Journal of Occupational and Environmental Hygiene, 5: 438–443
ISSN: 1545-9624 print / 1545-9632 online

DOI: 10.1080/15459620802115930

Workplace Performance of a Hood-Style Supplied-Air Respirator

Larry Janssen,[1] Jeanne Bidwell,[1] Karen Cuta,[1] and Thomas Nelson[2]

[1]3M Company, Occupational Health and Environmental Safety Division, St. Paul, Minnesota
[2]NIHS Inc., Wilmington, Delaware

This study evaluated the workplace performance of a hood-style supplied-air respirator during aircraft sanding operations. Air samples were collected inside and outside the respirators worn by workers during normal work activities. The samples were analyzed for chromium, strontium, and magnesium. These contaminants were not detected on any inside sample from the valid sample sets. Program protection factors (PPFs) were estimated for the valid sample sets using the limit of detection as the inside sample mass. When it was possible, PPF estimates were made using each element individually and a combination of all three elements. The PPF estimates were in the range of >11000 to >65000 regardless of the elements used in the calculation. Examination of the PPF estimates for different elements reveals the differences are largely artificial. The results indicate the tested respirator performed well above its assigned protection factor of 1000. No worker was overexposed to chromium, strontium, or magnesium during the study. This study also illustrates the difficulty in locating workplaces with sufficient contaminant concentration and duration to measure the capabilities of high-performing respirators.

Keywords airline respirator, program protection factor, respirator, respirator performance, supplied-air respirator, workplace protection factor

Address correspondence to: Larry Janssen, 3M Company, Occupational Health and Environmental Safety Division, 3M Center, Building 235-2E-91, St. Paul, MN; e-mail LLJanssen@mmm.com.

INTRODUCTION

In 2006, the U.S. Occupational Safety and Health Administration (OSHA) issued a final rule for assigned protection factors (APFs).(1) An APF is the level of respiratory protection that a respirator or class of respirators is expected to provide to employees when the employer implements a continuing, effective respirator protection program in accordance with the requirements of 29 CFR 1910.134.(2) The APF for a supplied-air respirator (SAR) with a hood is 1000, provided the respirator manufacturer has performance data that demonstrates a level of protection of 1000 or greater. If such evidence is not available, the APF is considered to be the same as a loose-fitting facepiece, i.e., 25. Workplace protection factor (WPF) data was considered by OSHA during the APF rulemaking process and is one method suggested to demonstrate performance. Specifically, OSHA suggested manufacturers might measure "WPFs of at least 10,000 or greater divided by a safety factor of 10" to show an APF of 1000 is appropriate for a specific hood-style respirator.(1,p.50168)

WPF studies estimate the protection provided by a properly selected, functioning, and maintained respirator when correctly worn and used under the conditions of the workplace.(3) The underlying assumption is that *all* elements of a respiratory protection program are in place and strictly followed. The WPF is defined as the workplace contaminant concentration the user would inhale if he or she were not wearing the respirator (C_o) divided by the contaminant concentration inside the respirator (C_i). Both C_o and C_i are determined from samples taken simultaneously while the respirator is worn and used during normal work activities. Program protection factor (PPF) measurements are similar to WPFs, except that they measure the protection a respirator provides in the context of a specific respiratory protection program.(3)

If *any* respirator program element is absent or poorly implemented, the PPF may be adversely affected. Common examples include poor respirator maintenance, lack of fit testing, and failure to wear the respirator at all times in the contaminated environment. If program deficiencies are large, such as respirators not worn during all exposures to contaminated environments or workers wearing negative pressure respirators with which they cannot pass a fit test, the difference between WPFs and PPFs is great. If program deficiencies are nonexistent or small, such as incomplete recordkeeping in an otherwise sound program, WPFs and PPFs are essentially the same.

One PPF study of supplied-air hoods was found in the peer reviewed literature. This study by Samimi et al.(4) reported on the performance of supplied-air abrasive blasting hoods. They measured silica dust concentrations inside and outside the hoods while workers performed their jobs using respirators that were not properly maintained or used by all the users. The authors did not calculate PPFs, but they concluded that two brands of the respirators offered "fair" respiratory protection when well maintained and properly worn.

One WPF study of a hood or helmet type respirator was also found in the peer reviewed literature.[(5)] In that study, Nelson et al. found no detectable strontium inside the supplied-air hood they tested. WPFs were reported only for sample pairs in which the outside concentration was at least 1000 times the inside concentration (based on the detection limit for strontium). This was a necessary criterion to determine if the respirator was performing at its expected APF of 1000. More recently, Janssen et al.[(6)] demonstrated that the additional multiplier of 10 times the APF, as recommended by Johnston et al.,[(7)] should provide a more representative measure of a respirator's workplace performance. However, this creates difficulty in finding workplaces with sufficient contamination to measure WPFs for high-performing respirators.

This objectives of this study were (1) to determine if the use of a rigorous acceptance criterion for WPF samples would allow actual WPFs to be determined for high-performing respirators; (2) to establish the feasibility of OSHA's suggested criterion of "WPFs of 10000 with a safety factor of 10" in demonstrating the adequate performance of hood-style respirators; and (3) to generate additional data to support the APF of 1000 for this particular device.

In this workplace study of a hood-style, supplied-air respirator, three technical deviations from the terms of the respirator's approval from the U.S. National Institute for Occupational Safety and Health (NIOSH) occurred. This necessitates that the study's results be described as PPFs rather than WPFs. Each deviation is described later. There is no reason to believe that they significantly affected the test results. No risk to workers was created by these deviations. Each technical deviation and a proper resolution were described to the company's management.

MATERIALS AND METHODS

The respirator tested was a NIOSH-approved, supplied-air hood (3M, St. Paul, Minn.), Model H-410 with Model W-2862 vortex cooling assembly, Model W-5114 breathing tube, and 15 or 30 m of W-9435 air supply hose. The workplace was an aircraft manufacturing plant. The respirators were worn by workers who used pneumatic sanders on small aircraft after application of paint primer and body filler.

The deviations from the terms of this respirator's NIOSH approval were as follows:

1. In keeping with their standard practices, the workers wore earmuff-style headsets under their hoods and tucked both the inner and outer shrouds into their protective coveralls. This is inconsistent with the user instructions, which specify that only the inner shroud be tucked into the clothing. The instructions do not address the use of headsets.
2. Due to recent engineering changes in the plant, air pressure at the respirators' point of attachment was approximately 655 kPa, which is 138 kPa greater than the specified operating pressure for the hose lengths used. The pressure used was below the maximum pressure of 862 kPa permitted for supplied-air respirators in the United States.[(8)] Airflow into the hoods was estimated to be 283–368 L/min based on the combination of pressure, hose length, and W-2862 valve settings used in the workplace, compared with laboratory measurements taken with a calibrated Fischer and Porter rotameter (The ABB Group, Norwalk, Conn.). These flow rates are within the range of 170–425 L/min required for hooded supplied-air respirators in the United States.[(8)]

   In addition, sound pressure levels generated by airflow into the hood were measured using the range of workplace pressures, hose configurations, and valve settings with a calibrated Model Q-200 noise dosimeter (Quest Technologies, Oconomowoc, Wis.). The measured values were below 72dB(A) for all operating conditions, well below the 80 dB(A) maximum permitted by NIOSH regulation.[(8)]
3. Most workers used 30 m of air supply hose made by joining two 15-m sections of W-9435 hose. The approval for this respirator does not permit joining 15-m hose sections. Any adverse effect this deviation had on airflow was incorporated into the measurements described earlier.

Breathing zone (C_o) samples were collected with Escort Elf personal sampling pumps (MSA, Pittsburgh, Pa.). Samples inside the hood (C_i) were collected in the wearer's breathing zone with PCX R4 pumps, (SKC Inc., Eighty Four, Pa.). The C_o sample flow rate was approximately 2 L/min, and the C_i flow rate was approximately 3.5 L/min. The higher C_i flow rate was chosen to increase the contaminant mass collected, if any were present inside the hood. All the pumps were calibrated at the start of each day and rechecked at the end of sampling with a Model 821-S1-L-1PS mass flow meter (Sierra Instruments, Inc., Monterey, Calif.). The C_o samples were collected on 0.8 μm mixed cellulose ester (MCE) filters (SKC Inc.). The C_i samples were collected on 0.8 μm polycarbonate (PC) filters (Millipore Corp., Bedford, Mass.), the preferred substrate for PIXE analysis of air samples. All the filters were mounted in 25-mm, three-piece (closed-face) cassettes.

An inlet probe built to the specifications of Liu et al.[(9)] was used on the C_i cassette to minimize particle entry loss. The cassette with probe was secured to the inside of the clear window of the hood with hook and loop fastener. The inlet probe was placed approximately midway between the nose and the mouth.

Thirteen men and two women volunteered to participate in the study. Five workers were sampled on each of 4 days. Five men from one crew were sampled on 2 consecutive days because of the work assignments on the second day. The remaining workers were sampled only on 1 day. All the workers were informed of the purpose and procedures of the study. They had been trained and medically evaluated by their employer before the study, in accordance with the OSHA respiratory protection regulation.[2]

Respirator donning and doffing, along with sample train connection and removal, was done in the sanding bays prior to the beginning and at the end of sanding. The integrity of the respirator and sample train were verified visually before starting the sampling pumps. Trained observers ensured the sampling equipment did not interfere with worker safety, verified proper respirator use, and recorded observations about work conditions. One observer was assigned to each test subject, who was monitored during the entire sampling period. At the end of sampling, both pumps were stopped before the respirator and samples were removed. Observers used clean nitrile gloves when handling the C_i samples to reduce the likelihood of contamination.

Samples were collected for an entire sanding period, which typically started in midmorning and ended the first or second hour after lunch. Observers noted pump function periodically throughout the sampling period. One C_i sample per day was collected on each worker. This was done in a further effort to maximize the contaminant mass collected if any were present in the hood. The C_o samples were changed at the worker's lunch break if the sample appeared to be heavily loaded.

The workers' breathing air supply was sampled to determine if the air contained measurable chromium, strontium, or magnesium. A stationary sample using a hood, vortex cooler, and air supply hose assembly was connected to the air supply. A C_i sample was collected for 432 min at a flow rate of 3.4 L/min. A 25-mm filter cassette with a polycarbonate filter and the same inlet probe as the rest of the C_i samples was used for this test.

Blank filters of each type were used to determine if sample handling caused contamination. They were uncapped and recapped by the observers and worn by workers in the same manner as the samples, except no air was drawn through them. The MCE blanks were positioned on the worker's shoulder alongside the C_o sample. The PC blanks were clipped inside the hood as close to the breathing zone as practical.

The C_i samples and PC blanks were analyzed with proton induced X-ray emission spectroscopy (PIXE). This analytical method simultaneously determines the presence of a wide range of elements (sodium through uranium) present on a sample. It does not distinguish the valence states of the atoms of the same element from one another. Detection limits per filter were 0.015 μg for chromium, 0.030 μg for strontium, and 0.156 μg for magnesium. The C_o samples and MCE blanks were analyzed for chromium, strontium, and magnesium by inductively coupled plasma/atomic absorption spectroscopy (AA) using NIOSH method 7300.[10] Detection limits were 1.5, 0.15, and 7.5 μg per filter for elemental chromium, strontium, and magnesium, respectively.

Criteria for rejecting sample sets were established prior to the study. These included:

1. Respirator malfunction, e.g., failure of the air supply
2. The C_i sample was contaminated, e.g., fell out of the hood or the worker removed the hood before the end of the sample period
3. The sample times for C_o and C_i sample times differed by more than 5 min
4. Low contaminant mass on the C_o sample. The more stringent recommendation of Johnston et al.[7] was used to determine the minimum acceptable C_o mass for valid WPF calculations for supplied-air hoods:

$$\text{Minimum } C_o \text{ Analyte Mass} = 10 \times \text{APF} \times \text{Mean Blank Analyte Mass} = 10000 \times \text{Mean Blank Analyte Mass}$$

If a contaminant were found on one or more blanks, a mean would be calculated by dividing the total mass found on the blanks by the number of blanks analyzed. In this case, masses below the detection limit would be assigned a value of zero. The calculated mean value would be used to correct the mass of an element found on the C_i sample before performing the PPF calculation. If an element were not detected on the PIXE blank samples, the PIXE detection limit would be used in place of the mean blank mass to determine the minimum acceptable C_o mass for that element. No mean blank mass calculation would be done, and blank correction would not be done in this case. In a similar manner, a criterion was established to allow PPFs to be estimated using the total mass of chromium, strontium, and magnesium for C_o. The minimum acceptable mass was set at 10000 times the combined detection limits for all three elements.

RESULTS

Review of the sampling results revealed that exposures on the third and fourth days of the study were qualitatively and quantitatively different from those measured on the first 2 days. This occurred because the aircraft sanded on the last 2 days had been sprayed with a different primer from those processed on the first 2 days. In addition, substantial amounts of body filler (the source of magnesium) were sanded on Days 3 and 4, while very little filler was used the first 2 days. Because of the large differences in exposures, the workers on the first 2 days were designated Similar Exposure Group 1 (SEG 1) and those on the second 2 days SEG 2. SEGs represent "groups of workers having the same general exposure profile for the agent(s) being studied ..."[11] The C_o sampling results for SEG 1 and SEG 2 were analyzed separately and are summarized in Table I.

The PIXE analysis of the C_i sample taken from the plant's breathing air supply did not contain measurable chromium, strontium, or magnesium. Analysis of the six PC blanks revealed 0.048 μg of chromium on one of them, resulting in a mean blank chromium level of 0.008 μg. Thus, the minimum acceptable C_o mass was 80 μg per filter for chromium. No strontium or magnesium was detected on the PC blanks. Ten thousand times the PIXE detection limits were 300 μg and 1560 μg for strontium and magnesium, respectively. Sample

TABLE I. C_o Mass and Concentration (GM, GSD) for All Samples

	Chromium	Strontium	Magnesium
SEG 1			
Mass (μg)	7.6 (5.7)	8.9 (2.2)	ND^A
Concentration (μg/m^3)	21.7 (5.4)	25.3 (2.5)	ND
SEG 2			
Mass (μg)	88.4 (3.8)	138 (3.9)	111 (11.3)
Concentration (μg/m^3)	244 (3.6)	381 (3.6)	305 (10.3)

Note: N=10 for all cells.
^{A}Not detected (<0.156 μg).

TABLE II. Summary of SEG 2 PPF Estimates for Chromium Exposures

Subject	Sample Duration (min)	C_i (μg/m^3)	C_o (μg/m^3)	PPF
15	171	<0.026	1706	>65000
16	203	<0.022	305	>14000
17	192	<0.023	1530	>65000
18	199	<0.022	432	>19000
19	201	<0.021	250	>11000

sets with C_o masses below these values were rejected because low C_o mass can result in a negative bias in WPF values.[6]

No chromium or magnesium was found on the MCE blanks. Strontium was found on three of these blanks at a mean mass 0.04 μg above the detection limit. Because the blank mass was very small relative to the mass on the C_o samples, no blank correction was necessary.

None of the 10 sample sets from SEG 1 met the 10000× acceptance criterion for C_o mass for any element. Two sample pairs were voided because of temporary loss of airflow during the sampling period. Another sample pair was voided because of a laboratory error. The chromium masses on the remaining C_o seven samples ranged from approximately 500 to 4600 times the mean blank mass. When the five samples with at least 1000× the mean blank mass (the APF for hoods) were divided by a C_i value estimated by dividing the PIXE detection limit for chromium by the sample volume, PPFs ranged from approximately 1200 to 2400. For strontium, the C_o multiples were between approximately 50 and 700 times the detection limit. Since none of the samples even met the 1000× criterion, PPF estimates were not made. Magnesium was not detected on any C_o sample from SEG 1.

One of the 10 sample sets for SEG 2 was rejected because C_o and C_i sample times differed by more than 5 min. Four of the remaining sample sets were excluded because of low mass (<10000× the mean blank value for chromium) on the C_o sample. The C_i sample from one pair of the rejected sample pairs had a chromium mass of 0.067 μg, similar to that found on the contaminated blank PC filter. It is believed that the chromium on this filter was also due to contamination, but that cannot be known with absolute certainty. If it is assumed the chromium on the C_i was due to inward leakage, the PPF estimate would be approximately 1400 for that sample pair. For all the SEG 2 sample sets rejected because of low chromium C_o mass, the multiples of the mean blank mass for chromium ranged from approximately 2100 to 5800. PPFs were estimated for the remaining three samples with C_o masses above 1000× the detection limit, as described above for the rejected SEG 1 samples. Values of 1900, 2100, and 2200 were calculated. For strontium and magnesium, the multiples of the detection limit ranged from approximately 930 to 2200 and 50 to 360, respectively. PPF estimates ranged from 3900 to 15000 for strontium and 9400 to 12000 for magnesium based on four samples and two samples greater than 1000× the detection limits, respectively.

Five of the sample sets from SEG 2 had a C_o chromium mass exceeding 80 μg. Because no chromium was detected on the valid C_i samples, C_i was estimated by dividing the PIXE detection limit for chromium by the sample volume. The C_o sample was divided by this value and rounded down to two significant figures. This procedure provides an estimate of the lower bound of the PPF. The results are shown in Table II.

Three of the five sample sets for which PPFs were calculated for chromium also had adequate C_o mass to estimate PPFs for strontium or magnesium, and a combination of all three elements. No strontium or magnesium was detected on any of these C_i samples, so their respective detection limits were used as the C_i mass and divided by the C_i sample volume. The C_o concentration was divided by this value to estimate the lower bound of PPF for each element. PPFs for all three elements were estimated by dividing the sum of C_o concentrations for the three elements by the sum of the three elements' PIXE detection limits. Results of these calculations are shown in Table III.

DISCUSSION

The deviations from the terms of the NIOSH approval during this study did not impair the respirators' function or create a hazard to the users. These observations were verified by taking appropriate airflow and sound pressure level measurements. Nonetheless, deviations from manufacturer-specified operating conditions should not be condoned. Operating pressure, hose length, and manner of joining hose sections for SAR are specified by the manufacturer when applying for NIOSH approval.[8] As noted earlier, all operating conditions in this study were well within the ranges permitted by the NIOSH approval regulation. That is, the respirator tested in this study could have received approval using the pressure and hose length combinations in this study had the manufacturer applied this way. However, because the respirators in this study were not operated in strict accordance with the terms of their

TABLE III. Summary of SEG 2 PPF Estimates for Strontium, Magnesium, and Combined Exposures

	Strontium			Magnesium			Sum of All Elements		
Subject	C_i (μg/m^3)	C_o (μg/m^3)	PPF	C_i (μg/m^3)	C_o (μg/m^3)	PPF	C_i (μg/m^3)	C_o (μg/m^3)	PPF
15	<0.052	2773	>53000	<0.271	6704	>24000	<0.349	11183	>32000
16	—	—	—	<0.226	3896	>17000	<0.291	4620	>15000
17	<0.046	2566	>55000	—	—	—	<0.311	7146	>23000

NIOSH approval, this study's results must be considered PPFs rather than WPFs.

Nearly all the workers used the vortex cooler on its maximum cooling setting, which means the airflow rates were generally at the lower end of the 283–368 L/min range. No worker was observed using the vortex beyond the midpoint of its range, where the flow rate of 368 L/min would be expected. It is also significant that the airflow range for NIOSH-approved assemblies using this hood and vortex cooler at the manufacturer-specified pressures is 195–405 L/min. This leads to the conclusion that the performance measured in this study is representative of performance under the manufacturer-specified conditions.

A simulated workplace protection factor study has shown that airflow is not the sole determinant of loose-fitting respirator performance.[12] In that study, Cohen et al. found that the performance of loose-fitting powered and supplied-air respirators did not increase with increasing airflow rate. Mean airflow rates in their study were in the range of 176 to 304 L/min. The only poorly performing device had a mean flow rate of 234 L/min. The authors attributed its poor performance to the lack of an adequate bib (shroud). This suggests that design features other than airflow contribute to a loose-fitting respirator's protective performance. This further supports the conclusion that the PPF measurements from this study are the equivalent of WPF measurements taken under recommended operating conditions. It is also important to note that the deviations from NIOSH approval did not create any hazard to the wearers. Air-generated noise levels were far below those permitted by NIOSH regulation.

The PPF estimates in Tables II and III demonstrate a very high level of performance for the SAR evaluated. It must be noted that the PPF estimates for a single element are largely a function of the C_o concentration, since the C_i is essentially constant, i.e., the mass detection limit divided by the C_i sample volume. Among different elements, the PPF estimate is also influenced by the differences in the detection limits for the elements. Thus, while differences in an individual's PPF estimates for different elements (Tables II and III) are numerically large in some cases, they are principally reflecting the differences in C_o and detection limits.

For example, Subject 17 had PPF estimates ranging from 23000 for all elements to 65000 for chromium alone. This difference is, because fundamentally, the C_i estimates are based on the combined detection limits for all three elements, 0.201 μg, and chromium, 0.015 μg, respectively. That is, the C_i estimates differ by more than an order of magnitude, while C_o changed by a factor less than 5. Even if it were assumed the C_i was an actual contaminant mass, the difference in percent penetration between PPFs of 23000 and 65000 is very small: 0.0043%–0.0015% = 0.0028%. Thus, it is easily seen that there is little value in comparing PPF or WPF estimates greater than 10000.

The criteria for minimum acceptable C_o mass used in this study (10000$\times$ detection limits or mean blank mass) are more severe than those used by Nelson et al.[5] They used a criterion of 1000 the detection limit in the only published WPF study of hood-style, supplied-air respirators. The criteria used in this study were chosen to increase the likelihood that a mean and distribution of WPFs (or PPFs) could be determined. Essentially, the underlying assumption is that the hood provides WPFs well above 1000. It is clear that a WPF of 25000, for example, cannot be measured if the C_o mass is only 1000$\times$ the analytical detection limit. The criterion of Nelson et al. was sufficient only to determine if the hood performed at its expected APF of 1000.

The Nelson et al.[5] study of aircraft sanding and painting measured strontium alone as the contaminant challenge. No strontium was detected on any C_i sample. The C_o mass was 10000$\times$ the detection limit for only 3 of 31 valid sample sets. The WPF estimates for these samples were >52000, >9200, and >22000, comparable with the PPF estimates in this study. Their WPF estimates for the samples with lower outside masses ranged from >920 to >11100. Nelson et al. concluded that an APF of 1000 is appropriate for hooded SAR. Because the WPF estimates were all "greater than" values, Nelson and colleagues could not estimate a mean WPF or describe a distribution of WPFs for the respirator they tested. That is, the utility of their data was limited by the C_o mass and detection limits. The same limitation applies to this study. However, because the C_i sample volumes in this study were, on average, 4.7 times greater than those of Nelson et al., the C_i concentration appears to be lower. Thus, at a similar C_o the PPF "greater than" estimate appears to be higher in this study; the respirator's actual performance may or may not be different from the device Nelson et al. studied. This again argues against comparing large WPF or PPF estimates with one another.

The criterion of 10 $\times$ APF $\times$ mean blank analyte mass for minimum acceptable C_o mass appears inadequate to measure a WPF or PPF distribution for hooded SAR because of their very high level of performance. In future studies, this problem could be mitigated to some degree with higher C_o sample volumes and increased sample duration where circumstances allow. Detection limits in the picogram range may be possible for some contaminants. However, in these authors' opinion, there is little value in quantifying WPFs or PPFs above 10000.

CONCLUSIONS

The hood-style, supplied-air respirator used in this study performed well above its APF of 1000. No worker was overexposed to chromium, strontium, or magnesium. Contaminant exposures were not sufficiently high to measure actual PPFs or determine a PPF distribution. This finding is consistent with previous work. It is difficult to locate workplaces with sufficient contaminant concentration for an adequate duration to measure a performance distribution for high-performing respirators. This will make it difficult to satisfy OSHA's suggestion of demonstrating "WPFs of 10000 with a safety factor of 10."

While they are not condoned, the minor deviations from operating conditions listed in the respirator's NIOSH approval did not appear to impact the respirator's performance in this study. Any differences between these PPFs and WPFs, if any, would be quite small.

ACKNOWLEDGMENTS

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.

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