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Electrostatic Respirator Filter Media: Filter Efficiency and Most Penetrating Particle Size Effects

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New electrostatic filter media has been developed for use in 42 CFR 84 negative pressure particulate respirator filters. This respirator filter media was not available for evaluation prior to the change from 30 CFR 11 to 42 CFR 84. Thus, characterization of this filter media is warranted. In this study, the new 42 CFR 84 electrostatic respirator filters were investigated with respect to filter penetration and most penetrating particle size. Three different models of N95 filters, along with one model each of the N99, R95, and P100 class filters were used in this study. First, three of each filter were loaded with a sodium chloride (NaCl) aerosol, and three of each filter were loaded with a dioctyl phthalate (DOP) aerosol to obtain normal background penetration results for each filter. Then, two new filters of each type were dipped in isopropanol for 15 seconds and allowed to dry. This isopropanol dip should reduce or eliminate any electrostatic charge on the fibers of each filter, as reported in the technical literature. These dipped filters, along with controls of each filter type, were tested on a TSI 8160 filter tester to determine the most penetrating particle size. These same filters were then tested against a NaCl aerosol to get final penetration values. Electret filters rely heavily on their electrostatic charge to provide adequate filter efficiencies, and correlations between penetration and a filter's electrostatic characteristics are found in the technical literature. In all six of the filter models tested, filter penetration values increased considerably and the most penetrating particle size noticeably shifted toward larger particles. These results are important in better understanding how these new filter materials perform under various conditions, and they indicate the need for additional research to define environmental conditions that may affect electrostatic filter efficiency.

Keywords Respirators, Filters, Electrostatic, Filter Efficiency, Most Penetrating Particle Size

Originally, electrostatic filters were promoted for use as high-efficiency filters for the filtration of polluted air and gases.[1,2] These corona-charged, split polypropylene fiber filters, or electret filters, had reported life expectancies (retained their electrostatic charge and capture efficiencies) of over a year, even at high temperatures and humidity levels.[1,2] When these electret filters were tested against sodium chloride (NaCl) or dioctyl phthalate (DOP) aerosol, they exhibited filtration efficiencies as high as 99.5 percent, with this efficiency being reduced only a few percent with filter loads as high as five percent (w/w).[1,2]

With electrostatic filters being commonplace in respirators today, more work is being done to evaluate changes in electrostatic filter performance under field and laboratory conditions. Brown et al. investigated the effects that various industrial-type aerosols had on the filtration efficiency of electrostatic filters.[3] Different types of fumes and industrial dusts were used, including foundry fettling and burning, lead smelting, coking, and silica and coal dusts. Blackford et al. also presented a closely related study using many of the same industrial aerosols.[4] During these two studies, filters were exposed to a mass load of aerosol, dried, weighed, and tested for sodium chloride penetration and pressure drop using the BS 4400 method.[5] The results presented in these studies show a monotonic increase in penetration due to some type of filter degradation. They determined that the principal mechanism of the degradation was a suppression of the electrostatic charge by the captured aerosol. General degradation characteristics were presented and basic theory was developed for this phenomenon.

Fissan et al. tested an electrostatic polycarbonate fiber filter against uncharged liquid DOP, neutralized DOP, or neutralized NaCl aerosols.[6] It was discovered that these aerosols provide very different results. The DOP aerosol lead to increased penetration with increased mass loading. The increased penetration was attributed to a change in the electric charge loading on the filter fibers, caused by the collection of DOP. They note that changes in the filter structure may also have occurred, but did not speculate as to the nature of these changes. In the cases of the NaCl aerosol, a dramatic drop in penetration with increased mass load occurred. They believe this behavior was the result of structural changes from filter clogging.

Another study looked at the filtration characteristics and loading effects of filtering facepiece respirators that were made from electrically charged filter media.[7] They found that the removal of submicrometer particles by the electrostatic forces on the filter fibers can be much stronger than the mechanical removal. An example is given that an older "dust-mist filtering facepiece" (certified under 30 CFR Part 11[8]) "with four times greater fiber charge than another facepiece of the same category was found capable of providing five times more protection than the other facepiece." In this study, it was also reported that either isopropanol or Static Guard (Alberto-Culver Company, Melrose Park, IL) can be used to reduce the fiber charge. An earlier study showed that some chemicals, such as distilled water, sodium chloride solution, and ethanol can be used to reduce fiber charge as monitored by increased aerosol penetration.[9] These studies reported here, along with others, also discuss the possible effects that environmental factors, such as relative humidity, extreme temperatures, chemicals, industrial aerosols, and aerosol particle size, can have on the electrostatic charge and filter efficiency of electrostatic filter material.[4,7,9,10]

In June 1995, the National Institute for Occupational Safety and Health (NIOSH) updated the certification test criteria for negative pressure air-purifying particulate respirators with the enactment of 42 CFR 84.[11] Under 42 CFR 84, there are nine classes of filters, namely three categories of resistance to filter degradation, each with three levels of filter efficiency. The three categories of resistance to degradation are labeled N, R, and P, and depend on the presence or absence of oil particles. N-series filters are *N*ot resistant to oil, and are recommended for use against solid aerosols. These filters are tested for certification against a sodium chloride aerosol. R-series filters are *R*esistant to oil, whereas P-series filters are oil-*P*roof. These filters (R and P) are recommended for use in all environments, including those with oil particles (i.e., lubricants and metalworking fluids). Within each series of filters, there are three levels of filter efficiency, namely, 95, 99, and 99.97 percent. The selection of filter efficiency is dependent on the amount of acceptable filter leakage.[12]

Since the initiation of 42 CFR 84, there has been a noticeable shift from particulate respirators using mechanical filters to those using alternative electrostatic filter media. Electrostatic filters continue to collect particles by mechanical (non-electrostatic) mechanisms, but a static charge on the fibers of the filter serves to enhance the attraction and capture of aerosol particles without significantly increasing the filter's breathing resistance.[3,13] Thus, an electrostatic filter has the potential to provide similar filter efficiency, compared to a purely mechanical filter, at a lower breathing resistance, making for a reportedly better filter and more user-friendly respirator.

A recent NIOSH study investigated electrostatic N95 filter media efficiency degradation resulting from intermittent sodium chloride exposures.[13] Here, N95 filters were treated at different time intervals with small loads of sodium chloride aerosol, and the effects on filtration efficiency degradation were determined. This study clearly shows that many of the filters tested in this intermittent fashion show significant signs of degradation, with many of them exceeding the five percent penetration threshold well before 200 mg NaCl had been loaded on the filter. This was the first study to indicate that temporal effects, in addition to simple aerosol exposures, can play a role in the degradation of electrostatic filter efficiency. These results clearly show that problems with efficiency degradation can exist under certain use patterns.

In this study, several new filter types that have been certified under the new 42 CFR 84 regulations were selected for characterization. In one set of experiments, the initial penetration and loading characteristics were measured using test protocols similar to those used in certification testing. In a second set of experiments, an attempt was made to deplete most or all of the electrostatic charge on filters of each type, using an isopropanol dip. Then, the penetration of a standard aerosol was measured after the charge was depleted and compared to that from control filters of each type. These data show the degree to which the new electrostatic filters certified under 42 CFR 84 rely on their electrostatic charge for particle collection and suggest that some extreme conditions can drastically reduce their particle collection efficiencies.

EXPERIMENTAL DESIGN

Three different models of N95 filtering facepiece respirators, along with one model each of N99, R95, and P100 class filters were tested in this study. All of each filter model were taken from the same manufacturing lot to eliminate possible lot-to-lot variations. Testing for filter penetrations at various particle sizes was done using a TSI CertiTest Model 8160 Automated Filter Tester (TSI Inc., St. Paul, MN)[14] with a DOP challenge aerosol. A TSI CertiTest Model 8130 Automated Filter Tester[15] was used with a DOP aerosol for conducting the NIOSH certification loading test for R- and P-series filters. Filters were also subjected to the loading test for N-series filters using sodium chloride, with the exception that the filters were not preconditioned, but tested as received. A TSI CertiTest Model 8110 Automated Filter Tester[16] with a Model 8118 motorized NaCl generator at 13,000 rpm was used for this purpose. In all cases, the TSI equipment used for these experiments produced a DOP or solid sodium chloride aerosol which meets the particle size and size distribution criteria set forth in 42 CFR 84 Subpart K, Section 84.181.[11] The NaCl aerosol must have a count median diameter (CMD) of 0.075 ± 0.020 micrometer and a geometric standard deviation (GSD) not exceeding 1.86, whereas the DOP aerosol must have a CMD of 0.185 ± 0.020 micrometer and a GSD not exceeding 1.60. Both aerosols were neutralized to the Boltzmann equilibrium state as outlined in the above regulations.

The Model 8110 and Model 8130 filter testers measure filter penetration by employing a forward light-scattering photometer. The challenge aerosol concentration was determined daily using a gravimetric technique. This allowed for the quantification of the load of NaCl or DOP deposited on a given filter per unit time. The aerosol particle size (count median diameter) and particle size distribution (geometric standard deviation) was determined using a TSI Model 3934 Scanning Mobility Particle Sizer (SMPS).[17–19] This instrument measures the size distribution of submicrometer aerosols by the electrical mobility detection method.

The Model 8160 filter tester measures filter penetration as a function of particle size. It employs a TSI Model 3071A Electrostatic Classifier (EC) to separate particles of various sizes producing a nearly monodispersed DOP aerosol (geometric standard deviation of less than 1.3) for testing. It also determines filter penetration by employing two TSI Model 7610 Condensation Nucleus Counters (CNC), one on the upstream side and one on the downstream side of the filter. The upstream CNC employs a dilution bridge to prevent the CNC from being exposed to excessive numbers of particles, thus resulting in a loss of count accuracy. Because the CNCs count the actual number of aerosol particles in the flow stream, instead of using a photometric mass-type average, the penetration results from the 8160 will be higher than those given by instruments using light-scattering photometers. Penetration using actual particle count will always be equal to or exceed a photometrically determined value. The 8160 is capable of testing over a particle size range of 0.015 μm to 0.4 μm and measuring efficiencies better than 99.99999 percent.

The three N95 filtering facepieces were tested at a continuous airflow of 85 ± 2 LPM. The remaining three filters, which are used in pairs on various elastomeric respirator models, were tested at a continuous airflow of 42.5 ± 2 LPM. The filters were tested as received from the manufacturer and no relative humidity pretreatment was performed on any filter prior to testing.

Two different series of experiments were conducted during this study. The first set was to perform aerosol loading tests on the filters, as received. Three of each filter type were exposed to a sodium chloride aerosol until it could be confirmed that a maximum penetration value was obtained. Additionally, three of each filter type were loaded with a DOP aerosol until 200 mg DOP loading (100 mg DOP for filters used in pairs) was obtained. In each case, the aerosol loading was continuous until the test was completed. NIOSH has recently become aware that intermittent aerosol loadings can lead to filter degradation and other unwanted effects, and were, therefore, avoided in this study.[13]

The second set of experiments involved dipping two of each filter type in isopropanol. When dipping each filter, care was taken to ensure complete submersion. Each filter was dipped for 15 seconds and promptly removed. The filters were given some time to drip and then allowed to air dry overnight. This isopropanol dip was performed to reduce or remove the electrical charge associated with the filter fibers, as reported by Chen et al., although they employed a one-hour isopropanol dip.[7] However, in tests comparing a 15-second isopropanol dip to a one-hour dip and a two-hour dip, we found no significant differences between the dipping times and their effect on filter efficiency degradation. Thus, only a 15 second dip was employed throughout this study. Once the filters were dry, they were tested, along with two control filters (as received) of each type, on the TSI 8160 filter tester to determine the effect on filter penetration and the most penetrating particle size. At the conclusion of the 8160 testing, all of these filters were tested on the TSI 8110 against NaCl to obtain a final sodium chloride penetration value. This value will serve as a comparison between the different test methods.

RESULTS AND DISCUSSION

Three filters of each filter type were tested according to the NIOSH criteria with NaCl, excluding the relative humidity preconditioning. These filters were continuously loaded with NaCl aerosol until a maximum penetration value was experimentally observed. Three different filters of each filter type were also tested using 42 CFR 84 certification standards for a DOP aerosol, loading each filter continuously with 200 mg of DOP (100 mg DOP for filters used in pairs). Table I shows the experimental data for the four N-series filters when tested against both a sodium chloride and a DOP aerosol. It can be seen that all four filters performed well against the NaCl challenge aerosol. However, the filter penetration increases dramatically (approximately tenfold) when challenged by a DOP aerosol. Manufacturer A's N95 filters showed maximum penetrations from 0.537 to 1.14 percent against NaCl, but maximum penetrations of 19.1 to 22.2 percent against DOP. The other N-series filters showed similar results with Manufacturer B's N95 filters showing NaCl penetrations of 2.33 to 2.66 percent, and DOP penetrations of 16.5 to 20.3 percent. Manufacturer C's N95 filters gave 1.97 to 2.23 percent penetration against NaCl and 34.8 to 36.2 percent against DOP, and Manufacturer D's N99 filters going from 0.150 to 0.360 percent against salt up to 1.77 to 3.95 percent with DOP. This increased penetration with DOP is, as expected, the result of the degrading effects of the DOP aerosol, and explains why N-series filters are only indicated for use against solid aerosols, not oils.[6] It can also give some insight to the possible consequences of using an N-series respirator in an environment containing oil particulates. DOP loading is much different than loading with a solid aerosol such as sodium chloride. A solid aerosol immediately begins to clog the pores of the filter and eventually forms a cake on the filter surface, greatly increasing the breathing resistance as loading occurs. On the other hand, DOP oil does not clog the filter pores, but simply coats the filter fibers. No filter cake is formed on the filter surface. Instead, the DOP liquid begins to wick through the filter, coating each fiber. This is supported by the fact that the filter resistance at the end of the DOP loading test has not significantly increased. There are no final resistance values included for the NaCl tests because the tests were terminated once a maximum penetration value could be experimentally observed, and not continued out to a 200 mg NaCl load. Thus, each test was stopped at a different point, making final resistance values meaningless.

Table II shows similar data for the R-series and P-series filters used in this research. It shows that the R95 filter and the P100 filter performed well against both sodium chloride and DOP. Here, again, the DOP penetrations are higher, but they remain well below the filters' designated level of filter penetration. The

TABLE I
Certification test data on N-series filters, as received

Filter	Sodium chloride aerosol: Initial penetration (%)	Sodium chloride aerosol: Initial resistance (mm H_2O)	Sodium chloride aerosol: Maximum penetration (%)	DOP aerosol: Initial penetration (%)	DOP aerosol: Initial resistance (mm H_2O)	DOP aerosol: Maximum penetration (%)	DOP aerosol: Resistance at end of testing (mm H_2O)
Manufacturer A N95 #1	0.760	8.3	1.14	1.15	8.3	19.1	8.6
Manufacturer A N95 #2	0.282	8.8	0.537	1.57	8.4	21.2	9.0
Manufacturer A N95 #3	0.358	8.5	0.611	1.73	7.8	22.2	8.1
Manufacturer B N95 #1	2.14	14.0	2.33	6.99	13.9	20.3	15.3
Manufacturer B N95 #2	2.54	13.3	2.66	6.01	14.2	18.4	15.7
Manufacturer B N95 #3	2.62	14.2	2.64	5.67	14.1	16.5	15.3
Manufacturer C N95 #1	2.10	13.9	2.14	5.30	13.0	36.2	13.8
Manufacturer C N95 #2	2.23	12.6	2.23	5.35	13.1	34.8	13.9
Manufacturer C N95 #3	1.90	13.3	1.97	5.51	13.2	35.4	13.9
Manufacturer D N99 #1	0.160	11.6	0.193	0.632	12.5	1.77	13.4
Manufacturer D N99 #2	0.132	11.2	0.150	0.679	12.7	1.93	13.7
Manufacturer D N99 #3	0.272	10.0	0.360	0.964	12.1	3.95	13.0

abnormal data for the P100 filters presented in Table II can be explained. The differences in penetration values can be explained by simple differences in test instruments. The TSI 8130 used for DOP loading will allow and printout a penetration reading of 0.000. However, the TSI 8110 used for sodium chloride aerosol exposures will not allow a zero reading for a valid test. The lowest penetration value given by the TSI 8110, for a valid test, is therefore 0.001 percent. The penetration readings of 0.002 percent can only be explained as differences in the individual P100 filters, as well as instrument fluctuations at very low penetration readings. The 10 to 17 percent differences in the initial resistance measured for the P100 filters are explained by differences in the individual P100 filters as well as differences between the filter testers. The TSI 8110 is a positive pressure instrument, meaning that the test aerosol is "pushed" through the filter. However, the TSI 8130 operates under negative pressure, so the aerosol is "pulled" through the filter being tested. This fundamental difference can account for the differences in initial resistance values shown in Table II. These data are consistent with previous data collected on these filters. All of the filters tested maintain their required level of filter efficiency when tested against their respective certification aerosol. Again, the increase in filter resistance when tested against DOP is relatively small, and no final resistance values are included for the NaCl tests for the reason mentioned above.

The results of the isopropanol dip study are presented individually for each filter. The TSI 8160 results for Manufacturer A's N95 filtering facepieces are shown in Figure 1. Similarly, results for N95 filters from Manufacturers B and C are plotted in Figure 2 and Figure 3, respectively. These three filters were all tested at a constant airflow of 85 ± 2 LPM. Figure 4, Figure 5, and Figure 6 present the results for Manufacturer D's

TABLE II
Certification test data on R-series and P-series filters, as received

Filter	Sodium chloride aerosol: Initial penetration (%)	Sodium chloride aerosol: Initial resistance (mm H_2O)	Sodium chloride aerosol: Maximum penetration (%)	DOP aerosol: Initial penetration (%)	DOP aerosol: Initial resistance (mm H_2O)	DOP aerosol: Maximum penetration (%)	DOP aerosol: Resistance at end of testing (mm H_2O)
Manufacturer D R95 #1	0.016	16.0	0.016	0.209	15.7	1.51	16.7
Manufacturer D R95 #2	0.013	14.9	0.013	0.144	15.4	0.812	16.4
Manufacturer D R95 #3	0.027	15.4	0.027	0.135	16.1	0.765	17.0
Manufacturer A P100 #1	0.001	21.1	0.002	0.000	23.8	0.000	24.1
Manufacturer A P100 #2	0.002	19.9	0.002	0.000	23.3	0.000	23.5
Manufacturer A P100 #3	0.002	19.1	0.002	0.000	23.2	0.000	23.4

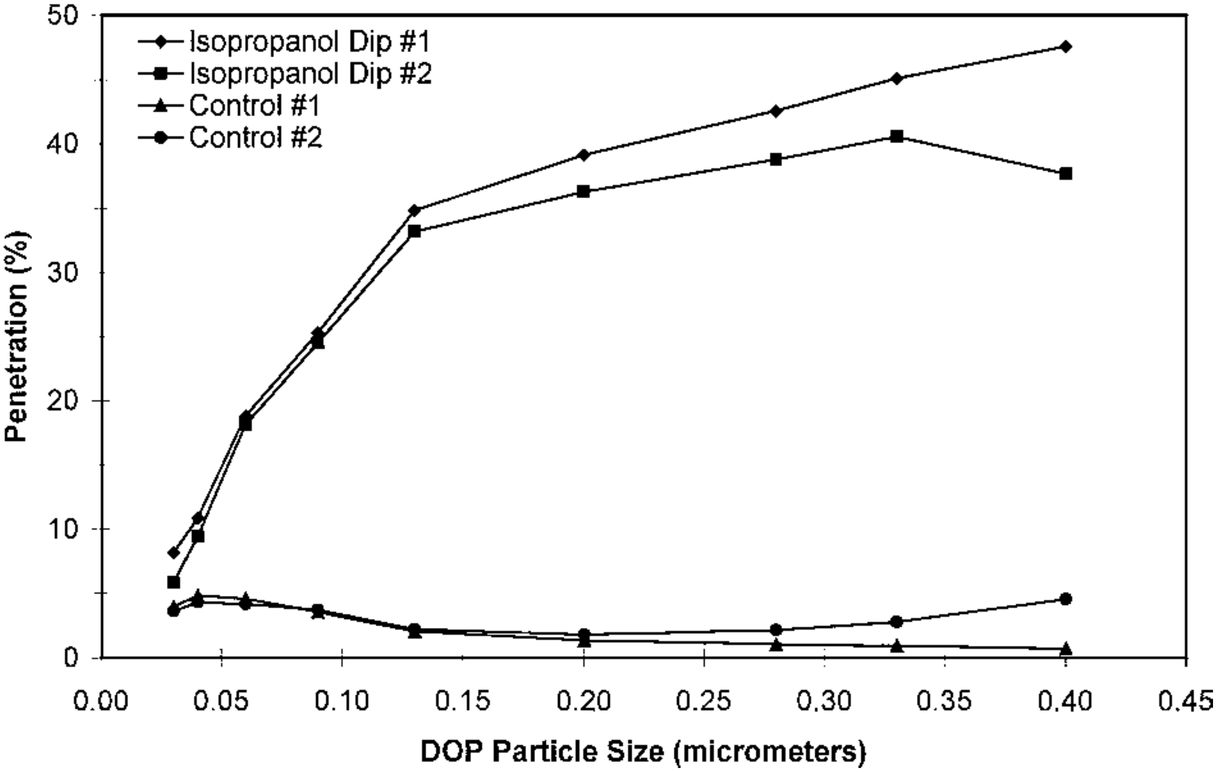

FIGURE 1
Manufacturer A N95 filtering facepieces.

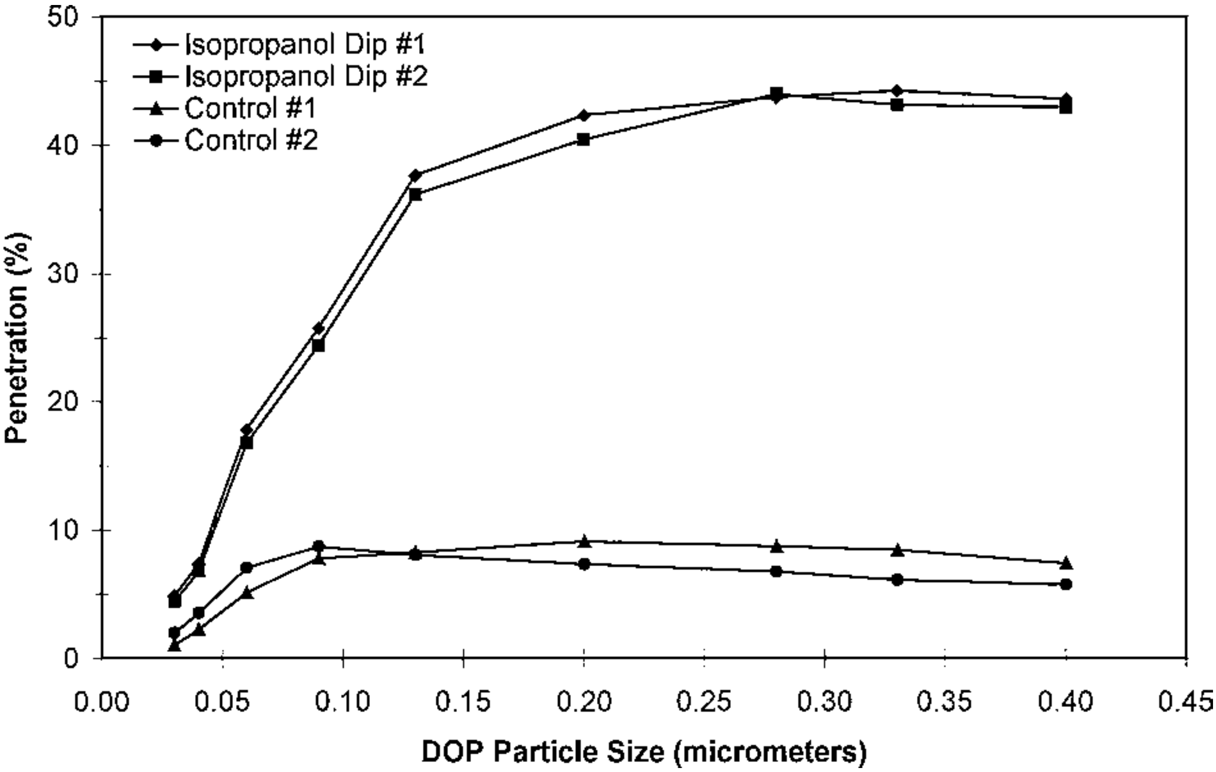

FIGURE 2
Manufacturer B N95 filtering facepieces.

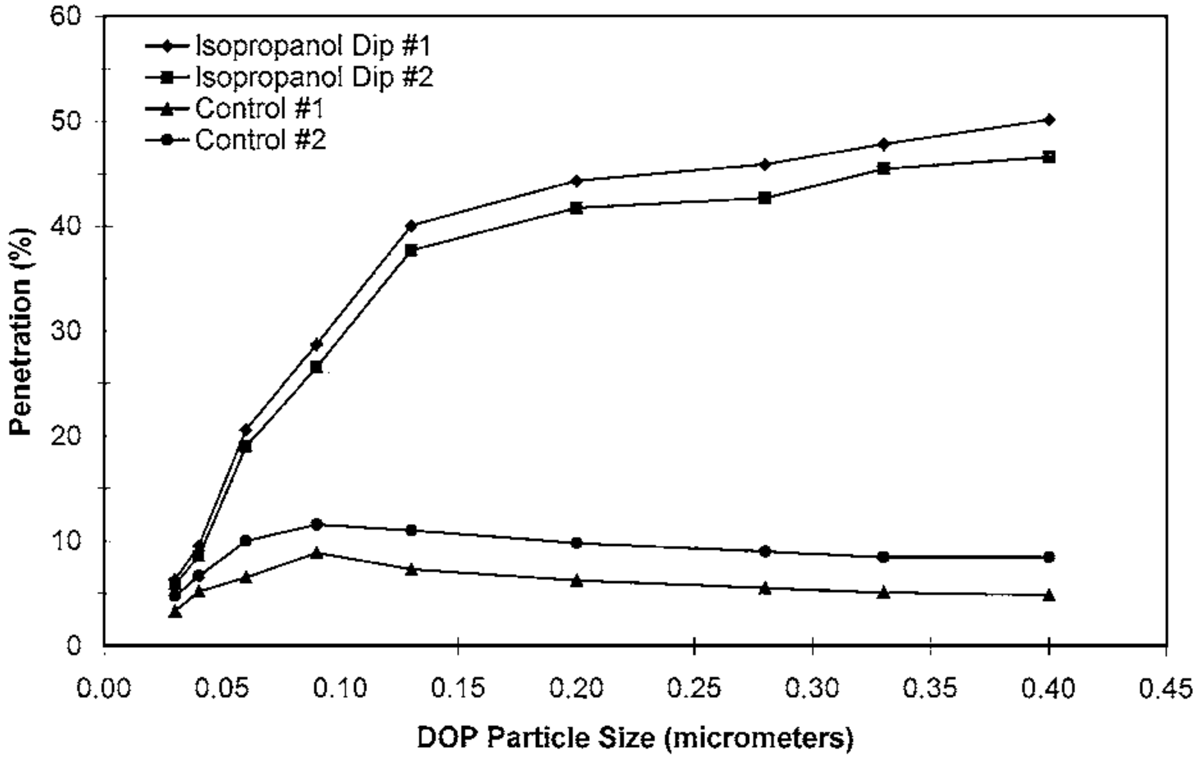

FIGURE 3
Manufacturer C N95 filtering facepieces.

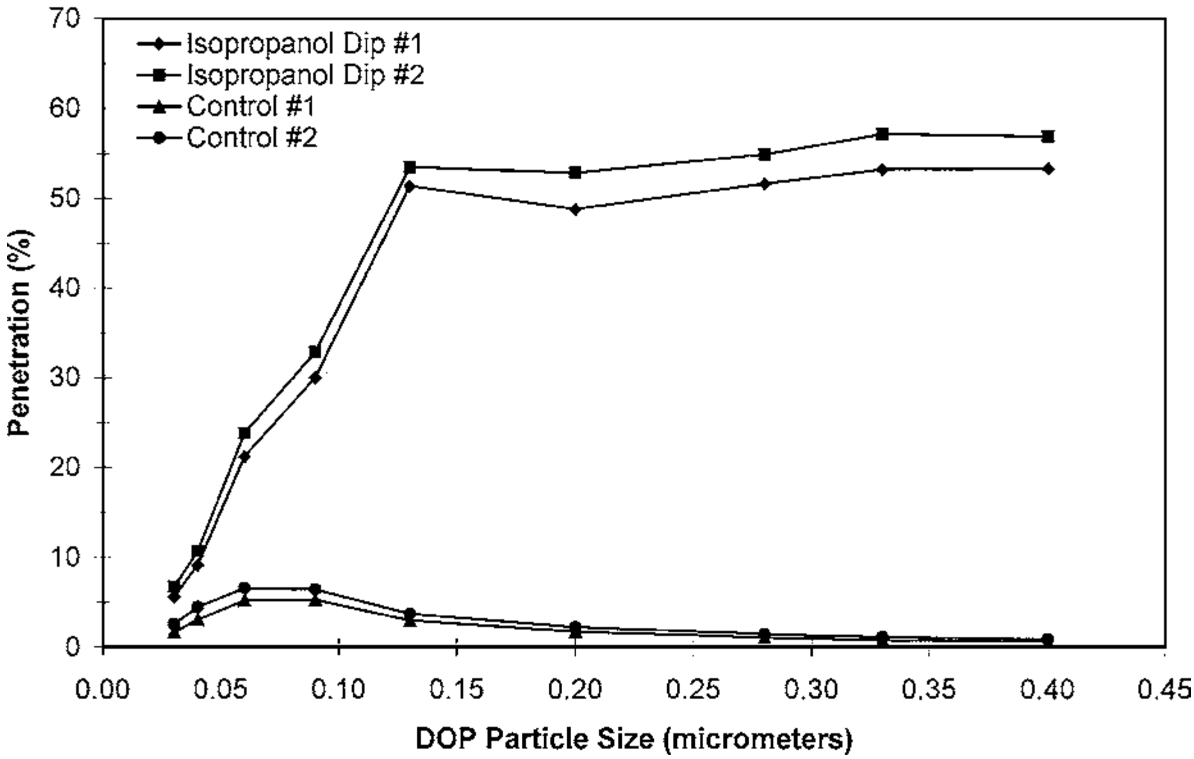

FIGURE 4
Manufacturer D N99 filters.

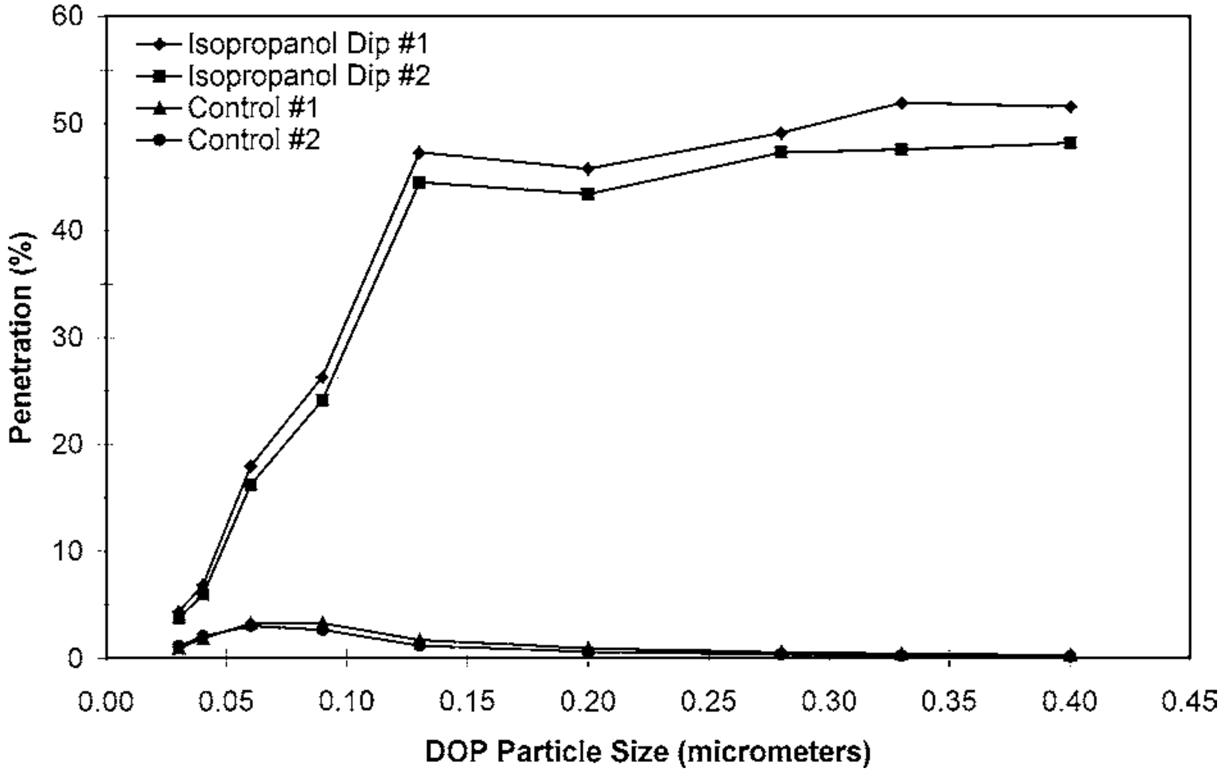

FIGURE 5
Manufacturer D R95 filters.

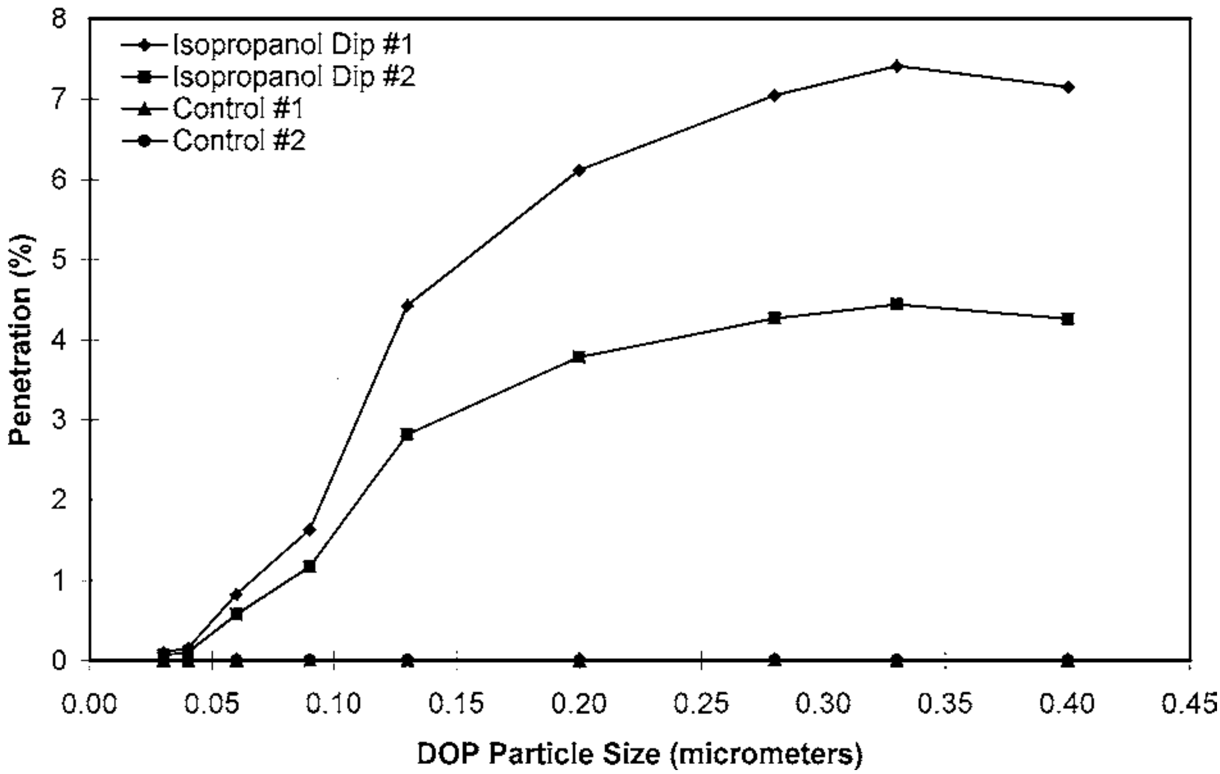

FIGURE 6
Manufacturer A P100 filters.

TABLE III
TSI 8110 final penetration test data on isopropanol dip study filters

	Controls (as received)		Isopropanol dip	
Filter	Final penetration (%)	Final resistance (mm H_2O)	Final penetration (%)	Final resistance (mm H_2O)
Manufacturer A N95 #1	0.570	7.7	35.5	8.5
Manufacturer A N95 #2	0.418	8.7	34.2	8.4
Manufacturer B N95 #1	2.42	13.2	39.3	13.3
Manufacturer B N95 #2	2.46	13.9	38.7	13.0
Manufacturer C N95 #1	1.94	13.1	43.5	12.4
Manufacturer C N95 #2	4.27	12.0	41.4	12.8
Manufacturer D N99 #1	0.250	13.5	49.2	12.3
Manufacturer D N99 #2	0.208	12.6	53.3	12.0
Manufacturer D R95 #1	0.031	18.4	49.9	14.9
Manufacturer D R95 #2	0.026	15.8	43.8	16.1
Manufacturer A P100 #1	0.001	19.4	3.92	18.7
Manufacturer A P100 #2	0.002	17.4	1.97	17.0

N99 and R95 filters, and Manufacturer A's P100 filters, respectively. These filters are used in pairs attached to various respirators and were tested at a constant airflow rate of 42.5 ± 2 LPM.

From these plots (Figures 1–6), it can clearly be seen that the charge on the electrostatic filter media, or the reduction thereof, has a profound effect on both filter efficiency and the most penetrating particle size. All of the filters having the electrostatic charge reduced or removed, show a dramatic increase in filter penetration (a decrease in filter efficiency). Manufacturer A's N95 filter showed an increase in maximum penetration from about 5 percent to around 45 percent. Similarly, the maximum penetrations increased from about 9 percent to 45 percent, 10 to 50 percent, and 6 to 55 percent for Manufacturer B's N95, Manufacturer C's N95, and Manufacturer D's N99, respectively. A similar effect was noticed with the R95 filter from Manufacturer D and Manufacturer A's P100 filters, with the penetration increasing from around 3 to about 50 percent for the R95 and 0.001 percent to over 7 percent for the P100, once the static charge had been diminished or eliminated by the isopropanol dip.

The graphs (Figures 1–6) also depict a definite shift in the most penetrating particle size. For all new filters, the most penetrating particles were generally in the 0.05 μm to 0.10 μm size range. However, once the electrostatic charge was reduced or removed from the filter fibers, the most penetrating particle size dramatically shifted toward larger sizes in the 0.25 μm to 0.35 μm range. In fact, the N-series filters and the R95 filter showed the largest shift in the most penetrating particle size, even still increasing at particles 0.40 μm in size. Because this is the upper limit of the size range that can be tested on the TSI 8160, it is conceivable that the actual size of the most penetrating particles could be larger still.

Once the 8160 testing was completed, all of the filters in the isopropanol dip study were tested on the TSI 8110 against sodium chloride. These results are presented in Table III and can be used as a means for comparison between instruments and an indicator of filter charge reduction. The isopropanol dip had little or no effect on the breathing resistance of any of the filters. However, the filter penetration values for the dipped (charge neutralized) filters showed a large increase. The N95 filters from Manufacturers B and C showed an increase in NaCl penetration of over an order of magnitude. The filter penetration for Manufacturer A's N95 and Manufacturer D's N99 filters increased over two orders of magnitude, while the penetration through the R95 and P100 filters increased over three orders of magnitude, due to the reduction or elimination of the static charge.

CONCLUSIONS

This study found that many of the new respirator filter materials being certified under 42 CFR 84 depend highly on electrostatic charge to provide adequate protection against aerosols. The benefits from an electrostatic filter can be great, but once the electric charge is reduced or eliminated, the filter efficiency is sharply affected. Our attempts to diminish or eliminate the charge of the filter fibers showed that all six of the filter types tested showed dramatic increases in penetration when tested against NaCl and DOP aerosols. The six filter types also exhibited a noticeable shift in the most penetrating particle size toward larger sizes. Determining the definite most penetrating particle size for each filter was hampered by the 8160 tester's large particle size limitation being 0.40 μm, yet the shift toward larger particles can clearly be seen. These results are important in better understanding how these new filter materials perform under extreme conditions. Although it is highly unlikely that a given respirator will have the electrostatic charge completely eliminated in the workplace, it is conceivable that some degree of charge reduction could result from everyday use, storage in adverse conditions or, more importantly, exposure to industrial aerosols, and could have an impact on overall filter performance. Additional studies need to be conducted in this area to investigate these possibilities.

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