

Efficiency of Degraded Electret Filters: Part II – Field Testing Against Workplace Aerosols

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ABSTRACT

Field tests were conducted to measure the efficiency of N95, R and P95 and P100 filters from two manufacturers against workplace aerosols. Three groups of each type of filter were tested: 1) untreated; 2) irradiated with ionizing radiation; and 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 NIOSH test conditions. Prior to exposure in the field, nearly all irradiated and isopropanol-dipped filters had laboratory penetration values higher than permitted for approval using NIOSH test conditions. The filters were exposed to either a grinding aerosol or an oil mist in a steel foundry. Results indicated that even filters with laboratory penetration values higher than permitted for NIOSH approval performed well under these field conditions. Only the isopropanol-dipped N95 filters from one manufacturer had mean field penetration greater than 1%. None of the R or P filters permitted detectable penetration of the oil mist. Some untreated and irradiated N95 filters from both manufacturers were also exposed to the oil mist. No detectable oil mist penetration was found. These results indicate that current NIOSH approved N, R and P series filters perform very well under workplace conditions. The worst-case conditions used in NIOSH testing provide a very large margin of safety in the event of exposure to degrading workplace conditions.

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

INTRODUCTION

This is the second of two articles describing a study conducted to measure the performance of electret respirator filters under workplace conditions. NIOSH filter classes N95, R or P95 and P100 from two manufacturers (identified as Manufacturer A and Manufacturer B) were used in the study. All the filters were electrets except the P100 filter from Manufacturer B, which was a fiberglass mechanical filter. Some of the filters were intentionally degraded with ionizing radiation or isopropanol (IPA) so that the penetration of laboratory aerosols exceeded the levels allowed by NIOSH approval regulations. Three groups of filters were designated: untreated, irradiated, and IPA-dipped. The procedures used to degrade the filters and the laboratory performance results are described in the first article (Janssen *et al.*, 2003).

This article describes the field testing portion of the study. In addition to measuring the performance of electrets in both untreated and degraded conditions, data were collected to assess three additional issues:

1. Comparative field performance of NIOSH class 95 filters and class 100 filters;

2. Comparative field performance of mechanical and electret type class 100 filters;
3. Performance of N series filters when exposed to an industrial oil aerosol. While N series filters are not NIOSH-approved for use in atmospheres containing oils, the possibility of incidental exposure or incorrect selection exists. This testing was done to determine if either situation would increase a user's risk of exposure.

MATERIALS AND METHODS

Sampling Procedures

The field testing was conducted in two locations in a steel foundry. The first location was a "swing grinding" booth. Untreated, irradiated and IPA-dipped N95 and P100 filters were tested in this location. Grinding was performed on large steel castings near the face of an exhaust booth. A slot at the top of the booth allowed grinding dust containing elemental iron to escape. Three sampling positions were identified along the length of the slot, such that the samples could be placed in the dust cloud escaping from the slot. The sampling plan was such that each treatment of each filter would be randomly rotated to every sampling position twice to reduce the likelihood of spatial bias. Exposure time for each filter was generally 50-60 minutes with sampling rates ranging from 20 to 27 L/min. Short sample times were used because initial filter penetration is typically higher than penetration after loading with a solid aerosol (Hinds, 1982). This also allowed a sufficient number of samples to be collected for statistical analysis in a reasonable period of time. The flow rates were equivalent to minute volumes of 40-54 L/min and were chosen to represent the upper limit of sustainable work for most individuals (Lumb, 2000).

The second sampling location was a large oil quenching tank. CITGO Quenchoil® Oil 0510 (CITGO Petroleum Corp., Tulsa, Okla.) was circulated in the tank at a level approximately 0.75 m below the face of the tank. Hot castings were periodically placed on a heavy mesh rack that was subsequently lowered into the oil. This operation generated high concentrations of oil mist. During periods when castings were not being quenched, lesser amounts of mist were generated by the circulation and air agitation of the oil. Three primary sampling positions were identified approximately 0.3 m above the surface of the oil. All treatments of R95, P95 and P100 filters were randomly rotated through these positions in a manner similar to that used in the grinding location. Most exposure times for these filters were approximately 60 minutes at flow rates of 20-27 L/min. Additionally, one P100 filter from each manufacturer was intermittently exposed every 30 minutes in a fourth location that was approximately 0.75 m above the surface of the oil. These filters were alternated every 30 minutes throughout the 3 1/2 days of the study. Each of these intermittently exposed filters received a total of six hours of exposure. This procedure was intended to determine if intermittent loading with an oil aerosol would cause filter degradation with a lower mass loading than would continuous loading. This phenomenon has been noted for certain solid aerosols (Moyer and Bergman, 2000). Because of the extreme heat and flame generated when hot castings were lowered into the oil, all filters were removed from their sampling locations during the quench and replaced when the heat and flame subsided.

Three untreated and three irradiated N95 filters from each manufacturer were also exposed to the oil mist in the same manner as the R95, P95 and P100 filters. These filters were each exposed for approximately 45 minutes. Additionally, one untreated N95 filter from each manufacturer was intermittently exposed to oil mist in the manner described above for P100 filters. They were alternately exposed every 30 minutes for four hours, resulting in a total exposure time of two hours per filter.

Sampling Train

Sample holders as shown in Figure 1 were constructed to allow air to be drawn through the respirator filters and collect samples downstream of the respirator filters (i.e., C_i samples). The C_i samples were intended to collect any aerosol contaminant that penetrated the respirator filter.



Figure 1. Sample holders unassembled (bottom) and assembled.

Each sample holder consisted of a filter connector from one respirator manufacturer's facepiece glued to the flared end of 32 mm outside diameter by 6 cm long ABS plastic hose connector. The opposite end of the connector was inserted into a section of 25 mm clear plastic tubing approximately 10 cm long and secured with a hose clamp. The inlet section of an open-face polystyrene filter cassette that held an appropriate 25 mm membrane filter was inserted into the opposite end of the 25 mm tubing. The outlet section of the cassette was then inserted into a second 10 cm section of 25 mm plastic tubing. During sampling, this connection was sealed with electrical tape. A quick-connect fitting was inserted into the downstream end of the second section of 25 mm tubing. A compressed air hose with a matching quick-connect fitting was attached to the sample holder and to a Gast 0211 Lab Model vacuum pump (Gast Manufacturing, Inc., Benton Harbor, Mich.). Airflow through the respirator filters and the C_i cassettes was in the range of 20-27 L/min. The flow rates were checked periodically during sampling with a rotameter calibrated against a dry gas meter.

An ambient (C_o) sample was paired with each C_i sample and collected simultaneously. An open-face polystyrene cassette that held an appropriate 25 mm membrane filter was clipped to the hose clamp on the sample holder at a point just behind the respirator filter. The cassette was connected to an MSA Escort® ELF (MSA, Pittsburgh, Penn.) or AMETEK ALPHA-3 (AMETEK, Inc., Largo, Fla.) personal sampling pump. Airflow rates for the C_o samples were approximately 2 L/min for the iron dust samples. Because preliminary sampling indicated that the filters might plug rapidly in a high oil mist concentration, the flow rate was approximately 1 L/min for the oil mist samples. The pumps were calibrated against a Series 820 Top-Trak mass flow meter (Sierra Instruments, Inc., Monterey, Calif.) and checked for proper flow rate before, during and after each day's sampling.

Analytical Methods

Membrane filters were chosen with consideration to contaminant, expected concentration and analytical method to be used. In the grinding area the C_o samples were collected on 0.8 μm pore size mixed cellulose ester filters (Millipore Corp., Bedford, Mass.). They were analyzed for elemental iron with inductively coupled plasma/atomic absorption spectroscopy (AA) using NIOSH method 7300 (NIOSH, 1994). The detection limit was 1.2 μg per filter. Because of the lower expected iron concentrations, the

grinding C_i samples were collected on 0.8 μm polycarbonate filters (Millipore) and analyzed with proton induced x-ray emission spectroscopy (PIXE). The detection limit for iron was below 0.019 μg per filter. All the oil mist samples were collected on 5 μm pore size PVC filters (Omega Specialty Instrument Co., Chelmsford, Mass.). They were analyzed by infrared spectrophotometry (IR) using NIOSH method 5026 (NIOSH, 1994). The detection limit was 9 μg per filter.

Two types of blank membrane filters were analyzed along with the test filters. The first were manufacturer blanks. These were filters (in their cassettes) randomly selected from their manufacturer's packaging. The cassettes were not opened nor taken into the workplace. The purpose of the manufacturer blanks was to determine if the filters carried elemental contamination from the manufacturing process. Field blanks were collected in the workplace. These cassettes were handled in the same manner as the test filters, except no air was drawn through them. They were briefly opened in the work environment and immediately resealed. The purpose of the field blanks was to determine if handling procedures contaminated the test samples.

Other Sampling Considerations

As evidenced by the analytical method chosen, very low concentrations of the contaminants were expected on the C_i samples, particularly for the untreated respirator filters. For this reason, respirator filter holders that used a retainer clipped to a base, which in turn attached to the connector on the sample holder, were sealed with electrical tape at the retainer/base joint. This was a precaution to prevent even minute amounts of contaminant from leaking through this joint. The N95 filters from both manufacturers and the R95 filters from Manufacturer B were taped in this manner. The other filters attached directly to the respirator filter connector with a threaded or bayonet fitting. Limited sampling in the grinding area with each manufacturer's untaped N95 filter holders indicated the taping was unnecessary.

Particle size sampling was performed with a five-stage cascade impactor (Nelson, Inc., Tallahassee, Fla.) in both sampling locations. The impactor samples were placed in the same locations as the test filters. The sampling was done on two consecutive days in each area.

RESULTS

Table I summarizes the results of the iron dust and oil mist ambient (C_o) samples. It is evident that aerosol generation of both operations was quite variable. Table II summarizes the mass loadings on the filters by filter type. These values also illustrate the variability of the workplace atmospheres. To place these filter loadings into perspective, each filter of a pair worn by a worker exposed for eight hours to the current TLV[®] of 5 mg/m^3 of either iron or oil mist (ACGIH, 2003) would accumulate approximately 25 mg loading at a moderate work rate. The same worker exposed to oil mist at the proposed TLV of 0.2 mg/m^3 (ACGIH, 2003) would accumulate approximately 1 mg of oil on each filter.

Iron penetration and mass efficiency for the N95 and P100 filters in the grinding operation are given in Tables III and IV. Mean initial laboratory penetration is also shown for comparison purposes. The mean field blank value for the C_i filters was 0.0362 μg of iron. This value was subtracted from the mass of iron reported on each C_i filter before calculating the C_i concentration. Mean penetration and mass efficiency for each filter treatment was then calculated as follows:

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

and

$$\% \text{ mass efficiency} = 100\% - \% \text{ penetration}$$

Table I. Ambient Sampling Data Summary

Filter	Contaminant	Median C _o Concentration (µg/m ³)	Range (µg/m ³)	Samples Below Detection Limit (%)
N95	Iron	232	60-30300	---
P100	Iron	640	386-7100	---
R95/P95	Oil mist	482 ^a	134-7380 ^b	70
P100	Oil mist	1161 ^a	145-6845 ^b	45
N95	Oil mist	1333 ^a	323-6020 ^b	6

^aMedian of detectable samples.^bRange of detectable samples.**Table II. Filter Mass Loading Summary**

Mass Loading (mg)				
<u>Iron Loading</u>	<u>N</u>	<u>Mean</u>	<u>S.D.</u>	<u>Range</u>
Manufacturer A-N95	19	1.95	4.04	0.10-16.7
Manufacturer B-N95	19	1.01	2.66	0.11-11.9
Manufacturer A-P100	18	2.28	3.40	0.07-10.1
Manufacturer B-P100	18	2.38	2.88	0.07-10.4
 <u>Oil Loading</u>	 <u>N</u>	 <u>Mean</u>	 <u>S.D.</u>	 <u>Range</u>
Manufacturer A-P95	18	0.26	0.45	ND ^a -1.70
Manufacturer B-R95	18	0.24	0.80	ND-3.39
Manufacturer A-P100	18	0.24	0.31	ND-0.85
Manufacturer B-P100	18	1.30	2.44	ND-7.90
Manufacturer A-N95	6	1.94	2.22	0.29-5.42
Manufacturer B-N95	6	1.35	1.29	ND-3.78
 <u>Intermittent Oil Loading</u>		 <u>Actual Loading</u>		 <u>Exposure Periods</u>
Manufacturer A-P100	1	21.2		12
Manufacturer B-P100	1	15.9		12
Manufacturer A-N95	1	5.17		4
Manufacturer B-N95	1	5.89		4

^a None detected.

Tables V through VII summarize the results of the oil mist sampling. These tables include mean initial penetration values only for those test filters that had measurable oil mist exposure. As no measurable oil was detected on any C_i filter, mass efficiencies could not be calculated.

The first cascade impactor measurement in the grinding area indicated the mass median aerodynamic diameter (mmad) for the iron aerosol was approximately 6.0 µm with a geometric standard deviation (GSD) of 4.6. The second impactor measurement in the grinding area revealed a mmad of 4.6 µm with a GSD of 2.9. The oil mist particle size was above 10 µm, the cutoff size of the first stage of the impactor. As such, mmad and GSD could not be determined for the oil mist.

Table III. N95 Filters: Mean Laboratory Penetration Before Exposure to Grinding Aerosol and Measured Workplace Iron Penetration

Treatment	N	Initial Laboratory Penetration (%)	Workplace Iron Penetration (%)	Mass Efficiency (%)
<u>Manufacturer A</u>				
Untreated	7	0.598	0.002 ^a	99.998
Irradiated	6	7.60	0.0673 ^a	99.933
IPA-Dipped	6	24.9	0.535 ^a	99.465
<u>Manufacturer B</u>				
Untreated	6	0.581	0.315 ^b	99.685
Irradiated	7	13.7	0.566 ^b	99.434
IPA-Dipped	6	61.2	4.27 ^b	95.730

Note: Values marked with the same letter are significantly different from one another (P<0.05).

Table IV. P100 Filters: Mean Laboratory Penetration Before Exposure to Grinding Aerosol and Measured Workplace Iron Penetration

Treatment	N	Initial Laboratory Penetration (%)	Workplace Iron Penetration (%)	Mass Efficiency (%)
<u>Manufacturer A</u>				
Untreated	6	<0.001	0.0006	>99.999
Irradiated	6	0.579	0.0008	>99.999
IPA-Dipped	6	0.0615	0.00002	>99.999
<u>Manufacturer B</u>				
Untreated	6	0.0058	0.00001	>99.999
Irradiated	6	0.0072	0.00009	>99.999
IPA-Dipped	6	0.0100	0.0114	99.989

Table V. P95 and R95 Filters: Mean Laboratory Penetration Before Exposure to Oil Mist and Measured Workplace Oil Mist Penetration

Treatment	N	Initial Laboratory Penetration (%)	Workplace Oil Mist Penetration (%)
<u>Manufacturer A P95</u>			
Untreated	3	0.797	ND ^a
Irradiated	3	8.20	ND
IPA-Dipped	1	1.06	ND
<u>Manufacturer B R95</u>			
Untreated	2	0.0720	ND
Irradiated	2	13.9	ND
IPA-Dipped	-	---	---

^a None detected.

Table VI. P100 Filters: Mean Laboratory Penetration Before Exposure to Oil Mist and Measured Workplace Oil Mist Penetration

Treatment	N	Initial Laboratory Penetration (%)	Workplace Oil Mist Penetration (%)
<u>Manufacturer A</u>			
Untreated	4	<0.001	ND ^a
Untreated-Intermittently Exposed	1	0.001	ND
Irradiated	2	0.842	ND
IPA-Dipped	2	0.0675	ND
<u>Manufacturer B</u>			
Untreated	3	0.0057	ND
Untreated-Intermittently Exposed	1	0.007	ND
Irradiated	4	0.0058	ND
IPA-Dipped	3	0.0097	ND

^a None detected.**Table VII. N95 Filters: Mean Laboratory Penetration Before Exposure to Oil Mist and Measured Workplace Oil Mist Penetration**

Treatment	N	Initial Laboratory Penetration (%)	Workplace Oil Mist Penetration (%)
<u>Manufacturer A</u>			
Untreated	3	0.495	ND ^a
Untreated-Intermittently Exposed	1	0.459	ND
Irradiated	3	6.29	ND
<u>Manufacturer B</u>			
Untreated	3	0.723	ND
Untreated-Intermittently Exposed	1	0.419	ND
Irradiated	2	13.8	ND

^a None detected.

DISCUSSION

Only the IPA-dipped N95 filters from Manufacturer B had mean iron penetrations greater than 1%. As indicated in Table III, these filters had a mean laboratory penetration greater than 61%. Nearly all the test filters had laboratory penetration above that permitted for their respective NIOSH approval categories, yet their workplace performance was very good. An analysis of variance (ANOVA) was performed among the three treatments of N95 filter from each manufacturer. Similarly, ANOVA was performed among the three treatments of P100 filter from each manufacturer. Statistically significant differences in penetration ($P < 0.05$) were found among the three treatments of each manufacturer's N95 filters. However, except for the IPA-dipped filters from Manufacturer B, the differences were numerically

very small and of little practical significance. No significant difference was found among the three treatments of P100 filters exposed to the grinding aerosol.

T-tests were used to compare the mean workplace iron penetration of each treatment of each manufacturer's N95 filters with the corresponding P100 of the same treatment. Workplace performance of both manufacturers' N95 filters was statistically equivalent to their P100 filters except for the IPA dip treatment ($P < 0.05$). This runs counter to the widely held belief that class 100 filters are "more protective" than class 95 filters based on their superior laboratory performance. Numerically higher penetration was allowed by the N95 filters of all treatments, but the absolute values were small and of little practical significance. Additionally, all workplace filter penetration values must be viewed in the proper context. Total penetration for half and full facepieces is generally assumed to be 10% and 2% (corresponding to assigned protection factors of 10 and 50), respectively (Asbestos, 2001; Cadmium, 2001). Thus, the contribution of filter penetration measured in this study is small relative to total expected penetration.

T-tests were used to compare the mean iron penetration of each treatment of Manufacturer A N95 filters with the same treatment of Manufacturer B N95 filters. Mean iron penetrations of each treatment of P100 filter from the two manufacturers was also compared with t-tests. Only in the case of the IPA treatment was there a significant difference between the two manufacturers' N95 filters ($P < 0.05$). This provides some indication of the margin of safety inherent in the NIOSH approval tests: Filters with up to 24.9% laboratory penetration performed extremely well against the iron aerosol.

Performance of the electret P100 filters was not significantly different than the mechanical P100 filters for any treatment. Thus, while severe degrading conditions reduced the laboratory performance of these electret filters, there was no workplace significance. Also, as noted in the companion paper, the conditions required to degrade the filters are not found in the workplace (Janssen *et al.*, 2003).

All properly selected NIOSH-approved filters are expected to perform very well in any workplace. This is because the laboratory conditions under which filters are tested and approved were deliberately chosen to represent "worst case" conditions (Federal Register, 1995). The test aerosols, dioctylphthalate (DOP) for R and P series and sodium chloride for N series filters, were chosen because they are "highly degrading" and "mildly degrading" to filter performance, respectively. Workplace particle sizes are nearly always larger than the approximately $0.3 \mu\text{m}$ mmad size (typically assumed to be "most penetrating") used by NIOSH (Hinds and Bellin, 1988). The 85 L/min per respirator assembly airflow rate used in laboratory testing represents heavy work, not sustainable for more than a few minutes by most workers (Lumb, 2000).

This study examined the performance of filters in both their approved condition and, except for the mechanical P100 filters, intentionally degraded to allow laboratory penetration greater than permitted by approval regulations. The results illustrate the differences between laboratory test conditions and real workplaces. In addition, the limitations of laboratory testing are brought to light. Filter performance modeling supports the concept that efficiency improves for particle sizes larger or smaller than the most penetrating range used in NIOSH testing. Similarly, decreasing flow rate through the filter is expected to improve efficiency (Hinds, 1982). The particle sizes found in both operations in this workplace are much more representative of environments where filters are used than are the $0.3 \mu\text{m}$ aerosols used for laboratory testing. Hinds and Bellin (1988) reported a mmad of $7.2 \mu\text{m}$ for foundry grinding operations and mmad from 2.1 - $16.8 \mu\text{m}$ for other foundry operations. They did not report size distribution data for oil mists, but reported mmad of 6.4 - $27.4 \mu\text{m}$ for spray painting and other mist-producing operations. The range of flow rates used in this study (equivalent to minute volumes of 40-54 L/min) was chosen to represent the upper limit of sustainable work for most individuals (Lumb, 2000). Again, this value is more representative of the conditions in which filters are used than is the 85 L/min flow rate used in laboratory testing. In large part, these real-world conditions account for the fact that the untreated filters performed much better in this study than their approval classifications suggest. They are also the reason that even the degraded filters performed well in this study.

These data also point to the appropriate interpretation of laboratory filter testing results. NIOSH laboratory tests can assure that all certified filters in a given class have a stated minimum level of performance when tested under uniform conditions. They can also discriminate among filters with significantly different laboratory performance levels. However, as the data in this study indicate,

laboratory performance does not correlate directly with workplace performance. Workplace performance will invariably be better. As such, a NIOSH filter certification should be viewed as a demonstration of "fitness for use" rather than an explicit predictor of workplace performance.

These study results also demonstrate the need to determine how (or if) workplace performance is affected when the laboratory performance of electret filters is degraded. For example, reports of decreased laboratory performance of electret filters following specific exposures to laboratory or workplace aerosols are found in the literature (Brown *et al.*, 1988; Martin and Moyer, 2000; Moyer and Bergman, 2000; Tennal *et al.*, 1991; Berardinelli *et al.*, 2002). These reports suggest to some that the observed reduction in laboratory performance would compromise worker protection if these filters were used in the workplace. The results of this study demonstrate that this suggestion is incorrect for the filters tested in these work environments. Filters with up to 25% laboratory penetration under current NIOSH test conditions allowed less than 1% penetration in the workplace. Only when laboratory penetration exceeded 61% did workplace penetration even approach an unacceptable level (defined as penetration greater than 5% for class 95 filters). These data clearly indicate that current NIOSH tests provide a very large margin of safety should degrading conditions be encountered in the workplace.

The safety margin provided by current approval testing is also demonstrated by the performance of the class 95 filters exposed to the quenching oil and the intermittently loaded class 100 filters. As noted in the companion paper, intermittent oil loading to the levels listed in Table II did not affect the laboratory performance of N95 or P100 filters. In this study no filter, including class N95 degraded to nearly 14% laboratory penetration, allowed penetration of the workplace oil mist. This is no doubt due to the reasons cited earlier: workplace particle sizes and workplace flow rates outside the worst-case conditions used in approval tests. It also appears that, in the event of a worker erroneously using an N series filter for exposure to oil mists, the worker would still be protected. Further testing in additional oil mist atmospheres is needed to confirm or refute this observation. However, it must be emphasized again that N series are not intended for use in atmospheres containing oil aerosols.

SUMMARY AND CONCLUSIONS

This study demonstrates that filter performance measured in the laboratory does not directly predict performance under workplace conditions. Even N95 filters intentionally degraded to a mean laboratory penetration of 61% permitted less than 5% penetration in the workplace. Penetration for all other untreated and intentionally degraded filters was well below 1%. Untreated and irradiated N95 filters had essentially the same workplace performance as their P100 counterparts. There was no difference in the workplace performance of electret and mechanical P100 filters. No N, R or P series filter allowed detectable penetration of an industrial oil mist.

It is apparent that the current NIOSH tests for N, R and P series filters assure that all approved filters will perform very well in the workplace. The tests provide an extremely large margin of safety in the unlikely event that electret filters are exposed to workplace conditions that would degrade their laboratory performance. Further, the data suggest that more severe laboratory testing will not improve filter performance in the workplace or increase worker protection.

Additional studies across a variety of workplaces and filter media would be useful to corroborate the results of this study.

REFERENCES

American Conference of Governmental Industrial Hygienists (ACGIH): Threshold Limit Values for Chemical Substances and Physical Agents. ACGIH, Cincinnati, OH, 2003.

Asbestos, 29 C.F.R. Part 1910.1001, (2001) pp 19-72.

-
- Berardinelli SP, Lawrence RB, Coffey CC, Kullman G, Moyer ES. Performance of selected N95 and P100 respirator filters to plant aerosols at a snack food production facility. Poster presented at the American Industrial Hygiene Conference and Exposition, San Diego, California, 2002 1-6 June.
- Brown RC, Wake D, Gray R, Blackford DB, Bostock GJ. (1988) Effect of industrial aerosols on the performance of electrically charged filter material. *Ann Occ Hyg* 32(3): 271-294.
- Cadmium, 29 C.F.R. Part 1910.1027, (2001), pp 135-229.
- Hinds WC. (1982) *Aerosol technology*. New York: John Wiley and Sons; pp 172-182. ISBN 0 471 08726 2
- Hinds WC, Bellin P. (1988) Effect of facial-seal leaks on protection provided by half-mask respirators. *Appl Ind Hyg* 3(5):158-164.
- Janssen LL, Bidwell JO, Mullins HE, Nelson TJ. (2003) Efficiency of degraded electret filters, Part I: laboratory testing against NaCl and DOP before and after exposure to workplace aerosols. *J. Int. Soc. Resp. Prot.*, 20:71-80.
- Lumb, AB. (2000): *Nunn's Applied Respiratory Physiology*, 5th ed Oxford: Butterworth-Heinemann; pp 133-134, 340-341. ISBN 0 7506 3107 4.
- Martin SB, Moyer ES. (2000) Electrostatic respirator filter media: filter efficiency and most penetrating particle size effects. *Appl Occup Env Hyg* 15(8):609-617.
- Moyer ES, Bergman MS. (2000) Electrostatic filter media efficiency degradation resulting from intermittent sodium chloride aerosol exposure. *Appl Occup Env Hyg* 15(8):600-608.
- National Institute for Occupational Safety and Health: NIOSH Manual of Analytical Methods (NMAM®), 4th ed. DHHS (NIOSH) Publication 94-113, Washington, DC: US Department of Health and Human Services/NIOSH, 1994.
- "Respiratory Protective Devices," *Federal Register* 60:110 (8 June 1995) pp 30335-30398.
- Tennal, KB, Mazumder MK, Saig A, Reddy RN. (1991) Effect of loading with an oil aerosol on the collection efficiency of an electret filter. *Part Sci and Tech* 9:19-29.