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# Aerosol Loading Performance of Electret Filter Media

In this study various types of flat sheet electret filter media including tribocharged polypropylene/acrylic, corona charged polypropylene, fibrillated electret film, and new advanced electret media have been compared with mechanical filter media (fiber glass) using aerosol filtration tests designed for particulate respirators. The number of layers, and thus the total mass and pressure drop, of the media were varied while the filter area exposed to the aerosol and the aerosol flow rate was held constant (constant face velocity). Tests included challenges with sodium chloride and dioctyl phthalate (DOP) aerosols per NIOSH 42 CFR 84 specifications for particulate respirator certification. Initial filtration efficiency and pressure drop and the same during loading were determined. Results revealed significant differences in filtration performance and loading behavior among the various media. It is concluded that respirators can be designed for all nine 42 CFR 84 classes using electret filter media without sacrificing low pressure drop, light weight, or user comfort.

**Keywords:** electret filter media, electrostatic, respirators

Fibrous electret filter media have been used in particulate respirators for many years. The electrostatic charge on electret filter media enhances the filtration efficiency over that of purely mechanical filters. The enhanced efficiency results in an electret filter with less breathing resistance (lower pressure drop) than a mechanical filter with the same efficiency and surface area. Respirators utilizing electret filter media can generally be made lighter in weight and more compact than those made from mechanical filter media. Therefore, electret filter media is especially suited to filtering facepieces. However, the efficiency of electret filter media can be reduced by exposure to certain aerosols;<sup>(1-5)</sup> mechanical filters are generally more resistant to this type of efficiency loss.

Recently a new NIOSH regulation for respiratory protection devices, 42 CFR 84, became law. The filter test method required by 42 CFR 84 for negative pressure respirator certification specifies minimum filtration efficiencies during loading of the respirator with a specified amount of most penetrating-size particles of solid sodium chloride aerosol or oily liquid dioctyl phthalate (DOP) aerosol. These loading tests have been shown to decrease the filtration efficiency of certain types of electret media.

Liquid aerosols from oils such as DOP with a relatively high dielectric constant can decrease

the filtration efficiency of electret filters. Liquids generally do not form a filter cake, as do solid particulates. Formation of a filter cake increases the efficiency of mechanical filtration.<sup>(5)</sup> Filter caking can have a significant effect on filtration for relatively fine fiber electret filter media when challenged by solid particulate aerosols.

Possible mechanisms for loss of filtration efficiency of electrostatic filters caused by certain aerosols are discussed by Brown<sup>(2)</sup> and include the following:

- (1) neutralization of the charge on the fiber by opposite charges on the captured aerosol particles,
- (2) screening of the fiber charge by a layer of captured particles, and
- (3) disruption of the charge-carrying part of the fiber by the aerosol, either by dissolution of the surface layer or by chemical reaction.

Tennal et al.<sup>(3)</sup> suggest that ionic conduction through an oil film on the fiber due to deposited droplets causes discharge of the electrets when liquid aerosols are involved.

Blackford et al.<sup>(4)</sup> tested seven industrial aerosols including coal dust, foundry fettling fume, foundry burning fume, carbon brick dust, lead smelting fume, lead battery dust, and ammonium chloride. Four different types of electrostatic material were used in the investigation: resin-wool,<sup>(6)</sup> large fibers made from fibrillated electret

TABLE I. Types of Filter Media Tested and Properties of a Single layer

Filter Media Type	Basis Weight (g/m <sup>2</sup> )	Thickness (mm)	Pressure Drop mmH <sub>2</sub> O @ 7.8 cm/sec	Effective Fiber Diameter <sup>(11)</sup> (μm)
Fiber glass (several types tested)	60–95	0.5–0.7	6–55	1–3
Tribocharged polypropylene/acrylic	150	3.2	0.8	31
Fibrillated polypropylene film	100	2.4	0.7	22
Electrostatic charged polypropylene BMF	60	0.9	3.2	8
N-type advanced electret	60	0.9	3.0	8
R-type advanced electret	60	0.9	2.8	8
P-type advanced electret	60	1.0	3.8	7

film,<sup>(7)</sup> and electrostatically spun material including a polycarbonate material produced from a solution<sup>(8)</sup> and a polypropylene material produced from the melt.<sup>(9)</sup> They reported increasing penetration with aerosol loading in all cases for all filter types.

Tennal et al.<sup>(3)</sup> tested a spun-type electret filter using mono-disperse bis-ethylhexyl sebacate liquid aerosols with zero charge and with an equilibrium charge distribution. The loading estimated to discharge the filter completely was calculated by assuming that each collected charge neutralized one charge of opposite polarity on the fibers of the filter. When the calculated results were compared with the experimental results, it was found that the calculation significantly underestimated the effect of the aerosol (by almost three orders of magnitude). It was also determined that there was no difference between the effect of loading with equilibrium charge droplets and zero charge droplets. Based on these results they concluded that direct neutralization of the fiber charges by charged aerosol is not the mechanism responsible for the reduction in filter efficiency with loading.

Whatever the mechanism, the potential reduction in filtration efficiency of electret filter media by the aerosols they filter is a concern to those responsible for respiratory protection. In the current study traditional and advanced electret filter media were tested with sodium chloride and DOP aerosols using the most penetrating particle size as specified in the respirator certification tests in 42 CFR 84.<sup>(10)</sup>

## MATERIALS AND METHODS

The chosen filter materials were typical of those used in commercially available particulate respirators. The general classes of materials tested and properties measured on a single layer of material are listed in Table I. Fiber glass filter media of varying fiber size and weight were purchased from Hollingsworth & Vose of West Groton, Mass. Tribocharged polypropylene/acrylic was obtained from All Felt Products, Inc. of Ontario, Calif., sold under the Technostat trade name. Fibrillated electret polypropylene film, electrostatically charged polypropylene blown microfiber (BMF), and advanced electret media (AEM), a new class of filter media developed by 3M of St. Paul, Minn., were all produced by 3M and included in this study.

The filter materials of Table I were tested as flat samples using a 6-inch diameter circular face area, at an aerosol flow rate of 85 L/min, following the test protocol specified by NIOSH for 42 CFR 84 respirator certification.<sup>(12,13)</sup> The area chosen for these tests is close to the area of most commercially available filtering facepiece respirators, so that respirator behavior should be similar

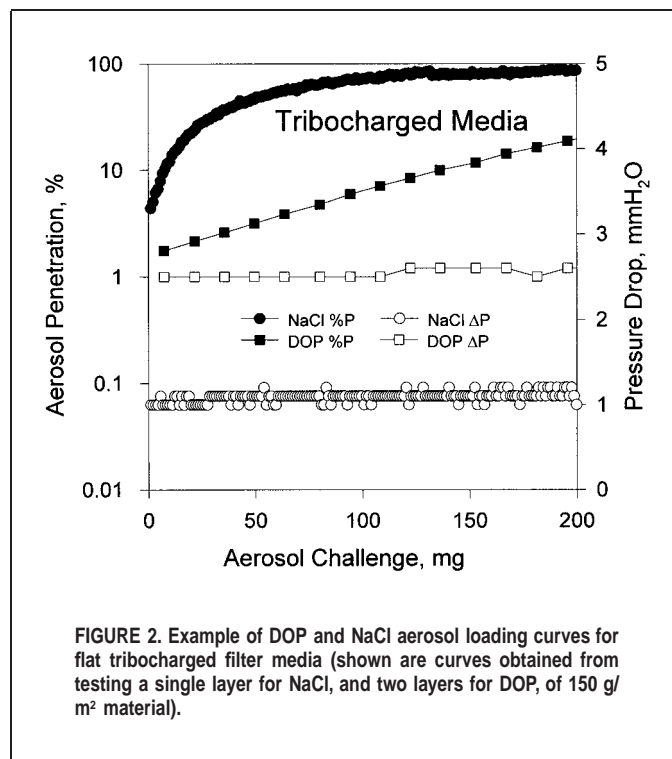
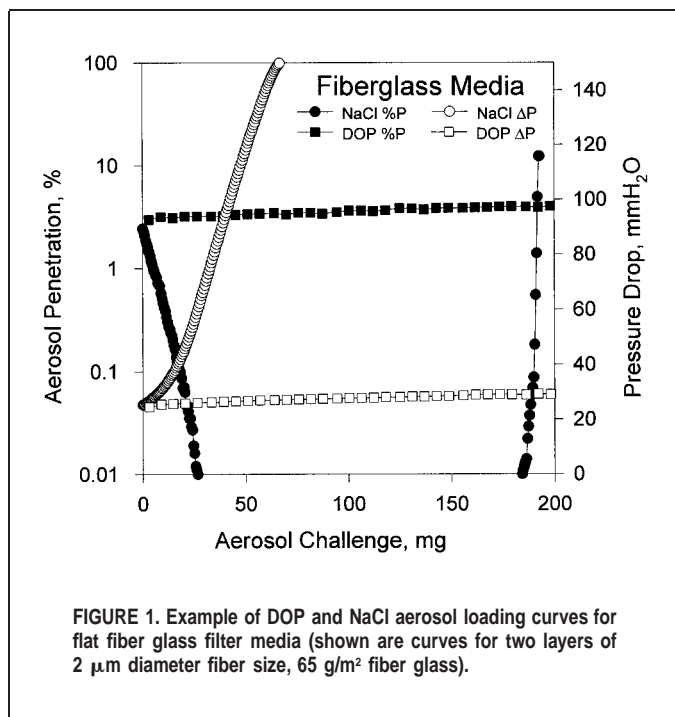
to that of the flat sheets. Two tests are used for certifying particulate respirator filter material under 42 CFR 84. For N-series particulate respirators, the maximum sodium chloride aerosol penetration during a 200-milligram loading test is specified. For R-series, the maximum DOP penetration during a 200-milligram loading test is determined, and for P-series it is further required that the DOP penetration must not be increasing at the end of the test. A TSI (St. Paul, Minn.) model 8130 automated filter tester was used for the N-series sodium chloride aerosol loading test, and a TSI model 8110 automated filter tester was used for the DOP aerosol loading test. Test conditions are outlined in Table II.

Additional samples of the filter materials were tested using multiple layered combinations. At least three different layered combinations, typically 1, 2, and 3 layers, were tested in triplicate to achieve a range in pressure drop and thickness. For each test both aerosol penetration and pressure drop were recorded as a function of the mass of aerosol challenged to the filter, to produce what is herein called a loading curve. The sodium chloride test typically lasted more than 2.5 hours for each sample, due to the low aerosol concentration, while the DOP test was normally completed in less than 30 minutes for each sample.

It should be emphasized that these tests were performed on flat samples of filter material using a constant surface area, and not on respirators. The area chosen in these tests is similar to that of most filtering facepiece respirators; however, results of testing on respirators may or may not be analogous, depending on the particular respirator design and filter construction.

TABLE II. Summary of Test Conditions Used

Test Condition	NaCl Aerosol Test (for N-series)	DOP Aerosol Test (for R- and P-series)
Instrumentation	TSI AFT model 8130	TSI AFT model 8110
Filter size	6" circle (182 cm <sup>2</sup> )	6" circle (182 cm <sup>2</sup> )
Aerosol material	sodium chloride (solid)	dioctyl phthalate (oily liquid)
Aerosol flow rate	85 L/min	85 L/min
Aerosol face velocity	7.8 cm/sec	7.8 cm/sec
Aerosol particle size (count median diameter)	0.08 μm	0.18 μm
Aerosol particle size (mass median diameter)	0.2 μm	0.3 μm
Aerosol concentration	15 mg/m <sup>3</sup>	100 mg/m <sup>3</sup>
Aerosol challenge	200 mg	200 mg



## RESULTS

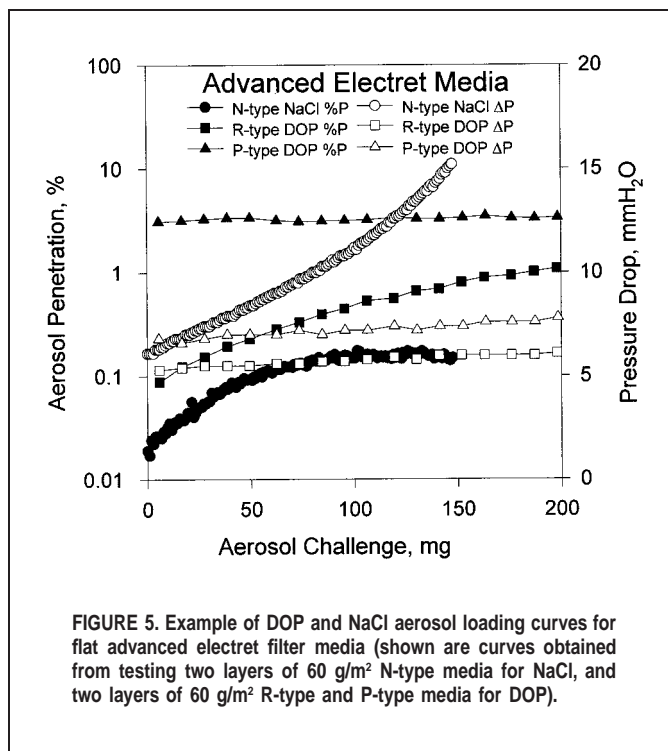
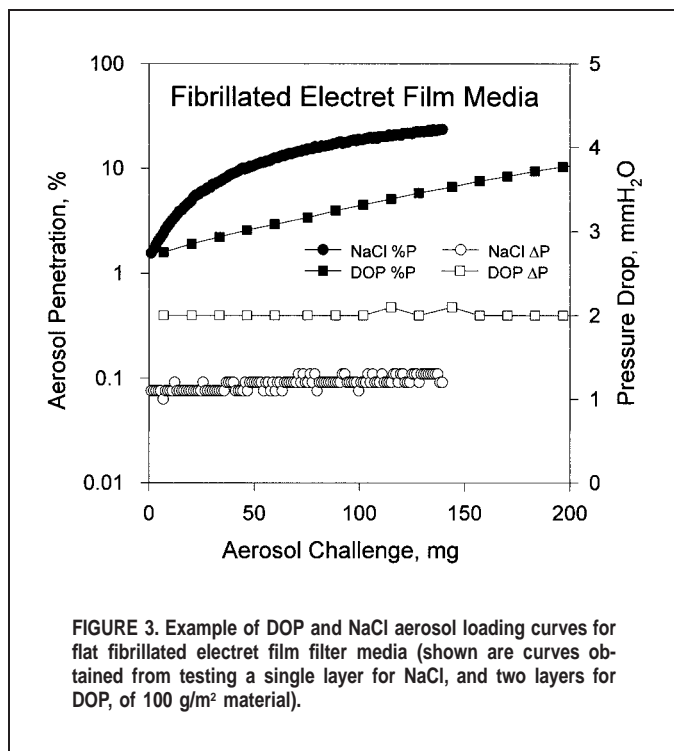
Typical DOP and NaCl loading curves for fiber glass media are shown in Figure 1 for two layers of medium with 2  $\mu\text{m}$  diameter fiber size and 65  $\text{g}/\text{m}^2$  basis weight. With DOP loading, a relatively constant penetration versus loading was observed, but it increased from about 3% initially to 4% penetration during the test. Pressure drop increased about 15% during the typical fiber glass media DOP test. With sodium chloride loading, the penetration rapidly decreased while the pressure drop rapidly increased. This is due to filter caking, where the solid particles build up on the surface of the media and contribute to the filtration by enhancing the mechanical filtration mechanisms while also increasing pressure drop.<sup>(14)</sup> During the test depicted in Figure 1 the pressure drop actually increased to the point that the fiber glass burst apart, as seen by the final dramatic increase in penetration. Because of this, fiber glass media as used in respirators normally require greater filter areas, accomplished by pleating. By using greater filter area, the aerosol face velocity and effective surface loading rate is significantly reduced, resulting in lower pressure drop and penetration.

Tribocharged filter media are produced by processing a blend of fibers that have a large triboelectric potential difference. The fibers are brushed against each other, resulting in charged fiber surfaces.<sup>(15)</sup> Tribocharged filter media are generally composed of large diameter fibers, which also tend to have a high level of electrostatic charge. The material is very thick and fluffy compared with fiber glass, and has a much lower pressure drop at any given penetration level. Typical loading curves for tribocharged filter media are shown in Figure 2 (shown are curves obtained for a single layer for NaCl, and two layers for DOP, of 150  $\text{g}/\text{m}^2$  material). During the 200-milligram DOP loading test, penetration typically increased an order of magnitude, in this case from an initial penetration of about 2% to 20%, while pressure drop remained essentially constant. This type of medium relies heavily on

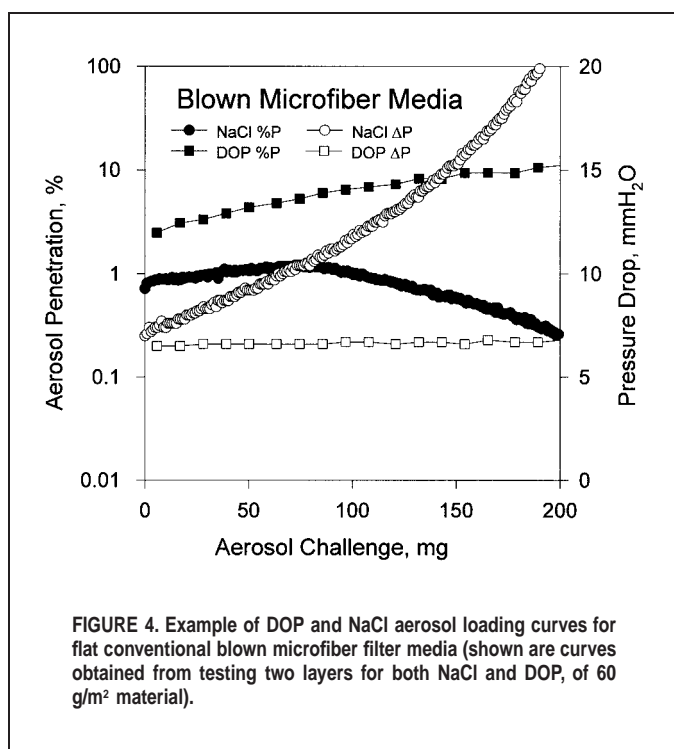
electrostatic charge enhancement for filtration, and because the collected oil aerosol particles mitigate the electrostatic charge, penetration continually increases with loading. Similar behavior is observed with sodium chloride loading; penetration also rapidly increases, in the case shown to more than 80%, while pressure drop remains constant. Because these large fiber, fluffy media do not form a filter cake, the pressure drop does not change much with loading, so it is well-suited for furnace or other ventilation filters where a rise in pressure drop is undesirable.

Fibrillated electret film media are produced by creating a surface charge on a film made of highly oriented plastic, then breaking the film into fibers and creating a fibrous web (fibrillation).<sup>(7)</sup> The filtration behavior of fibrillated electret film media is similar to that of tribocharged media, as may be seen in comparing Figure 3 with Figure 2. The fibrillated electret film of Figure 3 had lower basis weight than the tribocharged media of Figure 2, 100  $\text{g}/\text{m}^2$  versus 150  $\text{g}/\text{m}^2$ , yet exhibited slightly lower penetration and significantly lower pressure drop. Even at the lower basis weight, the fibrillated electret film is less affected by NaCl loading than the tribocharged media. Both fibrillated electret film and tribocharged media have large fiber size and high electric charge. Again, because caking occurs only very slowly, pressure drop remains relatively constant with particle loading, while penetration rapidly increases.

Electrostatically charged polypropylene blown microfiber, or conventional BMF, is widely used for filtering facepiece respirators. This filter medium is produced by extruding polypropylene through a multiorifice die to form fibers while also blowing the molten fiber stream out of the die and onto a collector with high-pressure air.<sup>(16)</sup> The BMF may be electrostatically charged by numerous methods.<sup>(17)</sup> Typical loading curves obtained for conventional BMF are shown in Figure 4 (results from two layers of 60  $\text{g}/\text{m}^2$  material shown). On exposure to oily liquid DOP aerosol, the BMF exhibited an increase in penetration from about 2% initially to 10%, a smaller increase than for the large fiber media previously discussed, but significantly more than fiber glass. With



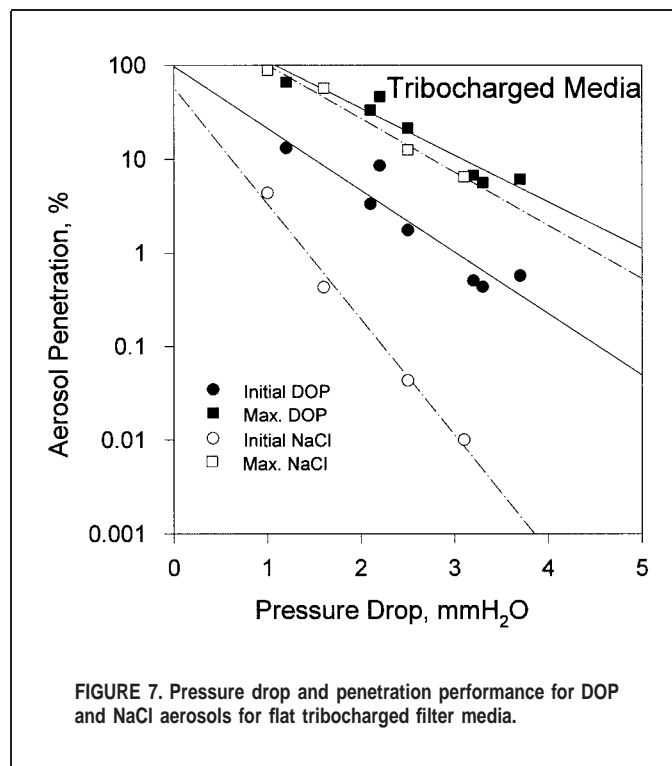
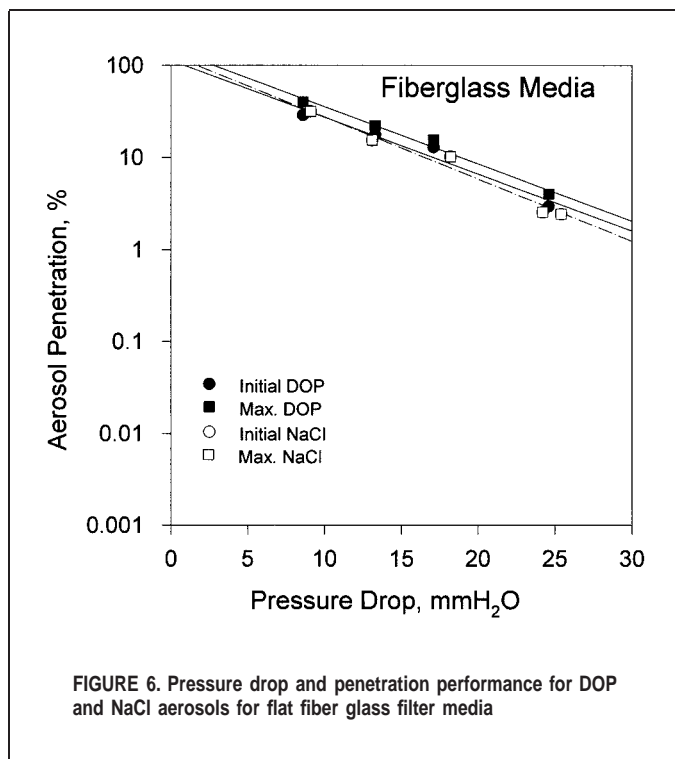
solid sodium chloride particle loading, a filter cake formed on the BMF, so that penetration decreased with loading, similar to fiber glass, but the cake formed more slowly, resulting in a more gradual increase in pressure drop. Overall, electrostatically charged BMF has characteristics between that of fiber glass, which has very small diameter fibers and essentially no electric charge, and tribocharged or fibrillated electret film media, that have large diameter fibers and high electric charge.



Over the past several years, 3M has developed technologies to improve the filtration characteristics of electrostatically charged BMF in both solid aerosol and oily mist environments. Loading curves obtained from two layers of 60 g/m<sup>2</sup> material are shown in Figure 5 in which filter media were designed for N, R, or P performance criteria. By increasing both the DOP resistance and level of electrostatic charge on the fibers, media suitable for NIOSH 42 CFR 84 R-series may be produced that have low pressure drop at a given DOP penetration level. The trade-off for this high-efficiency medium is increasing penetration with DOP loading. In the example shown in Figure 5, the loading behavior is similar to conventional electrostatically charged BMF, but with at least 10 times lower penetration at about the same pressure drop. Alternatively, by providing resistance to DOP and adjusting the charge level, media may be made that is suitable for the P-series of respirators, where constant or decreasing penetration during DOP loading is required. The loading curve for a P-type medium is shown in Figure 5 and is actually flatter than that for the fiber glass media previously shown, but with less than one-third the pressure drop at the same penetration. The trade-off for the flat P-type loading performance is greater pressure drop than the R-type media.

Like most other media, the R- and P-type media are actually more efficient filters of solid aerosols than oily liquids; however, for solid aerosols, even more advantage in pressure drop can be obtained through further charge level optimization. In the example of Figure 5, media were developed for NIOSH 42 CFR 84 N-series of respirators and were tested against sodium chloride aerosol. Compared with conventional BME, the pressure drop versus loading curves are nearly identical, but with the new N-type media, filter penetration is an order of magnitude lower at the same pressure drop and has from 10 to 35 times lower penetration than conventional electrostatically charged BMF.

After collecting multiple loading curves and assembling data from numerous layered combinations of a single type of filter medium, performance curves may be obtained in which penetration,



either initial or maximum during the loading test, may be plotted against another filter parameter such as pressure drop, thickness, or mass. While the loading curve indicates the behavior of a filter as it collects aerosol particles, the performance curve indicates the utility of that type of filter medium for providing a penetration level at a given pressure drop, thickness, or mass.

The first set of performance curves is shown in Figure 6, in which initial and maximum DOP and NaCl penetration are plotted against pressure drop for fiber glass media. In this type of plot, for the media indicated, one could predict the pressure drop and penetration of a filter as indicated by the fitted lines, as long as the same area is used (182 cm<sup>2</sup> in the case of this study). Higher performance filter media would have fitted lines with greater downward slope, or lower pressure drop at any given penetration. Increasing the filter area would shift the curve toward higher performance, with lower penetrations at all pressure drops. For the sodium chloride test the initial and maximum penetrations are the same, with data points falling on top of one another, which follows from the NaCl loading behavior observed in Figure 1. Since the DOP penetration was observed to rise slightly during the loading test, initial and maximum DOP performance are slightly different. In general, because of the lack of significant electrostatic charge, fiber glass media has poor filtration performance. For example, if a filter were to achieve 5% maximum DOP penetration, corresponding to a P95 respirator, using flat fiber glass media, the pressure drop would be at least 25 mmH<sub>2</sub>O, barely acceptable by 42 CFR 84 standards, and surely higher than what most users would find comfortable (using the 182 cm<sup>2</sup> filter area). For this reason fiber glass must be pleated to extend the filter area, and packaged in cartridges due to its fragility.

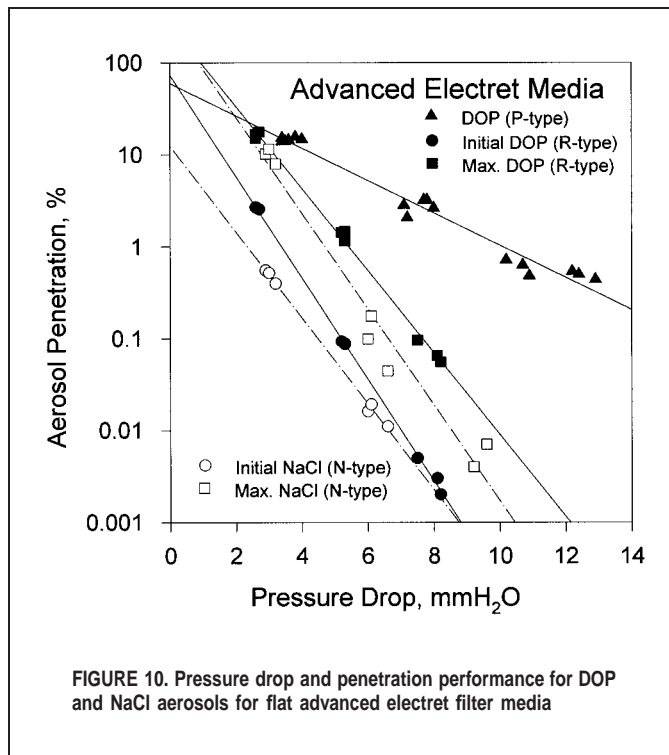
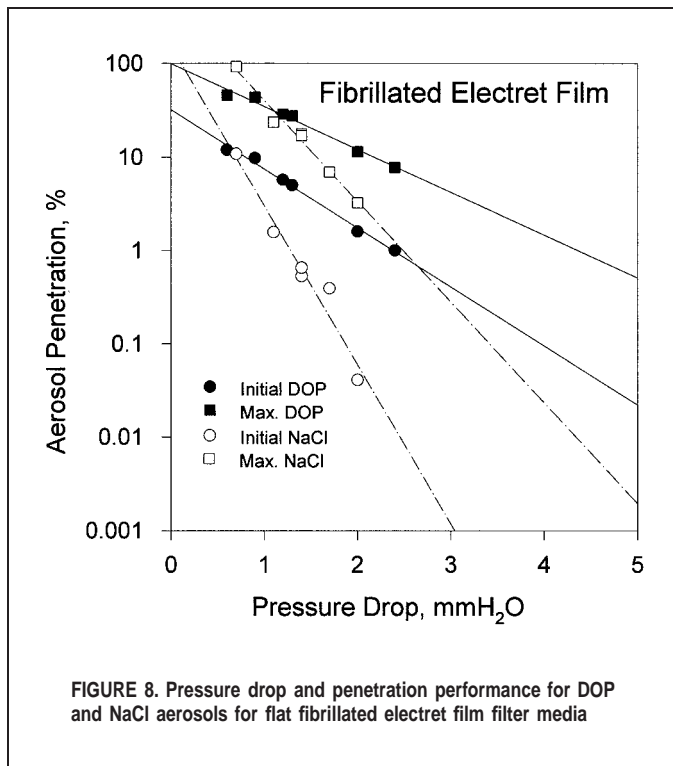
The pressure drop performance curves shown in Figure 7 depict results for tribocharged media. Comparing this data with that for fiber glass media, much greater filtration performance is apparent from the pressure drop scaling on the x-axis. The large difference between initial and maximum penetrations is the result

of the loading behavior shown in Figure 2. With the particular media tested in this study, the maximum DOP and NaCl penetrations were very close at all pressure drops. It is widely held that DOP aerosol is more penetrating than NaCl aerosol.<sup>(3)</sup> NIOSH 42 CFR 84 regulations incorporate this belief, since R-series respirators, tested against DOP, are assumed to be able to pass requirements for N-series respirators, tested against NaCl. Using the tribocharged filter media tested, however, it is possible to construct a respirator that would pass R95 requirements, but not N95.

Pressure drop performance curves for fibrillated electret film media are shown in Figure 8. In general, the observed performance was better than that of tribocharged media. Both media have large fibers and high electrostatic charge. The major difference was the distinction between DOP and NaCl behavior. The fibrillated film had significantly better performance than the tribocharged material during loading with NaCl.

In Figure 9, pressure drop performance for conventional blown microfiber electret filter media is shown. It may be seen that with BMF, DOP is always more penetrating; and in the 1% to 10% range, the maximum NaCl penetration is about the same as the initial DOP penetration. The penetration/pressure drop performance of this type of media is between that of the large fiber, high electric charge media and fiber glass.

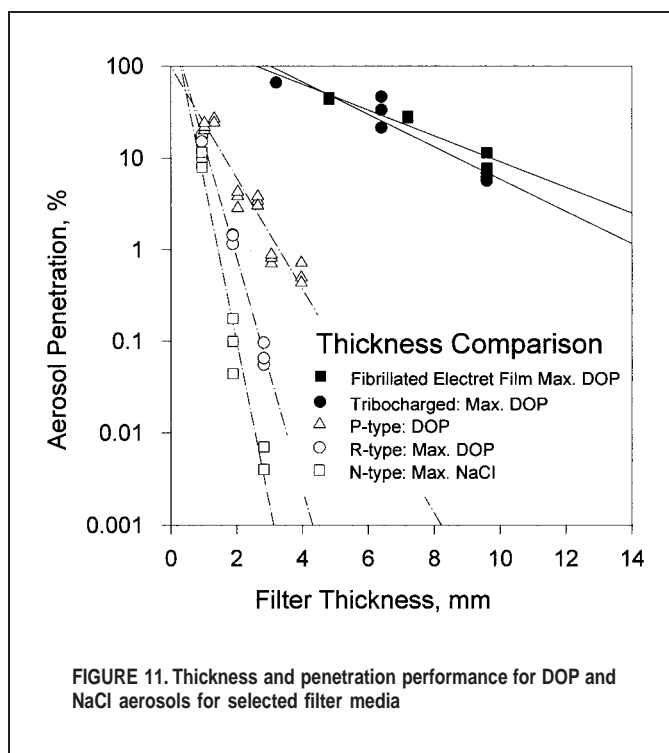
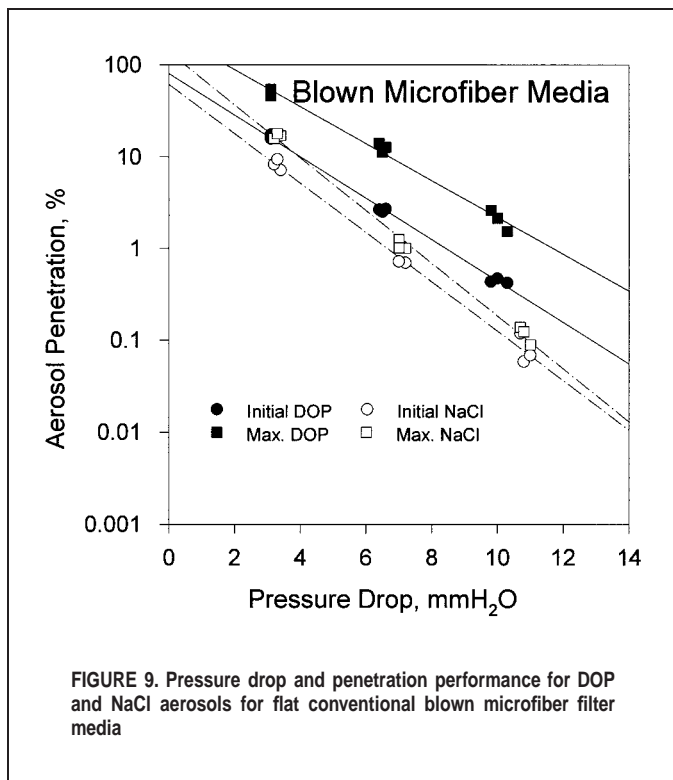
In Figure 10, pressure drop performance for various types of advanced electret media is depicted. For P-type media, the initial penetration is also the maximum value, so only a single DOP performance curve is shown. The only media acceptable for the P-series of respirators would be P-type media (Figure 10) and fiber glass (Figure 6). Comparing the two, P-type media have less than one-third the pressure drop of fiber glass at any penetration level. In comparing media for the R-series, conventional BMF (Figure 9) has higher pressure drop, about twice as high as R-type media (Figure 10) or tribocharged or fibrillated electret film media (Figures 7 and 8). For the N-series, conventional BMF (Figure 9)



again has pressure drop typically twice as high as N-type media (Figure 10) or tribocharged or fibrillated electret film media (Figures 7 and 8).

While the new R-type and N-type advanced electret media do not differ significantly from large fiber media in terms of pressure drop and penetration, they are very different in terms of the thickness required to reach a given penetration level. Shown in Figure

11 are thickness performance curves, in which penetration is plotted versus media thickness. The large diameter fiber media, both tribocharged and fibrillated electret film, are very thick in comparison with all of the advanced electret media. For example, at a maximum DOP penetration of 5%, corresponding to an R95 respirator, the tribocharged media would require a thickness of about 10 mm, compared to only 1.5 mm for the R-type BMF. The



significance for the respirator user is that a product made with R-type BMF will be thinner, lighter, and potentially more comfortable.

## DISCUSSION

To distinguish the seven types of filter media evaluated in this study, it is useful to characterize important properties. Fiber diameter is a very important feature of fibrous filters, and the fiber glass media had the smallest fibers of those tested; tribocharged and fibrillated film media had the largest fibers; and the blown microfiber media and advanced electret media were of intermediate fiber diameter. The differences in fiber diameter, coupled with the filter density, affect the tendency of the media to form a filter cake with solid aerosols. As a result, fiber glass (small fiber and high density) immediately cakes, BMF and AEM cake more slowly, and tribocharged and fibrillated electret film media (large fiber and low density) do not readily cake. For a motorized room air filter, a constant pressure drop with loading is an advantage. For a respirator, however, if penetration increases while pressure drop remains constant, the user may have no warning as the filter efficiency decreases.

The fiber diameter also directly relates to the media pressure drop and mechanical filtration mechanisms. A filter medium composed of larger diameter fibers relies more heavily on electrostatic charge for filtration efficiency. The magnitude of electrostatic charge has a great effect on loading behavior and performance. Increasing the level of electrostatic charge improves filtration performance in terms of initial penetration, but a higher charge also leads to more rapid penetration increase with aerosol loading. Thus, fiber glass media, with essentially no electrostatic charge, has low performance but very constant penetration with DOP aerosol loading; fibrillated electret film and tribocharged media, with high charge levels, have excellent initial performance but rapidly increasing penetration with loading; and BMF and advanced electret media, with moderate charge level, can have very good performance and flat or moderately increasing penetration with aerosol loading.

The lack of resistance to DOP loading in electrostatic filters has been identified in the past. The oily liquid aerosol droplets can spread over fiber surfaces, reducing the filtration enhancement from electrostatic charge, resulting in increasing penetration as a function of loading.<sup>(3)</sup> With recent advances in electret filter media, oily mist loading can exhibit the same behavior as fiber glass mechanical filters with essentially no change in penetration. Such filter media is especially well-suited for the new NIOSH P-series of respirators.

## CONCLUSION

In this research study it was observed that media without electrostatic charge has much lower filter performance, in terms of pressure drop at a given penetration level, than media that includes an electrostatic charge. For this reason, purely mechanical media, such as fiber glass, must generally be pleated to extend surface area and improve performance. In general, electrostatically charged filter media with large diameter fibers, such as tribocharged media or fibrillated electret film media, exhibited excellent initial filtration performance. However, when these media are loaded with aerosol particles, the penetration increases dramatically, with very little change in pressure drop.

Smaller fiber electrostatic media, such as conventional electrostatically charged BMF, have initial filter performance better than uncharged media, but generally not as good as large fiber media. With this smaller fiber media, solid aerosols can form a filter cake, causing penetration to decrease, while pressure drop increases with loading. With oily liquid aerosols, performance is similar to large fiber media, where penetration increases while pressure drop remains constant; however, the increase in penetration is less dramatic.

Using new electrostatically charged BMF technology, small fiber media can be made with improved resistance to oily liquid aerosols and greater levels of filtration enhancing electrostatic charge, leading to filters with much lower pressure drop than fiber glass media but with equal penetration and flat loading behavior, and pressure drop performance commensurate with the best large fiber media, while being thinner and lighter.

Significant differences exist among electrostatic filters in use today, with some media better suited for respirators than others. Generalizations cannot be made about the class as a whole. Conventional electrostatic media may suffer a loss in efficiency after extended exposure to certain aerosols, especially oily mist aerosols such as DOP. However, newer technology electrostatic media with higher electrostatic charge level and oily mist resistance exhibit improved overall filter efficiency while also eliminating efficiency loss due to aerosol loading. By taking advantage of this advancement in filter technology, respirators may be designed with media optimized for all NIOSH certification classes and types of aerosol challenges.

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