Thomas G. Grumbles ~~JJH:~~ ~~JCL:~~ TGG: RF CONOCO

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To Safety Directors Date 10/24

The enclosed article summarizes NIOSH research on PAPR's, Racal and 3M; in particular.

Basically they conclude the protection factor of 1,000, which is generally assigned PAPR's is too high.

Please be aware of this when using these devices in your operations.

TGG

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Workplace Protection Factor Measurements on Powered Air-Purifying Respirators at a Secondary Lead Smelter: Results and Discussion

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A study was conducted at a secondary lead smelter to evaluate the workplace performance of the 3M W-344 and Racal AH3 powered air-purifying respirators equipped with helmets and high efficiency filters. The research protocol developed for the study has been described in a companion paper. The results of the study indicate that the mean lead concentrations, measured inside the facepiece of both PAPRs, were significantly less than the OSHA lead exposure limit of 50 $\mu g/m^3$. The means of the workplace protection factor measurements on both PAPRs were significantly less than the PAPR selection guide protection factor classification of 1000. Correlation analysis of preshift quantitative fit factors and corresponding workplace protection factors indicated no linear association between these two measures of performance. This finding suggests that for PAPRs equipped with helmets and high efficiency filters quantitative fit factors as presently determined are not indicative of the workplace protection which the respirators provide. Since the PAPR protection factor classification of 1000 was originally based on quantitative fit factors, the lack of a demonstrated association between quantitative fit factors and workplace protection as found in this study may explain why their performance was significantly less than expected.

Introduction

The workplace performance of the 3M W-344 and Racal AH3 powered air-purifying respirators (PAPR) equipped with helmets and high efficiency filters has been evaluated in a secondary lead smelter while worn by workers and while mounted on stationary formed heads. The specific job tasks in which the PAPRs were to be used were selected on the basis of retrospective data about personal exposure to lead. Blast furnace and reverberatory furnace operator or helper and lead ingot caster were the jobs with the highest potential lead exposure which still complied with the OSHA/NIOSH protection factor limitation of 1000 for a PAPR.[1] The blast furnace and reverberatory furnace operators and helpers were responsible for monitoring the operation of the furnaces, tapping lead or slag when needed and for fluxing the molten lead after it has been tapped from the furnaces. Fluxing is done by adding various chemicals to the molten lead which form a variety of metal salts resulting in non-molten dross on top of the lead. The dross is "skimmed" from the top of the molten lead by hand with shovel ladles. The skimming activity is done mainly by the furnace helper. Once fluxed, alloying agents are added to the molten lead as desired. The pig caster operates a casting machine which takes the refined lead and meters it into 30 kg ingots.

Test Group and Data Collection

Based on exposure history, the job classifications selected for this study were furnace operators or helpers and pig casters. Two workers from each of these three job classifications during both the 7 a.m. and 3 p.m. shifts were selected to participate. No attempt was made to control the facial indices of the workers. Two workers per job classification per shift were chosen so that the PAPRs could be tested together. A total of twelve workers were used in the study. Each worker wore both models of PAPR twice, however, for the second wearing, he was not given the same specific 3M or Racal PAPR that he wore the first time. A complete description of the 3M Model W-344 and Racal Model AH3 used in the study is given in a companion paper.[2]

Because it was anticipated that relatively small, inboard leakages would occur, the inside and outside facepiece samples were collected over the full shift.

Statistical Analysis

These data were analyzed using the t-test, analysis of variance (ANOVA) and correlation analysis. These statistical tests all require that the data being analyzed must be normally distributed. However, it is generally believed that environmental occupational exposure data approximately follows a lognormal distribution. Testing of the data collected in this study showed it to be lognormally distributed as expected. A Kolmogorov-Smirnov test was run on randomly selected cells of the ANOVA to check the assumption of normality. Those results indicated that the log transformed data were far superior to the untransformed data in meeting this assumption. In addition to the Kolmogorov-Smirnov test for the analysis of variance, skewness and kurtosis of each variable distribution were calculated. The skewness is a description of the asymmetry of a distribution while kurtosis is a measure of the degree of peakedness of a

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distribution. For a normal distribution, the skewness and kurtosis are zero. The calculated values of these moments for various distributions are given in Table I. In all cases, the log-transformed data best approximate the normal distribution. Accordingly, the raw PAPR field data were log transformed and all statistical analyses were performed on the transformed data unless otherwise noted. In addition to geometric mean, geometric standard deviation and confidence intervals, certain performance aspects of each PAPR are also characterized by tolerance limits. The statistical tolerance limits furnish limits above or below that in which it can be confidently expected to find a prescribed percentage of individual items of the population.[3]

Methods and Materials

The protocol used in this study has been described in a companion paper.[2] Within the context of this report facepiece refers to that part of the helmet enclosure that covers the face, often times called the visor, shield or faceshield.

Results

Workplace Performance Tests

Sampling data collected on the Racal AH3 and 3M W-344 PAPRs, while worn by workers are presented in Tables II and III. The lead concentrations measured inside the facepiece of the Racal AH3 were found to range from 0.6 to 33.6 $\mu g/m^3$ with a geometric mean (GM) of 4.9 $\mu g/m^3$ and a geometric standard deviation (GSD) of 2.89. The 3M W-344 had lead concentrations inside the facepiece ranging from 0.2 to 66 $\mu g/m^3$ with a geometric mean of 5.5 $\mu g/m^3$ and a geometric standard deviation of 3.2. The 3M and Raca mean lead concentrations were not significantly different ($P > 0.05$). Within the range of ambient lead concentrations experienced during this study, both means were significantly ($P < 0.01$) less than the OSHA lead exposure standard of 50 $\mu g/m^3$. The two-sided 95% confidence interval limits on the means are respectively for the Racal AH3, 3.1 and 7.8 $\mu g/m^3$ and for the 3M W-344, 3.3 and 9.3 $\mu g/m^3$.

No significant difference ($P > 0.05$) was found between the mean lead concentrations measured outside the facepiece of either PAPR from which it is concluded that both experienced similar challenges of ambient lead concentration during the study. Analysis also indicated that the mean ambient lead concentration was significantly ($P < 0.05$) greater at the PAPR facepiece than at the inlet to the high efficiency filter(s) of the PAPRs. This result is not surprising since the worker participants spent most of their time facing their respective work stations from which lead emissions were occurring. The lead concentrations measured outside the PAPR facepiece represent an estimate of the lead exposure a worker would experience were he not wearing the respirator, therefore, it has been used in the calculation of workplace protection factor.

Associations between lead concentrations measured inside the facepiece and lead concentrations measured outside the facepiece or lead concentration challenging the filter(s) of the PAPRs were evaluated by linear regression analysis. With a 5 percent level of significance, a linear association was found on the Racal AH3 PAPR between the lead concentra-

TABLE I
Skewness and Kurtosis of Various Parameter Distributions

Parameter	Racal Skewness	Racal Kurtosis	3M Skewness	3M Kurtosis	Grouped Skewness	Grouped Kurtosis
Untransformed Inside Facepiece Concentration	1.87	2.96	3.29	12.36	3.14	12.35
Log-transformed Inside Facepiece Concentration	0.04	-0.41	-0.55	2.52	-0.27	0.97
Untransformed Outside Facepiece Front Concentration	1.38	1.73	3.07	11.18	2.40	7.82
Log-transformed Outside Facepiece Front Concentration	0.30	-0.96	1.15	1.13	0.69	-0.19
Untransformed Workplace Protection Factor	2.97	10.07	4.39	19.94	5.11	29.31
Log-transformed Workplace Protection Factor	0.67	-0.01	0.87	1.32	0.71	0.68
Untransformed Quantitative Fit Factors	0.71	0.13	1.78	3.14	1.12	0.74
Log-transformed Quantitative Fit Factors	-0.41	-1.31	0.17	-0.85	-0.08	-1.26

TABLE II
Lead Concentrations, Workplace Protection Factors and Quantitative Fit Factors Obtained With The Racal Model AH3 PAPR

Day/Shift	Work Activity[B]	Concentration $\mu g/m^3$ Inside Facepiece	Outside Facepiece Front	Outside Facepiece Rear	Workplace[A] Protection Factor	Fit Factor
	A	8.0	1095	806	137	13500
1 - a.m.	B	5.7	567	571	99	3000
	C	7.1	1018	-	143	21500
	A	1.7	366	375	211	7700
1 - p.m.	B	11.5	952	422	83	2200
	C	7.5	-	414	-	11500
	A	5.1	1727	972	341	15400
2 - a.m.	B	15.2	732	1440	48	2200
	C	17.0[C]	1165	1847	68[C]	17400[C]
	A	30.5	3621	-	119	20000
2 - p.m.	B	3.1	434	313	139	8300
	C	20.0	2000	1733	100	10700
	A	33.6	1424	1205	42	21700
3 - a.m.	B	9.7	847	992	87	2000
	C	14.6[C]	471	609	32[C]	1500[C]
	A	2.0	1984	508	1016	10500
3 - p.m.	B	1.6	459	939	292	31500
	C	4.3	409	637	95	13500
	A	3.1	2725	1340	867	6300
4 - a.m.	B	1.9	563	676	293	3100
	C	3.6	750	668	206	14200
	A	3.9	2221	-	571	2800
4 - p.m.	B	1.0	579	701	559	2000
	C	0.6	1443	464	2323	17000
Geometric Mean		4.9			205	7900
Geometric Std. Dev.		2.89			2.83	2.5
95% C.L. on Mean		3.1 - 7.8			128 - 325	5300-11700

[A]Calculated before inside facepiece concentration values were rounded to the nearest tenth and the outside facepiece concentration rounded to the nearest whole number.
[B]A - reverbatory furnace operator/helper; B - ingot caster; C - blast furnace operator/helper.
[C]Not used in data analysis due to sampling pump failure.

tion inside the facepiece and the lead concentration challenging the PAPR filters. While significant, the coefficient of determination (r^2) for the regression was only 0.23, which indicates that only 23 percent of the variation in the inside facepiece concentrations has been explained with the help of the lead concentrations challenging the filters. No such association was found for the 3M W-344 PAPR. A somewhat surprising finding for both PAPRs was that no linear association existed between lead concentration inside the facepiece and lead concentration outside the facepiece. However, if these same data were pooled, a linear association was found at a 5 percent level of significance. But even though significant, the regression model yielded a very weak coefficient of determination of only 0.12.

The workplace protection factors measured on the Racal AH3 were found to range from 42 to 2323 with a geometric mean of 205 and a geometric standard deviation of 2.83, and on the 3M W-344 the workplace protection factors were found to range from 28 to 5500 with a geometric mean of 165 and a geometric standard deviation of 3.57. Statistical t-test analysis indicated there was no significant difference ($P > 0.05$) between the means of the Racal and 3M workplace protection factors. Both means were also found to be significantly less ($P < 0.01$) than the current PAPR protection factor classification of 1000. The two-sided 95% confidence interval limits around the means of the workplace protection factor were respectively for the Racal AH3, 128 and 325, and for the 3M W-344, 94 and 292. The lognormal probability plot of the grouped workplace protection factor data is presented in Figure 1.

The pre-shift quantitative fit factors measured on the Racal AH3 were found to range from 2000 to 31 500 with a geometric standard deviation of 2.5 and on the 3M W-344 they were found to range from 1200 to 24 600 with a geometric mean of 5100 and a geometric standard deviation of 2.4. Analysis of the quantitative fit factor data indicated no significant difference ($P > 0.05$) between the means of the quantitative fit factor observed on both PAPRs. The two-sided 95% confidence interval limits about the means are as indicated in Tables II and III. The lognormal probability plot of the grouped quantitative fit factor data is presented in Figure 1.

It was thought that, in general, the better the quantitative fit factor achieved on a worker/PAPR combination, the

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TABLE III
Lead Concentrations, Workplace Protection Factors and Quantitative Fit Factors Obtained With The 3M Model W-344 PAPR

Day/Shift	Work Activity[B]	Concentration $\mu g/m^3$ Inside Facepiece	Outside Facepiece Front	Outside Facepiece Rear	Workplace[A] Protection Factor	Fit Factor
	A	4.1	697	742	170	4000
1 - a.m.	B	10.1	652	774	65	10300
	C	19.1	656	484	34	5300
	A	2.7	2484	-	913	1200
1 - p.m.	B	4.2	574	313	136	11000
	C	34.2[C]	-	548	-	2100
	A	4.3	1018	1028	235	24600
2 - a.m.	B	6.5	506	359	78	10900
	C	12.6	519	545	41	2500
	A	27.7	1271	724	46	2000
2 - p.m.	B	3.4	528	569	153	6700
	C	7.7	5464	-	714	3900
	A	6.8	1975	951	291	1900
3 - a.m.	B	5.6	695	612	123	12200
	C	14.2[C]	552	323	39[C]	5600[C]
	A	3.0	766	292	255	1400
3 - p.m.	B	1.8	451	438	245	8600
	C	2.3	472	237	209	2600
	A	3.2	850	740	267	2800
4 - a.m.	B	14.4	1227	392	85	6700
	C	13.2	439	-	33	2000
	A	0.2	1232	459	5500	6500
4 - p.m.	B	2.6	1625	354	619	23500
	C	66.0	1864	829	28	8500
Geometric Mean		5.5			165	5100
Geometric Std. Dev.		3.2			3.57	2.4
95% C.L. on Mean		3.3 - 9.3			94 - 292	3500-7500

[A]Calculated before inside facepiece concentration values were rounded to the nearest tenth and the outside facepiece concentration rounded to the nearest whole number.
[B]A - reverbatory furnace operator/helper; B - ingot caster; C - blast furnace operator/helper.
[C]Not used in data analysis due to sampling pump failure.

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better the workplace protection factor would be for that same combination. A correlation analysis was done to test for an association between the paired workplace protection factor and quantitative fit factor data. That analysis found no significant linear association in the data and resulted in coefficients of determination of 0.08 for the Racal AH3 and 0.01 for the 3M W-344. These associations were also evaluated with curvilinear regressions, however, again no significant regressions were found.

The study design was such that relationships between other statistics of quantitative fit factor and workplace performance could be investigated. As mentioned, statistical analysis indicated that the means of the workplace protection factor and means of the quantitative fit factor of both the Racal and 3M PAPRs were not significantly different. When these data are combined replicate workplace protection factor and quantitative fit factor data on the 12 workers involved in the study could be obtained. The geometric mean, geometric standard deviation and range of these data for each worker are shown in Table IV. The means of the workplace protection factor ranged from 40 to 883 and the means of the quantitative fit factor ranged from 2800 to 16 100. Correlation analysis on the mean workplace protection factor and mean quantitative fit factor data indicated no significant linear or curvilinear association. The coefficient of determination was less than 0.1.

Other possible relationships between quantitative fit factor and workplace protection factor would be to compare each worker's lowest observed quantitative fit factor to the mean of his workplace protection factor measurements or to his lowest observed workplace protection factor. That analysis, which was conducted on both the untransformed and log transformed data, found no significant associations. The coefficients of determination for these analyses were again less than 0.1.

In addition to workplace protection factor, another possible parameter to correlate with the quantitative fit factor is the lead concentration measured inside the facepiece of the PAPR. The geometric mean, geometric standard deviation and range on these lead concentration data are shown Table V for each worker. The mean lead concentrations measured inside the facepiece were found to range from 1.0 to 17.8 $\mu g/m^3$. Correlation analysis between each worker's mean inside facepiece concentration and his lowest quantita-

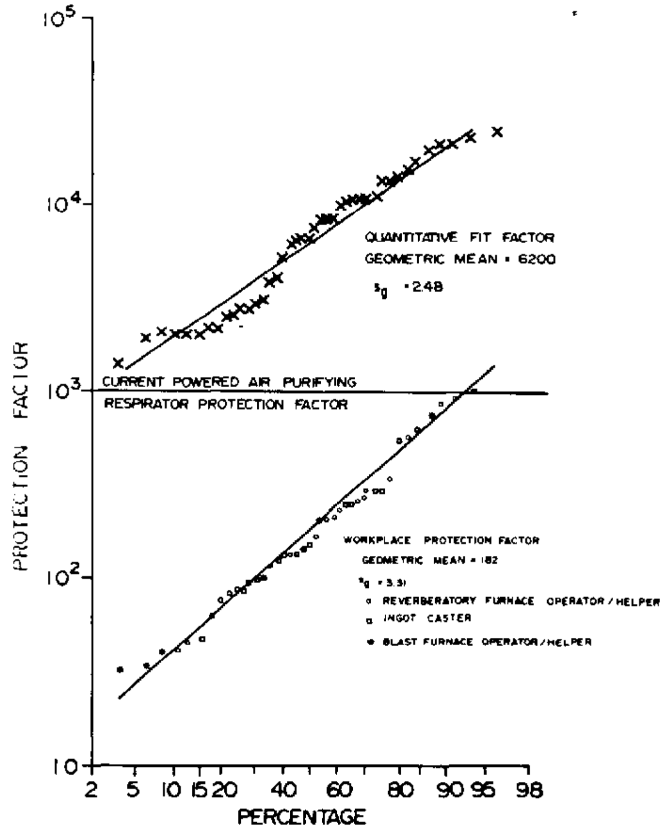

Figure 1 — Lognormal probability plots of grouped workplace protection factor and quantitative fit factor data on the 3M W-344 and Racal AH3 powered air purifying respirators equipped with helmets and high efficiency filters.

tive fit factor found no significant linear association in the data with a coefficient of determination of 0.13.

Initially, several factors other than fit were also considered as possible sources of variation in the workplace performance of the PAPRs. These factors were: day of the week; shift; and worker activity. Correlation analysis and

TABLE V
Lead Concentrations Measured Inside the Facepiece of Powered Air-Purifying Respirators Used on Study Participants

	Inside Facepiece Concentration ($\mu g/m^3$)		
Worker	GM (n=4)	GSD	Range
1	5.2	1.54	3.1 - 8.0
2	4.1[A]	1.27	3.2 - 5.1
3	4.4	1.77	1.9 - 6.5
4	12.1	1.27	9.7 - 15.2
5	8.2	1.88	3.6 - 14.2
6	15.8	1.17	13.2 - 19.1
7	2.7[A]	1.53	1.7 - 3.9
8	1.0[A]	4.15	0.3 - 2.7
9	2.9	2.83	1.0 - 11.5
10	2.7	1.51	1.6 - 4.2
11	3.0	3.35	0.6 - 7.7
12	17.8[A]	3.94	4.3 - 66

GM = Geometric Mean, GSD = Geometric Standard Deviation
[A](n = 3)

ANOVA indicated none of these factors or their interactions were significant sources of performance variation. However, there was some trend in the data to suggest that worker activity may be a possible source of variation which should be accounted for in field testing. Other factors which may be important but were not investigated are workrate and minute volume, head and body movement, and air current velocity and direction at the test site.

Formed Head Tests

The mean lead concentrations measured inside the facepiece of both PAPRs during manikin testing were significantly ($P < 0.01$) less than the OSHA lead exposure standard of 50 $\mu g/m^3$. These mean lead concentrations were not found to be significantly ($P > 0.05$) different. The geometric mean, geometric standard deviation and range of those lead con-

TABLE IV
Workplace Protection Factor and Quantitative Fit Factor Data for Study Participants

	Workplace Protection Factor			Quantitative Fit Factor		
Worker	GM (n=4)	GSD	Range	GM (n=4)	GSD	Range
1	300	2.17	137 - 867	7900	3.02	1900 - 24600
2	160	2.55	42 - 341	7800	2.75	2800 - 21700
3	129	1.78	78 - 293	6000	2.14	3100 - 12200
4	69	1.32	48 - 87	4200	2.25	2000 - 10300
5	83	2.35	39 - 206	8100	2.64	2500 - 21500
6	40	1.44	32 - 68	4100	3.03	1500 - 17400
7	194	2.86	46 - 571	2800	2.10	1400 - 7700
8	883	4.81	119 - 5500	6400	3.32	1200 - 20000
9	204	2.25	83 - 559	4000	2.12	2000 - 8600
10	242	2.05	136 - 619	16100	1.88	8300 - 31500
11	702[A]	3.35	209 - 2323	6700	2.44	2600 - 17000
12	64[A]	2.05	28 - 100	7100	2.32	2100 - 13500

GM = Geometric Mean, GSD = Geometric Standard Deviation
[A]n = 3

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TABLE VI
Lead Concentrations Measured Inside the Facepiece of Powered Air-Purifying Respirators Used on Manikins

Test Location	Racal Inside Facepiece Conc. ($\mu g/m^3$) GM (n = 4)	GSD	Range	3M Inside Facepiece Conc. ($\mu g/m^3$) GM (n = 4)	GSD	Range
Reverbatory Furnace	3.9	1.3	3.0 - 5.5	1.6	2.0	0.6 - 3.4
Caster	17.0	1.5	9.6 - 26.7	0.8	3.3	0.3 - 3.8
Blast Furnace	3.0[A]	2.3	1.4 - 7.4	2.8	2.0	1.0 - 4.3

[A]n = 3

centration data obtained during manikin testing are summarized in Table VI by test location.

Particle Size Analysis Results

Eight impactor samples were collected on each work activity for particle size analysis. Inspection of the impactor data indicated that the size range limits ($< 0.68\ \mu m$ to $> 17\ \mu m$) were inappropriate to allow complete determination of the aerosol size distribution. However, the impactor data did show that around the reverbatory furnace and ingot caster approximately 35% of the lead aerosol size distribution was larger than 17 μm and approximately 30% was smaller than 0.68 μm. This implies that high proportions of both lead dust and lead fume were present which is consistent with the nature of these operations. At the blast furnace, approximately 60% of the lead aerosol size distribution was larger than 17 μm and only about 8% was smaller than 0.68 μm indicating a large percentage of lead dust or agglomerated lead fume was present.

Discussion

Analysis of the lead concentration data collected from inside the facepiece of the 3M W-344 and Racal AH3 PAPRs indicates that the respirators were able to reduce the average lead exposure in this population of workers to a level significantly lower than the 50 $\mu g/m^3$ OSHA personnel exposure limit for lead. However, it would be prudent from the standpoint of worker health to consider the efficacy of these PAPRs based upon consideration of the exposure level of individual workers rather than the average exposure level of the worker population. Considering the geometric mean and geometric standard deviation of the pooled lead exposure data, a probability estimate can be made of the percentage of workers having exposures below a certain level. Based upon such a consideration and selecting a 0.95 probability level it would be concluded that workers in this population or other populations studied under similar conditions would have lead exposures of less than 32 $\mu g/m^3$. It is possible, by applying tolerance limits to these same data, to estimate the proportion (P) of lead exposures falling below a certain level at a specified level of confidence (γ). Setting $P = 0.95$ and $\gamma = 0.95$ it can be said with 95% confidence that 95% of the workers in this population or other populations studied under similar conditions would experience lead exposures of less than 53 $\mu g/m^3$. In regard to these estimates of lead exposure, it is worth noting again that the PAPRs were properly fitted, worn, used and maintained during the study and that ambient concentrations of lead ranged from 7 to 109 times the 50 $\mu g/m^3$ OSHA personnel exposure limit for lead.

It was assumed that lead concentrations measured inside the PAPR facepiece during manikin testing would reflect penetration through the PAPR filter(s) because PAPRs equipped with helmet enclosures having air supply rates greater than 170 Lpm are considered to operate as positive pressure devices. However, the lead concentrations observed appear to be of higher magnitude than what would be expected through the PAPR's high efficiency filter system, possibly implicating that other sources of leakage were occurring. A prime source of such potential leakage with helmet type enclosures is around the helmet facepiece. Cecala *et al.*[4] recently published a report of wind tunnel studies done to determine the effects of ambient air velocity and direction on the Racal AH21 PAPR. These studies were conducted with the PAPR operating at approximately 200 Lpm. They reported that the PAPR's efficiency dropped from levels close to 100% in static dust chamber tests to levels close to 94 percent (*i.e.*, protection factors of around 17) in the wind tunnel test at air velocities under 400 fpm (4.5 mph). They also reported that when the PAPR was not directly facing the air stream, its efficiency was reduced even further because contaminated air was forced into the helmet on the windward side along the facepiece shields. Their results suggest that the 200 Lpm airflow to the helmet enclosure was not sufficient to maintain "positive facepiece pressure" during the wind tunnel studies.

While the velocity and direction of air currents at the manikin test positions in this smelter were not measured, it is very likely that at times the air velocity was near or above 400 fpm. Therefore it is hypothesized that under the workplace conditions encountered the 170 Lpm or greater flow rate to the 3M and Racal helmet enclosures was not sufficient to prevent inboard leakage from occurring around the facepiece during the manikin tests. By extrapolating Cecala's laboratory results, the quantity of facepiece leakage would be, in part, a function of the air velocity and direction occurring at a particular test site on a particular day. Therefore, some of the variability observed in the lead concentrations measured inside the PAPR facepiece may be due to differing quantities of facepiece leakage.

The American National Standards Institute (ANSI) respirator standard states that "A respirator protection factor is a