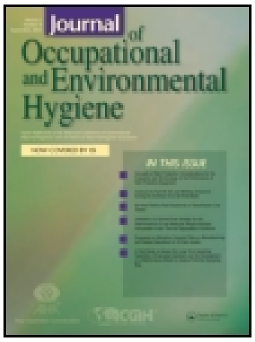

Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: http://www.tandfonline.com/loi/uoeh20

Powered, Air-Purifying Particulate Respirator Filter Penetration by a DOP Aerosol

Stephen Martin , Ernest Moyer & Paul Jensen

To cite this article: Stephen Martin , Ernest Moyer & Paul Jensen (2006) Powered, Air-Purifying Particulate Respirator Filter Penetration by a DOP Aerosol, Journal of Occupational and Environmental Hygiene, 3:11, 620-630

To link to this article: https://doi.org/10.1080/15459620600953995

Published online: 23 Oct 2007.

Journal of Occupational and Environmental Hygiene, 3: 620–630
ISSN: 1545-9624 print / 1545-9632 online
DOI: 10.1080/15459620600953995

Powered, Air-Purifying Particulate Respirator Filter Penetration by a DOP Aerosol

Stephen Martin,[1] Ernest Moyer,[1] and Paul Jensen[2]

[1]NIOSH, Division of Respiratory Disease Studies, Morgantown, West Virginia
[2]National Center for HIV, STD, and TB Prevention, Atlanta, Georgia

In 1995, new certification requirements for all nonpowered, air-purifying particulate filter respirators were put in place when 42 CFR 84 replaced 30 CFR 11. However, the certification requirements for all other classes of respirators, including powered air-purifying respirators (PAPRs), were transferred to 42 CFR 84 from 30 CFR 11 without major changes. Since the inception of 42 CFR 84, researchers have learned that the efficiency of electrostatic filter media, in contrast with mechanical filter media, can be rapidly degraded by oil aerosols. Further, confusion may exist among respirator users, since electrostatic PAPR filters have the same magenta color assigned to high-efficiency filters for nonpowered particulate respirators that have been tested and certified for use against oil aerosols (i.e., P100 filters). Users may expect that the magenta color of certified PAPR filters indicates suitability for use against oil aerosols. This may not be the case. To illustrate the potential degradation of electrostatic PAPR filters, new filters certified under 42 CFR 84 were tested using a TSI model 8122 Automated Respirator Tester against charged and neutralized DOP aerosols with intermittent loading schedules. The performance of a magenta-colored electrostatic PAPR filter—one for which the manufacturer's user instructions appropriately indicates is not suitable for use in oily environments—was compared with the performance of several mechanical PAPR filters. In tests against both DOP aerosols, the electrostatic PAPR filter showed a significant decrease in performance at DOP loadings exceeding 400 mg, whereas mechanical filters showed no significant change in the performance except at extremely high loadings. The decreased performance of the electrostatic PAPR filter was found to be significantly greater when tested against a neutralized DOP aerosol when compared with a charged DOP aerosol. While laboratory tests show that the filtration efficiency of this electrostatic PAPR filter degrades with exposure to DOP aerosol, the observed laboratory degradation may or may not affect workplace performance, as similar degradation has not been verified in workplace studies. Based on these laboratory results, a proposed method for evaluating high-efficiency PAPR filters is presented. This proposed method would ensure that high-efficiency PAPR filters (≥99.97% efficient and magenta in color) meet critical performance criteria when loaded.

Keywords aerosol, dioctyl phthalate (DOP), electrostatic, filter efficiency, powered air-purifying respirator (PAPR), respirator

Address correspondence to: Stephen Martin, NIOSH, Division of Respiratory Disease Studies, 1095 Willowdale Road, M/S H-2800.4, Morgantown, WV 26505; e-mail: smartin1@cdc.gov.

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of a commercial product or trade name does not constitute endorsement by the National Institute for Occupational Safety and Health (NIOSH) or the authors.

INTRODUCTION

In 1995, 42 CFR 84 replaced 30 CFR 11 as the certification regulation for all nonpowered, air-purifying particulate filter respirators.(1) The new nonpowered, air-purifying particulate filter respirators are tested under more demanding conditions than those previously required by 30 CFR 11 and should provide some increased level of filter efficiency, which could potentially enhance worker protection. However, only certifications of nonpowered, air-purifying particulate filter respirators were affected by the change to 42 CFR 84. Certification requirements for all other classes of respirators (i.e., chemical cartridge and canister, powered air-purifying respirator [PAPR], supplied air respirator [SAR], self-contained breathing apparatus [SCBA], etc.) were transferred to 42 CFR 84 without major changes. New testing and certification procedures for these other respirator classes will be addressed through future changes to 42 CFR 84.(2)

Presently, PAPR units and filters are still tested against the older 30 CFR 11 criteria that were transferred into 42 CFR 84 (Subpart KK-Dust, Fume, and Mist; Pesticide; Paint Spray; Powered Air-Purifying High Efficiency Respirators and Combination Gas Masks).(1) To receive National Institute for Occupational Safety and Health (NIOSH) approval under these certification criteria, PAPR filters are subjected to two tests. In the first test, filters must maintain a penetration value ≤0.03 percent against an instantaneous liquid dioctyl phthalate (DOP) aerosol exposure.(1) The second test is a 4-hour silica dust test, which is more of a total PAPR integrity test than an actual measure of filter performance. To pass this 4-hour test, the PAPR unit must maintain a flow rate above 115 L/min for a tight-fitting mask or above 170 L/min for a loose-fitting hood or helmet; the average penetration of 0.4–0.6 μm silica dust into the PAPR system must not exceed 1%.[(1)]

42 CFR 84 not only updated the certification testing criteria for nonpowered, air-purifying particulate respirators, it led to a major change in the respirator products available in the marketplace. There was a shift in nonpowered, air-purifying particulate filter respirators from older mechanical-type filter media to electrostatically enhanced filter media. Electrostatic filters continue to collect particles by mechanical (nonelectrostatic) mechanisms, but a static charge on the filter fibers serves to enhance the attraction and capture of aerosol particles without significantly increasing the filter's breathing resistance.[(3–5)] Thus, an electrostatic filter has the potential to provide an efficiency similar to a mechanical filter at a lower breathing resistance, which results in a reportedly better filter and more user-friendly respirator. However, loading an electrostatic filter can alter the static charge distribution on the filter surface, potentially affecting the filtration efficiency of that filter.[(5,6)] In fact, one of the disadvantages of electrostatic filter media is that certain use patterns or aerosol exposures can increase filter penetration.[(6–10)]

Another disadvantage is that breathing resistance through electrostatic respirator filter media does not increase significantly with aerosol loading, particularly with liquid aerosols. Thus, increased breathing resistance cannot be used as an indicator that the filters need to be changed. This was confirmed in a 3M Company study[(5)] where the performance of various types of flat sheet, electret filter media (similar to that used to produce respirator filters) and a mechanical fiberglass filter were tested against sodium chloride (NaCl) and DOP aerosols. Barrett and Rousseau[(5)] found that the magnitude of the electrostatic charge has a significant effect on the filtration efficiency of the filters. Against a DOP aerosol, a high level of electrostatic charge leads to improved initial efficiency but a more rapid increase in penetration with increased aerosol loading. The authors explained this phenomenon by saying "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."[(5,p.538)] In comparison, mechanical filter media with virtually no static charge (i.e., fiberglass) maintained more constant penetration values as DOP loading increased. This study also found that for most of the electret (i.e., electrostatic) filters, the pressure drop across the filters remained relatively constant as DOP loadings increased. Thus, "the user may have no warning as the filter efficiency decreases."[(5,p.538)]

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.[(3)] investigated the effects that various industrial-type aerosols had on the filtration efficiency of electrostatic filters. Several different fumes and industrial dusts were investigated, including foundry fettling and burning, lead smelting, coking, and silica and coal dusts. Blackford et al.[(9)] also presented a closely related study using many of the same industrial aerosols. In these studies, filters were exposed to a mass load of aerosol, dried, weighed and tested for NaCl penetration and pressure drop using the British Standard (BS) 4400 method (1969). The results showed a monotonic increase in penetration due to filter efficiency degradation. The authors determined that the principal mechanism of 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.[(3,9)]

Fissan et al.[(10)] tested an electrostatic polycarbonate fiber filter against aerosols similar to those used for NIOSH nonpowered, air-purifying particulate respirator certification under 42 CFR 84. Uncharged liquid DOP, neutralized DOP, and neutralized NaCl aerosols were used in this research. It was discovered that these aerosols provide very different results. Both DOP aerosols (neutralized and nonneutralized) lead to increased penetration with increased mass loading. The authors attributed this increased penetration to a change in the electric charge loading on the filter fibers, caused by the collection of DOP. They noted that changes in the filter structure may also have occurred but did not speculate as to the nature of these changes. In the case of the neutralized NaCl aerosol, a dramatic drop in penetration with increased mass load occurred. They believed 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 made from electrically charged filter media. Chen et al.[(11)] 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 11) "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."[(11)] It was also reported that either isopropanol or Static Guard (Alberto-Culver Company, Melrose Park, Ill.) can be used to reduce the fiber charge. This further verified an earlier study by Kanaoka et al.[(8)] that showed some chemicals such as distilled water, NaCl solution, and ethanol, when applied to electrostatic filters, can reduce fiber charge and result in increased aerosol penetration. Similar results were found in a more recent study conducted at NIOSH.[(12)] Different N-, R-, and P-series electrostatic filters certified under 42 CFR 84 were dipped for 15 sec in isopropanol and allowed to dry overnight. When tested the next day, the filters provided much lower efficiencies. This phenomenon was also accompanied by a shift in the most penetrating particle size toward larger particles.

Given the many laboratory studies on electrostatic filter degradation, actual workplace studies have been limited. Recent studies by Janssen et al.[(13,14)] were conducted on electrostatic respirator filters from two different manufacturers. Untreated filters and filters intentionally degraded with ionizing radiation and isopropanol dips were tested in the laboratory to establish pre-exposure penetration values. After exposing the filters to grinding aerosol or oil mist for up to an hour in a steel foundry, the filters were again tested in the laboratory to determine the postexposure penetration. It was reported that workplace exposures did not adversely affect the laboratory penetration results of any of the filters, including those that were intentionally degraded.[13] The actual penetration of the workplace aerosols through the untreated and intentionally degraded electrostatic filters was also measured. All filters maintained workplace efficiencies above their certified level of protection, even those intentionally degraded prior to exposure. The authors concluded that laboratory performance testing of respirator filters does not directly predict performance under workplace conditions.[14] Janssen also reached this conclusion on measuring the performance of electrostatic N95 filters loaded with high concentrations of cement dust at a concrete block manufacturing plant.[15]

Results of the three Janssen studies[13–15] show that laboratory-degraded filters may be capable of providing adequate protection in some workplace environments. However, the studies used short exposure times (less than one full work shift) that resulted in small aerosol loadings. Further, only a small sampling of NIOSH-approved respirator filters was tested, even though it was noted that high variability in performance can exist between similar respirator products from different manufacturers. The key point is that Janssen and colleagues[13–15] selected workplaces with airborne contaminants having relatively large aerosol particle sizes ($>4\ \mu$m mass median diameter). The previous works by Brown et al.[3] and Blackford et al.[9] showed electrostatic N95 filter degradation with workplace exposures to submicrometer fume-type aerosols.

A more recent study[16] on electrostatic ventilation filters showed the extent of degradation was dependent on particle size, with the most degradation being associated with submicrometer particles from evaporation-condensation processes. While the Janssen studies[13–15] contribute to the knowledge base regarding exposures to relatively large workplace aerosols, the more critical workplace exposures are to submicrometer aerosols, such as fume-type aerosols,[3,9] diesel particulate matter,[17–19] and aerosols produced during beryllium metal production.[20] These submicrometer workplace aerosols are more similar to those used to certify respirator products. Additionally, all testing done in the Janssen studies involved electrostatic nonpowered, air-purifying respirators. The higher, continuous airflow rates through PAPR filters can lead to increased loading rates and, therefore, higher total aerosol loads.

Little research has been conducted on electrostatic media used for PAPR filters. No references to electrostatic PAPR filter efficiency testing could be found. However, with the introduction of electrostatic filter media into PAPR filters, and the potential degradation associated with them, it is important to gain an understanding of how high-efficiency PAPR filters perform against various testing aerosols. Of particular interest is DOP, since it is currently used by NIOSH to certify high-efficiency (P100) electrostatic, nonpowered, air-purifying particulate respirators.

Our research was conducted to study PAPR filter efficiency degradation and propose a more stringent testing methodology if electrostatic PAPR filter efficiency degradation was determined to be a problem. Four models of 42 CFR 84-certified mechanical PAPR filters (see Table I) were tested using a TSI model 8122 Automated Respirator Tester (TSI Inc., Shoreview, Minn.) against charged and neutralized DOP aerosols with intermittent loading schedules. Mechanical PAPR filter performance was then compared with the performance of one new 42 CFR 84-certified, high-efficiency, electrostatic PAPR filter tested in the same fashion, although the manufacturer clearly states that the electrostatic filter should not be used in oily environments. Each PAPR filter tested (including the electrostatic model) were magenta in color and met all

TABLE I. Specifications and Testing Parameters

Filter	Filtration Mechanism	Standard Configuration	Use Against Oil Aerosols?	Approximate Surface Area	Minimum Certified Flow Rate	Testing Flow Rate	Testing Face Velocity
Racal P3[A]	Mechanical	3 filters	Yes	1065 cm^2[B]	57 L/min filter[C]	83 L/min filter	1.30 cm/sec
MSA OptiFilter XL	Mechanical	2 filters	Yes	1225 cm^2[B]	85 L/min filter[C]	100 L/min filter	1.36 cm/sec
3M W-3267	Mechanical	1 filter	Yes	1960 cm^2[B]	115 L/min filter[C]	147 L/min filter	1.25 cm/sec
Racal Air-Mate HEPA[A]	Mechanical	1 filter	Yes	2820 cm^2[B]	170 L/min filter[C]	224 L/min filter	1.32 cm/sec
3M AS-140	Electrostatic	1 filter	No[D]	754 cm^2[E]	170 L/min filter[C]	225 L/min filter[F]	4.97 cm/sec

[A] 3M Company acquired Racal in 1998, but the products tested were purchased before the buyout and were, therefore, Racal products.
[B] Calculated from manufacturer estimates.
[C] 115 LPM for tight-fitting PAPRs or 170 LPM for loose-fitting PAPRs divided by the number of filters used in the standard configuration.
[D] User instructions supplied with filter clearly state that these filters are NOT for use against oil aerosols.
[E] Calculated from actual filter measurements.
[F] Maximum flow rate attainable on the TSI 8122 Automated Respirator Tester.

certification requirements for high-efficiency PAPR filters outlined in 42 CFR 84.

The electrostatic, high-efficiency, 3M AS-140 PAPR filter (3M, St. Paul, Minn.), although not intended for use against oil aerosols, was included in this study for several reasons. Aside from being one of the first electrostatic PAPR filters on the market (if not the first), NIOSH does not limit high-efficiency electrostatic PAPR filters for use only against non-oil aerosols; this burden falls on the filter manufacturer. In this instance the manufacturer understood the potential for filter efficiency degradation and made the responsible decision to restrict the use of the filter to non-oil aerosols. They were not required to do this by any NIOSH regulation. Other manufacturers may not have the information to make such a determination or realize the importance of doing so. Furthermore, electrostatic filter efficiency degradation can result from exposures to aerosols other than oil. Previous research by NIOSH and others have shown that electrostatic filters can exhibit significant filter efficiency degradation when tested in the laboratory after exposure to asphalt[21] or diesel particulate,[22] neither of which is classified as an oil.

Additionally, 42 CFR 84.1100(d) states that "Particulate filters for powered air-purifying respirators approved under the provisions of this subpart shall be only high-efficiency (HEPA) as described in 84.1130(a)(4) and will carry a 42 CFR part 84 approval label." Thus, all high-efficiency PAPR filters (mechanical or electrostatic) are color-coded magenta, which is the same color as P100 filters. This is a confusing and potentially hazardous aspect of 42 CFR 84. Magenta-colored P100 filters are defined as high-efficiency filters for use against oil aerosols under 42 CFR 84 and are tested against a 200-mg DOP load. Many industrial hygienists and safety professionals, as well as respirator users, associate this magenta color with HEPA filters certified for use against oils. In the case of the 3M AS-140, filters are magenta in color but are not for use in oily environments, as stated by the manufacturer. If respirator users select this HEPA filter for use against oil aerosols based on filter color, without reading and fully understanding the user instructions, there could be potentially hazardous consequences. For these reasons, the electrostatic PAPR filter was included in the study.

METHODS

The approach to testing PAPR filters was to use a testing protocol that paralleled the certification testing criteria set forth in 42 CFR 84 for nonpowered, air-purifying particulate filters. Testing PAPR filters using the procedures described in this section would provide a more stringent "worst-case" test than those currently used to certify PAPR filters, by loading the filters with DOP oil, which is more degrading than solid aerosols.

Table I shows the PAPR filters tested in this study and gives some general testing parameters for each. Testing was performed on individual PAPR filters. Only one PAPR filter was tested at a time, regardless of the normal filter configuration of each PAPR system. In every case, filter models were taken from the same manufactured lot to eliminate any lot-to-lot variability from the results. All filters were purchased from a national distributor of safety equipment and supplies. The filters were tested as received from the distributor with no pretreatment of any kind.

To determine the experimental flow rate through each filter brand, two complete PAPR units (NIOSH-certified for use with the PAPR filters to be tested) were each fitted with new filters so that the flow rate of each PAPR unit could be measured. The airflow rate of the two new PAPR units was determined using the NIOSH/NPPTL Standard Testing Procedure, entitled "Determination of Air Flow for Powered Air Purifying Respirators."[23] The higher of the two flow rates was taken as the worst-case flow rate. This worst-case flow rate was divided by the number of filters attached to the PAPR unit under normal operating conditions to determine the maximum flow rate through an individual PAPR filter (42 CFR 84.1154(a) states that the resistance through all attached filters should be essentially equal). The flow rate and face velocity at which testing was performed for each filter is shown in Table I.

Testing for filter penetration was done using a TSI CertiTest model 8122 Automated Respirator Tester employing a DOP challenge aerosol. The 8122 tester measures PAPR filter penetration using a forward light-scattering photometer. The 8122 is capable of measuring filter penetrations of 0.001 percent (99.999% efficiency) and provides six to seven filter penetration results every 10 min during aerosol loading tests. The 8122's high output DOP aerosol generator produces an aerosol that meets the particle size (count median diameter [CMD] of 0.185 μm $\pm$ 0.020 μm) and size distribution (geometric standard deviation [σ_g] not exceeding 1.60) criteria used in the certification of nonpowered, air-purifying particulate respirators (42 CFR 84). For reference, this equates to a mass median diameter (MMD) of 0.36 μm $\pm$ 0.04 μm with a σ_g of less than 1.60.

The concentration of the DOP challenge aerosol was determined daily by taking two 1-hour gravimetric samples and using the average value. The TSI 8122 allows for the gravimetric determinations to be done during actual filter testing instead of before or after, as is typically the case with other filter testing instruments. Taking gravimetric samples during testing provided a more accurate account of the aerosol concentration during actual filter testing.

Before any daily testing was performed with the TSI 8122, the instrument was allowed to warm up for at least 1 hour. After the warm-up time, a series of five verification tests were performed using standard filter media. These verification tests were performed as outlined in the *TSI Model 8122 Instruction Manual*. The average penetration and resistance values were compared with a standard test curve for the instrument. If the average value fell within the 95% confidence interval on the standard curve, it was determined that the instrument was functioning properly and could be used for testing.

To test an individual PAPR filter, a test fixture was constructed to which the filter was attached and checked for possible leaks. The test fixture was placed in the test chamber of the TSI 8122 with all air lines properly connected. The 8122 was then adjusted to provide the necessary airflow rates. The total airflow through the test chamber was always kept at 400 ± 15 L/min. To maintain this flow rate, the airflow through the PAPR filter (secondary flow) was set to the flow rate value determined using the NIOSH/NPPTL Standard Testing Procedure[23] described above. The primary flow rate was then adjusted to make up the difference. Keeping the total flow rate around 400 L/min helped to maintain the aerosol particle size and keep the overall DOP aerosol concentration in the test chamber as constant as possible. Also, preliminary testing on the 8122 showed that a total flow rate of 400 L/min was the most efficient, effective, and stable operating condition.

Once the airflow rates were set, the filter was loaded with DOP aerosol for 8 hours consisting of two 4-hour loadings tests with a short pause in the middle. This pause was just long enough to replenish the DOP supply in the aerosol generator. All penetration results from the TSI 8122 tester were recorded on a laptop computer throughout each loading test.

Five PAPR filters of each model were tested against a charged DOP aerosol. A complete test for each filter included at least four 8-hour days of aerosol exposure with a 3-day break in the middle. The break was included to simulate a long weekend after which the same filters from the previous week might be used again. While each filter's testing included this 3-day break, the break did not always fall at the same point in the testing schedule for each filter.

The Racal Air-Mate HEPA filters were tested in a slightly different configuration inside the TSI 8122 testing chamber than the other three mechanical PAPR filters. The high testing flow rate (224 ± 5 L/min) for these filters is a result of the PAPR configuration. Racal Air-Mate HEPA filters are used alone on a blower supplying purified air to loose-fitting hoods and helmets and, thus, must provide a minimum of 170 L/min flow throughout the course of an 8-hour work shift. Because of the size and shape of these filters, they could not be tested with the same filter test fixture used for the other three mechanical filters. Instead, Racal Air-Mate HEPA filters were tested while enclosed in their approved blower assembly (no hood, helmet, or facepiece). The blower assembly was equipped with a foam gasket to prevent leakage around the filter. This gasket was changed after each filter's testing was complete. The entire blower assembly was then properly connected inside the TSI 8122 test chamber for aerosol exposure. The blower was never powered on but used only as a filter holder.

The electrostatic 3M AS-140 filters were tested similarly to the Racal P3, MSA OptiFilter XL (MSA, Pittsburgh, Pa.) and 3M W-3267 filters, in that a simple test fixture was used to mount an individual filter inside the TSI 8122 testing chamber. The test fixture used for the 3M AS-140 filters was supplied to NIOSH by the respirator manufacturer. A secondary flow rate of 225 L/min was used because this is the maximum airflow rate attainable on the 8122 without significant instrument modifications. 3M AS-140 filters in their standard configuration operate at airflow rates around 300 L/min, so the testing flow rate was lower than the normal operating flow rate.

On completion of testing with the charged DOP aerosol, two of each mechanical filter were tested against a neutralized DOP aerosol for comparison purposes. Five of the electrostatic PAPR filters were tested against the neutralized DOP aerosol because of the short testing times that were required. The tests with the neutralized aerosol were conducted in the same manner as the charged aerosol tests except they were stopped after only 2 or 3 days because of the large aerosol loads on the filters. Additional testing would have been meaningless. Also, no 3-day breaks were included during testing with the neutralized aerosol because the break had no effect on the test results with the charged aerosol.

Because of the high penetration results obtained while testing the electrostatic PAPR filter, they were subjected to a second series of tests. Four 3M AS-140 filters were exposed to each of the following loading tests: 100 mg charged DOP per day; 100 mg neutralized DOP per day; 200 mg charged DOP per day; 200 mg neutralized DOP per day; 400 mg charged DOP per day; and 400 mg neutralized DOP per day. The filters were loaded with their respective aerosol loads for 4 consecutive days. They were then stored in a plastic bag untouched for 3 consecutive days and tested again for only 5 min (about 60 mg DOP load) on the last day of testing (Day 5).

During all tests, the aerosol particle size (count median diameter) and particle size distribution (geometric standard deviation) were periodically determined using a TSI model 3934 scanning mobility particle sizer (SMPS). This instrument measures the size distribution of submicrometer aerosols by the electrical mobility detection method. This periodic check of the aerosol size distribution helped ensure the TSI 8122 maintained a test aerosol that met the criteria in 42 CFR 84.

RESULTS AND DISCUSSION

Table II summarizes the results for all of the mechanical PAPR filters tested against the charged DOP aerosol, and Table III shows the results from the neutralized DOP tests. The five Racal P3 filters tested with the charged DOP aerosol show that after four 8-hour days (5 days in the case of one filter) of testing, the maximum penetration values stayed below the 0.03% threshold value set forth for high-efficiency (P100 series), nonpowered, air-purifying particulate filters in 42 CFR 84. In fact, the maximum penetration values for these five Racal P3 filters only reached 0.015% at total DOP loads of 11,000 mg or more. The two Racal P3 filters tested against the neutralized DOP aerosol maintained penetration values below 0.03% at DOP loads exceeding 7600 mg.

The maximum penetration (P_{max}) and final penetration (P_{final}) values for the Racal P3 and other filters tested are shown in Tables II and III. The variability observed is a direct result of day-to-day differences in the testing system and subtle differences between individual filters. The total aerosol load on a given filter varies daily with small changes in flow rate

TABLE II. Ranges of 8-Hour Daily Penetration (P) Results for Five Filters of Each Type Tested on the TSI 8122 with the Charged DOP Aerosol

Filter	Testing Day[A]	$P_{initial}$ (%)	$P_{maximum}$ (%)	P_{final} (%)	P_{2000mg} (%)	Total DOP Load (mg)
Racal P3	1	0.001–0.004	0.003–0.010	0.001–0.001	0.001–0.010[B]	2500–2800
	2	0.001–0.003	0.007–0.012	0.001–0.001	—	5000–5600
	3	0.001–0.004	0.006–0.011	0.001–0.004	—	7600–8300
	4	0.002–0.004	0.007–0.012	0.002–0.005	—	10,100–11,000
	5[C]	0.003	0.015	0.002	—	13,900
MSA OptiFilter XL	1[D]	0.001–0.003	0.003–0.016	0.001–0.005	0.001–0.005[E]	2600–3100
	2	0.001–0.003	0.004–0.015	0.001–0.006	—	5900–6200
	3	0.001–0.004	0.004–0.013	0.001–0.002	—	8900–9100
	4	0.001–0.003	0.005–0.013	0.002–0.005	—	11,900–12,200
	5[D]	0.003	0.008	0.003	—	15,400
3M W-3267	1	0.003–0.004	0.007–0.011	0.004–0.007	0.004–0.011[F]	4300–5000
	2	0.005–0.009	0.013–0.027	0.012–0.021	—	8600–10,000
	3	0.020–0.027	0.032–0.041	0.022–0.034	—	13,000–14,900
	4	0.025–0.047	0.045–0.078	0.039–0.063	—	17,300–19,400
Racal Air-Mate HEPA	1	0.002–0.021	0.007–0.029	0.001–0.025	0.003–0.026[F]	8100–8700
	2	0.001–0.029	0.005–0.031	0.004–0.025	—	16,500–17,400
	3	0.003–0.031	0.010–0.037	0.005–0.027	—	24,800–26,100
	4	0.004–0.036	0.013–0.048	0.007–0.038	—	33,300–34,600

[A]Days of aerosol loading on the filters. The loading schedule for each filter incorporated 3 consecutive days where the filters were left untouched to simulate a long weekend. The weekend simulation did not fall at the same point in the loading schedule for each filter. However, no differences in penetration results were noticed as a result of the weekend simulation, regardless of where it occurred in the loading schedule.
[B]Maximum penetration at 667 mg DOP per filter (2000 mg total load divided by 3 filters).
[C]Only one filter was tested on Day 5.
[D]One filter was tested for 7 hours instead of 8 hours. This same filter was the only one tested on Day 5.
[E]Maximum penetration at 1000 mg DOP per filter (2000 mg total load divided by 2 filters).
[F]Maximum penetration at 2000 mg DOP per filter (2000 mg total load divided by 1 filter).

and aerosol concentration in the testing chamber. Taken over 8 hours, these differences are magnified. Care was taken to maintain proper flow rates and aerosol concentrations at all times, but this variability remains unavoidable. Regardless, there was no noticeable difference in the results obtained for the Racal P3 filters tested against the charged or neutralized DOP aerosol. Using a 2000 mg total PAPR load for reference, each Racal P3 filter would receive a continuous load of 667 mg

TABLE III. Ranges of 8-Hour Daily Penetration (P) Results for Two Filters of Each Type Tested on the TSI 8122 with the Neutralized DOP Aerosol

Filter	Testing Day	$P_{initial}$ (%)	$P_{maximum}$ (%)	P_{final} (%)	P_{2000mg} (%)	Total DOP Load (mg)
Racal P3	1	0.001–0.001	0.002–0.009	0.001–0.001	0.002–0.006[A]	2500–2800
	2	0.001–0.003	0.003–0.027	0.001–0.017	—	5100–5600
	3	0.002–0.017	0.010–0.022	0.002–0.011	—	7600–8400
MSA OptiFilter XL	1	0.001–0.001	0.003–0.004	0.001–0.001	0.001–0.002[B]	3100–3100
	2	0.001–0.001	0.004–0.005	0.001–0.001	—	6000–6200
	3	0.001–0.001	0.006–0.012	0.001–0.002	—	8700–9400
3M W-3267	1	0.003–0.004	0.013–0.016	0.005–0.006	0.013–0.014[C]	4400–4600
	2	0.007–0.009	0.015–0.022	0.014–0.015	—	8700–8900
	3	0.019–0.022	0.029–0.030	0.023–0.030	—	13,200–13,400
Racal Air-Mate HEPA	1	0.006–0.007	0.016–0.018	0.010–0.013	0.011–0.013[C]	8000–8400
	2	0.015–0.018	0.020–0.020	0.015–0.015	—	16,300–16,900

[A]Maximum penetration at 667 mg DOP per filter (2000 mg total load divided by 3 filters).
[B]Maximum penetration at 1000 mg DOP per filter (2000 mg total load divided by 2 filters).
[C]Maximum penetration at 2000 mg DOP per filter (2000 mg total load divided by 1 filter).

of DOP (2000 mg DOP divided by three filters in the standard configuration). The maximum penetration values for the filters at 667 mg continuous DOP load show no noticeable difference resulting from the aerosol charge.

The results for the MSA OptiFilter XL filters tested with the charged DOP aerosol show consistent results even after up to five 8-hour days of testing. All five filters maintained penetration values below 0.03% with DOP loads of 11,900 mg or more. The maximum penetration value for any of the OptiFilter XL filters exposed to the charged DOP aerosol was only 0.016%, which occurred during the first day of testing. The two OptiFilter XL filters tested against the neutralized DOP aerosol maintained aerosol penetrations below 0.03% for total DOP loads of over 8700 mg, with the maximum penetration value for either filter reaching 0.012%. Using a 2000 mg total PAPR load for reference, the maximum penetration values for the filters after 1000 mg continuous DOP load (2000 mg DOP divided by two filters in the standard configuration) showed no noticeable difference resulting from the aerosol charge distribution.

The five 3M W-3267 filters exposed to the charged aerosol all had maximum penetration values that did exceed the 0.03% threshold value sometime during the third day of testing. However, more than 8600 mg of liquid DOP aerosol had been loaded onto each filter before Day 3 testing began. This high loading rate was the result of the increased flow rate through the W-3267 filters compared with those tested earlier. When the testing was completed on each of the filters, the filter material was saturated with the DOP oil. The increased level of filter penetration toward the end of testing could be the result of small oil droplets coming off the backside of the filter material instead of actual test aerosol penetration. The two W-3267 filters tested against the neutralized DOP aerosol showed similar results, with both showing maximum penetration values of approximately 0.03% during the third day of testing, when more than 13,000 mg of liquid DOP aerosol had been loaded onto the filters. The similarity is further illustrated by the maximum penetration values for the filters with a reference of 2000 mg continuous DOP load (2000 mg DOP divided by one filter in the standard configuration). No differences resulted from the test aerosol charge at the 2000 mg load.

Three of the five 3M Racal Air-Mate HEPA filters tested against the charged aerosol showed maximum penetration values that exceeded the 0.03% threshold during the second day or early in the third day of testing. However, roughly 17,000 mg of liquid DOP aerosol had been deposited on these filters by the end of the second day of testing. The other two filters tested with the charged aerosol performed better than the previous three. In fact, the maximum penetration values for these two filters never exceeded 0.03% even with loads of over 33,000 mg DOP. An interesting observation when considering the penetration results for these filters is that, on completion of the testing on each filter, the media was completely saturated with DOP oil. In fact, when the filters were removed from the blower testing assembly, oil dripped from the filter media. Thus, it is conceivable the penetration results shown in Table II could have been affected by small oil droplets pulled off the downstream side of the filter during testing, particularly during the last 2 days. Tests on the two Racal Air-Mate HEPA filters against the neutralized DOP aerosol were only carried out for two 8-hour days because of the large DOP aerosol loads on the filters after that time. The daily testing results for these two filters are shown in Table III. Regardless of the aerosol charge, at a reference load of 2000 mg continuous DOP, the maximum penetration values are not noticeably different, and all of them are well under the 0.03% penetration threshold.

The four varieties of mechanical PAPR filters showed no noticeable differences in filter penetration when the results from the charged and neutralized DOP aerosols were compared. This is to be expected because the Racal P3, MSA OptiFilter XL, 3M W-3267, and Racal Air-Mate HEPA filters all use purely mechanical mechanisms to facilitate particulate capture. Additionally, because the testing schedule had no noticeable effect on overall mechanical filter performance, only the cumulative DOP load seems to have an effect. Thus, these mechanical PAPR filters could conceivably sit untouched for several days with no noticeable effect on performance.

For comparison, five electrostatic 3M AS-140 filters were tested using the TSI 8122 at 225 ± 5 L/min against the charged and neutralized DOP aerosols. The tests for the AS-140 filters lasted less than one 8-hour day due to high aerosol penetration results. The testing results for the AS-140 filters tested against both DOP aerosols are shown in Table IV. For the five AS-140 filters tested against the charged DOP aerosol, an average maximum penetration of 9.74% was seen at an average load of 3900 mg. In comparison, the five AS-140 filters against the neutralized DOP aerosol showed an average maximum penetration of 10.90% at an average load of only 3300 mg. These filters were all tested at a flow rate lower than optimum, so the penetration values at a worst-case flow rate could conceivably be higher. There is a noticeable increase in filter penetration when a neutralized DOP aerosol is used compared with a charged DOP aerosol. This difference can be seen using a 2000 mg continuous DOP load as a reference for comparison. The maximum penetration values at a 2000 mg charged DOP load ranged from 0.254–0.854%, whereas loads of 2000 mg of neutralized DOP gave maximum penetration values ranging from 1.20–1.87%. Whereas the difference at 2000 mg total DOP load is not statistically significant, it becomes statistically significant ($p < 0.05$) at DOP loads of about 3400 mg. This difference was even more evident in subsequent tests performed.

3M AS-140 filters were loaded intermittently with either the charged or neutralized DOP aerosol. The difference between the charged and neutralized aerosol was visually distinguishable at the 100 mg per day aerosol loading rate, although it was not statistically significant at any point during the 100 mg per day testing. For the four AS-140 filters loaded with the charged DOP aerosol, the maximum penetration values were all between 0.105% and 0.518% when the filters were tested on the last day (after sitting untouched for 3 consecutive

TABLE IV. Penetration (P) Results for 3M AS-140 Filters Tested on the TSI 8122 with DOP Aerosol

	$P_{initial}$ (%)	$P_{maximum}$ (%)	P_{final} (%)	P_{2000mg} (%)[A]	Total DOP Load (mg)
Charged aerosol					
Filter #1	0.020	6.626	6.585	0.854	3100
Filter #2	0.017	11.104	11.104	0.384	4200
Filter #3	0.019	8.637	8.187	0.254	4300
Filter #4	0.022	12.243	12.243	0.651	3900
Filter #5	0.023	10.089	10.089	0.468	3900
Neutralized aerosol					
Filter #1	0.017	18.136	18.120	1.206	4200
Filter #2	0.019	6.721	6.351	1.202	3000
Filter #3	0.018	8.320	8.320	1.662	3000
Filter #4	0.027	11.005	11.005	1.548	3400
Filter #5	0.020	10.435	10.435	1.865	3100

[A] Maximum penetration at 2000 mg DOP (2000 mg total load divided by 1 filter).

days). The four AS-140 filters loaded with 100 mg per day of the neutralized DOP aerosol had maximum penetration values of between 0.327% and 0.556% when tested on the last day, at which time the difference in penetration resulting from the aerosol charge became somewhat noticeable. Note that for both aerosols, there were some AS-140 filters having maximum penetration values over 0.03% during the second day of testing when less than 200 mg of aerosol had contacted the filter. Figure 1 shows typical results for AS-140 filters tested against the charged and neutralized DOP aerosols. At DOP loads above 400 mg (Day 5), it appears that the neutralized DOP aerosol is more penetrating than the charged aerosol when loaded on the AS-140 filters. This was expected because the AS-140 filters use an electrostatic filtration mechanism to facilitate particle capture. Electrostatic filter media rely on charge differential for particle attraction and capture. The difference between the charged and neutralized DOP aerosols became more noticeable with the 200 mg per day and 400 mg per day aerosol loadings.

The 3M AS-140 filters loaded with 200 mg charged DOP per day showed maximum penetration values between 0.080–0.154%, 0.352–0.708%, and 0.957–1.76% on Day 3, Day 4, and Day 5 of the testing, respectively. However, these values increased to 0.113–0.258%, 0.646–1.27%, and 1.94–3.21% for the neutralized DOP aerosol at corresponding 200 mg per day exposures. On Day 3, the difference in maximum penetration values became statistically different ($p < 0.05$). This difference is shown graphically in Figure 2 where typical results for the AS-140 filters exposed to 200 mg per day of the charged and neutralized DOP aerosols are presented. The increased

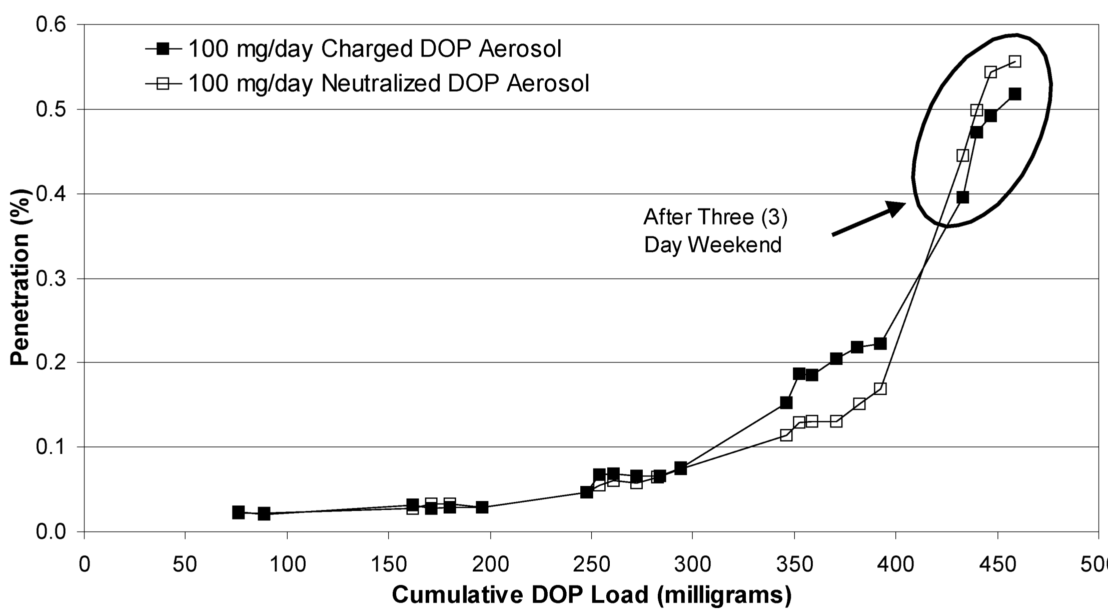

FIGURE 1. Typical results of electrostatic 3M AS-140 filters loaded with 100 mg charged and neutralized DOP aerosol per day

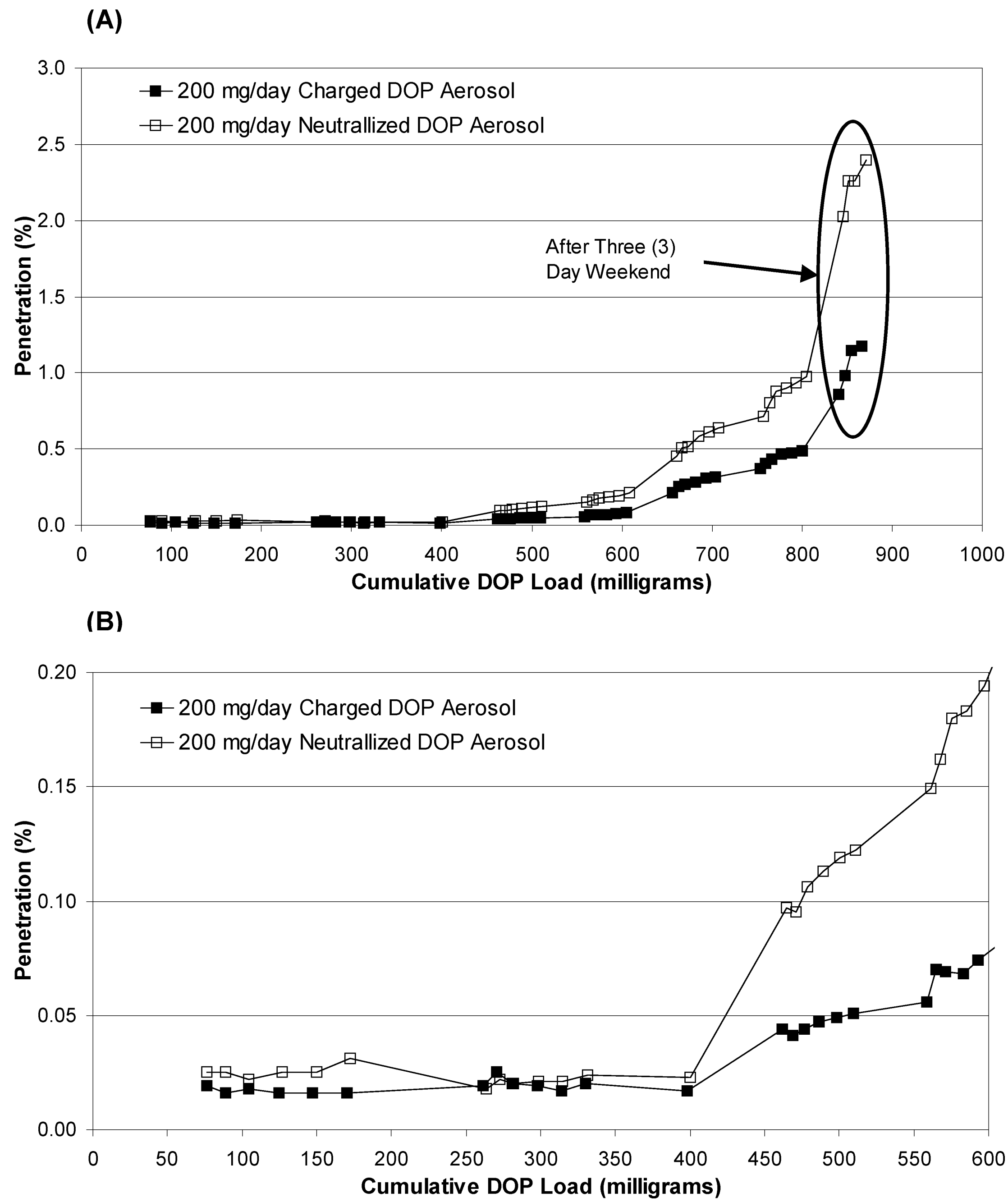

FIGURE 2. Typical results of electrostatic 3M AS-140 filters loaded with 200 mg charged and neutralized DOP aerosol per day: (A) all loading results; (B) closeup view of first 3 days of loading showing noticeable difference between charged and neutralized aerosol starting on Day 3 (after 400 mg loads)

penetration of the neutralized aerosol through the filter material is clearly demonstrated for the filters loaded with 200 mg of aerosol per day. None of the filters loaded with the charged aerosol exceeded 0.03% penetration during the first day of testing, but one of the filters loaded with the neutralized aerosol did exceed the 0.03% threshold value for high-efficiency filters on Day 1 (< 200 mg load).

The four 3M AS-140 filters loaded with 400 mg charged DOP aerosol per day gave maximum penetration values of between 0.061–0.126%, 0.600–1.190%, 2.78–4.41%, and 7.77–9.89% on Day 2, Day 3, Day 4, and Day 5 of testing, respectively. These values increased dramatically for the four filters loaded with 400 mg per day of the neutralized DOP aerosol, where maximum penetration values ranged between 0.137–0.172%, 1.09–1.85%, 5.04–8.08%, and 10.74–14.08% on Day 2, Day 3, Day 4, and Day 5, respectively. Here, the difference in penetration between the charged and neutralized DOP aerosols became statistically significant ($p < 0.05$) on

Day 2. Regardless of the aerosol charge, all of the AS-140 filters loaded with 400 mg per day gave maximum penetration values over 0.03% on the first day of testing.

The electrostatic 3M AS-140 filter data show that a potential for filter efficiency degradation exists with electrostatically enhanced PAPR filters. Accordingly, 3M Company states in the user instructions that the AS-140 filters should not be used against oil mists. The effectiveness of the static charge to aid in filtration was greatly affected by aerosol charge and aerosol loading rate. These laboratory results clearly showed that filter penetrations exceeded 0.03% when the electrostatic PAPR filters were exposed to an oil aerosol. The observed laboratory degradation may or may not affect workplace performance, as similar degradation has not been verified in workplace studies. Regardless, 42 CFR 84 does not require respirator manufacturers to include the filtration mechanism (electrostatic or mechanical) on product packaging or certification labels, so there is no way of knowing if a particular filter is electrostatically enhanced, without laboratory testing. If there is concern regarding products currently being used, the best means of determining the filtration mechanism is to contact the manufacturer directly.

CONCLUSIONS AND RECOMMENDATIONS

The four varieties of mechanical PAPR filters showed no noticeable differences in filter penetration when the results from the charged and neutralized DOP aerosols were compared. The results were different for the electrostatic 3M AS-140 filters tested. Continuous loading tests on the AS-140 filters were all terminated at less than 8 hours because of the high penetration values. The filters were noticeably less efficient at filtering the neutralized DOP aerosol than the charged aerosol. The effect of the aerosol charge became even more evident during the intermittent aerosol loading experiments. The electrostatic PAPR filters were less efficient at capturing the neutralized aerosol as the daily loadings increased from 100 mg to 400 mg per day, when compared with the intermittent charged DOP aerosol loadings.

Although the 3M AS-140 filters meet all PAPR filter certification requirements in 42 CFR 84, because the filters are magenta like P100 filters, respirator users could be confused if the user instructions are not carefully read and understood. If the filters are chosen for use against oil mists simply based on the magenta color, adverse consequences could result. Until the issue of filter color is addressed in the regulations, respirator manufacturers must follow the example set by 3M and limit the use of electrostatic PAPR filters, if necessary. Because electrostatic PAPR filter efficiency degradation could be a problem with any oil exposure (and possibly others), consideration should be given to alternate testing methods to certify PAPR filters that easily degrade for use in non-oil environments. A separate class of PAPR filters, similar to N100 nonpowered, air-purifying filters, should be discussed when changes to incorporate PAPRs into 42 CFR 84 are made. In addition, research into an appropriate PAPR test for non-oil aerosols should be encouraged.

NIOSH certification of a respirator product does not address all respirator characteristics, only those listed in 42 CFR 84. Filter efficiency degradation is currently not a characteristic fully addressed in 42 CFR 84. Each respirator manufacturer is responsible for the remaining performance characteristics of their products, so it is the responsibility of each respirator manufacturer to study and determine the magnitude of filter efficiency degradation of their products. Although there are multiple testing methods that could be used, the procedure presented here appears to be a viable testing method to monitor the effects of filter degradation on respirator filter performance.

ACKNOWLEDGMENTS

The authors would like to thank Bill Miller of the NIOSH Division of Respiratory Disease Studies, Field Studies Branch for his help with statistical analysis. We would also like to thank Molly Pickett-Harner for her editorial assistance.

REFERENCES

1. "Respiratory Protective Devices," *Code of Federal Regulations* Title 42, Part. 84, 1995. pp. 30336–30404.
2. **National Institute for Occupational Safety and Health (NIOSH):** *NIOSH Guide to the Selection and Use of Particulate Respirators Certified Under 42 CFR 84*. DHHS (NIOSH) Pub. No. 96-101. Cincinnati, Ohio: NIOSH, 1996.
3. **Brown, R.C., D. Wake, R. Gray, et al.:** Effect of industrial aerosols on the performance of electrically charged filter material. *Ann. Occup. Hyg. 32*: 271–294 (1988).
4. **Moyer, E.S., and M.S. Bergman:** Electrostatic N-95 respirator filter media efficiency degradation resulting from intermittent sodium chloride aerosol exposure. *Appl. Occup. Environ. Hyg. 15*: 600–608 (2000).
5. **Barrett, L.W., and A.D. Rousseau:** Aerosol loading performance of electret filter media. *Am. Ind. Hyg. Assoc. J. 59*: 532–539 (1998).
6. **Tennal, K.B., M.K. Mazumder, A. Siag, et al.:** Effect of loading with an oil aerosol on the collection efficiency of an electret filter. *Partic. Sci. Technol. 9*: 19–29 (1991).
7. **Baumgartner, H.P., and F. Loffler:** The collection performance of electret filters in the size range 0.01 μm–10 μm. *J. Aerosol Sci. 17*: 438–445 (1986).
8. **Kanaoka, C., H. Emi, and T. Ishiguro:** Time dependency of collection performance of electret filter. In *Aerosols*, B.Y.H. Lin, D.Y.H. Pui, and H.J. Fissan (eds.). New York: Elsevier Science Publishing, 1984. pp. 613–616.
9. **Blackford, D.B., G.J. Bostock, R.C. Brown, et al.:** Alteration in the performance of electrostatic filters caused by exposure to aerosols. In *Proceedings of the Fourth World Filtration Congress*, Ostende, Belgium. Filtration Society, London, 1986. pp. 7.27–7.33.
10. **Fissan, H.J., S. Neumann, and G. Schürmann:** Electrostatic enhanced filtration. In *Aerosols*, B.Y.H. Lin, D.Y.H. Pui, and H.J. Fissan (eds.). New York: Elsevier Science Publishing, 1984. pp. 581–584.
11. **Chen, C.C., M. Lehtimäki, and K. Willeke:** Loading and filtration characteristics of filtering facepieces. *Am. Ind. Hyg. Assoc. J. 54*: 51–60 (1993).
12. **Martin, S.B., and E.S. Moyer:** Electrostatic respirator filter media: Filter efficiency and most penetrating particle size effects. *Appl. Occup. Environ. Hyg. 15*: 609–617 (2000).

13. **Janssen, L.L., J.O. Bidwell, H.E. Mullins, and T.J. Nelson:** Efficiency of degraded electret filters: Part I-Laboratory testing against NaCl and DOP before and after exposure to workplace aerosols. *J. Int. Soc. Respir. Prot. 20*: 71–80 (2003).
14. **Janssen, L.L., J.O. Bidwell, H.E. Mullins, and T.J. Nelson:** Efficiency of degraded electret filters: Part II-Field testing against workplace aerosols. *J. Int. Soc. Respir. Prot. 20*: 81–90 (2003).
15. **Janssen, L.L.:** Efficiency and pressure drop effects of high concentrations of cement dust on N95 electret filters. *J. Int. Soc. Respir. Prot. 21*: 75–82 (2004).
16. **Raynor, P.C., and S.J. Chae:** The long-term performance of electrically charged filters in a ventilation system. *J. Occup. Environ. Hyg. 1*: 463–471 (2004).
17. **Haney, R.L., G.P. Saseen, and R.W. Waytulonis:** An overview of diesel particulate exposures and control technology in the U.S. mining industry. *Appl. Occup. Environ. Hyg. 12*: 1013–1018 (1997).
18. **Liuknone, L.R., J.L. Grogan, and W. Myers:** Diesel particulate matter exposure to railroad train crews. *AIHAJ 63*: 610–616 (2002).
19. **Cohen, H.J., J. Borak, T. Hall, G. Sirianni, and S. Chemerynski:** Exposure to miners to diesel exhaust particulates in underground nonmetal mines. *AIHAJ 63*: 651–658 (2002).
20. **Stefaniak, A.B., M.D. Hoover, G.A. Day, et al.:** Characterization of physiochemical properties of beryllium aerosols associated with prevalence of chronic beryllium disease. *J. Environ. Monit. 6*: 523–532 (2004).
21. **Larson, D.L.:** "Collection Efficiencies of Air Purifying Respirators Containing Electrostatic Filter Media." PhD disserration, Colorado State University, Fort Collins, Colorado, 1999.
22. **Berardinelli, S., M. Sandy, S. Martin, et al.:** "Performance of N-, R- and P-Series Respirator Filters Against Diesel Exhaust," Presented at the American Industrial Hygiene Conference and Exposition, New Orleans, La., 2001. *Abstracts*, p. 70.
23. **National Institute for Occupational Safety and Health (NIOSH), National Personal Protective Technology Laboratory (NPPTL):** Determination of Air Flow for Powered Air Purifying Respirators. NIOSH/NPPTL Standard Testing Procedure #RCT-APR-STP-0012. Revision 1.1, June 2005.