

Efficiency and Pressure Drop Effects of High Concentrations of Cement Dust on N95 Electret Filters

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ABSTRACT

Field tests were conducted to measure the effects of high concentrations of cement dust on the penetration and pressure drop of N95 electret respirator filters from two manufacturers. Three groups of each manufacturer's filter were tested: 1) untreated; 2) irradiated with ionizing radiation; 3) dipped in isopropanol for 15 seconds. The purpose of the irradiation and isopropanol treatments was to produce laboratory penetration values above those allowed for approval using "worst-case" NIOSH test conditions. Laboratory initial penetration values for the treated filters ranged from approximately 7% to 60% when tested using the NIOSH test procedures. The filters were then exposed to high concentrations of cement dust in a concrete block manufacturing plant. Dust loading on individual filters ranged from approximately 12 mg to 91 mg; mean dust loading by group was in the range of 31 to 40 mg. There was no significant difference in mean cement dust penetration among the three treatments for one manufacturer's filters. Cement dust penetrations for the second manufacturer's filter groups were statistically different from one another, but the highest mean penetration was only 0.228%. The workplace loading had minimal effect on pressure drop measurements. Laboratory aerosol penetration increased slightly for the untreated filters from both manufacturers, caused by masking of electrical charges on the media. Post-workplace laboratory penetration for the irradiated and IPA dipped filters from both manufacturers decreased significantly. This indicates improved mechanical efficiency with dust loading. These findings are consistent with predictions of filter performance modeling. As expected, current NIOSH approved N95 filters perform very well in very dusty conditions. Under the conditions of this study, filters with laboratory penetration values far in excess of those permitted for NIOSH approval were still very efficient in this workplace. This study provides additional assurance that users of currently approved N95 filters will not lose protection if some charge loss should occur in the workplace.

Keywords: Filters, respirator, electret, filter efficiency, filter penetration, breathing resistance

INTRODUCTION

Electrostatically-enhanced (electret) filters are widely used in particulate respirators. Electrets consist of electrically charged polymer fibers. The charges enhance their filtration efficiency, particularly for submicrometer aerosols, without a corresponding increase in pressure drop across the filter (Chen *et al.*, 1993). High levels of ionizing radiation, immersion in solvents and intermittent exposure to specific aerosols have been shown to reduce or eliminate the charges on electret filters, degrading their efficiency in removing submicrometer aerosols (Chen *et al.*, 1993; Chen and Huang, 1998; Moyer and Bergman, 2000; Martin and Moyer, 2000; Rousseau *et al.*, 2001). It has also been suggested that heavy aerosol loading may lower the efficiency of electrets by reducing or masking the electrical charges (Brown *et al.*, 1988). Janssen *et al.* (2003b) reported very good workplace performance of intentionally degraded

electret filters when mean loading with elemental iron or oil mist was below 3 mg/m³. The highest individual filter loadings were 16.7 mg for iron and 21.2 mg for oil mist.

This study was undertaken to determine the effect of heavy loading with a solid industrial aerosol on electret filter performance. Effects on both laboratory and workplace performance were evaluated. The study was conducted in conjunction with a workplace protection factor (WPF) study of a filtering facepiece N95 respirator reported elsewhere (Bidwell and Janssen, 2004).

MATERIALS AND METHODS

A thorough discussion of the experimental procedures, the logic behind them and workplace sampling equipment are presented elsewhere (Janssen *et al.*, 2003a, Janssen *et al.*, 2003b). This paper will summarize study procedures and present the results of the laboratory and workplace penetration and pressure drop testing.

National Institute for Occupational Safety and Health (NIOSH) class N95 filters from two manufacturers were used in this study. Class N95 filters were chosen because they are widely used for protection against industrial aerosols that do not contain oils. For NIOSH approval, these filters must permit no more than 5% penetration of a sodium chloride aerosol with a mass median aerodynamic diameter (mmad) of approximately 0.3 μ m, typically assumed to be the "most penetrating" particle size. A high flow rate of 85 L/min per respirator assembly and other "worst-case" conditions are also used during testing for NIOSH approval, including a 200 mg loading (CFR, 2002).

Each manufacturer's filters were divided into three groups for testing:

- Untreated, i.e., as they are normally used;
- Irradiated with X-rays; and
- Dipped in isopropyl alcohol (IPA).

As noted earlier, X-rays and IPA immersion are known to reduce or eliminate electrical charges on electrets. They were used in this study to simulate the possible effect of charge loss or masking due to loading with a workplace aerosol. An X-ray dose sufficient to degrade the filters to an initial penetration 6-14% under NIOSH test conditions was chosen. This range of initial penetration has been reported in laboratory studies of filter degradation (Moyer and Bergman, 2000; Martin and Moyer, 2000). The third group of filters was dipped in IPA for 15 seconds and air dried, as reported by Martin and Moyer (2000). There was no specific target value for initial penetration for the IPA-dipped filters.

Following the irradiation and IPA treatments, all three groups of filters were tested for initial laboratory penetration and pressure drop using the conditions and instrumentation specified in 42 CFR Part 84 (CFR, 2002). The NIOSH loading test was not used in this study.

The filters were then exposed to cement dust in the bagging area of a concrete block manufacturing plant. Individual bags were filled pneumatically (i.e., under positive pressure) with cement, resulting in considerable airborne dust. Sample holders described previously (Janssen *et al.*, 2003b) allowed air to be drawn through both a respirator filter and a 25 mm, 0.8 μ m polycarbonate filter (Millipore Corp., Bedford, Mass.) downstream of the respirator filter. These "C_i" samples were intended to collect any cement dust that penetrated the respirator filter. A Gast 0211 Lab Model vacuum pump (Gast Manufacturing, Inc., Benton Harbor, Mich.) was used to draw air through these filters at 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).

Each respirator filter/C_i combination was paired with an ambient (C_o) sample mounted within approximately 6 cm of the respirator filter. The C_o samples were collected on 25 mm, 0.8 μ m pore size mixed cellulose ester filters (Millipore) at a rate of 2 L/min with personal sampling pumps. All C_i and C_o samples were collected simultaneously with open face cassettes to reduce the likelihood of inlet particle loss. The sample duration ranged from 45 to 116 minutes for the samples collected.

Particle size sampling was done with an eight-stage Marple Personal Cascade Impactor (Thermo Anderson, Smyrna, Geor.). The impactors were placed in close proximity to the test filters.

Following the workplace exposures, the respirator filters were returned to the laboratory and retested for initial penetration and pressure drop using the NIOSH test procedures. The C_o samples were analyzed for silicon (Si) and calcium (Ca) with inductively coupled plasma/atomic absorption spectroscopy (AA) using NIOSH method 7300 (NIOSH, 1994). Detection limits were 5.0 and 2.5 μg per filter for Si and Ca, respectively. The C_i samples were analyzed with proton induced x-ray emission spectroscopy (PIXE). Detection limits were 0.133 μg per filter for Si and 0.152 μg per filter for Ca. The masses of Si and Ca were added and divided by the sample volume for both the C_i and C_o samples. Field blank and manufacturer blank filters were taken and analyzed as reported previously (Janssen *et al.*, 2003b).

RESULTS AND DISCUSSION

Results of the pre- and post-workplace laboratory penetration and pressure drop testing are shown in Table I. Workplace penetration, post-exposure change in pressure drop (ΔP) and mass loading values for individual respirator filters are presented in Tables II and III. Workplace penetration was calculated as follows:

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

It was not necessary to correct the C_i values for blank contamination since none was found on either set of blanks.

Table I. Laboratory Penetration and Pressure Drop for N95 Filters Before and After Exposure to Cement Dust (Mean and Standard Deviation)

Treatment	N	Pre-Workplace Initial Penetration (%)		Post-Workplace Initial Penetration (%)		Pre-Workplace Pressure Drop (mm water)		Post-Workplace Pressure Drop (mm water)	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Manufacturer A									
Untreated	6	0.426 ^a	0.171	0.584 ^a	0.136	11.8	0.550	12.0	0.549
Irradiated	6	7.03 ^b	1.58	6.23 ^b	1.34	11.4 ^c	0.492	12.1 ^c	0.618
IPA-Dipped	6	27.6 ^d	4.21	20.5 ^d	3.52	13.2	2.14	12.9	1.06
Manufacturer B									
Untreated	6	0.383	0.108	0.462	0.198	9.57 ^d	0.393	10.2 ^d	0.636
Irradiated	6	12.0 ^e	3.06	9.67 ^e	3.55	10.2 ^f	0.942	10.8 ^f	1.16
IPA-Dipped	6	60.2 ^g	2.99	51.7 ^g	4.51	9.78	1.03	10.3	1.10

Mean values marked with the same letter are significantly different from one another ($P < 0.05$).

Students T-tests indicated the post-workplace laboratory penetration for Manufacturer A untreated filters was significantly higher ($P < 0.05$) than the pre-workplace value (Table I). While the post-workplace laboratory penetration was higher for Manufacturer B untreated filters, the increase was not statistically significant. Because it is known that high aerosol loading can mask electrostatic charges on electret filters (Brown *et al.*, 1988, Chen *et al.*, 1993) an increase in laboratory penetration of the untreated filters is not unexpected.

While increased penetration caused by charge masking is discernable with "most penetrating" laboratory aerosols, Tables II and III indicate that there is no effect on penetration of this workplace aerosol. The mass median aerodynamic diameter of the cement dust was 4.7 μm with a geometric

standard deviation of 3.7. This particle size distribution is much more representative of work environments where filters are used than are the 0.3 μm "most penetrating" aerosols used for laboratory testing Hinds and Bellin (1988).

Table II. Manufacturer A: Workplace Penetration, Change in Pressure Drop (ΔP) and Loading Data (Si + Ca)

	Initial Laboratory Penetration (%)	Workplace Penetration (%)	ΔP (mm water)	Mass Loading (mg)
Untreated				
Filter Number				
9	0.769	0.016	0.5	36.8
80	0.389	0.617	-0.3	15.0
81	0.344	0.045	-0.3	12.5
82	0.363	0.007	0.3	82.1
83	0.305	0.019	0.3	28.5
84	0.386	0.021	0.4	30.4
Mean	0.426	0.121	0.2	34.2
Irradiated				
Filter Number				
101	5.02	0.029	0.7	18.6
102	8.96	0.020	0.9	36.1
103	8.77	0.014	0.7	49.8
109	7.21	0.011	0.5	61.6
123	6.16	0.038	0.6	15.1
124	6.08	0.032	0.8	20.4
Mean	7.03	0.024	0.7	33.6
IPA-Dipped				
Filter Number				
205	30.7	0.060	0.6	19.6
206	32.4	0.054	1.1	80.0
207	25.2	0.018	-0.3	35.3
208	20.6	0.083	0.3	12.8
209	28.6	0.027	-2.6	57.4
210	28.0	0.029	-1.3	21.2
Mean	27.6	0.045	-0.4	37.7

Mean workplace penetration values are not significantly different from one another ($P > 0.05$).

Mean ΔP values are not significantly different from one another ($P > 0.05$).

Mean mass loading values are not significantly different from one another ($P > 0.05$).

Table I also shows that the post-workplace laboratory penetration for the irradiated and IPA-dipped filters from both manufacturers was significantly less than the pre-workplace penetration value ($P < 0.05$). This effect is also expected, because loading with solid aerosols is known to increase mechanical efficiency as dust accumulates on the filter (Hinds, 1982).

While dust accumulation is also expected to increase pressure drop (breathing resistance) of the filter over time (Hinds, 1982), results of the pre- and post-workplace pressure drop measurements in Table I do not conclusively show this. The increase in the mean post-exposure pressure drop value was statistically significant ($P < 0.05$) for only three groups of filters. The IPA-dipped filters from Manufacturer A showed a small decrease in pressure drop after loading.

Table III. Manufacturer B: Workplace Penetration, Change in Pressure Drop (ΔP) and Loading Data (Si + Ca)

	Initial Laboratory Penetration (%)	Workplace Penetration (%)	ΔP (mm water)	Mass Loading (mg)
Untreated				
Filter Number				
601	0.368	0.016	1.6	35.0
602	0.348	0.025	0.5	24.8
603	0.594	0.008	0.9	71.3
604	0.378	0.049	0.3	12.0
614	0.310	0.025	0.2	22.0
615	0.298	0.024	0.3	23.1
Mean	0.383	0.024	0.6	31.4
Irradiated				
Filter Number				
702	10.9	0.023	0.7	23.2
707	12.8	0.049	0.8	40.4
714	8.35	0.021	0.1	26.5
717	15.0	0.109	0.1	28.5
719	15.9	0.225	0.4	27.4
722	9.27	0.012	1.3	67.0
Mean	12.0	0.073	0.6	35.5
IPA-Dipped				
Filter Number				
803	56.6	0.205	0.0	15.2
806	62.9	0.273	-0.2	29.4
810	60.1	0.176	0.0	15.0
812	63.0	0.200	2.5	91.3
815	56.6	0.187	0.3	29.4
816	62.1	0.327	0.4	58.9
Mean	60.2	0.228	0.5	39.9

Mean workplace penetration values are significantly different from one another ($P < 0.05$)

Mean ΔP values are not significantly different from one another ($P > 0.05$)

Mean mass loading values are not significantly different from one another ($P > 0.05$)

Further, the post-workplace pressure drop values for all the filters were far below the inhalation resistance of 60-140 mm water described by Love (1983) as "noticeable but well tolerated." NIOSH approval regulations permit a maximum initial inhalation resistance of 35 mm measured at a flow rate of 85 L/min (CFR, 2002), the flow rate used in the laboratory testing in this study. All filters were well below the 35 mm limit before and after loading in the workplace.

For individual filters, only the pressure drop values for the irradiated and IPA-dipped filters from Manufacturer B were reasonably well correlated with dust loading (adjusted $r^2 = 0.59$ and 0.77 , respectively). This suggests that these filters were progressively relying more heavily on mechanical filtration than the other groups of filters (Chen *et al.*, 1993). It should be noted that mean pressure drop increases were small, and similar to those seen in a previous study with much lower mass loadings (Janssen *et al.*, 2003b). It is therefore possible that these changes are within the normal range of measurement variability. Adjusted coefficients of determination for ΔP with mass loading are shown in Table IV.

Table IV. Coefficients of Determination (adjusted r^2) for Change in Pressure Drop After Workplace Exposure (mm water) versus Mass Loading (mg)

Treatment	r^2	
	Manufacturer A	Manufacturer B
Untreated	0.13	0.07
Irradiated	-0.10	0.59
IPA-Dipped	-0.25	0.77

It is likely that much higher loadings are necessary to increase pressure drop consistently for electret filters because of their low packing density (Brown, 1980; Hinds, 1982). The maximum areal densities (mass loading divided by filter area) in this study were 1.2 mg/cm² for Manufacturer A and 1.6 mg/cm² for Manufacturer B filters, respectively. These values are reasonably close to the loading the filters accumulate during NIOSH certification loading test (1.5 and 1.75 mg/cm² for Manufacturer A and B filters, respectively). Previous studies have shown very small increases in pressure drop at similar areal densities (Chen *et al.* 1993; Hinds and Kadrichu, 1994). These findings suggest that severe loading of electrets may be required before a respirator user would experience an increase in breathing resistance that would necessitate changing filters. Further, the amount of *change* in pressure drop that would be noticed by a respirator user is not precisely known. It is quite possible that most workers change electret respirator filters for reasons other than increased breathing resistance. It may be more likely they are replaced due to damage, loss or general hygiene well before unacceptable breathing resistance develops.

Hinds and Kadrichu (1994) also modeled the overall effect of loading on the protection expected of several types of particulate filter respirators, including a filtering facepiece respirator meeting the dust/mist approval criteria of 30 CFR Part 11 (CFR, 1989). These criteria allowed much higher initial penetration than the current N95 criteria found in 42 CFR Part 84. Their model considered both the beneficial effect of loading (reduced penetration) and its detrimental effect (increased pressure drop). They concluded that loading up to 1000 mg would improve protection for dust/mist respirators with quantitative fit factors of 100 or higher. For the filtering facepiece they modeled, 1000 mg would result in areal loading of 6.7 mg/cm² and a pressure drop increase of approximately 7 mm of water at 20 L/min. In terms of workplace exposure, this loading is equivalent to a full shift exposure to a dust concentration of 100 mg/m³ and a reasonable breathing rate of 10 m³ for the entire shift (approximately 21 L/min). It is unlikely that a particulate respirator would be used under these exposure conditions, as exposures this high result in reduced visibility, dust deposits in the eyes, ears, and nasal passages, skin injury, and other forms of physical irritation (Federal Register, 1989).

Most significant are the workplace penetration results shown in Tables II and III. Neither the irradiation nor IPA treatments had a significant effect on the workplace penetration of Manufacturer A filters. Penetration values for the three treatments of Manufacturer B filters were significantly different from one another ($P < 0.05$). However, the highest mean penetration value of 0.228% is far below the 5% laboratory penetration permitted for class 95 filters. Thus, the contribution of filter penetration to a worker's inhaled dose would be minimal, even for filters with mean laboratory penetration of approximately 60%. This is further evidence of the very large margin of safety inherent in the current NIOSH approval testing demonstrated in a previous study (Janssen *et al.*, 2003b). Thus, even if a workplace aerosol were to cause some loss of electrostatic charge during respirator use, the respirator user would still be more than adequately protected.

CONCLUSIONS

The NIOSH approved N95 filters used in this study performed very well in the workplace. In addition, filters intentionally degraded such that mean laboratory penetration was approximately 60% permitted minimal penetration of this workplace aerosol. This demonstrates that the worst-case certification tests

provide an extremely large margin of safety in the unlikely event that N95 electret filters are exposed to workplace conditions that would degrade their laboratory performance.

Filter loading in this study was much higher than in previous work. The charge-masking effect of loading with a solid aerosol was evident in laboratory testing of the untreated filters. Masking did not compromise the filters' workplace performance. Filter loading improved the laboratory performance of filters intentionally degraded to approximately 7 to 60% initial penetration using NIOSH test conditions. Pressure drop of the filters did not appear to be significantly affected by the mass loadings seen in this study.

This study supports previous work that found laboratory penetration measured using worst-case certification test conditions does not directly predict a filter's efficiency against workplace aerosols: filters perform much better under workplace conditions. This is expected because workplace particle sizes and airflow rates lie outside the worst-case conditions used in certification testing.

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