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Method for Measuring the Spatial Variability of Aerosol Penetration Through Respirator Filters

Fibrous filter media are widely used in respirators to remove airborne particulate matter from the inhaled airflow of workers. The N95 half-mask particulate respirator appears to be the most frequently used respirator under the new NIOSH regulation, 42 CFR 84. Considerable spatial variability in light penetration through the fibrous filter medium of an N95 respirator can be seen by visual observation when it is held to the light. This variability is due to the way in which the fibers are manufactured and laid down to form the filter medium. Similar spatial variability is expected in the aerosol penetration through the filters. Therefore, a test method has been developed for measuring the spatial variability in aerosol penetration. The main components of this method are an aerosol generator, a filter test stand with a movable sampling inlet, an aerosol size spectrometer, and an aerosol photometer. Measurements with the filter media of N95 respirators, tested at average filtration velocities corresponding to light, moderate, and heavy work loads, have shown spatial variations in aerosol penetration in excess of 100% relative to the average aerosol penetration for the entire respirator. N95 respirators are required to be at least 95% efficient (i.e., less than 5% penetrating) at the most penetrating particle size, when tested at 85 L/min. Tests with the new method have shown that the aerosol penetration of the most penetrating particles of about 0.1 μm diameter may locally be higher than 5%, while the average aerosol penetration of 0.1 μm particles is less than 5%.

Keywords: aerosol penetration, filter medium, respirator, spatial variability

Respirators are used in industry and in health-care facilities to protect workers against hazardous airborne particles and bacteria. Air-purifying, half-mask respirators are particularly prominent for respiratory protection. The filter medium is the main functional component of the respirator for removing airborne particulate matter. In an elastomeric half facepiece, consisting of a silicone or rubber facepiece with replaceable cartridge(s), the filter medium is contained in a cartridge or cartridges; in a disposable or single-use half-mask respirator, also referred to as a filtering facepiece, the filter medium is usually placed between a cover web on the outside and a supporting shell on the inside. While many high-efficiency respirator filters are made of folded fibrous paper media that do not contain any electrostatic charges, most of the less efficient filters consist of randomly laid nonwoven fibers, compressed natural wool, or

synthetic fiber felt. The latter two may be blended with each other. Most of the filter media used in filtering facepieces have electrostatic charge imparted to them during manufacturing.⁽¹⁾

When a respirator is worn, airborne particles are collected throughout the depth of the filter by diffusion, interception, inertial impaction, sedimentation and electrostatic attraction.⁽²⁾ The collection efficiency of a fibrous filter depends on its mechanical characteristics, such as fiber diameter, fiber orientation, packing density, and the electrostatic charge level on the fibers.⁽²⁻⁵⁾ For a given fibrous filter, the fiber diameters may range over a fairly wide size range.⁽⁶⁾ In addition, the fibers may not be uniformly packed in the filter mat. This can be observed easily by removing the cover web and support shell from a filtering facepiece and making a visual examination of the filter material. Spatial variations in fiber diameter, fiber orientation, packing density, and

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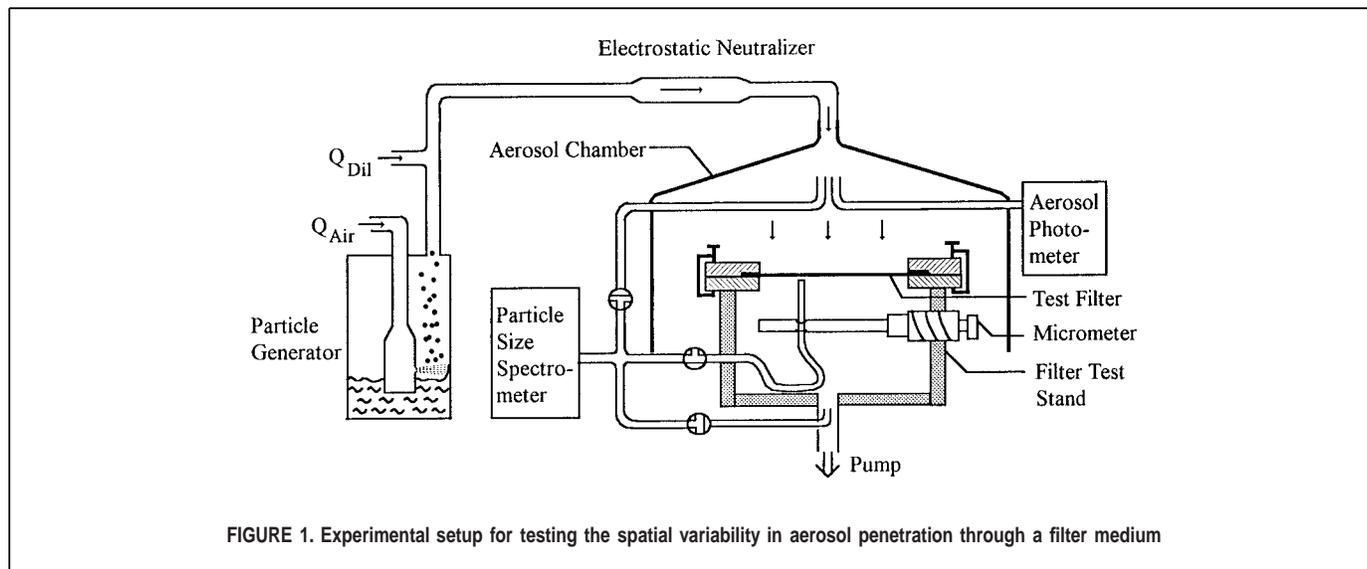


FIGURE 1. Experimental setup for testing the spatial variability in aerosol penetration through a filter medium

electrostatic charge level may result in significant variations of the collection efficiency throughout the filter medium.

Previous aerosol penetration studies have focused on the performance of large filter samples or entire respirators.⁽⁷⁻¹¹⁾ During a recent respirator filter study, the authors questioned the representativeness of a particular respirator filter sample. This question of representativeness may also be asked when only small filter samples are used.^(12,13) Therefore, the objective of this research was to develop a method for measuring the spatial variability in aerosol penetration through a filter.

EXPERIMENTAL METHOD, FILTER TEST STAND, AND MATERIALS

Figure 1 shows a schematic representation of the experimental setup, and Figure 2 highlights the important design considerations for testing the spatial variability in aerosol penetration through a filter medium. The experimental setup consists of three main parts: an aerosol generator, the filter test stand, and two aerosol analyzers. The test aerosol is generated from a liquid solution by use of a three-hole Collison nebulizer (BGI, Inc., Waltham, Mass.). The effluent flow, Q_{Air} , is typically 3 L/min. It is mixed with clean dilution air, Q_{Dil} , of about 10 L/min to dry the aerosol and to attain an aerosol concentration of about 7.8×10^7 particles/m³ for 0.27 μ m particles. The test aerosol then passes through an electrical charge neutralizer with a 10 mCi ⁸⁵Kr radioactive source (TSI, Inc., St. Paul, Minn.) to bring the electrical charge level of the aerosol to Boltzmann charge equilibrium before entering the testing chamber.⁽⁷⁾

The specially designed filter test stand is placed in the test chamber, as shown in Figure 1. In the present configuration the filter sample being tested is held between two plates by C-clamps. Flat rubber gaskets between the plates and the filter sample seal the space downstream of the filter from the space upstream. A micrometer-mounted sampling inlet located immediately below the filter sample measures the aerosol passed through the filter area that corresponds to the inlet dimension. The micrometer moves the inlet up to 5 cm (2 inches) in one direction. In principle, a two-way micrometer system could have been used to measure the spatial variability of aerosol penetration in two perpendicular directions. In the device used in this study, the location of

the first scan was marked on the test filter, and subsequent parallel scans were made by moving the filter perpendicularly to the scan direction. Care was taken not to scan any part of the filter that had previously been held between two plates.

In the test stand, an identical sampling inlet is mounted upstream of the filter in the center of the aerosol chamber. Both inlets, up- and downstream of the test filter, are connected by valves to an aerosol size spectrometer (model LAS-X, Particle Measuring Systems, Inc., Boulder, Colo.), which alternatively records the aerosol concentrations up- and downstream of the filter sample. Another sampling inlet, mounted in parallel with the upstream sampling inlet, is connected to an aerosol photometer (model RAM-S, MIE, Inc., Bedford, Mass.), which monitors the constancy with time of the upstream aerosol concentration in the test chamber.

To test a filter medium at conditions that are relevant to their use in the workplace, several test design conditions had to be satisfied. The principal ones are schematically represented in Figure 2. Figure 2A shows that the average flow velocity through the filter medium, V_{Filter} , depends on the average breathing flow rate, $Q_{Inhalation}$, and the effective filtration area, A_{Filter} . Typical breathing flow rates are approximately 30 L/min, 60 L/min, and 85 L/min under light, moderate, and heavy work loads, respectively.^(14,15) The new NIOSH regulation⁽¹⁶⁾ requires a flow rate of 85 L/min for the certification test of a respirator. Currently available disposable half-mask respirators contain filter media of about 170 cm². However, the exhalation valve, if present, and the material sealing the respirator against the face reduce the effective filter area to about 120 cm². The average filtration velocity has been determined by dividing the breathing flow rate by this effective filter area. For a respirator with an effective filtration area of about 120 cm², the average filtration velocities are, therefore, about 4 cm/sec, 8 cm/sec, and 12 cm/sec for light, moderate, and heavy work loads, respectively.

To investigate the spatial variability in aerosol penetration through a respirator filter, filter medium samples were cut from disposable half-mask respirators and clamped in the test stand, as shown in Figure 2B. The effective filtration area of each sample was 7×1.5 cm². The tested filter size is based on the 5-cm maximum linear movement limitation of the micrometer. The total filtration area of 10.5 cm² in the test stand was about one-tenth

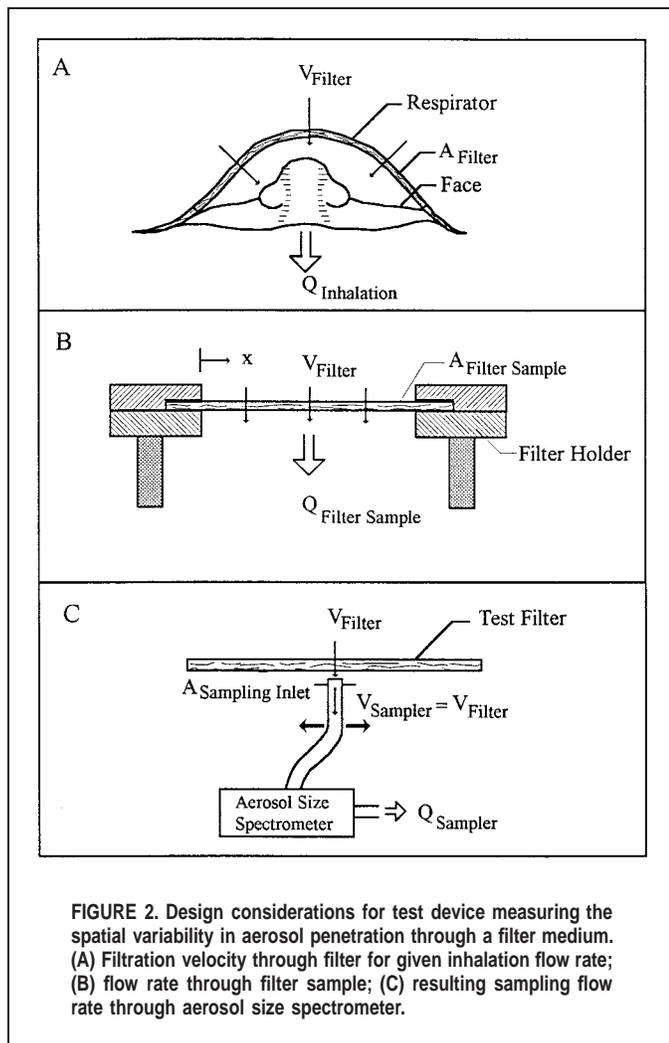


FIGURE 2. Design considerations for test device measuring the spatial variability in aerosol penetration through a filter medium. (A) Filtration velocity through filter for given inhalation flow rate; (B) flow rate through filter sample; (C) resulting sampling flow rate through aerosol size spectrometer.

of the effective respirator area. To test the filter samples at about the same filtration velocities as during actual wear, the suction airflow rate through each filter sample, $Q_{\text{Filter Sample}}$, was set at 2.5 L/min, 5.0 L/min, or 7.5 L/min, which approximately corresponds to filtration velocities under light, moderate, or heavy work loads, respectively.

As shown in Figure 2C, the movable aerosol sampling inlet below the test filter was connected to the LAS-X aerosol size spectrometer. The inner diameter of the sharp-edged sampling inlet was chosen so that the sampling flow rate through the sampling inlet is in the permissible range of the aerosol size spectrometer, and the air sampling velocity through the inlet, V_{Sampler} , equals the filtration velocity, V_{Filter} . Thus, the inner inlet diameter was chosen to be 0.5 cm, which requires flow rates through the LAS-X aerosol size spectrometer of about 0.05 L/min, 0.09 L/min, or 0.14 L/min for the three work load conditions. Since the sampling velocity is isokinetic or close to isokinetic relative to the flow through the filter, this experimental setup has a resolution of 0.5 cm in measuring aerosol penetration through a respirator filter.

The downstream sampling inlet is mounted as close as possible to the filter sample so that the aerosol size spectrometer registers only those aerosol particles that have penetrated through the filter area immediately above the inlet. As the inlet was moved along the x-direction (see Figure 2B), 11 concentration values of penetrated aerosols were measured in 0.5-cm intervals over a total

scan length of 5 cm, starting 1 cm from the left edge of the test filter. The aerosol penetration, P , through each 0.5 cm diameter area of the filter sample is obtained by dividing the downstream by the upstream aerosol concentration.

The test filter samples were cut from N95 half-mask respirators. These respirators have been certified by NIOSH under the new 42 CFR 84 regulation.⁽¹⁶⁾ They are tested with sodium chloride (NaCl) aerosol and are at least 95% efficient at the most penetrating particle size, which depends on the filter medium and flow conditions, and is generally in the 0.1 to 0.3 μm size range.⁽¹⁷⁾ One respirator, referred to as Company A, was chosen because its efficiency at the most penetrating particle size was well above the 95% level. A second respirator was chosen because it had an average efficiency at the most penetrating particle size of just above 95%.

The aerosol was generated from a 4% (by mass) solution of NaCl in distilled water, which resulted in an aerosol in the submicrometer size range. The aerosol concentrations were measured by the aerosol size spectrometer at the following four particle sizes: 0.13 μm , which approximately corresponds to the most penetrating particle size for the tested filter materials; 0.27 μm , which is about twice that size; and 0.45 and 0.6 μm , for which the efficiency is significantly higher than for the most penetrating particle size.

Prior to taking the reported data, the LAS-X aerosol size spectrometer was calibrated with monodisperse polystyrene latex (PSL) test spheres ranging from 0.2 to 2.0 μm in size (Bangs Laboratories, Inc., Carmel, Ind.). Before use, each suspension of PSL particles was deagglomerated for 5 minutes in an ultrasonic bath (model 220, Branson Cleaning Equipment Co., Shelton, Conn.). Since the aerosol size spectrometer is a laser-based optical scattering device, the recorded particle diameter, d_{opt} , is an equivalent optical diameter that equals the physical diameter of a PSL particle, but may be somewhat different in size for a NaCl particle. Exact knowledge of the particle size is not relevant for this test method, because its focus is on the spatial variability of aerosol penetration.

The aerosol upstream of the test filter was uniformly distributed. The concentration difference between the center and other positions along the x-axis was less than 3%. The photometer continuously recorded the upstream aerosol concentration throughout the experiments, while the aerosol size spectrometer alternatively measured up- and downstream of the test filter. The photometer data showed less than 1% variation in the upstream aerosol concentration during each period of successive upstream measurements with the aerosol size spectrometer.

For each linear scan, the aerosol penetration through each of the 11 filter areas was measured in random order. At each location, at least three measurements were taken from which the mean and standard deviation were calculated and plotted. Tests with respirator filters from two different manufacturers are shown to demonstrate the capability of the new test method.

RESULTS AND DISCUSSION

Aerosol penetrations through the filter media of the two manufacturers are shown in Figure 3 for different filter locations. The left side of Figure 3 shows that the aerosol penetration, P , of 0.13 μm particles through the filter medium of the N95 respirator manufactured by Company A and tested under moderate work load conditions varies from an average of 1.3% at $x = 2$ cm to an average of 4.8% at $x = 2.5$ cm. The corresponding filter efficiency, $E = 1 - P$, shown as the right-hand ordinate, varies from 98.7 to 95.2%. The mean of the 11 aerosol penetration values is 2.1%. The highest local penetration measured at $x = 2.5$ cm is 128%

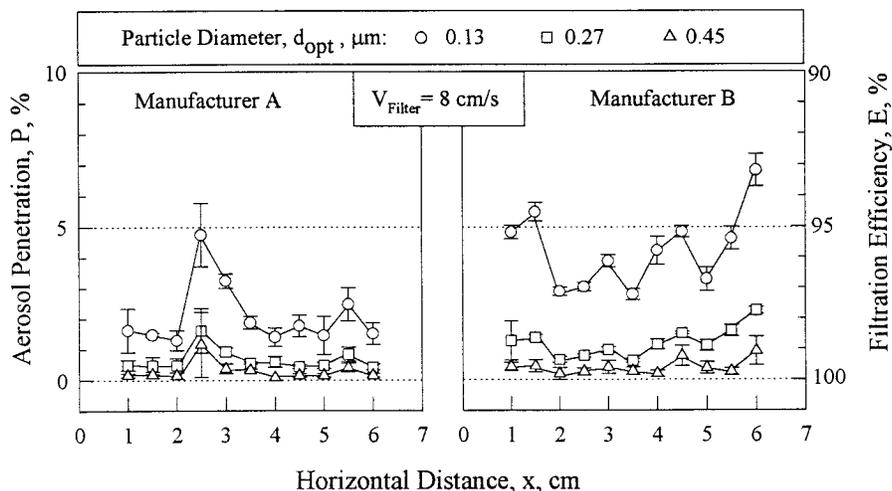


FIGURE 3. Spatial variation in aerosol penetration through two N95 filter media, measured at a filtration velocity of 8 cm/sec corresponding to the breathing flow rate under moderate work load conditions

higher than the average, and the lowest penetration at $x = 2$ cm is 38% lower than the average. This scan is typical for the filter medium of Company A. It shows considerable spatial variability.

As seen in Figure 3, the spatial variations in aerosol penetration are similar for 0.27 μm and 0.45 μm particles. However, the variations are not seen as easily for the 0.45 μm particles, because the aerosol penetration values are closer to zero. For 0.6 μm and larger particles, the aerosol penetration values are close to zero and their spatial variations are difficult to resolve. They are, therefore, not shown in Figure 3.

For the filter medium manufactured by Company B, the average aerosol penetration of 0.13 μm particles is 4.2%, that is, twice the aerosol penetration of the filter medium manufactured

by Company A when tested under the same conditions. The highest 0.13 μm particle penetration found at $x = 6$ cm is 62% higher and the lowest penetration found at $x = 3.5$ cm is 33% lower than the average penetration, (i.e., there is less spatial variability of aerosol penetration than for the filter manufactured by Company A). Visual observation of the filter medium confirmed less spatial variability of the fiber distribution in the filter of Company B.

Figure 4 shows the spatial variability in aerosol penetration through Filter Medium A at the three filtration velocities that correspond to light, moderate, and heavy work loads. The highest filtration velocity of 12 cm/sec approximately corresponds to the certification test flow rate of 85 L/min. As seen, the average aerosol penetration of NaCl particles of approximately the most penetrating size (0.13 μm) is 3.7% at the certification flow rate, well below the upper limit of $P = 5\%$ ($E = 95\%$). However, the highest aerosol penetration for this scan is 7.6% at $x = 2.5$ cm ($E = 92.4\%$). Thus, this figure clearly shows that local areas of a filter may have aerosol penetrations well in excess of the permitted average value. Expressed differently, local areas of a filter may have efficiencies well below the permitted average value. The other two curves for lower filter velocities show similar spatial variations in aerosol penetration. The middle curve for $V_{\text{Filter}} = 8$ cm/sec is the same as the top curve of Figure 3A. The penetration values are lower at lower filter velocities, because the submicrometer particles have more time to be removed by the electrically charged fibers.⁽⁹⁾ Thus, filter media are more efficient in removing aerosol particles at light or moderate work loads, that is, at flow rates below the certification flow rate of 85 L/min.

Although the aerosol penetration may locally be higher than the certification value, the respirator still passes the certification test, if the aerosol penetration through the entire respirator is below the certification limit.

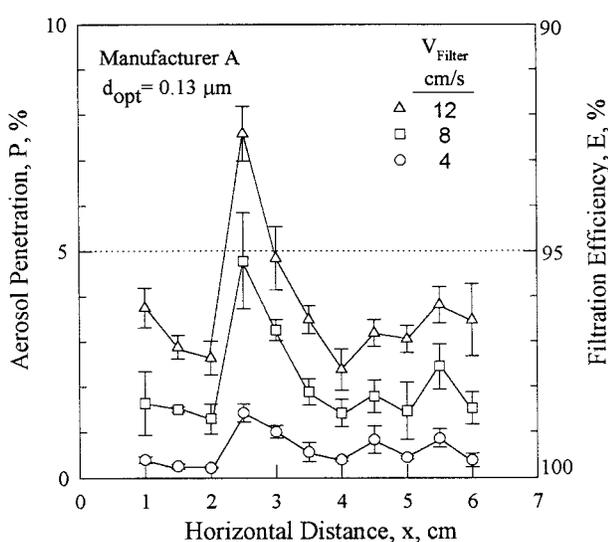


FIGURE 4. Spatial variation in aerosol penetration through an N95 filter medium, tested at filtration velocities corresponding to breathing under light, moderate, and heavy work loads

CONCLUSIONS

The test stand and experimental setup have been designed to measure the spatial variability in aerosol penetration through a respirator filter medium at flow conditions that correspond to actual wear of the respirator. Spatial variations of over 100% from

the average aerosol penetration have been measured in tests with filter media of N95 respirators certified under the new NIOSH regulation 42 CFR 84. The degree of variability depends on the manufacture of the filter medium, and is observed most easily at the most penetrating particle size (ca. 0.1 to 0.3 μm). Tests at the filtration velocity that corresponds to the certification test flow rate of 85 L/min have shown that local areas of an N95 respirator filter may have aerosol penetrations well in excess of the 5% limit ($E = 95\%$), while the average aerosol penetration through the entire respirator is well below this limit.

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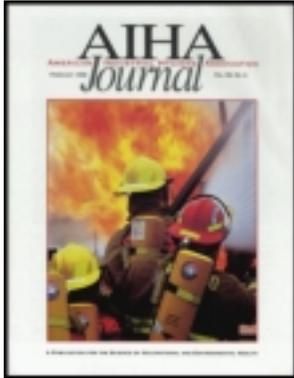
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