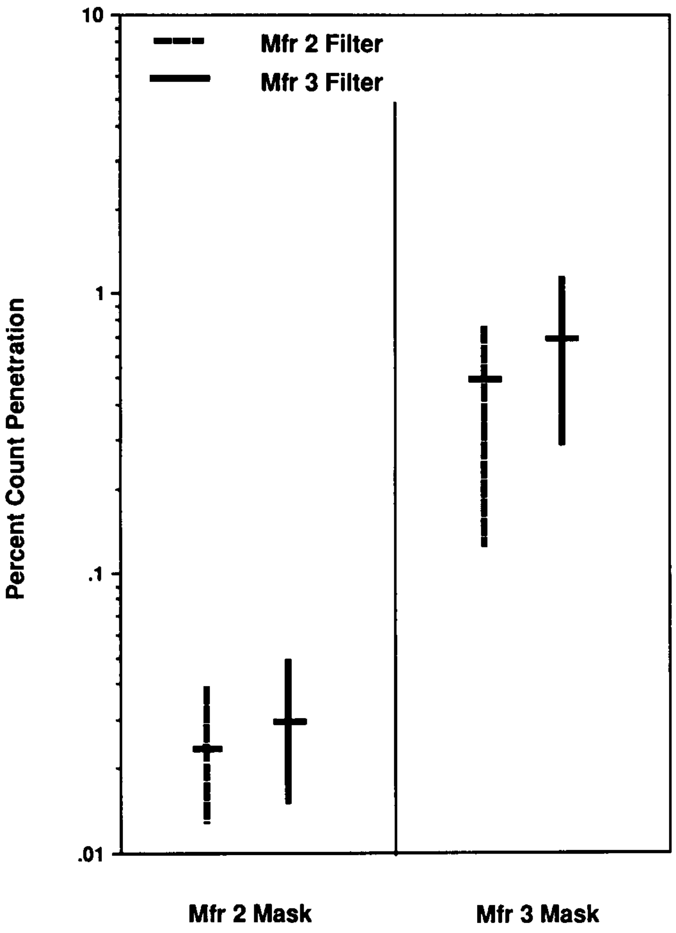

Figure 7—Results with switched filters and facepieces for Manufacturers #2 and #3.

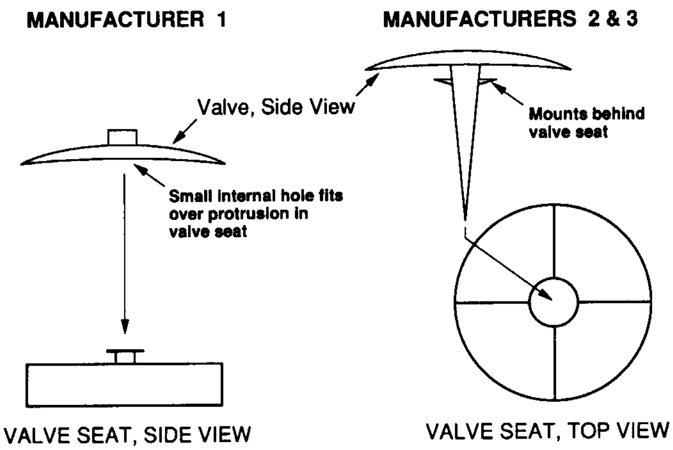

Figure 8—Description of exhalation valves.

There is no obvious explanation for the apparent failure of Manufacturer #3's exhalation valves. All three manufacturers' exhalation valves are of essentially similar design, consisting of a slightly concave rubber disc (Figure 8). Those of Manufacturers #2 and #3 are attached to the valve seat by a long, thin stem projecting from the center of the disc, which is pulled through an opening in the valve seat; Manufacturer #1's valves are attached by slipping a reinforced hole in the valve's center over a plastic protrusion on the valve seat. The valves of Manufacturer #1 also differ slightly in shape from those of Manufacturers #2 and #3 in that they are not entirely concave, but rather consist of an inner flat portion and a slightly concave outer component.

Work by the Los Alamos National Laboratory, using a polydisperse Di-2-Ethylhexyl Sebacate (DEHS) aerosol (no size distribution was indicated) found that, after 5–6 min at a cyclic flow at a work rate of 622 kg-m/min, the penetration through exhalation valves of similar design was less than or equal to 0.01%.(19)

Using small particles (0.2 μm) and longer testing periods (60 min) Burgess and Anderson(20) evaluated the performance of "mushroom" valves similar to those used in the respirators the present authors tested. Penetration of new valves was typically less than 0.01% even at airflow rates higher than those used in the present experiments. Used valves exhibited lower instantaneous penetration than did new valves. This improvement in performance was thought to be the result of valve and seat conditioning. Discarded valves exhibited exceptionally low opening pressures, thought to be caused by incomplete seating and warped valve diaphragm elements. (No evaluation of aerosol penetration through discarded valves was reported.) The findings of Burgess and Anderson suggest that during the life cycle of an exhalation valve performance may at first improve because of conditioning, but will eventually degrade because of warping and other physical changes.

Dust/Mist Respirators in an Asbestos Atmosphere

The authors' results with amosite indicate that (with properly functioning exhalation valves) dust/mist filter penetration would be expected to be less than 0.1%. Even when exhalation valves failed (i.e., Manufacturer #3, cyclic flow), the typical count penetration was less than 1%.

Recent work by Ortiz et al.,(21) using UICC chrysotile asbestos at relatively low concentrations (5–50 f/cm^3), found similar values of count penetration (less than 0.1%) for electret and resin-impregnated wool felt respirator filters, for 1-hr tests at a continuous flow of 0.032 m^3/min.

Although asbestos penetration through these filters was relatively low under the authors' experimental conditions, current regulations do not allow the use of dust/mist respirators in asbestos atmospheres. This is in part because factors such as high humidity, high temperature, or exposure to oil or solvent mists can degrade filter performance; and in part because charged particles may be collected with different efficiencies than the neutralized aerosols used in the authors' experiments.(21,22)

CONCLUSIONS

This study suggests that the results of respirator tests using silica aerosols may not be indicative of the performance that will be experienced when respirators are challenged with asbestos aerosols. Furthermore, the study indicates that greater aerosol penetration occurs under conditions of cyclic flow than under steady flow. Finally, it appears that the stress on exhalation valves under cyclic flow may be sufficient to induce valve failure and thereby dramatically increase aerosol penetration into the respirator.

NIOSH testing methods, which rely on assessment of mass penetration of silica aerosols under steady flow conditions, should be reconsidered. In addition, methods for evaluating the life-cycle performance of respirator components such as exhalation valves should be developed.

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