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Field Performance Measurements of Half-Facepiece Respirators: Steel Mill Operations

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Field Performance Measurements of Half-Facepiece Respirators: Steel Mill Operations

Ambient and in-facepiece samples to evaluate the protection provided by negative-pressure, half-facepiece respirators were collected on workers in different areas of a steel mill including a sinter plant and a basic oxygen process shop. Protection was assessed by workplace protection factors (WPF). All the in-facepiece concentrations were dramatically less than the corresponding ambient concentration levels or permissible exposure limits. The geometric mean (GM) ambient and in-facepiece concentrations of iron were found to vary among tasks. Significant differences were also found to occur between the GM ambient exposure levels in which some of the respirators were used. Significant differences in respirator performance as measured by WPF or in-facepiece iron concentration were observed among different brands of respirators. For all job classifications and at all levels of airborne exposure, the fifth percentile estimates for the WPF distributions for each brand of respirator were all greater than 20.

Keywords: assigned protection factor, dust exposures, half-facepiece respirators, in-facepiece sampling, workplace protection factors

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This study was undertaken to evaluate workers' exposures (in-facepiece concentrations) to dusts and the protection provided by dust/mist, elastomeric and disposable, half-facepiece respirators. The workplace protection factor (WPF), a ratio of ambient and in-facepiece concentration, was calculated as an index of respirator performance.[1] Various production processes within a steel manufacturing facility were chosen because they were known to have exposures to iron (Fe) and calcium (Ca) dust. Specific details of the site selection process are given in an earlier work.[2]

Earlier studies as part of this overall research project were also conducted in three brass foundries and an aircraft painting operation.[3,4] In the foundry operations, workers' exposures to zinc and lead dusts and fumes were measured while they wore dust/fume/mist, elastomeric and disposable, half-facepiece respirators.[3] In the aircraft paint-spraying operations, exposures to metal pigments in paint overspray were evaluated during the use of elastomeric half-facepiece respirators, equipped with combination high efficiency filter and organic vapor cartridge air-purifying elements.[4]

The research protocol used for this study was patterned after other published respirator field study protocols but incorporated several new aspects of sampling and analytical methodology not previously employed in those studies. The findings about the new methodologies are described in a previous article.[2] The study results for foundry and paint-spraying operations are reported in other companion articles.[3,4] This article presents ambient and in-facepiece concentrations and WPF ratios measured on workers using elastomeric and disposable dust/mist half-facepiece respirators during various steel mill operations.

The data from these field studies, when used with WPF data collected by other researchers and research organizations, can be used to evaluate and set assigned protection factor (APF) levels for half-facepiece respirators.

METHODS AND MATERIALS

The methods and materials for the overall study have been described in detail in the study protocol article.[2] That protocol article should be referred to for further detailed information. Only a brief summary of the protocol is provided here along with specific modifications made to accommodate particular aspects of the steel mill environment.

Worker and Respirator Selection and Fit Testing

Workers were solicited from the hourly employees of the sinter plant and basic oxygen process (BOP) shop. All workers participating in the study were volunteers. Their job titles included laborer, mechanical maintenance, electric shop, boiler repair, and flux unloading.

The half-facepiece respirators evaluated in the study were the Cabot Safety (formally AO) 5-Star® silicon facepiece equipped with R30® dust/mist (DM) filters (Cabot Safety, Southbridge, Mass.); the MSA Comfo II® facepiece equipped with Type F® DM filters (MSA Co., Pittsburgh, Pa.); the Scott Model 65® facepiece equipped with 642-D® DM filters (Scott Aviation, Lancaster, N.Y.); the 3M 8710® (3M Co., St. Paul, Minn.); and Gerson 1710® (Safety and Health, Middleboro, Mass.) DM disposable respirators. Respirators were randomly assigned to the workers, and a respirator's suitability to be worn by a particular worker was assessed with quantitative or qualitative fit testing. Workers were able to wear only those respirators for which they had achieved a satisfactory fit test. The individual respirator brands worn by workers are detailed in Table I. Number of brands worn by workers ranged from one to four with only one replication. Details of both fit-testing procedures have been previously reported.[2]

In July 1995 the National Institute for Occupational Safety and Health (NIOSH) promulgated new certification regulations (42 CFR 84).[5] The new regulations designate nine classes of filters using three categories of resistance to filter efficiency degradation (N, P, and R) and three levels of filter efficiency (95, 99, and 100). This study took place before the newer brands of respirator filters with the new designations were available.

WPF Sample Collection

Ambient Fe concentrations were measured at the sinter plant as well as the BOP shop while ambient Ca concentrations were measured only at the flux receiving department of the BOP shop. Estimates of ambient airborne concentration outside the respirator were made with traditional lapel sampling methods as described in the study protocol article.[2] A flow rate of 1.5 L/min was used for Co sample collection. The in-facepiece sample was collected through a probe inserted through the facepiece. The sampling train used for in-facepiece sampling was similar to the ambient sampling train. Rates for in-facepiece sampling were approximately 1.5 L/min.

Approximately 20 percent of the workers involved with WPF testing were equipped with a working blank (WB), i.e., a cassette loaded with a filter. The WBs were handled in exactly the same manner as the WPF sample cassettes. The capped WB cassette was attached to the worker in an area close to the breathing zone. Each time the WPF sampling cassettes were capped or uncapped, the WB cassette was capped or uncapped. The average value of the blank filters served as a correction factor to estimate the background contamination level of the exposure agent. In addition, manufacturer's blanks (MB), i.e., unused cassettes loaded with unused filters and kept in a laboratory, were also sent to be analyzed as laboratory blind samples for the purpose of further validating the results obtained with blank cassettes.

The respirator and sampling trains worn by study participants were donned in a "clean area," which was a "nonsmoking" lunch room. This area was used to remove and don sampling equipment and respirators at all break periods and at the end of each WPF sampling period.

Sampling pumps in both sampling trains were always started or stopped simultaneously. Sampling pumps were started only after the respirator had been successfully donned. Sampling pumps were stopped before a worker was permitted to remove his respirator.

Sample Analysis

In-facepiece samples, WBs, MBs, and impactor samples were analyzed by proton induced X-ray emission (PIXE) analysis (Element Analysis Corp., Lexington, Ky.). Briefly described, PIXE is an X-ray spectroscopic technique that can be used for nondestructive, simultaneous analysis of solid or liquid aerosol filter samples. The detection limits for the in-facepiece samples ranged from 0.2 ng/cm² to 7.6 ng/cm² for Fe with a mean of 2.2 ng/cm² (5.5 ng per sample). The detection limits for specific elements vary based on such factors as atomic number, irradiation time, matrix interferences, detector efficiency, and beam intensity. The average error associated with PIXE analysis of the in-facepiece samples was 8.1%.

Ambient samples were analyzed for Fe or Ca by atomic absorption (AA) analysis.[2] The detection limit for this analytical method is 1.4 μg per sample. Its precision or relative standard deviation is 2–6%. This change in analytical procedure was necessitated by the heavy dust loading of the ambient samples. Heavy dust loading on a filter can affect the accuracy of the PIXE analysis. In addition, the dust that impacts on the surface of the filter, behind the cassette inlet, was visibly observed to dislodge from some of the ambient cassette filters during normal handling of the sampling trains. In the professional judgment of the research staff, this was due to heavier dust loadings on some samples. To account for this loss of dust from the filter, the interior surface of each ambient sample cassette was acid washed. This wash solute and an acid digest of the cassette filter were combined and analyzed by AA for Fe or Ca.

This problem was not thought to be of concern with the lighter dust loadings occurring on the in-facepiece samples. As a precaution, however, the cassettes of a subsample of the in-facepiece samples along with all the WBs and MBs were washed as part of the PIXE analysis. The wash was filtered and that filter subsequently analyzed by PIXE to determine the amount of material lost to the interior surfaces of the filter cassettes. Results on this subset of in-facepiece samples, discussed in detail later in this article, indicated that these filters were not loaded enough to have dust loss.

WPF

WPF is a measure of how well the respirator works when properly used and conscientiously worn. It is calculated by dividing the ambient concentration by the concentration measured inside the respirator. The fifth percentile estimate of the WPF distribution was determined for each respirator brand tested. The fifth percentile estimate was determined based on the geometric mean (GM), geometric standard deviation (GSD), and a z value corresponding to the selected percentile of WPF.[6]

Impactor Sample Collection

Impactor sampling was done to determine the size distribution of the ambient particles produced by or existing in particular work activity areas. The impactor samples were collected as area samples by a seven-stage cascade impactor (PIXE International Corp., Tallahassee, Fla.). Impactor sampling was conducted for 30 to 90 minutes at flow rates of about 1 L/min. This sampling gave impactor stage effective cut-off diameters of 16, 8, 4, 2, 1, and 0.5

TABLE I. Ambient Concentrations (Co), In-facepiece Concentrations (Ci), and WPF Reported as Iron (Fe) or Calcium (Ca)

Task	Worker Code	Resp. Mfg.	Asv[A] (L)	Co (μg/m³)	ISV[B] (L)	Ci (μg/m³)	WPF	Exposure/ Plant
Flux unloading	54	Cabot	210	11,100	206	1.14	9700	Ca/BOP
Flux unloading	54	MSA	70	13,900	71	7.01	1980	Ca/BOP
Flux unloading	54	Scott	171	95,400	178	4.47	21,300	Ca/BOP
Boiler repair	65	Gerson	99	1430	94	77.10	19	Fe/BOP
Boiler repair	65	Cabot	56	830	53	3.32	250	Fe/BOP
Boiler repair	65	3M	63	1870	58	18.00	104	Fe/BOP
Boiler repair	65	Scott	53	790	50	6.87	114	Fe/BOP
Laborer	53	Cabot	145	90	137	0.27	330	Fe/BOP
Laborer	64	Cabot	202	240	183	2.35	103	Fe/BOP
Laborer	64	Scott	188	320	178	0.80	398	Fe/BOP
Electric shop	56	3M	86	5230	81	35.20	150	Fe/sinter
Electric shop	56	Gerson	60	840	63	15.50	54	Fe/sinter
Electric shop	56	Cabot	79	5380	75	49.60	108	Fe/sinter
Electric shop	56	Scott	153	1610	164	1.50	1070	Fe/sinter
Laborer	55	Gerson	87	2540	104	5.94	430	Fe/sinter
Laborer	55	MSA	94	8310	88	20.70	400	Fe/sinter
Laborer	55	3M	102	4860	104	1.52	3190	Fe/sinter
Laborer	55	Cabot	70	1170	72	7.12	160	Fe/sinter
Laborer	57	Gerson	131	450	134	2.24	200	Fe/sinter
Laborer	57	Scott	182	870	180	1.38	630	Fe/sinter
Laborer	57	3M	142	1030	135	6.70	154	Fe/sinter
Laborer	58	3M	98	430	102	0.62	688	Fe/sinter
Laborer	58	Cabot	112	1250	116	9.92	125	Fe/sinter
Laborer	59	3M	79	1660	84	4.64	360	Fe/sinter
Laborer	59	Scott	50	340	50	6.02	56	Fe/sinter
Laborer	59	Cabot	106	1850	112	2.52	740	Fe/sinter
Laborer	60	MSA	127	3640	125	9.90	370	Fe/sinter
Laborer	60	Gerson	89	680	89	10.50	64	Fe/sinter
Laborer	60	Cabot	115	2220	123	2.58	860	Fe/sinter
Laborer	60	Scott	130	840	117	8.79	96	Fe/sinter
Laborer	62	3M	103	830	92	5.64	150	Fe/sinter
Laborer	62	Scott	119	970	119	4.34	225	Fe/sinter
Laborer	62	MSA	106	5720	117	26.60	215	Fe/sinter
Laborer	62	Gerson	115	970	128	3.03	320	Fe/sinter
Laborer	63	MSA	70	2080	71	0.72	2870	Fe/sinter
Laborer	63	Scott	78	2440	71	8.60	280	Fe/sinter
Laborer	63	Gerson	98	1060	109	10.90	97	Fe/sinter
Laborer	63	3M	80	1840	84	9.50	194	Fe/sinter
Mech. maint.	61	MSA	72	2820	68	2.62	1070	Fe/sinter
Mech. maint.	61	Gerson	44	5730	44	20.90	270	Fe/sinter
Mech. maint.	61	Cabot	60	1410	56	0.66	2140	Fe/sinter
Mech. maint.	49	3M	86	20,100	89	5.03	3990	Fe/sinter
Mech. maint.	49	MSA	48	6690	53	4.68	1430	Fe/sinter
Mech. maint.	49	Scott	110	16,100	114	45.80	350	Fe/sinter
Mech. maint.	50	Scott	79	1820	79	1.65	1100	Fe/sinter
Mech. maint.	50	Gerson	95	1500	100	33.60	45	Fe/sinter
Mech. maint.	50	MSA	102	980	104	2.88	340	Fe/sinter
Mech. maint.	50	3M	134	670	120	2.46	274	Fe/sinter
Mech. maint.	51	MSA	147	1380	132	59.40	23	Fe/sinter
Mech. maint.	51	Gerson	117	1440	118	8.59	170	Fe/sinter
Mech. maint.	51	Cabot	123	2780	115	12.80	220	Fe/sinter
Mech. maint.	52	Cabot	90	560	97	3.81	150	Fe/sinter
Mech. maint.	52	Gerson	113	7950	116	29.40	270	Fe/sinter
Mech. maint.	52	Scott	66	2660	70	41.10	65	Fe/sinter

Note: All samples were collected only during day shift.
[A]ASV = ambient sample volume (liters).
[B]ISV = in-facepiece sample volume (liters)

APPLIED STUDIES

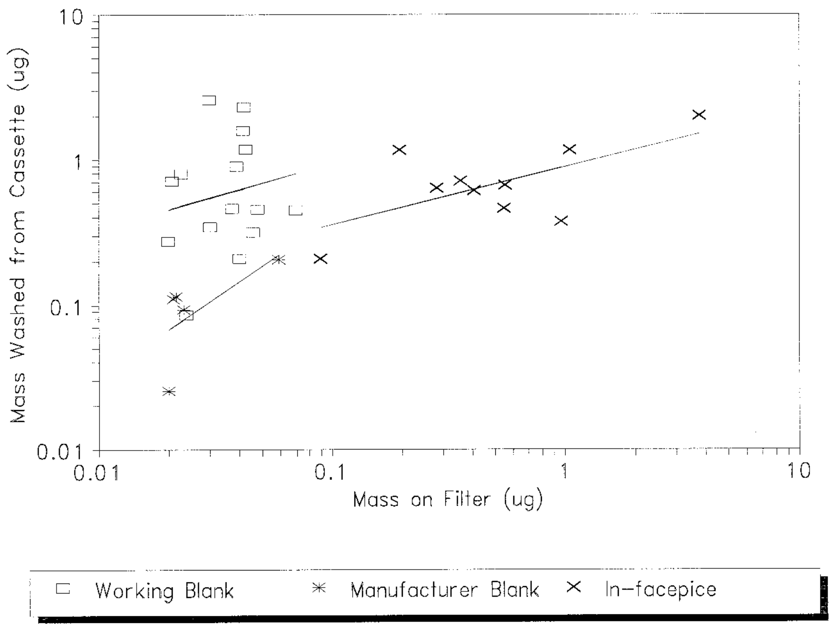

FIGURE 1. Correlation between the mass of iron on cassette filters versus that washed from the cassette walls for blank and in-facepiece cassettes used in the sinter plant

μm. The impactor data were analyzed using Distfit® software (TSI Inc., St Paul, Minn.).

Statistical Analysis

The WPF data were analyzed using analysis of variance and correlation analysis. These statistical tests require that the data being analyzed be normally distributed. The ambient concentration, in-facepiece concentration, WPF data, and the log-transformation of these data were checked for normality using the Shapiro-Wilk test. The log transformation of the concentration and WPF data was checked because environmental data is commonly found to be lognormally distributed.[7]

Statistical analysis was performed by using the Statistical Analysis System (SAS®) software (SAS Institute Inc., Cary, N.C.). The SAS Univariate procedure was used to identify potential outliers in the ambient and in-facepiece concentration distributions. The SAS General Linear Models procedure was used to identify significant differences in ambient concentrations, in-facepiece concentrations, and WPF data. Duncan's multiple range test was performed to compare means and detect significant differences between means. A significance level of 5% was used in all cases. No analysis was performed with the Ca exposure data due to the limited number of observations.

RESULTS AND DISCUSSION

Working Blank and Manufacturer Blank

Fifteen WB samples were collected and analyzed. Five MB samples were used as laboratory blinds and also analyzed. The average total mass (total for all elements including Fe measured by PIXE analysis) on the WB filters was 0.099 μg. The average mass of Fe on these filters was 0.037 μg. The average total mass on the MB filters was 0.244 μg, and the average mass of Fe was 0.029 μg.

The average total mass measured on the MBs appeared to be greater than the average total mass found on the WBs. No reason was readily apparent to account for this observation. However, the mass of elemental Fe was about the same for both sets of filters. This is illustrated in Figure 1 (reading values from the X-axis), which shows that the mass of Fe found on the filters of the WBs and MBs generally range within the same limits of 0.02 to 0.09 μg. This suggests that the Fe observed on the WB filters is probably the result of filter manufacturing rather than systematic contamination from cassette assembly and handling. Since outside and in-facepiece sampling cassettes were handled in similar fashion to the WB cassettes, it is probable that they were not subject to any systematic contamination during cassette assembly, handling, and analysis and that any random contamination that occurred was very small.

Statistical analysis of the mass data from the WB samples indicated that the elemental mass of Fe was not significantly dependent on the activities of the workers or date of sampling. Therefore, the mass loadings on the WBs were averaged. The average mass for Fe was then used as a background correction factor for estimating the contamination level of Fe. The mass of Fe on each ambient or in-facepiece filter was corrected by subtracting the average mass for Fe on the WBs (0.037 μg) from the original ambient or in-facepiece filter mass. All the masses of Fe on the ambient filters were much greater than 0.037 μg. The smallest mass of Fe found on the ambient filters was 9 μg. The average mass of Fe on the in-facepiece filters was 1.26 μg, which was also much greater than 0.037 μg. However, the masses of Fe on the in-facepiece filters for Workers 53 and 61 (0.038 and 0.060 μg, respectively) were less than two times the background. Instead of subtracting the background Fe mass from the masses of Fe on these filters, the masses corrected for background were set at 0.037 μg of Fe.

Washing of a Subset of In-Facepiece Cassettes

To evaluate whether filter loss was occurring with the lightly loaded in-facepiece cassettes, as was observed with routine handling of the

TABLE II. Geometric Means of Iron or Calcium Concentrations and WPFs by Task

Task/Plant	N	GM Co (μg/m^3)	GSD	GM Ci (μg/m^3)	GSD	GM WPF	GSD
Iron							
Boiler repair (BOP shop)	4	1150^A	1.5	13.3^A	3.9	86^A	3.0
Laborer (BOP shop)	3	190^B	2.0	0.8^B	2.9	240^A	2.1
Electric shop (sinter plant)	4	2480^A	2.5	14.2^A	4.8	175^A	3.6
Laborer (sinter plant)	24	1430^A	2.3	4.9^A	2.6	290^A	2.8
Mech. Maint. (sinter plant)	16	2650^A	2.9	8.2^A	3.9	320^A	4.1
Calcium							
Flux unloading (BOP shop)	3	24500	2.6	3.3	2.1	7400	2.7

Notes: GM Co = geometric mean ambient concentration; GM Ci = geometric mean in-facepiece concentration; and GM WPF = geometric mean workplace protection factor. Column means with the same superscript (A or B) are not significantly different (α = .05). Calcium is used to measure the WPF for the flux-unloading task.

heavily loaded outside cassettes, cassette washing was done on a subset of 10 of the 51 in-facepiece iron oxide samples and compared with wash data from the WB cassettes. In Figure 1 the amount of material washed from the cassette is plotted against the amount of material collected from the filter of the cassette. The amount of material washed from the cassettes can be read from the Y-axis.

The average mass of Fe washed from the cassettes of the WBs (0.841 μg) was not significantly different from that washed from the in-facepiece samples (0.799 μg). This strongly suggests that Fe dust collected on the in-facepiece filters was not dislodged during handling. Therefore, the remaining in-facepiece cassettes were not washed and no cassette wash data from the in-facepiece samples was included in the calculation of in-facepiece concentrations.

Ambient Exposure

A total of 57 WPF samples (57 ambient and 57 in-facepiece concentration data points) were collected at the sinter plant and BOP shop. Two of the ambient samples and their resulting WPF data sets were excluded from analysis due to pump failure during sampling, and a third data point and its WPF data point was excluded because of a misnumbered cassette. The remaining 54 ambient samples were evaluated.

Ambient exposures are expressed only in terms of elemental Fe or Ca. Based on the normality test, the null hypothesis that the log-transform of ambient concentrations is normally distributed is accepted. For presentation, analysis, and discussion, ambient exposure concentration data were treated as being lognormally distributed.

Ambient Fe or Ca exposures measured on each worker/respirator combination are summarized in Table I. In the sinter plant, Fe exposures, denoted as Co in Table I, ranged from 340 to 20,100 μg/m^3. In the BOP shop, Fe exposures ranged from 90 to 1870 μg/m^3 whereas Ca exposures at the flux-unloading station ranged from 11,100 to 95,400 μg/m^3. Assuming that these partial shift samples are representative of a full 8-hour shift sample, then most of the measured ambient Fe exposures (49 of 51 observations) would not exceed the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) of 10,000 μg/m^3 as Fe. However, all of the measured Ca exposures exceeded the OSHA PEL of 6000 μg/m^3 (Ca fraction of the molecular weight of calcium carbonate $\times$ 15,000 μg/m^3).

None of the ambient Fe exposures exceeded 10 times the PEL value, and 2 of the 3 ambient Ca exposures did not exceed 10 times the PEL value. Thus, half-facepiece respirators (maximum use concentration 10 times the PEL) were a suitable selection for the tasks included in this study.

The ambient sampling results are summarized by job title and location in Table II. The analysis of variance performed on the log-transformed ambient Fe exposure data indicated that exposure data were dependent on plant and job title. During the sampling period none of the worker groups had GM airborne exposures to Fe that exceeded the PEL. It can also be noted from Table III

TABLE III. GM of Iron Concentrations and WPF by Respirator

Respirator	N	GM Co (μg/m^3)	GSD	GM Ci (μg/m^3)	GSD	GM (WPF)	GSD	5th percentile (WPF)
MSA	8	3130^A	2.1	7.3^{A,B}	4.3	427^A	4.3	39
Cabot	11	1020^B	3.2	3.7^B	4.1	280^{A,B}	2.7	56
Scott	11	1300^B	3.0	5.2^{A,B}	3.8	252^{A,B}	2.9	45
3M	10	1930^{A,B}	3.1	5.1^{A,B}	3.2	377^A	3.7	44
Gerson	11	1510^{A,B}	2.4	12.3^A	2.9	123^B	2.7	24
All	51	1580	2.9	6.1	3.7	260	3.3	37

Notes: GM Co = geometric mean ambient concentration; GM Ci = geometric mean in-facepiece concentration; and GM WPF = geometric mean workplace protection factor. Column means with the same superscript (A or B) are not significantly different (α = .05). Data collected for flux-receiving task at the BOP shop were excluded from this analysis due to different exposure agent.

that significant differences were found to occur between the GM ambient exposure levels in which some of the respirators were used. This occurred strictly as a matter of chance.

In-Facepiece Sampling Results

Elemental mass information is available for analysis since in-facepiece samples collected at the sinter plant and BOP shop were analyzed by PIXE analysis. The major components of the in-facepiece filter mass are Fe, chlorine (Cl), silicon (Si), Ca, potassium (K), and sulfur (S). Their average percentage of the total mass were 30.5, 17.6, 13.3, 11.7, 6.5, and 5.6%, respectively. Chlorine, most likely as chlorinated salts, was present in such large quantity because of the perfuse sweating of the workers. The sources of the Si and S are not known.

The in-facepiece concentrations of Fe or Ca measured on each worker/respirator combination are also given in Table I and denoted as Ci. In the sinter plant, in-facepiece concentrations of Fe ranged from 0.62 to 59.4 $\mu g/m^3$. In the BOP shop, in-facepiece concentrations of Fe ranged from 0.27 to 77.1 $\mu g/m^3$ whereas Ca exposures at the flux-unloading station ranged from 1.14 to 7.01 $\mu g/m^3$. The in-facepiece Fe concentrations were found to be lognormally distributed. As a result, all subsequent analysis was done on the transformed data.

The in-facepiece sampling results are summarized by job title and location in Table II. The GM concentration levels measured inside the half-facepiece respirators for workers of each job title and location were dramatically less than the GM ambient exposure levels experienced by those workers. The GM in-facepiece Fe concentration for the laborers in the BOP shop was significantly lower than the mean in-facepiece Fe concentration measured for other tasks. When the in-facepiece concentration data were summarized by respirator, significant difference in in-facepiece concentration was found among respirators (Table III).

WPFs

The WPF data were also found to be lognormally distributed. As a result, all subsequent analysis was done on the transformed data. The results of individual WPF calculations for each worker/respirator combination are provided in Table I. WPF calculations for the sinter plant and BOP shop were based on Fe concentrations, whereas for the flux-unloading task at the BOP shop they were based on Ca. The WPF values, measured on the flux-unloading workers at the BOP shop where the workers were exposed to Ca, appeared to be higher than those measured for other tasks where the workers were exposed to Fe.

The GM WPF values for each job title and location are summarized in Table II. The highest GM WPF value, 320, was observed on the mechanical maintenance workers at the sinter plant. This value, while considerably higher than the GM WPF calculated for the other worker groups, was not significantly higher. This was due to the large variation of the WPF values within each worker group. This group of workers also had the highest ambient Fe exposures.

When these data were evaluated by respirator brand several significant differences were observed in the data. These results are summarized in Table III. The GM ambient exposure that occurred with the MSA were significantly higher that those that occurred with the Cabot and Scott respirators. The GM in-facepiece concentration experienced with the Gerson respirator was significantly higher than the in-facepiece concentration experienced with the Cabot respirator. The MSA and 3M respirators had significantly higher GM WPF values than the Gerson respirator.

The fifth percentile estimates for the distributions of the WPF values for each respirator and the pooled WPF value for all respirators are also summarized in Table III. The fifth percentile estimates, based on WPF distributions for individual brands of respirators, were all greater than 20, ranging from 24 to 56. The fifth percentile estimate based on the pooled WPF data was 37. The individual brand fifth percentile WPF estimates all exceeded the half-facepiece assigned protection factor of 10 by at least a factor of 2.

Correlation Analyses

To investigate the possible effect of ambient exposure level on the resulting WPF measurements, a correlation analysis was performed to evaluate the correlation between ambient Fe exposures and the corresponding levels of in-facepiece Fe concentrations. The analysis found that log-transformed Co and Ci data are not strongly correlated ($R^2=0.26$). However, the linear regression model is still significant at the 5% significance level. The intercept (-1.23) and slope (0.63) of the regression equation are significantly different from zero.

Measured WPF values and in-facepiece concentrations were found to be significantly, negatively, correlated with an R^2 of 0.42, indicating that WPF values decreased with increasing in-facepiece exposure levels. The regression equation based on log-transformed data was

$$\log(\text{WPF}) = 2.88 - 0.59 * \log(\text{Ci})$$

On the other hand, measured WPF values and ambient exposure levels were only weakly correlated ($R^2=0.11$). These results suggest that the significant differences observed in ambient concentration levels among different brands of respirators were not an important source of bias in the WPF measurements. Therefore, the observed significant differences in WPF measurements found between the Gerson and MSA and 3M respirators could not be attributed to differences in ambient exposure levels.

Particle Size Results

Results of the particle size analysis are summarized in Table IV, which gives the mass concentration of Fe on each stage of each impactor sample and provides summary statistics for each impactor sample. The fractions of respirable dust and fractions of less than 1 μm particles for each impactor sample are also given in the table. For most of the impactor samples the percent of Fe concentrations in particles having a cut size <8 μm ranged from 60 to 80% of the total Fe concentration. The percentage of Fe concentrations in particles having a cut size between 4 and 8 μm ranged from 10 to 20% of the total Fe concentration. The percentage of Fe concentrations in particles having a cut size <1 μm ranged from 1 to 2% of the total Fe concentration.

In an earlier report, the mean aerodynamic particle sizes for zinc aerosols produced by a number of processes in foundry operations were found to be less than 4 μm.[3] The zinc aerosols produced by the shake-out and mold-making activities had the largest mean sizes (8.9 and 13.1 μm). In contrast, the Fe aerosols produced by the steel mill operations ranged from 6.9 to 14.7 μm and appeared to be higher than those observed in the foundry operations. The fraction of respirable mass (FRM) in the foundry operations ranged from 0.115 to 0.871. The FRMs in the steel mill operations ranged from 0.066 to 0.227 and were much smaller than FRMs in the foundry operations.

In the foundries, the percentage of zinc in particles greater than 8 μm ranged from 25 to 77% of the total zinc mass as compared

TABLE IV. Mass Concentrations and Aerodynamic Particle Size (D_p) Distributions of Iron for the Impactor Samples

Cut off Diameter (μm)	Particle Size Range	Laborer Sinter	Laborer Sinter	Boiler Repair BOP	Laborer Sinter	Laborer Sinter	Laborer Sinter	Laborer Sinter	Laborer Sinter
		Job Title							
<0.5	<.50	21.0	15.5	7.7	3.1	4.2	2.0	13.4	1.8
0.5	0.5–1	23.7	7.9	20.2	11.0	18.9	3.3	15.0	11.5
1	1–2	107.0	13.6	27.1	33.9	69.5	8.0	7.8	33.0
2	2–4	357.0	12.0	109.0	106.0	240.0	23.8	8.9	39.0
4	4–8	351.0	54.0	350.0	85.0	741.0	203.0	34.0	118.0
8	8–16	696.0	140.0	613.0	303.0	923.0	150.0	42.0	254.0
>16	>16	976.0	310.0	977.0	42.0	1950.0	434.0	110.0	909.0
Total concentration (μg/m³)		2530.0	553.0	2100.0	584.0	3940.0	823.0	231.0	1370.0
Mean D_p (μm)		9.5	12.3	11.9	6.9	12.0	12.5	8.5	14.7
Median D_p (μm)		12.7	17.5	15.0	9.4	15.8	16.7	15.0	19.5
Fraction of respirable mass		0.176	0.097	0.086	0.227	0.093	0.072	0.204	0.066
Mass fraction <1 μm		0.018	0.042	0.013	0.024	0.006	0.006	0.123	0.010

with 60 to 80% of the total iron mass in particles greater than 8 μm at the steel mill.[3] On the other hand, the percentage of zinc in particles less than 1 μm ranged from 5 to 25%. The percentage of zinc in this particle size fraction was considerably higher than the percentage of iron (1 to 2%) in this same particle size fraction of the steel mill aerosols.

The GM WPF value, pooled for respirators, observed in foundry operations was 114, which is less than one-half of the GM WPF value of 260 observed in steel mill operations.[3] These results further support the possible association between WPF measurement and particle size as discussed previously.[3] Higher WPFs were measured at workplaces or activities associated with larger particle size and lower FRMs. This association may be expected in a scenario in which the face seal leaks may be physically small, resulting in low amounts of inboard penetration and particle size dependency of the penetration through these leaks.

Very large particles (physical diameter >10 μm) have been found to penetrate respirators.[2] Thus, face seal leaks may not be small all the time. These observations may be expected in a scenario in which at some time intervals, catastrophic failure of the face seal could occur, producing physically large leaks and resulting in significant inboard penetration. These findings support the premise that in real world conditions of the workplace, face seal leaks are dynamic, changing their location, size, and geometry during and between wearing periods.

SUMMARY AND CONCLUSIONS

From the element analysis data the major components of the total airborne mass for the in-facepiece samples were Fe, Cl, Si, and Ca. Only 2 of 51 measured ambient Fe concentrations exceeded the OSHA PEL value of 10,000 μg/m³. They did not exceed 10 times the PEL value. All the measured ambient Ca concentrations exceeded the PEL value of 6000 μg/m³, but only 1 exceeded 10 times the PEL. Thus, the half-facepiece respirators evaluated in this study were a suitable selection for the workplace environment and tasks encountered in the sinter plant and BOP shop. All the in-facepiece concentrations were dramatically less than the corresponding ambient concentration levels.

The GM ambient and in-facepiece concentrations of Fe were found to vary among tasks. Significant differences were also found to occur between the GM ambient exposure levels in which some of the respirators were used. The highest GM WPF value achieved at the sinter plant was seen with mechanical maintenance workers. However, no significant difference was found in the GM WPF values for different tasks at the sinter plant.

Significant differences in respirator performance as measured by WPF or in-facepiece Fe concentration were observed among different brands of respirators. The MSA and 3M brands DM half-facepiece respirators had a significantly higher GM WPF value than the Gerson brand DM half-facepiece respirator. The Gerson brand DM half-facepiece respirator also had a significantly higher GM in-facepiece Fe concentration than the Cabot brand DM half-facepiece respirator. The fifth percentile estimates for the WPF distributions for each respirator were all greater than 20.

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