

Performance of Four Class 95 Electret Filters Against Diesel Particulate Matter

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ABSTRACT

This study was done to assess performance of four Class 95 respirator filters exposed to diesel engine exhaust. NIOSH-certified electret filters from two manufacturers were used. N95 filters from each manufacturer were tested. P95 and R95 filters from Manufacturer X and Y, respectively, were also tested. Only R and P series filters are typically recommended for diesel exposures. Prior to diesel exposure, laboratory penetration and pressure drop were measured using applicable NIOSH certification conditions, except there was no loading test. The filters were then exposed to diesel engine exhaust from a portable air compressor. Each type of filter was divided into three groups for different exposure patterns: 1) a single exposure of 1-2 hours; 2) a single exposure of approximately 8 hours; or 3) two exposures on different days totaling approximately 8 hours. After the diesel exhaust exposure, laboratory penetration and pressure drop were retested using NIOSH test conditions. Mean laboratory penetration of Manufacturer X N95 filters increased to a high of 0.79% for the 8-hour exposure. N95 filters from Manufacturer Y showed larger increases in mean laboratory penetration, reaching 19.7% for the intermittent exposure. P95 filters remained far below 1% laboratory penetration for all exposures. Mean laboratory penetration for R95 filters increased with all exposures, up to 11% for the 8-hour exposure. Penetration of the particulate portion of the diesel exhaust was measured as elemental carbon (EC) for each group of filters using NIOSH method 5040. P95 filters did not permit detectable EC penetration. The highest mean EC penetration for any group was 4.31% for Manufacturer Y N95 filters exposed intermittently. Because of design differences among N95 filters, they should not be used for diesel particulate exposures. The R and P95 filters tested in this study would provide acceptable filtration for workplaces, where exposure conditions are less harsh than these experimental conditions.

Keywords: Filters, respirator, electret, filter efficiency, filter penetration, diesel particulate matter

INTRODUCTION

Diesel engine exhaust is a complex mixture of gaseous and particulate substances (NIOSH, 2002). Gaseous components include carbon monoxide, carbon dioxide and oxides of nitrogen (e.g., NO and NO₂). The particulate portion consists of a mixture of soot, lubricating oil, unburned or partially burned hydrocarbons and water. Because of potential adverse health effects ranging from respiratory irritation to lung cancer, occupational exposure to diesel particulate matter (DPM) in underground metal and nonmetal mines is regulated in the United States by the Mine Safety and Health Administration (MSHA) (Federal Register, 2005). The 8-hour time-weighted average personal exposure limit (308 µg/m³) is expressed as elemental carbon (EC). MSHA chose EC as a surrogate for DPM because it correlates

strongly with DPM concentration and more accurately represents DPM exposure than does the alternative, total carbon (TC), in the mine environment (Federal Register, 2005).

Since respiratory protection may be necessary to reduce workers' DPM exposures, it is important to understand the performance of respirator filters exposed to DPM. The National Institute for Occupational Safety and Health (NIOSH) approves three series of particle-filtering respirators in the United States, designated N, R and P (Federal Register, 1995). Within each series, three levels of efficiency in removing the laboratory test aerosols are certified: 95%, 99% and 99.97%. N-series filters are not required to demonstrate resistance to the potentially "degrading" effects of oils, (Federal Register, 1995) and are therefore not intended for use in workplace atmospheres that contain oily aerosols. In this context, "degrading" means that exposure to an agent may cause an increase in filter penetration measured under laboratory test conditions. R and P series filters must demonstrate oil resistance when tested with dioctyl phthalate (DOP), which is described as a "highly degrading" oil aerosol (Federal Register, 1995). As a result both R and P filters can be used in workplace atmospheres that contain oily aerosols as well as those that do not. Of significance to this paper, diesel exhaust has been reported to degrade the laboratory performance of certain NIOSH-certified, electrostatically-enhanced (electret) respirator filters (Berardinelli *et al.*, 2001). Electret filters, which consist of electrically charged polymer fibers, are widely used in particulate respirators. The charges enhance their filtration efficiency, particularly for submicrometer aerosols, without a corresponding increase in pressure drop across the filter (Chen *et al.*, 1993).

Berardinelli *et al.* (2001) only reported the changes in laboratory penetration before and after DPM exposure. They did not evaluate the efficiency of the filters against the DPM or EC. However, other field studies of deliberately degraded electret filters have shown good to excellent performance (more than 95% mass efficiency) against typical workplace aerosols (Janssen *et al.*, 2003; Janssen, 2004). Therefore, the study that is the subject of this paper was undertaken with the following two objectives:

1. To determine if the laboratory penetration of four class 95 electret filters is affected by exposure to diesel exhaust;
2. To determine if the four NIOSH-certified class 95 electret filters effectively reduce exposure to DPM, expressed as EC.

It should be noted that the MSHA final rule was published after this study was undertaken, and specifies only R100 and P100 filters for negative pressure respirators used for DPM protection (Federal Register, 2005). However, other regulatory agencies, e.g., the Occupational Safety and Health Administration, have not limited filter selection for the industries they regulate.

METHODS

Four NIOSH-certified class 95 filters from two respirator manufacturers (designated Manufacturer X and Manufacturer Y) were used in this study. The filters were chosen from those available for sale at the time of the study. Class N95 filters from both manufacturers were chosen because the earlier study of Berardinelli *et al.* (2001) reported the greatest degradation in this class of filter. The P95 filter from Manufacturer X and the R95 from Manufacturer Y were also selected. Manufacturer X does not sell an R95, and Manufacturer Y does not sell a P95. Consequently, they will be identified only as R and P filters without reference to their manufacturer.

Prior to exposure to diesel exhaust, all the filters were tested for initial laboratory penetration and pressure drop using the applicable conditions and instrumentation specified in 42 CFR Part 84 (Federal Register, 1995). That is, N-series filters were tested with sodium chloride and R and P series filters were tested with DOP using a TSI Certitest® Model 8130 Automated Filter Tester (TSI, St. Paul, MN). The NIOSH minimum 200 mg loading test (Federal Register, 1995) was not used in this study since the test filters were to be loaded with DPM. In addition to the filters to be exposed to DPM, filters were tested for use as unexposed controls. This was done so any possible effect of repeated laboratory testing (before and after the test filters were exposed to DPM) could be assessed.

A 40 horsepower portable air compressor (Ingersoll Rand, Montvale, NJ) was used as a source of diesel exhaust. The exhaust stream was ducted from the compressor using a flexible exhaust hose approximately 10 cm diameter by 6.1 m long (Crushproof Tubing Co., McComb, OH). The hose directed the exhaust into a 152 x 76 x 190 cm storage shed (Rubbermaid Home Products, Fairlawn, OH) with an internal volume of approximately 2.2 m³. The exhaust entered the shed via a 12 cm diameter opening approximately 30 cm from the top of one side panel. The doors on the shed were left slightly open during the testing (approximately 10 cm) to prevent the buildup of heat and moisture from the exhaust stream.

"LT" sample holders described previously (Janssens *et al.*, 2003) were used to mount the test filters. These sample holders allowed air to be drawn through both a respirator filter and a 25 mm quartz fiber filter supported with a cellulose backup pad (SKC Inc., Eighty Four, PA) in an open-face cassette downstream from the respirator filter. These "C_i" samples were intended to collect any DPM that penetrated the respirator filter. A Gast 0211 or 0322 Lab Model vacuum pump (Gast Manufacturing, Inc., Benton Harbor, MI) was used to draw air through each LT sampler at a nominal flow rate of approximately 25 L/min. This value was chosen to represent the minute volume (50 L/min through a pair of filters) at the upper limit of sustainable work for most individuals (Lumb, 2000). The vacuum pumps were located outside the shed and were connected to the samplers via 9.5 mm compressed air hose passed through a 12 cm diameter opening at the bottom rear corner of the shed.

Respirator filter/C_i combinations were placed near the center of the shed approximately 30 cm above the floor. Seven to 10 samples were collected simultaneously. Because the volumetric output of the compressor was more than an order of magnitude greater than the maximum sample volume withdrawn, the small difference in number of samples collected simultaneously was judged to be insignificant. Three to seven ambient (C_o) samples were collected during the same exposure periods as the respirator/C_i filter combinations to characterize the atmosphere in the shed. The C_o samples were on the same plane and encompassed the entire length occupied by the as the C_i samples. The C_o samples were collected on 37 mm quartz fiber filters (SKC Inc., Eighty Four, PA) in open-face cassettes using MSA Escort® ELF personal sampling pumps (MSA, Pittsburgh, PA) with a flow rate of 2 L/min.

Groups of respirator filters of each type were exposed in one of three patterns: 1) a single exposure of 1-2 hours; 2) a single exposure of approximately 8 hours; or 3) two exposures on different days totaling approximately 8 hours (subsequently called intermittent exposure in this paper). These patterns were chosen to mimic potential usage in a workplace and to ascertain possible adverse effects of intermittent loading and storage on filter penetration as reported by Moyer and Bergman (2000). The study was designed to test six filters from each manufacturer in each exposure pattern. However, seven Manufacturer X N95 filters inadvertently received a single 8 hour exposure.

The particle size distribution of the DPM was measured gravimetrically with an eight-stage Marple Personal Cascade Impactor (Thermo Anderson, Smyrna, GA). The impactor was placed in the center of the shelf holding the test filters for a period of 5.6 hours. The flow rate was 2 L/min per the vendor's instructions. So that some comparison of DPM loading between this study and that of Berardinelli *et al.*, loading values for filters used in this study were estimated by multiplying each C_i sample volume by the total mass concentration obtained from the cascade impactor measurement.

Following the DPM exposures, the respirator filters were returned to the laboratory and retested for initial penetration and pressure drop using appropriate NIOSH test procedures. The unexposed control filters of each type were also retested. The C_i and C_o samples were analyzed for EC using evolved gas analysis according to NIOSH method 5040 (NIOSH, 2004). The detection limits for EC were 1.3 µg and 3 µg for the C_i and C_o samples, respectively. Blank samples were collected for both the C_i and C_o samples. These cassettes were handled in the same manner as the test filters, except no air was drawn through them. They were briefly opened at the DPM test site and immediately resealed. The purpose of the field blanks was to determine if handling procedures contaminated the test samples.

Penetration of EC through each respirator filter tested was calculated as follows:

$$\% \text{ penetration} = \frac{C_i}{C_o} \times 100$$

Where $\bar{C}_0$ = the mean of the C_0 samples for the time period over which a given C_i sample was collected.

It was not necessary to correct C_i or C_0 laboratory results for blank contamination since no EC was found on either set of blanks.

The potential effects of filter and exposure time/pattern on the log-transformed EC penetration were examined using the General Linear Model technique. Tukey simultaneous confidence intervals were used for pairwise comparisons.

RESULTS

Results of the pre- and post-DPM exposure laboratory penetration testing of the respirator filters are shown in Tables I and II. Student's T-tests revealed that, except for the intermittently exposed R95 filters ($p=0.081$), all mean post-exposure laboratory penetration values were significantly different from the pre-exposure values ($p<0.05$). The changes in the penetration for the untreated control groups were small. They were likely due to the effects of repeated testing with test agents chosen for their degrading properties (Federal Register, 1995) or variability inherent in the test equipment and procedures.

The post-exposure pressure drop values were not appreciably different from the pre-exposure measurements for any of the test filters or the unexposed controls. Therefore, those results are not presented and they will not be discussed further.

The distribution of C_0 for EC was not significantly different from lognormal ($p=0.428$). The geometric mean C_0 value for EC was $61.6 \mu\text{g}/\text{m}^3$ with a geometric standard deviation of 2.6. Penetration results for EC are presented in Table III. The particle size analysis revealed a mmad of $1.8 \mu\text{m}$ with a geometric standard deviation (GSD) of 4.4. The total mass concentration measured with the impactor was $5.4 \text{ mg}/\text{m}^3$.

Because the P95 filter did not have detectible EC penetration (and therefore no mean or standard deviation), those results were excluded from the GLM analysis. Analysis of the penetration data for the remaining filters revealed the following:

- 1) The EC penetration values for the two N95 filters were significantly different from one another ($p<0.001$);
- 2) The Manufacture Y N95 penetration of EC was significantly different from the R95 ($p=0.027$);
- 3) The EC penetration for single 8-hour exposure was significantly different from the 2 hour exposure ($p=0.01$);

The filter/exposure time interaction was not statistically significant ($p=0.310$).

DISCUSSION

It is evident from Tables I and II that exposure to DPM increased the penetration of laboratory aerosols for all the filters tested. However, in the case of the P95 filters the change was negligible, i.e., from nondetectable to just above the detection limit of the filter tester. The mass penetration of EC was lower than the post-DPM laboratory aerosol penetration for all the filters. This outcome was expected, since the test conditions were designed to simulate a workplace exposure rather than the deliberate "worst case" conditions of NIOSH laboratory testing (Federal Register, 1995). That is, the test conditions of nominal "most penetrating" particle size ($\sim 0.3 \mu\text{m}$ mmad), charge-neutralized challenge aerosol and high (85 L/min) flow rate of the NIOSH test protocols were chosen to maximize filter penetration. The fact that DPM penetration was lower than the post-exposure laboratory penetration is important, since adequate filtration of workplace aerosols is a factor in respirator wearer protection.

Table I. Laboratory Penetration (%) for N95 Filters before and after DPM Exposure (Mean and Standard Deviation)

<u>Manufacturer X</u>		
	Pre-DPM Exposure	Post-DPM Exposure
<u>Unexposed Controls</u>		
Mean	0.22 (n=6)	0.24 (n=6)
SD	0.06	0.06
<u>2-Hour Exposure</u>		
Mean	0.24 (n=6)	1.12 (n=6)
SD	0.04	0.69
<u>8-Hour Exposure</u>		
Mean	0.26 (n=7)	2.71 (n=7)
SD	0.06	0.95
<u>Intermittent Exposure</u>		
Mean	0.22 (n=6)	1.88 (n=6)
SD	0.03	0.75
<u>Manufacturer Y</u>		
	Pre-DPM Exposure	Post-DPM Exposure
<u>Unexposed Controls</u>		
Mean	0.58 (n=6)	1.24 (n=6)
SD	0.09	0.35
<u>2-Hour Exposure</u>		
Mean	0.61 (n=6)	12.1 (n=6)
SD	0.16	9.4
<u>8-Hour Exposure</u>		
Mean	0.64 (n=6)	11.5 (n=6)
SD	0.18	5.6
<u>Intermittent Exposure</u>		
Mean	0.79 (n=6)	19.7 (n=6)
SD	0.29	17.1

All post-exposure penetration values are significantly different from their pre-exposure value ($p < 0.05$).

Table II. Laboratory Penetration (%) for R95 and P95 Filters before and after DPM Exposure (Mean and Standard Deviation). Six filters were exposed in each group. Filters not included in the mean were below the detection limit.

<u>P95</u>		
	Pre-DPM Exposure	Post-DPM Exposure
<u>Unexposed Controls</u>		
Mean	<0.001 (n=1)	0.001 (n=3)
SD	---	0.001
<u>2-Hour Exposure</u>		
Mean	<0.001 (n=2)	0.002 (n=6)
SD	---	0.001
<u>8-Hour Exposure</u>		
Mean	<0.001 (n=1)	0.003 (n=6)
SD	---	0.002
<u>Intermittent Exposure</u>		
Mean	<0.001 (n=1)	0.002 (n=6)
SD	---	0.001
<u>R95</u>		
	Pre-DPM Exposure	Post-DPM Exposure
<u>Unexposed Controls</u>		
Mean	0.21 (n=6)	0.30 (n=6)
SD	0.06	0.07
<u>2-Hour Exposure</u>		
Mean	0.16 (n=6)	2.76 (n=6)
SD	0.04	1.80
<u>8-Hour Exposure</u>		
Mean	0.18 (n=6)	11.0 (n=6)
SD	0.08	9.00
<u>Intermittent Exposure</u>		
Mean	0.22 (n=6)	8.94 ^a (n=6)
SD	0.11	9.91

^a p=0.08. Except for the P95 control filters, all remaining post-exposure penetration values are significantly different from their pre-exposure value (p<0.05).

Table III. Elemental carbon penetration (%) for all test filters (mean and standard deviation). Each group consisted of six filters except as noted. Filters not included in the mean were below the detection limit.^a

	Manufacturer X N95	Manufacturer Y N95
<u>2-Hour Exposure</u>		
Mean	0.65 (n=2)	3.71 (n=6)
SD	---	2.42
<u>8-Hour Exposure</u>		
Mean	0.94 ^b (n=6)	4.04 (n=6)
SD	0.42	0.38
<u>Intermittent Exposure</u>		
Mean	0.59 (n=5)	4.31 (n=6)
SD	0.35	3.76
	P95	R95
<u>2-Hour Exposure</u>		
Mean	<DL	0.55 (n=4)
SD	---	0.05
<u>8-Hour Exposure</u>		
Mean	<DL	2.09 (n=6)
SD	---	1.76
<u>Intermittent Exposure</u>		
Mean	<DL	1.04 (n=4)
SD	---	0.46

^aDetection limits (DL) were <0.50% for 2-hour exposures and <0.29% for 8-hour and intermittent exposures.

^bA seventh sample was below the detection limit.

The results of this study are in general agreement with the findings of Berardinelli *et al.* (2001) for the N95 and R95 filter categories. However, the two studies are not entirely comparable since Berardinelli *et al.* did not examine EC penetration and this study did not measure DPM loading.

In both studies, there was a considerable difference in post-DPM exposure laboratory aerosol penetration between filters of the same class from different manufacturers. In the Berardinelli *et al.* study, DPM loadings ranging from 5-24 mg reduced the laboratory efficiency of N95 filters to less than 95%. The estimated loading values in this study were in that range for the two-hour exposures. This is the point at which some of the Manufacturer Y N95 filters began to allow laboratory aerosol penetration above 5%. In contrast, all Manufacturer X N95 filters exposed for 8 hours remained below 5% penetration at estimated DPM loading on the order of 60-70 mg. Berardinelli *et al.* concluded that R and P series filters performed well at DPM loading up to 50 mg. The penetration of some of the R95 filters exposed for 8 hours (continuously or intermittently) in this study allowed mean laboratory penetration above 5% at DPM loads above 60 mg. The P95 filters were essentially immune to the effects of DPM at any loading seen in this study.

The DPM loading values in both this study and Berardinelli's were much higher than would be anticipated in any work environment. For example, MSHA reported the highest mean whole DPM exposure (i.e., not only EC) from a survey of 31 mines was $610 \mu\text{g}/\text{m}^3$ (Federal Register, 2005). At a 40 L/min work rate, a pair of filters worn by a worker would accumulate approximately 11.7 mg of DPM (~5.9 mg per filter) in an 8-hour workshift. Under these conditions it would take more than 8 days to reach a DPM load above 50 mg. If adequate performance is defined as maintaining a mean laboratory penetration below 5%, it appears that Manufacturer X N95 and P95 filters could be used for that long without concern. If the criterion for adequate performance is set at EC penetration below 5%, R95 filters from this manufacturer could be used under these conditions as well. However, it is likely filters would be replaced before 8 days of use because of general hygiene considerations or damage to the filters.

This study also reveals important differences among the four electret filters. The results indicate that manufacturers select different electret media, or combinations of electret media, to produce filters within the N, R and P series defined in 42 CFR 84. The resulting filters react differently when exposed to degrading aerosols such as DPM. Because N series filters are not required to demonstrate resistance to oils, Manufacturer Y has apparently chosen electrets with minimal resistance to oil degradation. Manufacturer X uses electrets with much higher resistance to degrading aerosols in its N95 filter. It is because of this permissible difference in approved N95 filters that they should not be used against potentially degrading aerosols. It should be restated that, although Manufacturer Y N95 filters' laboratory performance was significantly degraded by these high DPM exposures, the penetration of the workplace hazard (EC) remained below 5%. The same degradation pattern was seen, though less pronounced, in the R95 filters.

CONCLUSIONS

DPM is appropriately classified as a degrading workplace aerosol. In this study, the laboratory penetration of N95 and R95 electret filters was increased by exposure to DPM. The P95 laboratory penetration showed a negligible increase following DPM exposure. None of the filters permitted mean EC penetration greater than 5%.

The R95 and P95 filters tested in this study demonstrated acceptable filtration efficiency for DPM. The same was true of Manufacturer X N95 filters. However, since N series filters are not permitted for use against degrading (oily) aerosols, they should never be used for protection from DPM.

Acknowledgements

The authors want to thank Suresh Kalatoor, Marvin Jones and Alan Rousseau for their help with the study design, and Mic Luinenburg for his assistance with the statistical analyses.

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