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ASSIGNED PROTECTION FACTORS FOR TWO RESPIRATOR TYPES BASED UPON WORKPLACE PERFORMANCE TESTING

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Abstract—An industrial hygiene study was conducted in a primary lead smelter in the United States to investigate the appropriateness of the protection factors assigned to half-mask negative pressure air-purifying respirators and to powered air-purifying respirators. Personal sampling was conducted to determine actual workplace protection factors for respirators representing each of these respirator classes. Although the determination of assigned protection factors is influenced by the degree of confidence desired, a value of 10 was concluded to be generally acceptable for the half-mask negative pressure air-purifying respirator when used under the given study conditions. However, even an assigned protection factor of 500 was indicated to be an inappropriately high value for the half-mask powered air-purifying respirator, and a value not in excess of 50 is suggested as appropriate.

INTRODUCTION

Protection factors have been assigned to various classes of respirators as a guidance for respirator selection. These are intended to be used as measures of the anticipated protection that can be expected from a respirator used in the workplace. For example, 10 is widely accepted as the assigned protection factor for a half-mask negative pressure air-purifying respirator with high efficiency filters (BSI, 1974; Pritchard, 1976; U.S. Department of Labor, 1978; ANSI, 1980; Birkner, 1980), while half-mask powered air-purifying respirators with high efficiency filters have been assigned protection factors of 500 (BSI, 1974), 1000 (Pritchard, 1976; U.S. Department of Labor, 1978) and 3000 (ANSI, 1980; Birkner, 1980).

It is generally assumed that a properly used and properly maintained respirator will provide a level of protection equal to or greater than its assigned protection factor for the vast majority of wearers. Assigned protection factors have, however, not been based on actual measurements of workplace protection factors. Instead, they have been based on laboratory tests in which a group of respirator wearers perform a specific regimen of head and body movements while in a test chamber containing a challenge aerosol. It has generally been assumed that these laboratory tests are predictive of the protection that will be provided in the workplace. To date, however, the few checks that have been reported have called this into question (Myers and Peach, 1983). The purpose of this study is to investigate the accuracy of the protection factors mentioned above by

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determining if the vast majority of workplace protection factors, measured in a particular workplace setting, do exceed these assigned values.

As used here, a workplace protection factor, PF_w, is a measure of the effectiveness of a properly functioning and properly used respirator for a particular individual in a particular workplace setting and is defined by $PF_w = C_o/C_i$ (MYERS *et al.*, 1983). In this equation, C_o is the time-weighted average (TWA) contaminant concentration outside the respirator which would be inhaled if the respirator were not used, and C_i is the TWA contaminant concentration inside the respirator facepiece which is inhaled by the respirator wearer.

Workplace protection factors were measured for two respirator types: (1) a half-mask negative pressure air-purifying respirator with high efficiency filters and (2) a half-mask powered air-purifying respirator with high efficiency filters. Mine Safety Appliances manufactures both the respirator types used in this study and the three facepiece sizes available for each type are identical.

WORKPLACE SETTING

The workplace setting for this study was the sinter plant and blast furnace area of a primary lead smelter in the United States. These areas were chosen because personal sampling by environmental staff indicated that relatively high lead concentrations were likely in both areas. High challenge concentrations were deemed necessary in order to increase the likelihood that lead concentrations in the respirator facepiece would be large enough to be accurately measured. In addition, the sinter plant and blast furnace areas were selected because the characteristics of the lead portion of the aerosols in each area were dissimilar. Dust is the predominant form of lead in the sinter plant, while lead fume predominates in the blast furnace area. Eleven environmental samples taken with a Marple cascade impactor at various locations in the sinter plant produced aerodynamic mass median diameters for lead ranging from 9–16 μm. Geometric standard deviations of these samples ranged from 2.5–5.1. Eight impactor samples taken at various locations in the blast furnace area produced aerodynamic mass median diameters for lead which ranged from 1–8 μm. Geometric standard deviation for these samples ranged from 9.5–28.5. Selecting two work areas with dissimilar aerosol characteristics was based upon a desire to produce study results which would indicate the workplace performance of the two respirator types when used under the diverse conditions generally present in a primary lead smelter.

When a respirator is used in an atmosphere containing more than one contaminant, it may be appropriate to assume that workplace protection factors achieved from measurements of only one of the contaminants could be influenced by the portion about which nothing is known, to the extent that achieved values would not accurately reflect true respirator performance. The aerosols in both the sinter plant and blast furnace areas contained approximately 50% lead. While the composition of the remaining 50% is unknown for both areas, impactor sampling demonstrated that the size distribution of airborne lead particulate very closely resembled that found for the total airborne particulate. Therefore, while the workplace protection factors for both respirator types were determined from lead analysis alone, the achieved values can be assumed to also represent the performance of each respirator against the total challenge aerosol.

SAMPLE POPULATION

The study population consisted of 25 male workers who met the following three criteria. Firstly, a study participant had to work routinely in either the sinter plant or blast furnace area of the primary lead smelter. Such workers routinely used respirators in these areas.

Secondly, each study participant was to have been scheduled to work the same job for two consecutive days. This requirement was believed necessary in order to provide both respirator types with as similar a lead aerosol challenge as possible. One respirator was used on the first day and the other on the following day.

Thirdly, each study participant was required to achieve a fit factor of at least 250, determined by quantitative testing, while wearing the half-mask negative pressure air-purifying respirator, since this value was required by the management of the lead smelter at the time of this study.

METHODS

Since workplace protection factors are defined in terms of properly functioning respirators, the following steps were taken to ensure that each respirator was functioning properly. Each respirator was examined to ensure that it was comprised of appropriate parts and assembled in its NIOSH/MSHA approved configuration. Dimensional measurements of critical components were made to ensure that they were within manufacturer's specifications. All filters were tested to ensure that filter penetration was less than 0.03% when challenged with an aerosol of di-octylphthalate having an aerodynamic mass median diameter of 0.3 μm. In addition, complete respirators were required to maintain in-mask concentrations of lead below 50 μg m^{-3} when challenged by a lead fume aerosol for 4 h. Challenge lead concentrations ranged from 14 mg m^{-3} to 30 mg m^{-3} and had an aerodynamic mass median diameter of approximately 0.6 μm, with a geometric standard deviation of approximately three.

The concentrations of lead outside the respirator facepiece and inside the respirator facepiece were measured simultaneously with two separate sampling trains while each study participant was engaged in normal work activities. The sampling trains were worn for as much of the 8-h work shift as possible. Each sampling train consisted of a 37 mm two-piece closed-face Millipore cassette containing an AA filter and an AP10 support pad, and connected by a 86 cm (34-in.) length of 0.635 cm ($\frac{1}{4}$-in.) i.d. Tygon tubing to a calibrated personal sampling pump operating at 2 l. min^{-1}. The filter cassette of the first sampling train was attached to the shirt lapel of each participating worker to collect a sample representative of the lead exposure that would be experienced if the worker were not wearing the respirator. The filter cassette of the second sampling train was connected to an inlet probe inserted through the facepiece so as to collect an in-mask sample at a location approximately between the nose and upper lip. The inlet probe used for the collection of in-mask samples complied with Davies' criteria for sampling through inlet tubes (Davies, 1968) and its sampling efficiency has been experimentally defined (Liu *et al.*, 1982). While it was not possible to quantify the influence of the in-mask sampling flow rate upon the workplace protection factors presented in this article, we believe that a sampling flow rate of 2 l. min^{-1} is too low to affect this study's overall results significantly.

The quantity of lead contained on sample filters was determined by atomic absorption spectroscopy according to NIOSH method S-341 (NIOSH, 1977a). All lapel samples were analysed by flame atomic absorption and the limit of detection ranged from 2 to 5 μg of lead per lapel sample filter. All in-mask samples were initially analysed by flame atomic absorption, with those samples containing less than 10 μg of lead analysed by graphite furnace atomic absorption. The vast majority of in-mask samples were analysed by both methods. The limit of detection for in-mask samples was 0.2 μg of lead per in-mask sample filter.

Respirators and sampling trains were donned and removed in a lead-free area separate from the actual work area of the lead smelter. All sampling pumps and the blower of the powered respirator were started and stopped always in a lead-free area. Sampling pumps were started after each respirator was completely donned and functioning properly; sampling pumps were stopped before a respirator was removed. Each worker was instructed not to remove or manipulate the respirator during testing. To ensure that this requirement was followed, the activities of each worker were monitored continually.

Before a respirator was replaced after a worker's break period, the inside of the facepiece was wiped with a moist towel to protect against accidental lead contamination. Additionally, before a powered respirator was replaced, battery voltage was checked for acceptability and air-flow rate was verified to exceed 115 l. min^{-1}. According to manufacturer's requirements, batteries were replaced after 4 h of use. All respirators were thoroughly cleaned and sanitized after each workshift.

Marple cascade impactors with Apiezon grease-coated slides were used to collect environmental samples at various locations at the study site. Sampling locations were selected as close as possible to those positions where study participants were most frequently situated. To analyse the lead content of the slides used during sampling, samples were wet-ashed with nitric and perchloric acids and the perchloric acid was removed by heating at a low temperature. Residues were redissolved in dilute nitric acid, transferred to 10 ml volumetric flasks, diluted to the mark and mixed. The resulting solutions were analysed by an aspiration method along the lines of NIOSH method S-341. Slides which were found to contain 10 μg or less were re-analysed by the graphite furnace method described by NIOSH Method P & CAM 214 (NIOSH, 1977b). The limit of detection for samples analysed by aspiration and graphite furnace atomic absorption spectorscopy was 0.2 μg of lead.

RESULTS

The results of this study are presented in Table 1 for the negative pressure respirator and in Table 2 for the powered respirator. The lapel and the in-mask concentrations are presented in the centre two columns. The workplace protection factors, the ratio of these two concentrations, are presented in the last column. Values in parentheses represent the estimated probable error range derived from the uncertainty in the analytical methods for measuring lead collected by the two sampling trains.

These results are uncorrected for an effect which may cause an overestimation of the workplace protection factors. Because of lung deposition, the in-mask lead concentration is lower during exhalation than during inhalation. The average in-mask concentration measured during this study, therefore, is lower than the true inhaled lead concentration. SMITH *et al.* (1980) have suggested that this dilution from exhaled air

TABLE 1. LAPEL AND IN-MASK SAMPLE CONCENTRATIONS AND WORKPLACE PROTECTION FACTORS FOR WORKERS WEARING MSA HALF-MASK NEGATIVE PRESSURE AIR-PURIFYING RESPIRATORS

Worker	Job title	Lead concentration ($\mu g\ m^{-3}$)		Workplace Protection Factor: $\left(\frac{\text{Lapel concentration}}{\text{In-mask concentration}}\right)$
		Lapel	In-mask	
Sinter plant workers				
S1	Mix room man	1200	1.2	1000 (±210)
S2	Mix room helper	2400	2.0	1200 (±250)
S3	South end man	860	4.8	180 (±38)
S4	Operator	2200	12	180 (±38)
S5	Helper	570	1.4	410 (±86)
S6	Helper	28 000	13	2200 (±460)
S7	Operator helper	1300	12	110 (±23)
Blast furnace workers				
B1	Operator	110	0.92	120 (±25)
B2	Helper	460	1.2	380 (±80)
B3	Utility man	420	2.1	200 (±42)
B4	Operator helper	190	<0.22	860
B5	Utility man	92	1.7	54 (±11)
B6	Head operator	880	28	31 (±6)
B7	Operator	160	0.98	160 (±34)
B8	Head operator	210	6.1	34 (±7)
B9	Utility man	400	<0.23	1700
B10	Operator helper	490	2.9	170 (±36)
B11	Operator	200	19	10 (±2)
B12	Helper	2900	30	97 (±20)
B13	Helper	750	1.2	620 (±130)
B14	Head operator	670	1.6	420 (±88)
B15	Operator	340	12	28 (±6)
B16	Utility man	470	3.9	120 (±25)
B17	Utility man	280	12	23 (±5)
B18	Helper	420	2.2	190 (±40)

*Values in parentheses are to be used for obtaining 95% confidence limits.

influences in-mask sample concentrations by approximately 10%. BALLANTYNE and SCHWABE (1981) have commented that, although there are considerations about the effects of inhalation/exhalation upon in-mask samples, these errors are probably insignificant. The in-mask sample concentration values in Tables 1 and 2 are uncorrected for the effects of dilution by the exhaled breath.

Probability plots of lapel lead concentration values revealed that they were adequately described by a log-normal distribution. Therefore, before conducting statistical analysis of lapel lead concentration values, a logarithmic transformation of the original data was performed. Statistical analysis using the Student's t-test statistic at a significance level of 0.05 indicated that there was no significant difference between the geometric mean lapel concentration values of Table 1 and Table 2 ($P = 0.5$). The lapel lead concentration values of Table 1 have a geometric mean of 580 $\mu g\ m^{-3}$ with a geometric standard deviation of 3.4. The lapel lead concentration values of Table 2 have a geometric mean of 480 $\mu g\ m^{-3}$ with a geometric standard deviation of 2.2.

Five in-mask lead concentrations were below the level of detection. Concentration values for these samples are reported, however, and were determined from the least

TABLE 2. LAPEL AND IN-MASK SAMPLE CONCENTRATIONS AND WORKPLACE PROTECTION FACTORS FOR WORKERS WEARING MSA HALF-MASK POWERED AIR-PURIFYING RESPIRATORS

Worker	Job title	Lead concentration ($\mu g\ m^{-3}$) Lapel	Lead concentration ($\mu g\ m^{-3}$) In-mask	Workplace Protection Factor: $\left(\frac{\text{Lapel concentration}}{\text{In-mask concentration}}\right)$
Sinter plant workers				
S1	Mix room man	460	20	23 (±5)
S2	Mix room helper	630	1.2	520 (±110)
S3	South end man	1400	1.6	880 (±180)
S4	Operator	870	4.8	180 (±38)
S5	Helper	590	1.5	390 (±82)
S6	Helper	2500	2.7	930 (±200)
S7	Operator helper	1800	2.9	620 (±130)
Blast furnace workers				
B1	Operator	250	0.57	440 (±92)
B2	Helper	1700	2.1	810 (±170)
B3	Utility man	700	2.9	240 (±50)
B4	Operator helper	320	1.9	170 (±36)
B5	Utility man	240	0.36	670 (±140)
B6	Head operator	220	1.4	160 (±34)
B7	Operator	430	1.2	360 (±76)
B8	Head operator	95	<0.23	410
B9	Utility man	210	0.95	220 (±46)
B10	Operator helper	350	<0.25	1400
B11	Operator	190	<0.22	860
B12	Helper	710	3.2	220 (±46)
B13	Helper	520	5.5	94 (±20)
B14	Head operator	410	0.69	590 (±120)
B15	Operator	350	1.7	210 (±44)
B16	Utility man	680	0.48	1400 (±290)
B17	Utility man	160	0.96	170 (±36)
B18	Helper	760	0.48	1600 (±340)

* Values in parentheses are to be used for obtaining the 95% confidence limits.

amount of lead detectable by the analytical method and the sampled volume of air. These in-mask lead concentration values, two values in Table 1 and three values in Table 2, are preceded by '<' symbols.

The workplace protection factors for both the negative pressure and the powered respirator also were found to be adequately described by log-normal distributions and the two distributions are shown in Figs 1 and 2. The straight line shown on each figure is a least squares fit to the data. The workplace protection factors for the negative pressure respirator have a geometric mean of 180 and a geometric standard deviation of 4.1. The workplace protection factors for the powered respirator have a geometric mean of 380 and a geometric standard deviation of 2.6.

From the distribution of workplace protection factors for the negative pressure respirator shown in Fig. 1, we see that approximately 98% of the workplace protection factors would be expected to be at or above 10, 90% would be expected to be above 30, and 75% would be expected to be above 100.

Similarly, Fig. 2 indicates for the powered respirator that approximately 98% of the workplace protection factors would be above 50, 90% would be above 110, 75% would

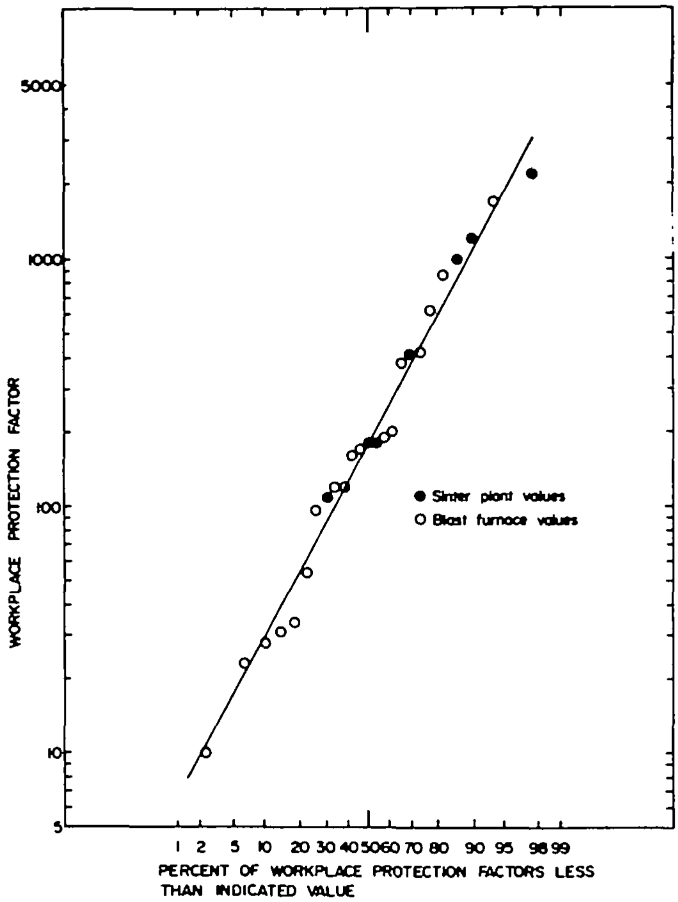

FIG. 1. Log-normal probability plot of workplace protection factors achieved by lead smelter workers wearing half-mask negative pressure air-purifying respirators.

be above 200, 40% would be above 500 and only 25% would be above 1000. It seems, therefore, that neither 3000, 1000 nor 500 is appropriate as an assigned protection factor for the powered air-purifying respirator. This observation is consistent with information presented by MYERS and PEACH (1983).

Before discussing these results further, a more precise definition of assigned protection factor is necessary. One possibility that has been suggested (MYERS *et al.*, 1983) is to define the assigned protection factor, PF_a, in terms of a specified proportion of the workplace protection factors expected to exceed PF_a. For the purpose of this discussion we will specify this proportion to be 95%. Once this proportion is specified, the value of PF_a can be read directly from the regression lines of Figs 1 and 2. Or, equivalently, PF_a can be calculated from the following equation when, as in this case, the distribution is log-normal

$$PF_a = \langle PF_w \rangle / (S_g)^z.$$

In this equation, $\langle PF_w \rangle$ is the geometric mean of the measured workplace

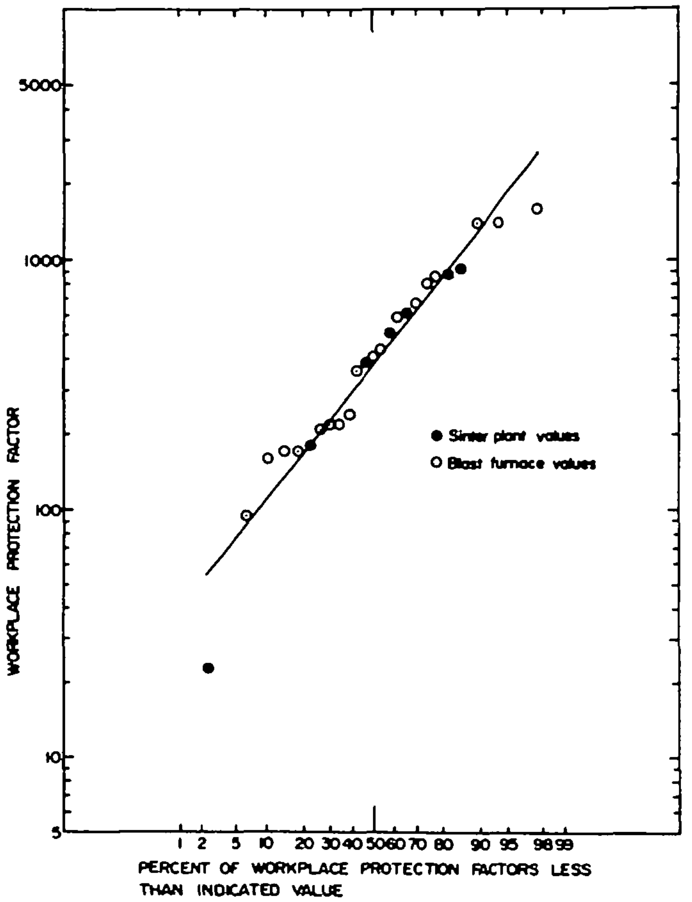

Fig. 2. Log-normal probability plot of workplace protection factors achieved by lead smelter workers wearing half-mask powered air-purifying respirators.

protection factors, S_g is the geometric standard deviation and z is the value corresponding to the selected proportion of workplace protection factors.

The assigned protection factor, PF_a, for the negative pressure respirator evaluated in this study would be given by $PF_a = 180/(4.1)^{1.64} = 18$, where 1.64 corresponds to the selected proportion of 95% and where 180 and 4.1 are the geometric mean and geometric standard deviation quoted previously. Similarly, for the powered respirator, the assigned protection factor is given by $PF_a = 380/(2.6)^{1.64} = 79$. Therefore, when the assigned protection factor is so defined, the use of a PF_a of 10 for the negative pressure respirator is not discredited; however, even the use of a PF_a of 500 for the powered respirator is inappropriate.

A second approach which has been suggested (Myers *et al.*, 1983) is to define the assigned protection factor in terms of a one-sided lower tolerance limit above which we may predict with a specific confidence level that 95% of the workplace protection factors lie. This approach is more conservative, because it takes into consideration the uncertainty associated with the sample mean and sample standard deviation resulting from limited sample size. When so defined, the assigned protection factor, PF_a, is a function of the selected confidence level, γ, as well as the selected proportion, P, of workplace protection factors that exceed the value of PF_a

$$PF_a = PF_a(\gamma, P).$$

The method of NATRELLA (1966) was used to compute the assigned protection factors for the two respirators of this study as a function of γ and P. These results are shown in Fig. 3 and indicate that at a confidence level of 90% ($\gamma = 0.9$) approximately 95% ($P = 0.95$) of the negative pressure respirator workplace protection factors exceed a value of 10. At the same confidence level approximately 95% of the powered respirator workplace protection factors exceed 50. Therefore, if we choose to define PF_a in terms of a 90% confidence level, this second definition of PF_a indicates that an assigned protection factor of 10 is appropriate for the negative pressure respirator and that an assigned protection factor of 50 is appropriate for the powered air-purifying respirator.

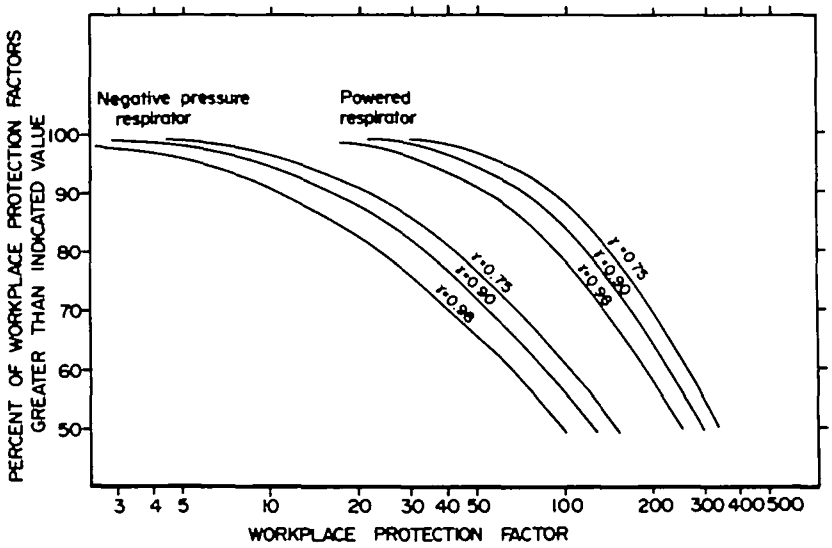

FIG. 3. Tolerance limit curves for half-mask negative pressure respirators and half-mask powered air-purifying respirators. γ = confidence coefficient.

CONCLUSION

This study's purpose was to investigate the appropriateness of currently assigned protection factors for two respirator types by evaluating the workplace performance of each type in a primary lead smelter. We conclude that, to the extent that the environmental conditions of this study site are representative of conditions that would be found in other workplace settings where these respirator types are used, an assigned protection factor of 10 is appropriate for the half-mask negative pressure air-purifying respirator evaluated in this study. This study's results also indicate that an assigned protection factor of 500 for the half-mask powered air-purifying respirator is inappropriately high for this device. Rather, an assigned protection factor not greater than 50 is suggested as more appropriate.

It is also important to emphasize that the reported workplace protection factors of this study were achieved by individuals who had been screened for study participation based upon achievement of a quantitative fit factor of 250 while wearing a half-mask negative pressure air-purifying respirator. Typically, quantitative fit tests are not performed prior to assigning a powered air-purifying respirator to a worker. Therefore, this study's results may overestimate the workplace protection factors which would be achieved by a general worker population that had not been so screened.

Additional field studies should be performed under a variety of workplace conditions to evaluate the performance of negative pressure respirators and powered air-purifying respirators other than those described here.

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