Performance of an N95 Filtering Facepiece Respirator in a Grinding Operation

Larry Janssen, Jeanne Bidwell, and Nicole McCullough

3M Company, Building 235-2E-91, St. Paul, MN 55144 USA
Email: lljanssen@mmm.com

Thomas J. Nelson

NIHS Inc., 2401 East Mall, Ardentown DE 19810 USA

ABSTRACT

This study evaluated the workplace performance of an N95 filtering facepiece air purifying respirator in the grinding room of an aluminum and magnesium alloy foundry. Air samples were collected inside and outside the respirators worn by workers who were properly trained and qualitatively fit tested. Several pairs of samples were collected on five workers on four consecutive days, resulting in 56 valid sample sets. The samples were analyzed for aluminum and magnesium. While the ambient atmosphere had adequate contaminant concentrations to measure facepiece contaminant penetration at the levels expected for half facepiece respirators, many of the in-facepiece samples did not have detectible aluminum or magnesium. A workplace protection factor (WPF) estimate was calculated for each sample pair, the values rounded down to two significant figures and a rank and percentile function performed. Individual WPF estimates ranged from 24 to 9,100. The 50th percentile value was greater than 1,100 and the lower 5th percentile was greater than 71. It is believed that this level of respirator performance was due to the stationary nature of the work and relatively low work rate. This respirator's performance clearly supports the assigned protection factor of 10 typically used for half facepiece respirators. However, these results do not suggest that the assigned protection factor should be increased.

Keywords: WPF, respirator, workplace protection factor, filtering facepiece

INTRODUCTION

Workplace protection factor (WPF) measurements provide an estimate of the protection provided in a workplace, under the conditions of that workplace, by a properly selected, fit tested and functioning respirator while it is correctly worn and used (AIHA, 2002). When it is available for a particular class of respirator, WPF data is often considered when setting the APF (Nelson, 1996; Federal Register, 2006). Assigned protection factors (APFs) represent the level of respiratory protection that a properly functioning respirator or class of respirators would be expected to provide to properly fitted and trained users in the workplace (AIHA, 2002). APFs are used as part of the respirator selection process to help assure users are adequately protected.

Several WPF studies of class N95 filtering facepiece respirator performance have been performed since these devices first appeared on the market in late 1995 (Colton and Bidwell, 1999; Bidwell and Janssen, 2004; Lee *et al.*, 2005; Janssen *et al.*, In Press). These studies have typically collected WPFs on groups of workers, with each worker sampled on one or two shifts. It is most common to present the data as a single distribution of WPF values collected during the course of a study.

Recently, Janssen *et al.* (In Press) also reported daily time-weighted average WPFs (WPF_{TWA}) for workers sampled on two work shifts, and the distribution of WPF_{TWA} over the course of the study. They reasoned that their approach allowed insight into longer-term protection individual respirator wearers would be expected to receive.

This study was designed to build on that approach by repeatedly sampling the same individuals over the course of a four day study. It was intended to allow the study of individual WPF measurements, daily and weekly WPF_{TWA} distributions and to evaluate the variability of WPF measurements within and between test subjects. Because the WPF values were very high, it is not possible to present these distributions in any meaningful way. Therefore, WPFs are reported as a single distribution with discussion of why this unusually high level of performance was found.

MATERIALS AND METHODS

Respirators and Test Subjects

The study was performed in the grinding room of a foundry manufacturing aluminum and magnesium alloy castings. The work performed during the study was essentially stationary. Grinding on smaller castings was performed while standing at fixed bench top work stations. Work on large castings intermittently required leaning forward and occasional sitting as well as standing upright. All the workers used a variety of hand-held pneumatic abrasive tools to finish the castings. The time-weighted average work rate was subjectively estimated to be low, in accordance with published guidelines (ISO, 2004).

The respirator tested was the 3M model 8210 N95 filtering facepiece respirator (3M, St. Paul, MN). This respirator was routinely used in the grinding room prior to the study. The purpose and procedures of the study were explained to the workers and their supervisors. Five men volunteered and qualified to participate in the study by passing a Bitrex^{TM} qualitative fit test (CFR, 2005). The men were clean-shaven where the respirator's sealing edge touched the face, and had been fit tested, medically evaluated and trained in proper use of the respirator under the existing respiratory protection program prior to the study. Three of the men worked exclusively on aluminum alloy castings, and the other two worked on magnesium alloys only. The aluminum and magnesium work areas were in the same room but separated by a distance of approximately 10 meters.

Sample Collection

In-facepiece samples (C_i) were collected via a sampling probe built to the specifications of Liu *et al.* to minimize entry losses of particles ≥5 µm (Liu *et al.*, 1984). The probe was positioned in the center of the facepiece at a level near the area between the wearer's nose and upper lip. The probe extended into the respirator approximately one centimeter.

A 3-piece 25 mm sample cassette holding a 0.8 µm pore size polycarbonate filter with a plastic support pad (Millipore Corp., Bedford, MA) was attached directly to the probe outside the facepiece for collection of the C_i sample. A cassette heater used in previous studies (Colton and Bidwell, 1999; Bidwell and Janssen, 2004) was used to reduce condensation of water vapor from exhaled breath inside the C_i sample cassette. The heater bonnet fit snugly over the cassette and contained a coiled heating element powered by a rechargeable Ni-Cd battery. A moisture collection bottle filled with Drierite (W.A. Hammond Drierite, Xenia, OH) was connected to the pump inlet to remove water vapor and condensed water.

The ambient air (C_o) samples were collected in the workers' breathing zone with 0.8 µm pore size mixed cellulose ester (MCE) filters (Millipore) in a 3-piece, closed face 25 mm cassette. The C_i and C_o samples were collected simultaneously with Escort^{TM} Elf personal sampling pumps (MSA, Pittsburgh, PA), at a flow rate of approximately 2.5 L/min. The pumps were calibrated at the beginning of each day with a calibrated Sierra TopTrak, Model 821-S1-L-1PS mass flowmeter (Sierra Instruments, Inc., Monterey, CA) using an appropriate inline filter cassette. The pumps were visually monitored for proper flow throughout the shift and rechecked with the mass flowmeter at the end of each shift.

Each study participant wore the sampling trains on four consecutive days. Three or four sample sets were collected on each worker throughout the work shift. The change interval generally coincided with the worker's break or lunch time. In some instances a C_i sample was invalidated when the in-facepiece sample fell off the probe during sampling, or if the worker removed the respirator before sampling was terminated. If sufficient time remained before a scheduled break, the invalidated sample was replaced with fresh cassettes. Sample sets were considered to have been collected simultaneously if C_o and C_i sample times differed by no more than five minutes.

Particle size sampling was done with eight-stage Marple Personal Cascade Impactors (Thermo Anderson, Smyrna, GA). Stationary samples were taken in both the aluminum and magnesium grinding areas while workers performed their jobs. The samples were collected for eight hours at a flow rate of 2 L/min.

Trained observers were used to ensure sample validity and to ensure the equipment did not interfere with worker activities or create safety hazards (e.g., entanglement of tubing). The observers also verified proper respirator use and recorded observations about work conditions. Because the five workers were quite close to one another and rarely left their work stations, three observers were able to constantly monitor the sample collection.

Respirator donning and removal, along with sample train connection and removal, were done in a clean break room to minimize the likelihood of sample contamination. The integrity of the respirator and the sample train were verified before the subjects entered the contaminated work areas. Both sampling pumps were started after the respirator was donned and the sample cassettes connected. At the end of sampling, both pumps were stopped before the respirator and samples were removed.

Field blanks were collected to assess potential sample contamination caused by handling procedures. These cassettes were uncapped and recapped by the observers, then worn by workers in the same manner as the samples. No air was drawn through the field blanks. Manufacturer blanks were randomly selected, unused filters of each type employed in the study. These were sent to the analytical laboratories in their unopened cassettes to determine if background contamination was present on the filters.

Sample Analysis

The C_i samples were analyzed with proton induced x-ray emission spectroscopy (PIXE). The detection limits for aluminum and magnesium were 0.103 µg and 0.124 µg per filter, respectively. C_o samples and cascade impactor samples were analyzed by inductively coupled plasma-atomic emission spectroscopy using NIOSH method 7300 (NIOSH, 2006). The detection limits were 7.5 µg per filter for both aluminum and magnesium.

Five C_i samples and one blank were analyzed using scanning electron microscopy (SEM). The C_i samples were selected to provide a range of loading levels. This analysis allowed individual particles collected on the filter's surface to be visually examined and the particle size estimated. The samples were mounted on an aluminum stub without the addition of conductive coating. They were then examined using the Model FEI XL30 Environmental Scanning Electron Microscope (FEI Co., Hillsboro, OR). Elemental analysis of the particles was conducted using X-Ray Microanalysis (XRMA) with an ultrathin window. This is sensitive to elements having an atomic number greater than or equal to that of carbon. The particles were photographed using secondary electron imaging (SEI), which is a technique used to image surface morphology of a sample, and backscattered electron imaging (BSEI) which is used to image near surface compositional differences in a sample. Areas of high average atomic number appear as light areas in BSEI images. Photomicrographs were taken of the surface at a viewing angle normal to the surface of the stub.

RESULTS

Six of 63 sample sets were lost because the cassette was knocked off the facepiece probe, equipment failure or because the worker removed the respirator before sampling was terminated. One additional sample was voided because the C_o and C_i sample times differed by more than five minutes, resulting in 56 valid sample pairs. Review of the analytical results revealed that magnesium constituted less than 4% of the total mass on the C_o samples in the aluminum grinding area. In addition, the magnesium mass on only six of the 34 C_o samples in aluminum grinding met the criterion for sufficient mass challenge recommended by Johnston *et al.* (1992). For these reasons the C_o challenge for the aluminum grinders was based solely on the aluminum mass concentration. In contrast, the total mass on the C_o samples in the magnesium grinding area contained 72% and 28% magnesium and aluminum, respectively. Therefore, the masses of the two elements were combined for the C_o challenge for the magnesium grinders. The geometric mean (GM) and geometric standard deviation (GSD) of the C_o values in each work area are presented in Table I.

Table I. Summary of C_o Sampling Data

	Aluminum Concentration, $\mu g/m^3$ (GM, GSD)	**Magnesium Concentration, $\mu g/m^3$ (GM, GSD)**
Aluminum Grinding	729, 2.2	-----
Magnesium Grinding	190, 1.1	399, 2.4

The mass of aluminum was below the detection limit for 17 of 34 (50%) of C_i samples in the aluminum grinding area. In these cases an imputed value equal to half of the detection limit for aluminum was used for the C_i mass in accordance with published recommendations (Hornung and Reed, 1990). Eighteen of 22 C_i samples (82%) for the magnesium grinders did not have detectible magnesium and 16 of the 22 (72%) were below the detection limit for both aluminum and magnesium. In these cases the sum of the imputed values, i.e., half the detection limit for each element, was used. Four of 22 C_i samples (19%) for the magnesium grinders had a detectible mass of either aluminum or magnesium. For these samples, half the detection limit for the other element was added to the measured value to estimate C_i. WPFs for all the samples were then calculated using the relationship $\mathrm{WPF} = \frac{C_0}{C_i}$ and rounded down to two significant figures. The resultant WPFs are shown in Table II.

WPF studies typically find a lognormal distribution of WPFs, which is described by its geometric mean and geometric standard deviation. However, because more than half of the WPFs in this study were calculated using imputed values, any attempt to describe a distribution would be artificial. Therefore, the measured WPFs were analyzed with a rank and percentile procedure. This analysis revealed a 50^{th} percentile value greater than 1,100 and a lower 5^{th} percentile greater than 71.

The cascade impactor samples revealed that mass median aerodynamic diameters (mmad) in the two grinding areas were essentially the same. The mmad in aluminum grinding was approximately 11 µm with a geometric standard deviation of approximately 2.2. In the magnesium grinding area the mmad was 10.5 µm with a geometric standard deviation of approximately 2.1.

Table II. Summary of WPF Sampling Data

Worker Number (Sampling Day)	Area	C_i Sample Duration (min)	C_i Sample Mass[a] (µg)	C_i (µg/m^3)	C_o Sample Duration (min)	C_o Sample Mass[a] (µg)	C_o (µg/m^3)	WPF	% Rank
1 (1)	Al	98	0.052[b]	0.224	98	500	2057	9100	100
2 (2)	Al	101	0.052[b]	0.214	101	479	1867	8700	98.1
3 (2)	Al	90	0.052[b]	0.241	90	283	1263	5200	96.3
3 (4)	Al	146	0.052[b]	0.147	146	242	671	4500	94.5
4 (4)	Mg	171	0.114[c]	0.262	171	453	1047	3900	92.7
3 (3)	Al	143	0.052[b]	0.152	147	212	584	3800	89.0
3 (4)	Al	96	0.052[b]	0.221	96	200	850	3800	89.0
4 (1)	Mg	103	0.114[c]	0.432	103	416	1630	3700	85.4
3 (1)	Al	203	0.247	0.513	204	983	1905	3700	85.4
3 (4)	Al	60	0.052[b]	0.345	60	176	1183	3400	83.6
4 (1)	Mg	49	0.114[c]	0.950	49	364	2881	3000	81.8
3 (3)	Al	102	0.052[b]	0.212	102	131	520	2400	80.0
2 (4)	Al	99	0.052[b]	0.216	99	115	484	2200	78.1
3 (1)	Al	97	0.052[b]	0.226	97	118	481	2100	76.3
1 (4)	Al	101	0.052[b]	0.225	103	97	394	1700	72.7
2 (2)	Al	173	2.48	5.964	173	4500	10241	1700	72.7
4 (2)	Mg	130	0.114[c]	0.345	130	183	557	1600	70.9
2 (1)	Al	78	0.052[b]	0.273	78	80	411	1500	69.0
4 (2)	Mg	172	0.114[c]	0.261	177	175	391	1400	56.3
3 (3)	Al	113	0.052[b]	0.192	117	81	280	1400	56.3
2 (3)	Al	102	0.052[b]	0.230	102	82	335	1400	56.3
5 (1)	Mg	102	0.114[c]	0.470	102	168	678	1400	56.3
5 (4)	Mg	172	0.114[c]	0.251	172	148	355	1400	56.3
1 (3)	Al	71	0.052[b]	0.305	71	73	430	1400	56.3
1 (3)	Al	99	0.052[b]	0.219	99	72	307	1400	56.3
4 (4)	Mg	91	0.358	1.567	90	497	2183	1300	52.7
4 (3)	Mg	143	0.114[c]	0.329	143	159	443	1300	52.7
5 (3)	Mg	175	0.114[c]	0.269	175	146	336	1200	50.9
5 (3)	Mg	124	0.114[c]	0.377	125	137	439	1100	49.0
2 (4)	Al	62	0.052[b]	0.333	62	52	348	1000	47.2
2 (1)	Al	150	0.303	0.828	150	291	779	940	45.4
5 (2)	Mg	119	0.114[c]	0.377	122	104	347	910	41.8
5 (2)	Mg	100	0.114[c]	0.449	100	100	409	910	41.8

2 (1)	Al	70	0.393	2.239	70	344	1974	880	40.0
5 (3)	Mg	96	0.114[c]	0.491	97	102	421	850	38.1
5 (4)	Mg	94	0.114[c]	0.459	95	90	389	840	36.3
5 (4)	Mg	123	0.114[c]	0.371	125	93	307	820	34.5
5 (1)	Mg	88	0.114	0.544	88	88	410	750	32.7
4 (3)	Mg	91	0.545	2.474	90	334	1479	590	29
1 (4)	Al	87	0.503	2.522	89	317	1490	590	29
3 (2)	Al	61	0.656	4.199	61	351	2274	540	27.2
3 (2)	Al	103	0.414	1.676	102	169	665	390	25.4
4 (3)	Mg	175	1.59	3.762	175	602	1371	360	23.6
3 (4)	Al	93	0.306	1.358	93	98	428	310	21.8
1 (3)	Al	145	1.81	5.244	145	506	1442	270	20.0
4 (2)	Mg	95	0.888	3.680	95	216	906	240	18.1
2 (2)	Al	45	0.569	5.244	49	132	1061	200	16.3
5 (1)	Mg	194	0.931	2.016	194	187	397	190	14.5
1 (1)	Al	173	2.07	5.043	173	354	825	160	12.7
2 (3)	Al	178	1.29	3.275	177	180	424	120	10.9
1 (2)	Al	96	0.923	3.923	96	91	395	100	9.0
3 (2)	Al	172	3.06	6.943	171	291	673	96	7.2
1 (2)	Al	144	0.918	2.603	144	75	217	83	5.4
1 (3)	Al	69	1.10	6.664	73	83	479	71	3.6
5 (2)	Mg	91	2.55	10.939	89	85	390	35	1.8
1 (1)	Al	100	3.04	12.825	100	78	316	24	0

---

[a] C_i and C_o sample values are the mass of aluminum only for the aluminum (Al) grinders and the sum of aluminum and magnesium (Mg) masses for the magnesium grinders.
[b] The mass on the sample was less than the detection limit for aluminum. The value listed is half of the detection limit.
[c] The mass on the sample was less than the detection limit for both aluminum and magnesium. The value listed is the sum of half of the detection limit for each element.

All five C_i samples analyzed by SEM showed particles that contained aluminum, magnesium or a combination of the two metals as major components. This indicates that they are particles generated during the grinding process. Particles identified on the SEM samples ranged up to 20 µm in diameter. Four of the five C_i samples contained multiple aluminum and/or magnesium particles that ranged from 5 to 20 µm in size. The sample with the lowest detectible mass loading contained one particle which was approximately 20 µm in size with aluminum as a major component; there were no particles with magnesium on this filter. This is an expected finding since the sample was taken in the aluminum grinding area. Figure 1 shows a particle with aluminum as a major component that is approximately 20 µm in diameter. Figure 2 shows a particle with an approximate diameter of 10 µm that is composed mainly of magnesium. Only carbon and oxygen were identified as major components of the single particle identified on the blank sample shown in Figure 3. This suggests the particle is most likely a fragment of the polycarbonate filter material rather than contamination from the workplace aerosols.

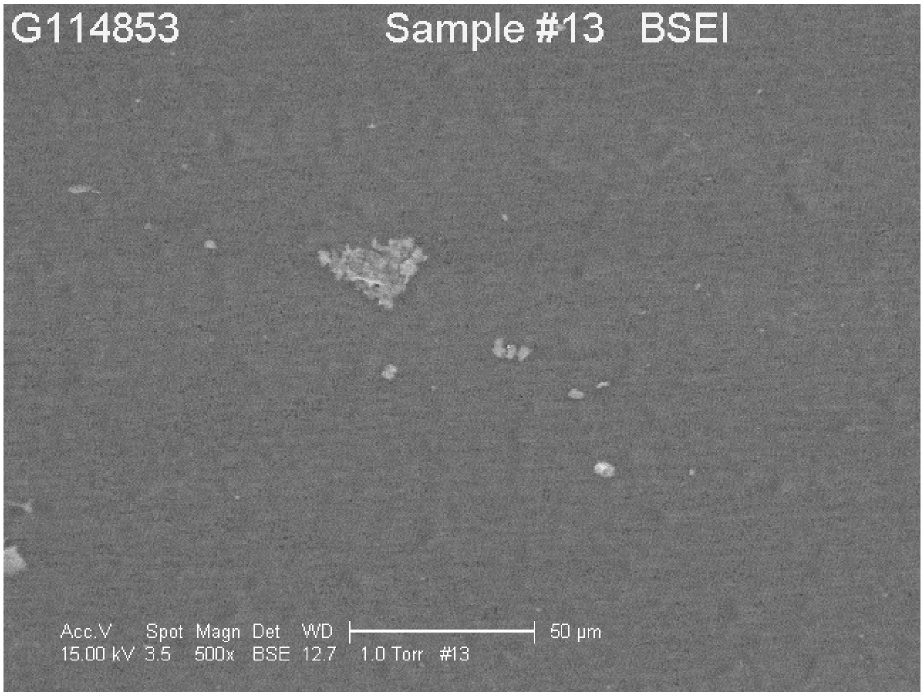

Figure 1. Photomicrograph of particles found on a C_i sample from one of the aluminum grinders. Aluminum was identified as a major component of the large particle the left-center of the photo.

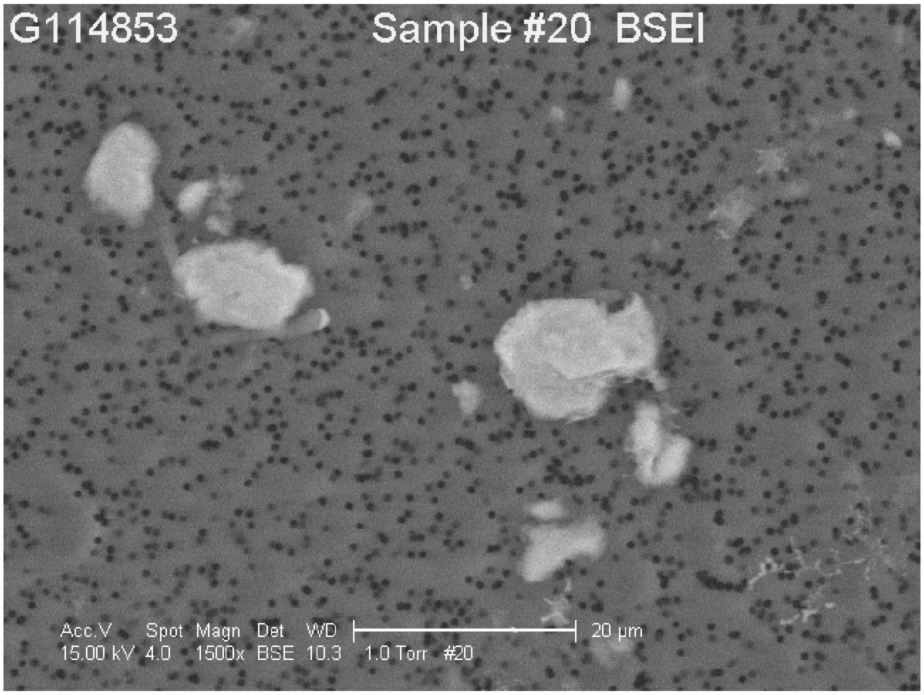

Figure 2. Photomicrograph of particles found on a C_i sample from one of the magnesium grinders. Magnesium was identified as a major component of the large particle in the right-center of the photo.

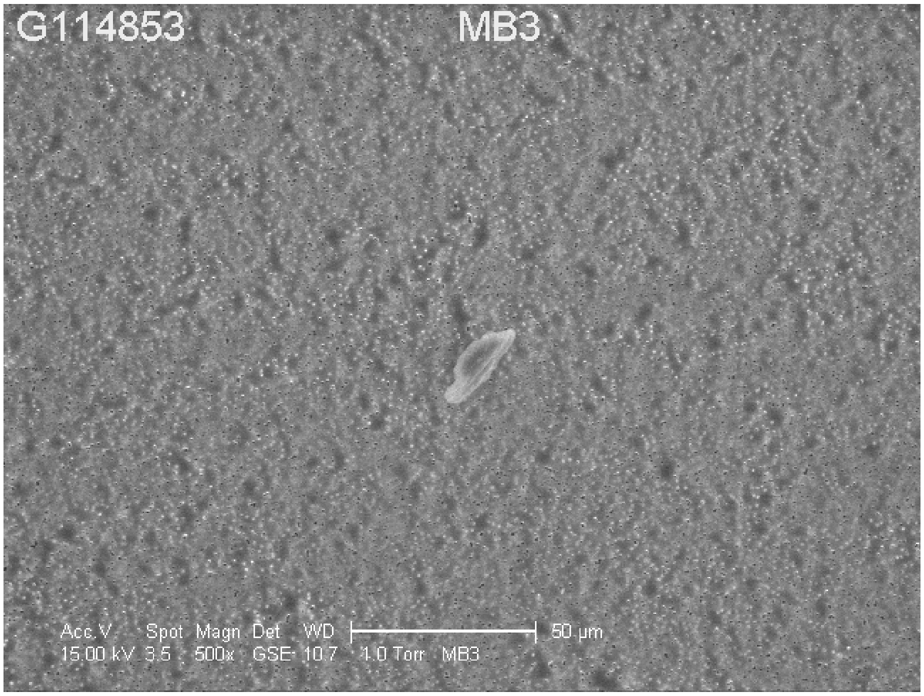

Figure 3. Photomicrograph of the surface of a blank polycarbonate filter. The particle shown is likely a fragment of the filter material.

DISCUSSION

The estimated WPFs in this study were well above the APF of 10 typically assigned to half facepiece respirators. They were also higher than reported in the majority of WPF studies of half facepieces, which typically find lower 5th percentile WPFs in the range of 10-60 (Nelson, 1995; Bidwell and Janssen, 2004; Liu *et al.*, 2006; Janssen *et al.*, In Press). However, WPFs comparable to those found in this study have been reported by Dixon and Nelson (1984) and Zhuang and Myers (1996). Dixon and Nelson reported a GM WPF of 3400 with a lower 5th percentile of 390 for an elastomeric half facepiece with HEPA filters used for protection from lead aerosols. Zhuang and Myers found a GM WPF of 3405 and a lower 5th percentile of 516 for three half facepiece respirators with combination HEPA/organic vapor cartridges evaluated in a paint spraying application. Fifth percentile WPF values as high as 2077 were also found for subgroups of painters in that study.

No particular characteristic of challenge aerosol, half facepiece respirator type, measured fit factor or work activity has been shown to correlate with WPF measurements. For example, the Occupational Safety and Health Administration (OSHA) performed several detailed analyses of available WPF data to determine if filtering facepiece and elastomeric half facepiece respirators perform differently (Federal Register, 2006). Their analyses revealed that the lower 5th percentiles of all the data evaluated were approximately 18 and 12 for filtering and elastomeric facepieces, respectively, and OSHA concluded that both values supported the same APF of 10.

In a paper describing a WPF study of a negative pressure full facepiece respirator, Janssen and Bidwell (2007) summarized available data regarding the hypotheses that WPF may be related to aerosol size or quantitative fit factor. They concluded that neither could be shown to correlate with WPF measurements. The positive correlation between C_o concentration and WPF suggested by some was examined by Janssen *et al.* (In Press) in another filtering facepiece WPF study. They found that only a very weak to weak correlation was shown by existing published studies. Thus, it is not likely any of these common hypotheses were responsible for the unusually high WPFs measured in this study.

Myers *et al.* (1996) proposed that for some periods faceseal leaks may be nonexistent; for other time periods physically small leaks may exist; and for some intervals large, temporary leaks occur due to the respirator moving on the face. Janssen *et al.* (In Press) expanded on this notion, noting that the size of respirator faceseal leaks may be affected by facial movements, sweating and jarring of the respirator through work activities. Indeed, the test exercises used in fit test protocols and simulated workplace protection factor (SWPF) studies are intended to mimic workplace activities and assess, to some degree, their effect on the facepiece to face seal (Hyatt, 1976; Crutchfield and Van Ert, 1993).

In the United States, fit test exercises typically consist of normal and deep breathing, side to side and up and down head movements, talking, jogging in place and/or bending at the waist (CFR, 2005). SWPF studies may add maneuvers such as scooping pebbles, moving bricks, raising the arms and other movements thought to be more representative of the workplace (Cohen *et al.*, 2001). In either type of study, these maneuvers are performed in a controlled manner and sustained for one or two minutes (CFR, 2005; Cohen *et al.*, 2001).

In contrast, activities in a given workplace can vary widely; their duration may vary from an instantaneous event to a task lasting more than an hour. These authors have observed workers jumping from (stopped) forklift trucks, working in cramped areas in a supine position with arms overhead, and bumping their respirator with empty cement bags while wearing WPF sampling trains. Because of the integrated nature of WPF sampling, it is not possible to measure the isolated effect of these events on the facepiece seal. However, it is likely that they have some at least temporary, adverse effect on the seal. The main work activity associated with these grinding jobs was more similar to the activity level of a fit test or SWPF study than the heavy industrial tasks for which lower WPFs have been reported (Nelson, 1995; Bidwell and Janssen, 2004; Liu *et al.*, 2006; Janssen *et al.*, In Press).

It must be restated that the sampling pattern used in this study was chosen to allow investigation of daily and weekly protection received by individual respirator users, and also allow intra- and inter-subject variability in WPF to be studied. As a result, only five workers were sampled for WPFs. It is possible that this small group of workers had very good and very stable fits that contributed to the high WPFs measured. Since it would be impractical to retest these workers in a different workplace environment with higher levels of work activity, there is no way to confirm or refute this possibility.

It has been previously suggested that leakage into the respirator during wear is particle-size dependent and that smaller particles will more easily penetrate to the inside of the respirator via faceseal leaks (Hinds and Kraske, 1987; Holton *et al.*, 1987; Lee *et al.*, 2005). The presence of large metal particles on the filters sampling air from inside the facepiece (C_i) demonstrates that although the workplace protection factor of the respirator was very high, some particles do enter the facepiece. The size and composition of these particles indicate that large temporary leaks permit penetration of particles irrespective of the particle size. The high workplace protection factors confirm that while the majority of time, during use, leakage is non-existent or very small, leaks can occur that allow leakage of particles of varying sizes. This is consistent with what has been found in other research (Meyers *et al.*, 1995 and 1996; Janssen *et al.*, In Press).

CONCLUSIONS

Very high WPFs were measured on a group of five workers wearing a class N95 filtering facepiece respirator. Because more than half the WPF values were calculated using imputed values for C_i samples with no detectible penetration, analyses of their distribution and variability within and between test subjects could not be meaningfully performed. It is believed that the stationary nature of these workers' jobs contributed to the high level of respirator performance. WPF studies in facilities with higher levels of work activity generally report lower WPFs. Therefore, the WPFs in this study should be considered atypically high. While the study's results clearly support the APF of 10 for this class of respirator, they do not suggest that the APF should be raised. In addition, examination of air samples taken inside the facepiece during wear (C_i) revealed particles of aluminum and magnesium with diameters up to approximately 20 µm. This demonstrates that leakage into well-fitting respirators is not limited to sub-micrometer particles.

Acknowledgements

The authors would like to thank the company management, the workers who volunteered to participate in the study and the observation team for their assistance.

REFERENCES

American Conference of Governmental Industrial Hygienists (ACGIH) (2006) Threshold Limit Values for Chemical Substances and Physical Agents. ACGIH, Cincinnati, OH.

American Industrial Hygiene Association (AIHA) Respiratory Protection Committee: Respirator Performance Terminology. [Letter to the Editor]. *Am. Ind. Hyg. Assoc. J. (63)*:132 (2002).

“Assigned Protection Factors; Final Rule,” *Federal Register 71*:164 (24 August 2006) pp. 50122-50192.

Bidwell, J.O. and Janssen, L.L. (2004) Workplace performance of an N95 respirator in a concrete block manufacturing plant. *J. Int. Soc. Resp. Prot. 21(III-IV)*:94-103.

Code of Federal Regulations (CFR) (2005) "Respiratory Protection," Title 29 (6), Section 1910.134. pp. 419-444.

Cohen H.J., Hecker, L.H., Matthies, D.K., Johnson. J.S., Bierman, A.H., Foote, K.L. (2001) Simulated workplace protection factor study of powered air-purifying and supplied air respirators *AIHAJ* 62(5):595-604.

Colton, C.E. and Bidwell, J.O. “A Comparison of the Workplace Performance of a Dust/Mist and Two N95 Particulate Half Facepiece Respirators.” (1999) Paper presented at the American Industrial Hygiene Conference, Toronto, Ontario, Canada.

Crutchfield, C.D. and Van Ert, M.D. (1993) An examination of issues affecting the current state of quantitative respirator fit testing. *J. Int. Soc. Resp. Prot. 11(2)*:94-103.

Dixon, S.W. and Nelson, T.J. (1984) Workplace protection factors for negative pressure half-mask facepiece respirators. *J. Int. Soc. Resp. Prot. 2(4)*:347-361.

Hinds, W.C. and Kraske, G. (1987) Performance of dust respirators with facial seal leaks: II. predictive model. *Am. Ind. Hyg. Assoc. J. 48(10)*:842-847 (1987).

Holton, P.M., Tackett, D.L. and Willeke, K. (1987) Particle size-dependent leakage and losses of aerosols in respirators. *Am. Ind. Hyg. Assoc. J. 48(10)*:848-854.

Hornung, R.W. and Reed, L.D. (1990) Estimation of average concentration in the presence of nondetectable values. *Appl. Occup. Environ. Hyg.* 5(1):46-51.

Hyatt, E.C. (1976) Respirator Protection Factors (Report No. LA-6084-MS). Los Alamos Scientific Laboratory.

International Organization for Standardization (ISO) (2004) *Ergonomics Of The Thermal Environment -- Determination Of Metabolic Rate* (ISO 8996). International Organization for Standardization, Geneva, Switzerland.

Janssen, L.L. and Bidwell, J.O. (2007) Performance of a full facepiece air purifying respirator against lead aerosols in a workplace environment. *J. Occup. Environ. Hyg.* 4:123-128.

Janssen, L.L., Nelson, T.J. and Cuta, K.T. Workplace protection factors for an N95 filtering facepiece respirator. *J. Occup. Environ. Hyg.* (In Press).

Johnston, A.R., Myers, W.R., Colton, C.E., Birkner, J.S. and Campbell, C.E. (1992) Review of respirator performance testing in the workplace: issues and concerns. *Am. Ind. Hyg. Assoc. J.53(11)*:705-712.

Lee, S.A., Adhikari, A., Grinshpun, S.A., McKay, R., Shukla, R., Zeigler, H.L. and Reponen, T. (2005) Respiratory protection provided by N95 filtering facepiece respirators against airborne dust and microorganisms in agricultural farms. *J. Occup. Environ. Hyg.* 2:577-585.

Liu, B.Y.H., Sega K., Rubow, K.L., Lenhart, S.W. and. Myers, W.R. (1984) In-mask sampling for powered air purifying respirators. *Am. Ind. Hyg. Assoc. J. 45(4)*:278-283.

Liu, Y., Stowe, M.H., Dhimiter, B. Woskie, *et al.* (2006) Respiratory protection from isocyanate exposure in the autobody repair and refinishing industry. *J. Occup. Environ. Hyg. 3*:234-249.

Myers, W.R. and Zhuang, Z. (1998) Field performance measurements of half-facepiece respirators: steel mill operations. *Am. Ind. Hyg. Assoc. J. 59:*789-795.

Myers, W.R., Zhuang, Z. and Nelson, T.J. (1996) Field performance measurements of half-facepiece respirators: foundry operations. *Am. Ind. Hyg. Assoc. J. 57*:166-174.

Myers, W.R., Zhuang, Z., Nelson, T.J., Sides, S. and Wilmes, D. (1995) Field performance measurements of half-facepiece respirators-study protocol. *Am. Ind. Hyg. Assoc. J.*56:765–775.

National Institute for Occupational Safety and Health: *NIOSH Manual of Analytical Methods (NMAM) Fourth Ed.* P.C. Schlecht, and P.F O'Connor, Eds. [DHHS (NIOSH) 94-113]. (Online) Available at http://www.cdc.gov/niosh/nmam/default.html. Accessed May 8, 2006.

Nelson, T.J. (1995) The assigned protection factor of 10 for half-mask respirators. *Am. Ind. Hyg. Assoc. J. 56:* 717-724.

Nelson, T.J. (1996) The assigned protection factor according to ANSI. *Am. Ind. Hyg. Assoc. J. 57:*735-740.

“Respiratory Protection; Final Rule,” *Federal Register 63*:5 (8 January 1998) pp. 1152-1300.

Zhuang, Z. and Myers, W.R. (1996) Field performance measurements of half-facepiece respirators: paint spraying operations. *Am. Ind. Hyg. Assoc. J. 57:*50-57.