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# Performance of a Full Facepiece, Air-Purifying Respirator Against Lead Aerosols in a Workplace Environment

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*This study evaluated workplace performance of a full facepiece, negative pressure, air-purifying respirator with P100 filters in a lead refining plant. Air samples for lead were collected inside and outside the respirators worn by workers who were properly trained and quantitatively fit tested. Trained observers assisted in the study to ensure sample validity. Three to four pairs of air samples per day were collected from each worker for a total of 52 valid sample sets. Lead was found on all the outside samples, and concentrations were below the detection limit for all but one of the inside samples. The single measurable inside sample yielded a workplace protection factor (WPF) of 297. WPFs for the rest of the samples were estimated using the assumption that lead was present at the detection limit for the in-facepiece samples. Calculated WPFs were rounded down to the nearest 100 then subjected to a rank and percentile function. The 5th percentile WPF was approximately 900 using this approach. These WPFs exceed the assigned protection factor (APF) of 50 for this respirator class recommended by the National Institute for Occupational Safety and Health and listed by the Occupational Safety and Health Administration. These results support the APF of 50 for this respirator and indicate the respirator provided adequate protection as used in this study.*

**Keywords** respirator performance, respiratory protection, workplace protection factor, WPF

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## INTRODUCTION

In the United States, workers exposed to lead aerosols at concentrations up to 50 times the permissible exposure limit (PEL) of 50 $\mu g/m^3$ are required to wear, at a minimum, a full facepiece, negative pressure, air-purifying respirator with class 100 filters.[1] This requirement is based on the presumption that this respirator will provide a fiftyfold reduction in the ambient contaminant exposure. That is, the respirator has an assigned protection factor (APF) of 50. The APF represents 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.[2] 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.[2] Because WPFs are a direct measurement of respirator performance capabilities in a specific work environment, they provide data to help support, refute, or establish APFs.

No study of full facepiece, negative pressure respirator performance in the peer-reviewed literature meets the stated criteria[2] for a WPF study. For example, workplace performance measurements from full facepiece respirator studies in which fit testing was not performed are not considered WPFs. Therefore, this study was done to provide performance data for this common respirator type.

## MATERIALS AND METHODS

### Respirators and Test Subjects

The respirator tested was a NIOSH-approved model 6000 full facepiece (3M, St. Paul, Minn.) equipped with model 2097 P100 filters. Workers routinely wore this respirator at their jobs prior to the study. Eighteen men voluntarily participated as test subjects after having the purpose and procedures of the study explained to them. All the subjects were clean shaven. They had been medically evaluated, trained in proper use of the respirator, and quantitatively fit tested with the Portacount Plus (TSI, Inc., St. Paul, Minn.) by their employer in accordance with applicable Occupational Safety and Health Administration (OSHA) regulations.[3]

The work performed during sampling included lifting and stacking lead ingots, skimming dross from molten lead, operating a blast furnace, sweeping and shoveling, and driving forklift trucks. The average work rate was estimated to be moderate in accordance with published guidelines.[4]

### Sample Collection

In-facepiece samples ($C_i$) were collected via a sampling probe patterned after a design by Liu et al.[5] to minimize entry losses of particles $\geq 5$ $\mu$m. Because of the characteristics of the full facepiece tested, the probe in this study was approximately 8 cm long. It could be threaded far enough into the facepiece, inside the nosecup, so that its inlet was approximately 1 cm

from the test subject's mouth. A thread sealant was used to prevent leakage around the probe where it was screwed into the facepiece.

A 3-piece, 25-mm sample cassette containing a 0.8 $\mu$m pore size polycarbonate filter (Millipore Corp., Bedford, Mass.) was attached directly to the probe outside the facepiece for collection of the $C_i$ sample. A cassette heater used in previous studies[6,7] was used to prevent 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.

The ambient air ($C_o$) samples were collected in the workers' breathing zone with 0.8 $\mu$m pore size mixed cellulose ester (MCE) filters (Millipore). In accord with earlier studies,[7] the same sampling probe used for $C_i$ sampling was attached to the $C_o$ cassette inlet. The $C_i$ and $C_o$ samples were collected simultaneously with Escort Elf personal sampling pumps (MSA, Pittsburgh, Pa.) at a flow rate of 2 L/min. The pumps were calibrated at the beginning of each day with a Sierra TopTrak, Model 821-S1-L-1PS mass flow meter (Sierra Instruments, Inc., Monterey, Calif.) using an appropriate inline filter cassette. The pumps were monitored visually for proper flow throughout the shift and rechecked with the mass flow meter at the end of each shift. The mass flowmeter's accuracy was verified with a soap film flowmeter.

Three or four sample sets were collected on each test subject throughout the work shift. The change interval generally coincided with a 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 a fresh $C_i$ sample cassette.

Particle size sampling was done with an eight-stage Marple Personal Cascade Impactor (Thermo Anderson, Smyrna, Ga.). Two area samples were taken in areas representative of where workers performed their jobs. The samples were collected for approximately 3 hours at a flow rate of 1.9 L/min, consistent with the manufacturer's recommendations.

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 hoses). The observers also verified proper respirator use and recorded observations about work conditions. One observer was assigned to each test subject, whom they monitored throughout the sampling period.

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 unused filters of each type used in the study. These were sent to the analytical laboratories in their 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), which is the preferred analytical method for $C_i$ samples on most WPFs because of its high sensitivity, i.e., very low detection limits. It is a nondestructive X-ray spectroscopic method that allows simultaneous analysis of a wide range of elements present in aerosols collected on filters. Energetic protons are used to expel inner shell electrons in the target atoms. Characteristic X-ray energies are emitted by each element when the inner shell vacancies are refilled. The X-ray energy intensity is proportional to the mass of the element present in the sample.[6] The detection limit for lead was 0.019 $\mu$g per filter at an X-ray energy of 10.551 keV. $C_o$ samples and cascade impactor samples were subjected to inductively coupled plasma analysis using NIOSH method 7300.[8] The detection limit for lead was 0.38 $\mu$g per filter.

### Inlet Probe Evaluation

The inlet probe used for sample collection was substantially longer than those used in previous WPF studies (8 cm vs. 2 cm). Additionally, no data exists to support the use of any inlet probe on the $C_o$ cassettes. For these reasons, area sampling was done to assess potential effects on the $C_o$ sample results. Three $C_o$ sampling trains in one of the following configurations were used:

1. 8 cm inlet probe on the cassette
2. 2 cm inlet probe on the cassette
3. No inlet probe on the cassette

The samples were collected within approximately 10 cm of one another in one of the areas where workers performed their jobs. Flow rates, collection media, and analytical procedures were the same as the $C_o$ personal samples.

## RESULTS

Results of the 52 valid sample sets are shown in Table I. No lead contamination was found on the polycarbonate blanks. Mean contamination was well below 1 $\mu$g of lead for the manufacturer blank and field blank MCE filters, so the $C_o$ values were not blank corrected. Thirteen $C_i$ samples were invalidated because the cassette was knocked off the facepiece probe, and two more were invalidated because the worker lifted the respirator facepiece to talk during sampling. Because only one valid $C_i$ sample had a detectable lead concentration, it was not possible to determine a WPF distribution. Therefore,

**TABLE I. Summary of WPF Sampling Data**

| Subject[A] | Sample Duration (min) | $C_i$ Sample Volume (L) | $C_i$ ($\mu g/m^3$) | Sample Duration (min) | $C_o$ Sample Volume (L) | $C_o$ ($\mu g/m^3$) | WPF[B] | Rank (%) |
|---|---|---|---|---|---|---|---|---|
| 11 | 142 | 301 | < 0.063 | 191 | 420 | 1280 | > 20200 | 100 |
| 1 | 165 | 343 | < 0.055 | 165 | 370 | 1107 | > 19900 | 98 |
| 16 | 145 | 305 | < 0.062 | 145 | 323 | 1045 | > 16700 | 96 |
| 8 | 81 | 189 | < 0.101 | 81 | 172 | 1491 | > 14800 | 94.1 |
| 5 | 128 | 293 | < 0.065 | 128 | 276 | 951 | > 14600 | 90.1 |
| 8 | 142 | 331 | < 0.057 | 142 | 301 | 840 | > 14600 | 90.1 |
| 3 | 120 | 286 | < 0.067 | 156 | 339 | 966 | > 14500 | 88.2 |
| 16 | 40 | 84 | < 0.226 | 108 | 241 | 2500 | > 11000 | 86.2 |
| 7 | 121 | 269 | < 0.071 | 121 | 260 | 750 | > 10500 | 84.3 |
| 9 | 120 | 258 | < 0.074 | 120 | 257 | 705 | > 9500 | 82.3 |
| 9 | 97 | 209 | < 0.091 | 97 | 208 | 805 | > 8800 | 80.3 |
| 4 | 143 | 305 | < 0.062 | 143 | 296 | 473 | > 7500 | 78.4 |
| 9 | 119 | 256 | < 0.074 | 119 | 255 | 495 | > 6600 | 76.4 |
| 18 | 117 | 249 | < 0.076 | 117 | 264 | 465 | > 6100 | 74.5 |
| 17 | 88 | 190 | < 0.100 | 91 | 201 | 602 | > 6000 | 72.5 |
| 17 | 147 | 318 | < 0.060 | 167 | 369 | 358 | > 5900 | 70.5 |
| 10 | 129 | 275 | < 0.069 | 173 | 388 | 397 | > 5700 | 68.6 |
| 1 | 128 | 266 | < 0.071 | 128 | 287 | 377 | > 5200 | 64.7 |
| 18 | 86 | 183 | < 0.104 | 85 | 192 | 541 | > 5200 | 64.7 |
| 6 | 93 | 192 | < 0.099 | 93 | 197 | 459 | > 4600 | 62.7 |
| 10 | 122 | 260 | < 0.073 | 122 | 273 | 334 | > 4500 | 60.7 |
| 10 | 114 | 243 | < 0.078 | 114 | 255 | 325 | > 4100 | 56.8 |
| 12 | 81 | 190 | < 0.100 | 62 | 132 | 416 | > 4100 | 56.8 |
| 13 | 94 | 213 | < 0.089 | 94 | 206 | 322 | > 3600 | 54.9 |
| 11 | 40 | 87 | < 0.219 | 40 | 88 | 751 | > 3400 | 52.9 |
| 12 | 131 | 307 | < 0.062 | 115 | 245 | 206 | > 3300 | 49 |
| 16 | 45 | 95 | < 0.201 | 45 | 100 | 668 | > 3300 | 49 |
| 3 | 47 | 112 | < 0.170 | 48 | 104 | 547 | > 3200 | 41.1 |
| 14 | 84 | 179 | < 0.106 | 84 | 189 | 343 | > 3200 | 41.1 |
| 15 | 150 | 324 | < 0.059 | 150 | 318 | 190 | > 3200 | 41.1 |
| 17 | 80 | 173 | < 0.110 | 110 | 243 | 353 | > 3200 | 41.1 |
| 6 | 82 | 169 | < 0.112 | 82 | 174 | 356 | > 3100 | 39.2 |
| 5 | 40 | 92 | < 0.207 | 40 | 86 | 590 | > 2800 | 37.2 |
| 14 | 70 | 149 | < 0.127 | 70 | 158 | 356 | > 2700 | 33.3 |
| 15 | 91 | 197 | < 0.097 | 91 | 193 | 264 | > 2700 | 33.3 |
| 9 | 48 | 103 | < 0.184 | 48 | 103 | 476 | > 2500 | 29.4 |
| 11 | 97 | 212 | < 0.089 | 151 | 337 | 231 | > 2500 | 29.4 |
| 1 | 82 | 171 | < 0.111 | 82 | 184 | 271 | > 2400 | 25.4 |
| 4 | 97 | 207 | < 0.092 | 97 | 201 | 225 | > 2400 | 25.4 |
| 13 | 103 | 234 | < 0.081 | 103 | 226 | 191 | > 2300 | 23.5 |
| 1 | 83 | 180 | < 0.105 | 83 | 183 | 229 | > 2100 | 21.5 |
| 13 | 81 | 184 | < 0.103 | 77 | 169 | 206 | > 1900 | 17.6 |
| 15 | 41 | 89 | < 0.215 | 41 | 87 | 412 | > 1900 | 17.6 |
| 2 | 86 | 194 | < 0.098 | 90 | 191 | 169 | > 1700 | 15.6 |
| 3 | 74 | 176 | < 0.108 | 74 | 161 | 183 | > 1600 | 13.7 |
| 1 | 89 | 193 | < 0.098 | 122 | 270 | 139 | > 1400 | 11.7 |
| 5 | 66 | 134 | < 0.142 | 67 | 145 | 172 | > 1200 | 7.8 |
| 13 | 98 | 222 | < 0.085 | 97 | 212 | 108 | > 1200 | 7.8 |
| 4 | 107 | 228 | < 0.083 | 107 | 221 | 79 | > 900 | 5.8 |
| 16 | 43 | 90 | < 0.210 | 53 | 118 | 172 | > 800 | 3.9 |
| 2 | 94 | 212 | < 1.364 | 94 | 199 | 404 | > 200[c] | 1.9 |
| 14 | 102 | 217 | < 0.087 | 84 | 189 | 9 | > 100 | 0 |

[A] Some subjects were sampled on more than one day.
[B] WPF values are rounded down to the nearest 100.
[C] WPF calculated using the detectable $C_i$ value was 297.

**TABLE II. Sampling Results of Inlet Probe Evaluation**

| | Lead concentration ($\mu g/m^3$) | | |
|---|---|---|---|
| **Sample Set** | **No Inlet Probe** | **2-cm Inlet Probe** | **8-cm Inlet Probe** |
| 1 | 543 | 622 | 534 |
| 2 | 245 | 480 | 452 |
| 3 | 265 | 188 | 129 |
| 4 | 236 | 451 | 371 |
| 5 | 1714 | 1348 | 1518 |
| 6 | 760 | 820 | 1259 |
| Mean | 627 | 710 | 651 |

**ANOVA**

| Source of Variation | SS[A] | df[B] | MS[C] | F[D] | p-value | F crit[E] |
|---|---|---|---|---|---|---|
| Between groups | 21991.14 | 2 | 10995.57 | 0.041892 | 0.959085 | 3.682317 |
| Within groups | 3937140 | 15 | 262476 | | | |
| Total | 3959131 | 17 | | | | |

[A] = Sum of squares.
[B] = Degrees of freedom.
[C] = Mean square.
[D] = F-statistic.
[E] = Critical F value.

a conservative estimate of respirator performance was made by assuming lead at the detection limit was present in the $C_i$ samples reported below the detection limit. This mass value was divided by the $C_i$ sample volume for an estimate of the upper bound of $C_i$ concentration. The corresponding $C_o$ sample was divided by this $C_i$ estimate to approximate a lower bound of WPF for the sample pair. Finally, a rank and percentile function was performed, leading to a lower 5th percentile WPF estimate of approximately 900. Those results are also shown in Table I.

The results of the probe evaluation sampling are shown in Table II. A one-way analysis of variance showed the measurements were not significantly different from one another.

The cascade impactor samples revealed particle size distributions of 10.2 $\mu$m mass median aerodynamic diameter (MMAD) in the general work area and 7.5 $\mu$m MMAD in the casting area. The geometric standard deviations for these locations were 2.7 and 2.9, respectively. Although these results indicate that large particles were predominant, 6.5% and 13.6% of the mass in the general work area and casting area, respectively, were found in particles less than 2 $\mu$m in aerodynamic size. Therefore, it appears likely the worker exposures consisted of both dust and fume particles.

## DISCUSSION

### WPF Results

Inspection of Table I reveals that approximately 33% of the $C_o$ concentrations exceed 10 times the PEL of 50 $\mu g/m^3$ for lead. The highest exposure sampled was 50 times the PEL. Therefore, the full facepiece respirator was properly selected for this work environment in accordance with U.S. regulations.[1]

All the estimated WPFs in this study were well above the APF of 50 typically assigned to this class of respirator. Previous authors have analyzed WPF values as a function of $C_o$[7,9–11] or sought correlation between WPFs and quantitative fit factors (QNFFs).[12–15] Because all but one of the $C_i$ measurements in this study were below the detection limit for lead, it is not meaningful to attempt these analyses. Clearly, it can be said that in this study the respirator performed very well, providing much more than the expected fiftyfold reduction in exposure.

Several factors may have contributed to the high level of respirator performance seen in this study. As noted earlier, most of the users were experienced in the use of this particular respirator. However, two of the test subjects were new hires, starting work and undergoing training and fit testing the week the study was conducted. All the test subjects were conscientious in properly donning and wearing the respirators, excepting the few instances of inadvertent lifting of the facepiece noted earlier.

The QNFFs in this study were well above the minimum of 500 required to pass the fit test,[3] ranging from approximately 2600 to nearly 24,000. It is possible that the high degree of fit resulted in the high WPF values measured. However, several half facepiece WPF studies have not shown a significant correlation between QNFFs and WPFs.[11–13] Consistent with the definition of WPF,[2] each of the studies included only subjects with acceptable fit factors of 100 for half facepieces.[3] Zhuang et al.[14] and Han[15] both reported a correlation ($r^2$ = 0.55 and 0.38, respectively) between QNFFs and workplace measurements for half facepiece respirators. Their studies

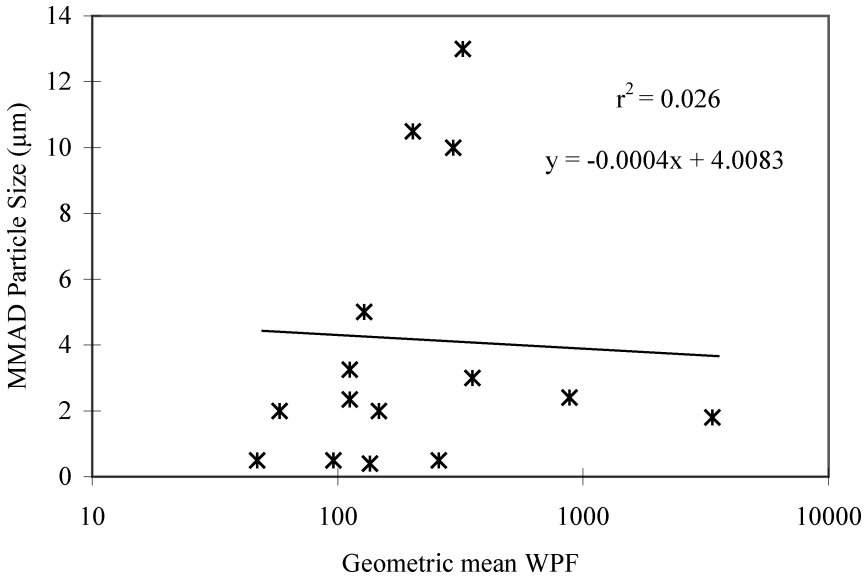


**FIGURE 1.** Analysis of particle size vs. WPF[22]

included both acceptable and unacceptable QNFFs in their regression analysis. Thus, the workplace measurements of Zhuang et al. and Han were actually program protection factors (PPFs) rather than WPFs.[2]

Poorly fitting respirators are not permitted in compliant respiratory protection programs and are not within the definition of WPF. In contrast, PPF represents the protection provided by a respirator used in the context of a specific respiratory protection program.[2] Thus, the PPF takes into account the detrimental effects of program deficiencies (such as poorly fitting respirators) on respirator performance. It is important to note that contaminant exposures were below the occupational exposure limits in both the Zhuang et al.[14] and Han[15] studies, so workers with poorly fitting respirators were not exposed to hazardous contaminant concentrations.

When Zhuang et al.[14] analyzed their data using only the WPF values (i.e., only measurements made on adequately fitting respirators were included), the correlation coefficient was reduced to 0.32. When the Han[15] data is analyzed using workplace measurements collected only on respirators with fit factors above 100, no significant correlation remains ($r^2 = 0.002$). Therefore, because this full facepiece study included only QNFFs well above 500, it is unlikely the high fit factors were correlated to or directly responsible for the high performance level seen. It can be said only that achieving these high QNFFs may have contributed to the very good protection seen.

As noted earlier, the MMAD of the aerosol challenge in the plant where the study took place was relatively large. The P100 filters used in this study were demonstrated to be at least 99.97% efficient under the severe challenge conditions of the certification test.[16] It can therefore be assumed that filter penetration in this WPF study was essentially zero. It has been demonstrated that leakage through a fixed, artificial faceseal leak decreases with increasing particle size.[17–19]

Some investigators have suggested that this phenomenon might cause the WPF to increase with increased particle size because particles larger than a few micrometers are less likely to penetrate the faceseal than submicrometer particles.[20,21] However, Wallis et al.[21] also noted that their data suggested that some activities could cause short duration "gross leaks." Myers et al.[6] used electron microscopy to demonstrate that particles $\geq$ 10 $\mu$m are found on $C_i$ WPF samples, further refuting the suggestion that respirator faceseal leaks are a fixed size. Finally, an analysis of 15 WPF studies of half facepiece respirators do not support the hypothesis that WPF values increase with increasing particle size (Figure 1).[22] Geometric mean WPF values in the analysis ranged from 47 to 3360, and reported particle sizes from 0.4 to 13 $\mu$m. It is evident in Figure 1 that there was essentially no correlation between particle size and WPF ($r^2 = 0.026$). Thus, it is unlikely that the large particle sizes in this study were the reason for the high level of performance.

Finally, this study was somewhat unusual in that the investigators did not provide training or fit testing to the test subjects. Each of those activities was carried out by their employer in the normal course of the existing respiratory protection program. No deficiencies in any aspect of the respirator program were apparent during the course of the study. These observations support the concept underlying existing respiratory protection regulations.[3] That is, respirators that are used in the context of a sound respiratory protection program meet or exceed their expected level of performance.

## Results of Inlet Probe Evaluation

As shown in Table II, the sample results generated with the 8-cm inlet probe used in this study were not significantly different from the 2-cm probe or the cassette with no inlet probe ($p>0.95$).

The inlet probe serves three purposes in a WPF study:

1. It provides a mechanism to connect the $C_i$ sample cassette to the test subject's respirator.
2. It allows the $C_i$ sample to be properly positioned in the subject's breathing zone.
3. Its design minimizes inlet losses for particles larger than 5 $\mu$m.[5]

Specifically, Liu et al.[5] estimated that an average of less than 15% of 10-$\mu$m particles would be lost when sampling in tight-fitting, powered, air-purifying respirator facepieces.[5] The inlet probe has traditionally been used on the $C_o$ sample to equalize potential particle losses, if any occur, with the $C_i$ sample.[7] Note that this assumption requires that the $C_i$ and $C_o$ particle size distributions be approximately the same, which is impractical to determine in WPF studies.

Because particles larger than 10 $\mu$m have been shown to penetrate into half facepiece respirators,[6] it is critical to minimize particle losses for $C_i$ samples in a WPF study. This is true because individual particle mass increases as a cube function with diameter increases, that is, mass = volume $\times$ density. Because the volume of a sphere is given by $\frac{\pi \times d^3}{6}$ a "large" particle, e.g., 5 $\mu$m, carries 1000 times (rather than 10 times) the mass of a 0.5 $\mu$m particle. Therefore, loss of a single large particle could significantly underestimate $C_i$, for which a very small mass is typically measured. This would result in an overestimation of WPF. In contrast, the mass collected on $C_o$ samples is generally at least two orders of magnitude greater than the $C_i$ mass. Thus, if a small percentage of large particles is lost at the $C_o$ sample inlet, its impact on the total mass is not great. Furthermore, if particles are lost to the cassette inlet because no probe is used, $C_o$ will be underestimated. This is a conservative error, since the net result would be an underestimate of WPF. Therefore, use of any inlet probe on $C_o$ samples is generally not critical to WPF measurement. Its use should be considered optional. For example, it may be prudent to use the inlet probe on $C_o$ cassettes if the ambient contaminant concentration is marginally high enough to measure the expected WPF.

## CONCLUSIONS

The full facepiece respirator tested in this study provided WPF values well above its APF of 50. Exposures to lead inside the facepiece were all far below the PEL, indicative of appropriate protection. These results indicate that this class of respirator performs very well when properly selected, worn, and used in the context of a sound respiratory protection program.

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## REFERENCES

1. **"**Lead," *Code of Federal Regulations* Title 29 (7), Section 1910.1025. 2003. pp. 104–135.
2. **American Industrial Hygiene Association (AIHA) Respiratory Protection Committee:** Respirator performance terminology. [Letter to the Editor]. *Am. Ind. Hyg. Assoc. J. (63)*:132 (2002).
3. "Respiratory Protection," *Code of Federal Regulations* Title 29 (6), Section 1910.134. 2005. pp. 419–444.
4. **International Organization for Standardization (ISO):** *Ergonomics of the Thermal Environment—Determination of Metabolic Rate* (ISO 8996). [Standard] Geneva: International Organization for Standardization 2004.
5. **Liu, B.Y.H., K. Sega, K.L. Rubow, S.W. Lenhart, and W.R. Myers:** In-mask sampling for powered air purifying respirators. *Am. Ind. Hyg. Assoc. J. 45*:278–283 (1984).
6. **Myers, W.R., Z. Zhuang, T.J Nelson, S. Sides, and D. Wilmes:** Field performance measurements of half-facepiece respirators-study protocol. *Am. Ind. Hyg. Assoc. J. 56*:765–775 (1995).
7. **Bidwell, J.O., and L.L. Janssen:** Workplace performance of an N95 respirator in a concrete block manufacturing plant. *J. Int. Soc. Resp. Prot. 21(III–IV)*:94–103 (2004).
8. **Schlecht, P.C., and P.F. O'Connor (eds.):** *NIOSH Manual of Analytical Methods(NMAM),* Fourth Edition. Pub. No. DHHS (NIOSH) 94-113. (Online) Available at http://www.cdc.gov/niosh/nmam/default.html. Accessed April 5, 2005.FIX SPACING.9.
9. **Myers, W.R., and Z. Zhuang:** Field performance measurements of half-facepiece respirators: Steel mill operations. *Am. Ind. Hyg. Assoc. J. 59*:789–795 (1998).
10. **Myers, W.R., and Z. Zhuang:** Field performance measurements of half-facepiece respirators: Foundry operations. *Am. Ind. Hyg. Assoc. J. 57*:166–174 (1996).
11. **Zhuang, Z., and W.R. Myers:** Field performance measurements of half-facepiece respirators: Paint spraying operations. *Am. Ind. Hyg. Assoc. J. 57*:50–57 (1996).
12. **Dixon, S.W., and T.J. Nelson:** Workplace protection factors for negative pressure half-mask facepiece respirators. *J. Int. Soc. Resp. Prot. 2(4)*:347–361 (1984).
13. **Gaboury, A., D.H. Burd, and R.S. Friar:** Workplace protection factor evaluation of respiratory protective equipment in a primary aluminum smelter. *Appl. Occup. Environ. Hyg. 8*:19–25 (1993).
14. **Zhuang, Z., C.C. Coffey, P.A. Jensen, D.L. Campbell, R.B. Lawrence, and W.R. Myers:** Correlation between quantitative fit factors and workplace protection factors measured in actual workplace environments at a steel foundry. *Am. Ind. Hyg. Assoc. J. 64*:730–738 (2003).
15. **Han, D.:** Correlations between workplace protection factors and fit factors for filtering facepieces in the welding workplace. *Ind. Health 40*:328–334 (2002).
16. **"**Approval of Respiratory Protective Devices," *Code of Federal Regulations* Title 42 Subpart K. 2005., pp. 538–541.
17. **Hinds, W.C., and G. Kraske:** Performance of dust respirators with facial seal leaks: I. Experimental. *Am. Ind. Hyg. Assoc. J. 48*:836–841 (1987).
18. **Chen, C.C., J. Ruuskanen, W. Pilacinski, and K. Willeke:** Filter and leak penetration characteristics of a dust and mist filtering facepiece. *Am. Ind. Hyg. Assoc. J. 51*:632–639 (1990).
19. **Chen, C.C., and K. Willeke:** Characteristics of face seal leakage in filtering facepieces. *Am. Ind. Hyg. Assoc. J. 53*:533–539 (1992).
20. **Hinds, W.C., and G. Kraske:** Performance of dust respirators with facial seal leaks: II. Predictive model. *Am. Ind. Hyg. Assoc. J. 48*:842–847 (1987).
21. **Wallis, G., R. Menke, and C. Chelton:** Workplace field testing of a disposable negative pressure half-mask dust respirator (3M 8710). *Am. Ind. Hyg. Assoc. J. 54*:576–583 (1993).
22. "Respiratory Protection—Assigned Protection Factors," Rulemaking Docket H049C, Exhibit 9-16 (2003). Washington, D.C.: U.S. Department of Labor, Occupational Safety and Health Administration, (Docket Office), 2003.