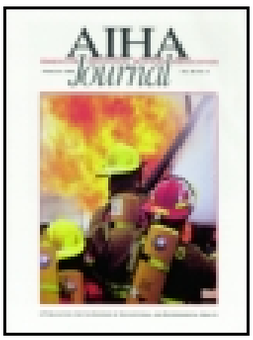

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Correlation Between Quantitative Fit Factors and Workplace Protection Factors Measured in Actual Workplace Environments at a Steel Foundry

AUTHORS
Ziqing Zhuang[a]
Christopher C. Coffey[b]
Paul A. Jensen[b]
Donald L. Campbell[b]
Robert B. Lawrence[b]
Warren R. Myers[c]

[a]National Personal Protective Technology Laboratory, National Institute for Occupational Safety and Health (NIOSH), 626 Cochrans Mill Road, Pittsburgh, PA 15236;
[b]Division of Respiratory Disease Studies, NIOSH, 1095 Willowdale Road, Morgantown, WV 26505;
[c]Department of Industrial and Management Systems Engineering, West Virginia University, Morgantown, WV 26506

Past studies have found little or no correlation between workplace protection factors (WPFs) and quantitative fit factors (FFs). This study investigated the effect of good- and poor-fitting half-facepiece, air-purifying respirators on protection in actual workplace environments at a steel foundry and the correlation between WPFs and FFs. Fifteen burners and welders, who wore respirators voluntarily, and chippers participated in this study. Each subject was fit-tested with two respirator models each with three sizes, for a total of six fit-tests. Models and sizes were assigned this way to provide a wide range of FFs among study participants. Each worker donned the respirator twice per day (at the beginning of the shift and following the lunch break) for 2 days. Quantitative FFs were first obtained for each donning using the PortaCount Plus™ in a separate room. Without redonning the respirators, workers performed normal work for 1 to 2 hours, and WPFs were measured by collecting ambient and in-facepiece samples simultaneously. A second fit-test was conducted without disturbing the respirator. FFs were obtained by averaging the results from the first and second fit-tests. The resulting FFs had a geometric mean (GM) of 400 (range=10–6010) and a geometric standard deviation (GSD) of 6.1. Of the 55 valid donnings, 43 were good fitting (FFs≥100) and 12 were poor fitting (FFs<100). The WPFs had a GM of 920 (range=13–230,000) and a GSD of 17.8. The WPFs were found to be significantly correlated with the FFs (R^2=.55 and p-value=.0001). Therefore, FF was shown to be a meaningful indicator of respirator performance in actual workplace environments.

Keywords: half-facepiece respirators, in-facepiece sampling, quantitative fit-test, workplace protection factors

For approximately 10 years, beginning in the early 1970s, it was assumed that quantitative fit-test results were indicative of the performance of a respirator in the workplace.[1,2] If this assumption is true, a correlation should exist between measured respirator fit and measured respirator protection. During the 1980s and 1990s the National Institute for Occupational Safety and Health (NIOSH) and others conducted studies of how respirators performed in actual workplaces.[3–9] These studies measured the amount of protection provided by the respirator by measuring the concentrations of workplace contaminants inside and outside of the respirator. In addition, efforts were made to establish the relationship of quantitative fit factors (FFs) and workplace protection factors (WPFs). However, significant correlation between the two was found on only one respirator at one work site.[10]

Because workplace studies had consistently found no correlation between quantitative FFs

and WPFs, two studies took a new approach using breath analysis and found a relationship between FFs and performance.[11,12] The breath analysis approach eliminates particle size effects, increases test rigor by using a more challenging test agent (i.e., vapor instead of an aerosol), and eliminates in-mask sampling problems by using exhaled breath as an index of worker exposure. Respirator performance is directly related to actual exposures received by the test subject's lung. Decker and Crutchfield[11] found a significant correlation (R^2 = .82) between FFs obtained with a controlled negative pressure device and protection factors (i.e., Freon® concentration in a chamber divided by Freon concentration inside the respirator measured with the breath-analysis technique).

Coffey et al.[12] compared FFs from six quantitative fit-test methods with exposure dose of Freon-113 while subjects wore nonpowered, air-purifying, half-facepiece respirators. FFs of two fit-test methods (corn oil and ambient aerosol) were found to be significantly correlated with the wearers' measured exposure doses. A strong correlation between exposure dose of Freon-113 and FFs was found (R^2=.71; p-value=.001) when all of the data for the three fit-test methods with the highest correlations were analyzed. But when only the FFs of 100 or greater for the three fit-test methods with the highest correlations were analyzed, little correlation was found between exposure dose of Freon-113 and FFs (R^2=.10; p-value>.05). These results may provide a possible explanation of why previous workplace studies found little to no correlation between quantitative fit-test results and WPFs. For a worker to participate in a workplace study, he or she must have passed an accepted fit-test in accordance with Occupational Safety and Health Administration (OSHA) regulations (Title 29, *Code of Federal Regulations,* 1910.134).[13] Thus, previous workplace studies attempted to correlate only FFs of 100 or greater with WPFs. Because the study by Coffey et al.[12] was a simulated WPF study, persons having FFs less than 100 were included.

The purpose of this present study was to investigate the effect of good- and poor-fitting half-facepiece, air-purifying respirators on protection in actual workplace environments at a steel foundry and the correlation between WPFs and quantitative FFs. This study was designed in such a way that the FFs varied over a wide range. This article presents the protocol for the present study and results of correlation analyses of ambient and in-facepiece concentrations, FFs, and WPFs measured on workers using elastomeric half-facepiece respirators. Factors affecting the correlation between WPFs and FF are also identified and discussed.

METHODS AND MATERIALS

Facility Selection

The steel foundry was selected because it met the following criteria.

- Some jobs existed for which ambient concentrations were less than OSHA permissible exposure limits (PELs), and respirators were not required, but workers wore respirators voluntarily, and all aspects of a respiratory protection program existed (i.e., the company had a complete respirator program and workers were experienced respirator users).
- Half-facepiece, nonpowered air-purifying respirators were in use.
- Workers were trained in the use of at least one brand of half-facepiece respirator, and management was willing for them to be trained to use the other brand of respirators employed in the study.
- Job tasks existed that allowed uninterrupted respirator wear and required a minimum of 1 hour to complete.

Worker Selection, Instruction, and Monitoring

Fifteen workers were selected to participate in this study from a pool of workers who met certain criteria. Their job titles included burner, welder, and chipper. Worker volunteers were selected based on the following considerations.

- They wore respirators as part of their routine, normal work activity.
- Their exposure to the airborne particulate agent was less than the OSHA PEL even if a respirator was not worn, based on previous sampling results; if their previous exposure measurements were greater than the OSHA PEL but less than 10 times the PEL, they were allowed to wear a respirator only with a FF greater than or equal to 100.
- They met the criteria specified in Title 29, *Code of Federal Regulations,* 1910.134 for respirator wearers, such as exclusion of beards, sideburns, and so forth.[13]
- They had been evaluated by a doctor and had medical approval to use a respirator.

Each worker was instructed how to properly don and use his respirator. These instructions were provided in accordance with the respirator manufacturer's instructions regarding the use of the respirator. Each worker participating in this study was also given explicit instructions not to remove the respirator or lift the body of the respirator from his face while in his work area. Workers were allowed to reposition the facepiece in the work area if it slipped or they needed to alleviate pressure points, but it had to be done by sliding the facepiece on the face. To assure that these requirements were not disregarded, and to monitor the integrity of the sampling trains, the activities of the workers were observed periodically when air samples were collected.

Worker Facial Dimension Measurement

Workers' lip length and face length were measured with a sliding caliper. Their face widths were measured with a spreading caliper. For workers in areas where contaminant concentrations were so low that respirators were not necessary, the facial dimensions were used to aid in selecting respirator size to have a wide range of FFs.

Respirator Selection, Inspection, and Use

Two NIOSH approved half-facepiece, nonpowered air-purifying, elastomeric respirators were included in this study. Specific brands/models were selected in part based on initial contact with the test site regarding what brand was used. They were 3M 6000 series respirators (3M, St. Paul, Minn.) and MSA Comfo® II respirators (MSA, Pittsburgh, Pa.). These respirators were equipped with P-100 filters.

Respirators were probed for in-facepiece sampling and checked for sources of leakage at the facepiece-probe interface. Respirator probing was done to minimize any impact of the probe and accompanying in-facepiece sampling train on the fit and function of the respirator. The respirators probed for use in the field testing were also used for quantitative fit-testing and training. All respirators were maintained by the research field team according to the manufacturer's instructions. Respirators were cleaned, and the valves, head straps, facepiece body, filter attachments, and so forth were inspected for damage at the end of each test period. Air-purifying filters were changed at the end of each test period.

Fit-Test Procedures

The two elastomeric respirators were available in three sizes. Workers were first fit-tested with each respirator model and size. Fit-tests were performed using the TSI Portacount Plus™ (model 8020; TSI, St. Paul, Minn.). These fit-tests used six exercises each lasting only 30 sec, because the purpose of these fit-tests was to more rapidly select a respirator for later use by each worker. Thus, the results are not reported. The size assigned to each worker was selected based on the six exercise FFs and worker facial dimensions to assure a wide range of FFs in this study. Some workers were allowed to wear respirators with FFs less than 100. Each worker wore only one respirator model and size.

A standard fit-test was conducted before and after each WPF sample was collected. Fit-testing was done in a room near the working areas. Four TSI Portacount Plus fit-test instruments were used to detect the aerosols, with the same probe used for in-facepiece sampling. The quantitative fit-test protocol used in the study is detailed in Title 29, *Code of Federal Regulations*, 1910.134.[13] The method entailed performing eight exercises for approximately 1 min each, except for the grimace exercise, which was performed for 15 sec. FFs were obtained for each exercise. An overall FF was calculated from FFs for each exercise except grimacing. An overall FF of 100 or above constituted a pass.

WPF Sample Collection

Workers wore the test respirators for the period of time that constituted their normal work shift or normal respirator use time. WPF samples were collected over two separate time periods during a shift. One WPF sample (simultaneous sampling of ambient and in-facepiece) was taken at the beginning of the shift and a second WPF sample right after lunch break. Sampling periods lasted at least 1 hour and up to 2.5 hours of respirator wear. Workers were sampled on two different shifts, so four WPF samples were collected for each worker.

Ambient Sampling. Estimates of ambient airborne concentration outside the respirator (C_o) were made with traditional personal sampling methods and collected as total dust samples. Cassettes used to collect C_o samples were attached to the lapel in the general area of the worker's breathing zone. Cassettes were attached to the right or left lapel at the discretion of those "suiting up" the workers for testing. Ambient sampling was done with a setup employing a 25-mm closed-faced cassette, hose, and sampling pump. No probe was used on the C_o samples to minimize sample losses, and C_o might have been underestimated. Each cassette incorporated a polypropylene backup pad and a mixed cellulose ester membrane filter (SKC, Eighty Four, Pa.) with pore size of 0.8 μm. A flow rate of 2 L/min was used.

In-facepiece Sampling. The in-facepiece samples (C_i) were also collected as total dust samples. The sampling train was consistent with the C_o sampling train. The in-facepiece samples were collected by a probe inserted through the facepiece of the respirator. The probe was located in an area roughly opposite and 6.5 mm (¼ inch) in front of the wearer's mouth. The inlet probe used for the collection of in-mask samples complies with Davies's criteria for sampling through inlet tubes, and its sampling efficiency has been experimentally defined.[14] A detailed description of this in-facepiece sampling procedure and its associated sampling bias and precision was reported by Myers and Hornung.[15] The 25-mm closed-faced cassette was attached directly to the facepiece probe. Each cassette incorporated a polypropylene backup pad and a polycarbonate filter (SKC) with pore size of 0.8 μm. The sampling rate for in-facepiece samples was approximately 2 L/min. The in-facepiece sample was a continuous sample collected over the inhalation and exhalation phases of the respiratory cycle. The presence of liquid condensate in the in-facepiece cassette was controlled through the use of a cassette heating bonnet (3M). The heating bonnet used a rechargeable battery to energize a heating wire in the bonnet.

Personal Sampling Pumps. Constant flow personal sampling pumps used for sampling were Gilian® HFS513 (Sensidyne, Clearwater, Fla.). They were calibrated using a DryCal DC-Lite primary flow meter (BIOS International, Pompton Plains, N.J.) and a completely assembled sampling train at the study site. Calibration was checked prior to and immediately after each complete WPF sampling day. These flow rate measurements were averaged. If the flow rate of a pump deviated from the targeted flow rate of 2 L/min by more than 5%, the pump was recalibrated before it was reused. The operation of each pump was monitored, roughly every 15–20 min, throughout the WPF sampling period.

Working Blank and Manufacturer's Blank. Working blank (WB) cassettes were used to measure potential contamination of ambient and in-facepiece sample filters that might result from handling the filters and cassettes during assembly, sample collection, and analysis. The average mass on the filters of the WBs was used as a correction factor (i.e., to account for background contamination) for the mass levels on the ambient and in-facepiece filter samples. The WBs were handled like the WPF sample cassettes in all ways. The capped WB cassette was attached to the worker close to his breathing zone. Each time the WPF sampling cassettes were capped or uncapped, the WB cassette was capped or uncapped. Each worker participating in this study was equipped with a WB cassette during one WPF sample collection.

Manufacturer's blanks (MB) were unused filters loaded into unused cassettes. The MBs were used to determine whether appreciable amounts of background contamination existed on the filters or cassettes by virtue of the raw materials used, the manufacturing process, or other factors. These MB samples were analyzed immediately after being assembled.

Sampling Procedure. The respirator and sampling trains were donned in a room near the work areas. The room was also where equipment was removed at the end of each worker's sampling period. New cassettes were used at the start of each new WPF sampling period. After the inlet caps were removed, the C_i sampling cassette was attached to the respirator and the C_o sampling cassette was placed on the lapel. The tubing for each sample was fitted with a quick disconnect. The pumps of the ambient and in-facepiece sampling trains were started or stopped simultaneously. A research team member was assigned to monitor each worker or small group of workers (usually three or fewer) in close proximity. The monitors observed respirator use and mediated problems workers had during the WPF sampling.

WPF. A WPF is a measure of the protection provided in the workplace, under the conditions of that workplace, by a properly selected, fit-tested, and functioning respirator while it is correctly worn and used.[16] It is calculated by dividing the ambient concentration (C_o) by the concentration measured inside the respirator (C_i). Because of the way respirators were assigned to individual workers in this study, the WPF values measured for FFs less than 100 should not be used to assess the performance of a respirator model or a class of respirators.

Particle Size Sample Collection

Area impactor samples were also collected in this study. The impactor samples were used to determine particle size distributions

TABLE I. Job Title and Facial Anthropometrics of Workers and Assigned Respirator Size

Worker	Job Title	Face Length (mm)	Face Width (mm)	Lip Length (mm)	Face Size	Respirator	Size
1	burner	121	155	59	8	3M	medium
2	burner	115	130	51	7	MSA	medium
3	burner	121	130	53	8	3M	small
4	chipper	110	130	53	5	3M	medium
5	welder	125	160	56	10	MSA	medium
6	welder	111	135	55	5	MSA	medium
7	welder	120	149	57	8	3M	medium
8	chipper	125	130	57	10	MSA	large
9	chipper	124	138	55	10	MSA	large
10	chipper	105	140	57	5	3M	medium
11	chipper	125	139	49	9	3M	large
12	welder	120	142	55	8	3M	small
13	burner	127	136	53	10	3M	large
14	burner	120	127	56	8	MSA	medium
15	burner	121	144	58	8	MSA	small

Note: Workers' face sizes were determined based on the current half-mask fit-test panel;[21] workers 3, 12, and 15 were intentionally assigned small respirators instead of medium or large sizes to have a wide range of fit factors; worker 5 was assigned a medium respirator instead of a large size.

and the appropriate agent to measure WPF. Iron was selected as the agent to measure respirator performance in this study based on its particle size distribution characteristics.

Sample Analysis

The C_i sample filters, WBs, and MBs were analyzed by proton induced X-ray emission (PIXE) analysis.[17] Briefly described, PIXE is an X-ray spectroscopic technique, which can be used for nondestructive, simultaneous analysis of solid or liquid aerosol filter samples. The detection limit for iron was 0.0043 μg per sample.

The C_o and impactor sample filters were analyzed by inductively coupled plasma (ICP) method, because filter mass might be underquantified by PIXE due to heavy loading on the filters. The samples were digested and analyzed according to NIOSH Method 7300 for filter digestion.[18] The limit of detection was 1 μg per sample for iron. The limit of quantitation was 3 μg per sample for iron.

TABLE II. Summary of MBs and WBs

	Iron Mass (μg)		
Sample No.	MB Filters (Polycarbonate)	WB Filters (Polycarbonate)	MB Filters (Mixed Cellulose Ester)
1	0.050	0.064	3.4
2	0.053	0.028	1
3	0.043	0.068	2
4	0.070	0.044	1
5	0.071	0.085	2
6		0.089	1
7		0.086	2
8		0.077	0.5
9		0.062	2
10		0.092	1
11		0.039	
12		0.040	
13		0.044	
14		0.053	
15		0.070	
Mean	0.058	0.063	1.6
SD[A]	0.012	0.021	0.85

Note: The MB and WB polycarbonate filters were analyzed by PIXE and used to determine the background contamination for in-facepiece samples; the MB mixed cellulose ester filters were analyzed by ICP and used to determine the background contamination for ambient samples.
[A]Standard deviation.

Statistical Analyses

Data were analyzed using correlation analysis. WPF was the dependent variable, and the independent variable was FF. Statistical analysis was performed by using the Statistical Analysis System (SAS®) software.[19] Regression analyses were done on the log-transformed data.

The data for impactor samples were further analyzed using a spreadsheet program. The microcomputer spreadsheet was used to fit a smooth curve to grouped (histogram) particle size data, that is, the cascade impactor data. This method was based on the assumption that multimodal particle size distributions could be adequately described by a linear combination of weighted lognormal distributions. This method yielded a fitted smooth curve and estimates of the parameters of each underlying distribution: geometric mean (GM), geometric standard deviation (GSD), and the percentage (a) each underlying distribution contributes to the overall distribution.[20]

RESULTS

Job title, face size, and the respirator brand/size assigned for each worker are provided in Table I. Workers' face sizes were determined using the current fit-test panel for half-masks, which classifies faces into sizes 1 to 10 based on lip length and face length.[21] Three workers with face size 8 were supposed to wear medium or large respirators, but they were asked to wear small respirators. Another worker with face size 10 was asked to wear a medium respirator. These workers were later found to have poor-fitting respirators, that is, FFs were less than 100 for some donnings.

The results of the MB and WB samples are summarized in Table II. The mean mass on the WB polycarbonate filters analyzed by PIXE was 0.063 μg, which was not statistically significantly different from the mean mass of 0.058 μg on the MB polycarbonate filters. This mean value (0.063 μg) was used as a correction

TABLE III. Ambient Sample Volume (V_o), Ambient Iron Concentrations (C_o_Fe), In-Facepiece Sample Volume (V_i), In-Facepiece Iron Concentrations (C_i_Fe), Workplace Protection Factors (WPF), and Fit Factors (FF)

Worker	Test Date	Sampling Period	V_o (m^3)	C_o_Fe ($\mu g/m^3$)	V_i (m^3)	C_i_Fe ($\mu g/m^3$)	WPF	FF
1	9/12/00	A	0.180	4710	0.234	59.8	79	554
1	9/13/00	A	0.200	12,900	0.179	668	19	108
1	9/13/00	B	0.120	7690	0.143	0.03	230,000	848
2	9/12/00	A	0.229	5970	0.235	0.09	68,600	931
2	9/12/00	B	0.153	5030	0.157	11.9	422	217
3	9/13/00	A	0.326	8440	0.284	260	32	18
3	9/13/00	B	0.172	10,700	0.149	225	48	19
3	9/14/00	A	0.248	19,400	0.253	587	33	13
3	9/14/00	B	0.146	18,800	0.149	1080	17	10
4	9/14/00	A	0.154	10,400	0.144	1.89	5520	6010
4	9/14/00	B	0.123	8220	0.114	1.10	7460	594
4	9/15/00	A	0.151	4390	0.144	8.60	510	136
4	9/15/00	B	0.124	9320	0.118	0.26	36,200	794
5	9/14/00	A	0.301	3140	0.302	54.0	58	26
5	9/14/00	B	0.113	2460	0.114	6.49	379	210
5	9/15/00	A	0.250	3710	0.243	19.4	191	484
5	9/15/00	B	0.133	642	0.129	9.69	66	397
6	9/11/00	A	0.203	4260	0.199	69.8	61	70
6	9/11/00	B	0.137	4920	0.134	13.9	354	246
6	9/12/00	A	0.240	3470	0.245	48.4	72	62
6	9/12/00	B	0.178	4260	0.185	126	34	11
7	9/11/00	A	0.263	1260	0.271	7.05	178	2320
7	9/12/00	A	0.141	422	0.261	0.96	439	587
7	9/12/00	B	0.222	881	0.238	10.4	85	80
8	9/14/00	A	0.258	3310	0.250	69.5	48	261
8	9/14/00	B	0.131	6210	0.127	2.62	2370	2670
8	9/15/00	A	0.220	2580	0.229	3.70	697	653
8	9/15/00	B	0.123	940	0.128	5.59	168	123
9	9/11/00	A	0.269	15,600	0.263	0.26	61,100	926
9	9/11/00	B	0.120	4850	0.118	0.10	48,000	4940
9	9/12/00	A	0.275	3200	0.278	0.13	24,100	3500
9	9/12/00	B	0.137	4200	0.138	0.03	143,000	1450
10	9/14/00	A	0.250	15,100	0.252	148	102	1340
10	9/14/00	B	0.141	1410	0.142	9.93	142	2050
10	9/15/00	A	0.206	5590	0.215	1.90	2940	2900
10	9/15/00	B	0.140	2960	0.145	26.9	110	124
11	9/11/00	A	0.121	4550	0.123	0.03	138,000	2890
11	9/11/00	B	0.109	3160	0.111	0.16	19,400	4850
11	9/12/00	A	0.282	6210	0.290	24.3	255	824
11	9/12/00	B	0.144	1220	0.148	3.47	350	2400
12	9/12/00	A	0.316	423	0.307	5.13	83	126
12	9/12/00	B	0.230	895	0.223	0.02	51,400	1160
12	9/13/00	B	0.139	865	0.139	65.4	13	15
13	9/13/00	A	0.274	4480	0.268	1.62	2774	1470
13	9/13/00	B	0.171	2580	0.167	0.02	110,000	3700
13	9/14/00	A	0.203	13,100	0.114	0.99	13,300	1150
13	9/14/00	B	0.144	12,100	0.133	3.19	3780	2090
14	9/13/00	A	0.227	7100	0.066	0.10	74,300	1280
14	9/13/00	B	0.181	2400	0.163	0.65	3680	2520
14	9/14/00	A	0.221	8800	0.216	1.68	5230	672
14	9/14/00	B	0.147	8380	0.143	1.57	5330	1170
15	9/13/00	A	0.275	4350	0.276	1.91	2270	1620
15	9/13/00	B	0.149	6530	0.150	55.1	118	76
15	9/14/00	A	0.186	5350	0.183	279	19	15
15	9/14/00	B	0.149	9520	0.147	2.32	4100	228

factor for the in-facepiece samples. Because the masses on some in-facepiece sample filters were small, the corrected masses were less than the limit of detection (0.004 μg) or even less than zero, thus, the corrected masses were assigned a value of 0.004 μg. This resulted in a conservative estimate of WPFs. Nine of the 10 MB mixed cellulose ester filters analyzed by ICP had filter mass less than the limit of quantitation (3 μg), which was three times the limit of detection. The mean iron mass was 1.6 μg, which was much less than the iron mass seen on the ambient samples. Thus, the ambient samples did not need to be corrected for handling error.

A paired t-test did not show significant difference between the

TABLE IV. Summary of Parameters From Regression Analyses

	Dependent Variable (Y)	Independent Variable (X)	Constant (a)	Coefficient (b)	R^2	p-Value
All data	Log(WPF)	Log(FF)	−0.087	1.17	0.55	0.0001
FF < 100	Log(WPF)	Log(FF)	0.601	0.714	0.71	0.0006
FF ≥ 100	Log(WPF)	Log(FF)	−0.523	1.32	0.32	0.0001
FF ≥ 500	Log(WPF)	Log(FF)	1.91	0.580	0.03	0.3683
All data	Log(WPF)	$Log(C_i)$	3.583	−0.949	0.90	0.0001
	Log(WPF)	$Log(C_o)$	1.052	0.529	0.03	0.2087
	$Log(C_i)$	$Log(C_o)$	−1.041	0.467	0.02	0.2663

Note: The regression equation is Y = a + b * X.

FF measured before the work period and the FF measured after the work period. This suggested that either the face seal did not change substantially during the work period, or if the facepiece was substantially disturbed during the work period, the seal tended to restabilize to FFs not statistically different from the initial. For the purpose of this analysis the arithmetic average of initial and final FFs was calculated and subsequently called and reported as "FFs."

A total of 58 WPF samples was collected. Three samples were voided due to pump failures. Table III summarizes the ambient iron concentrations, in-facepiece iron concentrations, WPFs, and FFs for each observation. Normality tests failed to reject the hypotheses at a significance level of 1% that the log-transformed ambient concentrations, in-facepiece concentrations, WPF data, and FFs came from normal distributions. The WPFs had a GM of 920 (range=13–230,000) and a GSD of 17.8. The FFs had a GM of 400 (range=10–6010) and a GSD of 6.1. Of the 55 valid donnings, 43 were good fitting (FFs≥100) and 12 were poor fitting (FFs<100). The GM WPF for good fitting was 2210 with a GSD of 14.0. The fifth percentile was 29, which was well above the assigned protection factor of 10 required of this class of respirators. For poor-fitting donnings the GM WPF was 40 (GSD=2.0), which was significantly smaller than the GM WPF for the good-fitting donnings. The fifth percentile was only 13.2. Thus, good-fitting respirators based on quantitative fit-tests had significantly higher WPFs than poor-fitting respirators.

The log-transformed WPF data and in-facepiece iron concentration (C_i_Fe) data were strongly correlated (R^2=.90 and p<.01). However, the log-transformed WPF data and ambient iron exposure (C_o_Fe) data were not significantly correlated (R^2=.03 and p>.05). A correlation analysis was also performed to evaluate the association between ambient iron exposures (C_o_Fe) and the corresponding levels of in-facepiece iron concentration (C_i_Fe). But the log-transformed C_i data and C_o data were not significantly correlated (R^2=.02 and p>.05). The regression parameters are summarized in Table IV.

Significant correlation was found between WPF and FF when the data were analyzed together (Figure 1). The slope of log WPF against log FF was 1.17 in this model, and the R^2 value was 0.55 (Table IV). The slope was not significantly different from 1 (p>.05). When only FFs less than 100 (the pass/fail level) were analyzed, the R^2 value was increased to 0.71. In contrast, the R^2 value was only 0.32 when FFs greater than or equal to 100 were analyzed. There was no significant correlation between WPF and FF (R^2=.03 and p>.05) when FFs greater than or equal to 500 were analyzed.

The data were also analyzed to evaluate the ability of FFs for a particular donning to predict the respirator performance for all donnings. The log-transformed WPFs were first averaged for each subject, and the mean for each subject became the dependent variable. The independent variable was the FF for a particular donning. Significant correlation was found between the mean log-transformed WPFs and the FFs for the first donning (R^2=.43, p=.0083). This significant correlation held true for the second, third, and fourth donning. That is, FFs for a particular donning can predict future respirator performance.

The mass fraction per stage for the impactor samples is summarized by job title in Table V. Iron concentrations of all stages are also reported in the table. The mean iron concentration of all stages did not exceed the OSHA exposure limit of 10,000 μg/m³ regardless of job titles. The particle size data for each task were generally well fitted with two mode distribution models. The parameters (GM, GSD, and a) are reported in Table V. The mean particle diameter for mode 1 for burners was similar to that for chippers. This trend was also true for mode 2. The area under the curve for the first mode for burners was larger than that for chippers, indicating burners were exposed to more smaller particles than chippers.

DISCUSSION

Since at least 1986 a number of questions have surrounded quantitative fit-testing, such as whether a respirator that gives proper fit during a quantitative fit-test will provide adequate protection on the actual job. Past WPF studies were conducted to

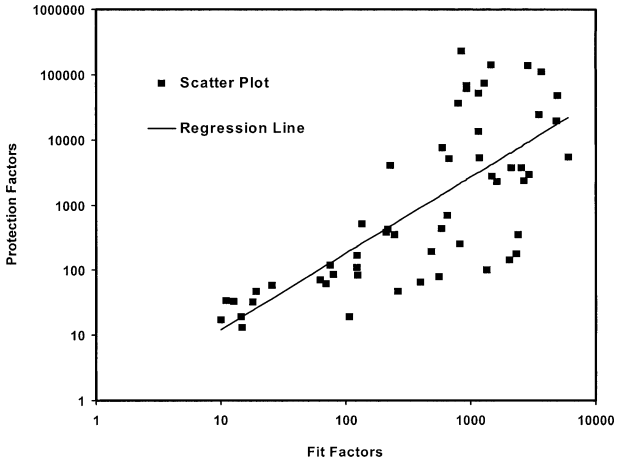

FIGURE 1. Plot of WPFs against FFs and the regression line

TABLE V. Mass Fraction and Aerodynamic Particle Size (D_p) Distributions of Iron by Job Title

Stage	Cut-Point Diameter (μm)	Particle Size Range	Mass Fraction			
			Burners (n = 5)		Chippers (n = 5)	
			Mean	(SD)	Mean	(SD)
1	21.3	>21.3	0.177	0.054	0.178	0.049
2	14.8	14.8–21.3	0.122	0.030	0.190	0.019
3	9.8	9.8–14.8	0.123	0.028	0.184	0.012
4	6.0	6.0–9.8	0.115	0.025	0.157	0.013
5	3.5	3.5–6.0	0.117	0.018	0.158	0.018
6	1.55	1.55–3.5	0.064	0.006	0.058	0.004
7	0.93	0.93–1.55	0.034	0.024	0.009	0.004
8	0.52	0.52–0.93	0.048	0.024	0.014	0.003
F	<0.52	<0.52	0.200	0.093	0.052	0.025
Iron (μg/m³) all stages			1576.3	660.0	3834.8	1368.4
Mode 1		a	0.09		0.015	
		Mean D_p (μm)	0.90		0.85	
		GSD	1.1		1.1	
Mode 2		a	0.91		0.985	
		Mean D_p (μm)	15.8		14.4	
		GSD	2.9		2.5	

address those questions. But correlation between WPFs and quantitative FFs was not found. This study is the first to find a significant correlation between WPFs measured in actual workplace environments and quantitative FFs.

Because previous studies did not find correlation between WPFs and FFs, theories on why FFs did not correlate with WPFs were developed, such as (1) the standard quantitative fit-test exercises do not mimic closely enough the movements of the worker while normal job activities are performed; (2) differences in breathing rate of the worker occur during the quantitative fit-testing and while performing job tasks; (3) the face-seal penetration of the quantitative fit-test agents could be different from that of workplace contaminants; and (4) moisture in the breath could lower the quantitative fit-test results artificially.[4] Others have suggested that the following assumptions on which quantitative fit-tests are based may not be valid: (1) aerosol fit-test results can be applied to all other types of contaminants; (2) aerosol samples taken inside the respirator are representative of the exposure the wearer is actually receiving; and (3) exercise protocols used during quantitative fit-testing make them more predictive.[22]

Crutchfield[22] suggested that the solution to the problem is to develop a universal test protocol. This universal fit-test protocol would adjust the quantitative fit-test results to resolve the differences in aerodynamic properties between the aerosols used during the quantitative fit-testing and those aerosols in the workplace against which the respirator would be used. Crutchfield also suggested that the capability of aerosol test systems to measure leaks on human subjects should be compared with a primary leak-flow measurement system.

The results from this study confirm the observations in the study by Coffey et al.[12] that compared the FFs from six quantitative fit-test methods under laboratory conditions against the received exposure dose of 1,1,2 trichloro-1,2,2 trifluoroethane (Freon-113). Quantitative FFs have now been found to be relevant to respirator performance in actual workplace environments. When all of the data were analyzed, a statistically significant correlation between WPFs and FFs was found (R^2=.55; p=.0001). However, an R^2 value of .55 for all data was statistically significant, but might not be decisive enough to conclude that FFs were reliable (i.e., "meaningful") predictors of workplace performance (i.e., 45% of variability was unexplained). An R^2 value of .71 was obtained for FFs below 100. When only the FFs of 100 or greater were analyzed, only a weak correlation was found between WPFs and FFs (R^2=.32; p=.0001). This observation may be attributed to the large variation in WPF values and FF values for FFs greater than 100. This study also explained that one of the reasons FFs were not correlated with WPFs in previous field studies was that WPFs were only measured on good fitting respirators, that is, FFs greater than 100.

Another reason this study found significant correlation between WPFs and FFs was that WPF samples were collected without redonning of the respirators. In most previous WPF studies, fit-tests were conducted first and WPF samples were collected on later days.[7–9] FFs and WPFs were collected on different donnings of the same respirator. There was one exception; Dixon and Nelson[4] found no correlation between FFs and WPFs, even though their study did not involve removing the respirator.

Zhuang et al.[23] analyzed a data set of 20,974 PortaCount fit-tests conducted at various workplaces to determine whether PortaCount FFs are affected by ambient concentration. The ambient concentrations were divided into five levels (≤2000; >2000 and ≤4000; >4000 and ≤ 6000; >6000 and ≤12,000; and >12,000 particles/cm³) and Duncan's multiple range test was performed to determine if the FFs vary among the five levels. Geometric mean overall FFs increased three- to fivefold as the ambient concentration increased from less than 2000 particles/cm³ to greater than 12,000 particles/cm³ in both the half-facepiece and the full-facepiece data sets (p<.01). In this study, ambient concentrations and particle size distributions in the room where fit-tests were conducted might have played an important role in finding the correlation between WPFs and FFs. The fit-test room was inside the workshop where WPF samples were collected, and the door was open while fit-tests were conducted and remained open most of the time during WPF data collection. Particle size data were not collected in the fit-test room. The ambient concentration data was obtained from the PortaCount FF data. Particles greater than 2 μm are not detected well by the PortaCount due to inertia losses in the sample line and the dynamics of the condensation nuclear counter sensor. Of the 106 fit-tests for which ambient concentration data were recorded, ambient concentrations for 100 fell into only two of the five levels (>6000 and ≤12,000; and >12,000 particles/cm³). FFs were not

affected by ambient concentration level ($p>.05$). Thus, there was no artifact in the FF measurement in this study. In addition, particle sizes in the fit-test room might be close to those in the workshop. Future WPF studies should collect ambient concentration and particle size data in the room where fit-tests will be conducted.

Another speculation regarding the difficulty in finding correlation between the WPF and FF is that the quantitative fit-test is not long enough. A simulated WPF study was conducted to compare the quantitative FFs from the more standard set of six exercises lasting 8 min with the quantitative FFs from a more comprehensive set of 17 exercises lasting 30 min.[24] The subjects in the study wore full-facepiece respirators and were fit-tested using six exercises. The subject then performed 17 exercises for 30 min, during which FFs were measured for each exercise. The results indicated that quantitative FFs were not significantly different between the two sets of exercises.

Another recent study was conducted by Coffey et al.[25] to quantitatively fit-test 21 N95 respirator models to evaluate their laboratory performance and to determine whether their laboratory performance could be improved when the first donning was used as a surrogate fit-test to screen out poor-fitting respirators. Each respirator model was tested on a panel of 25 subjects with varying face sizes. Four total penetration tests were conducted for each subject/respirator combination, resulting in a total of 100 measurements for each respirator model. When the first donning was used as a surrogate fit-test to separate the subjects into two groups (one passing the fit-test and the other failing the fit-test), significant differences in total penetration and face-seal leakage were found between the two groups ($p=.0003$). The results showed that the laboratory performance of an N95 respirator was greatly enhanced when quantitative fit-testing was performed to screen out poor fits. This observation was consistent with that in this study, that is, good-fitting respirators based on quantitative fit-tests ($FF\geq100$) had significantly higher WPFs than poor-fitting respirators ($FF<100$).

CONCLUSIONS

Significant correlation was found between WPFs and FFs when measurements were made during the same donning of the respirator. Workers with higher FFs in the fit-test tended to have higher WPFs during the work periods, when there was no removal and redonning of the respirator in the time between the measurement of the WPF and FF. Thus, the study suggested that there was some value in using fit-tests to identify workers who have poor respirator fit with a particular respirator model. In that sense the study supported the relevance of fit-testing as part of a respirator program. The study also supported the possible use of laboratory tests (similar to fit-tests) as a surrogate for workplace tests. The study did not take into account the considerable donning-to-donning variation in both FFs and WPFs. Thus, these results should not be taken to indicate that a measured FF will be predictive of subsequent WPFs after the respirator has been redonned. In that case the variation introduced by redonning must be taken into consideration.

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