Measuring Performance of a Half-Mask Respirator in a Styrene Environment

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A workplace protection factor (WPF) study was conducted with a half-mask air-purifying respirator during fiber glass boat production. Styrene was the measured analyte, and the geometric mean WPF found was 39.7. Analytical detection limits, sample contamination, and pulmonary elimination from previous exposures or from skin absorption were identified as important considerations that can bias the WPFs measured. There were significant differences in the mean concentrations found inside the respirator when analyzed by time period. An increase in the concentration found inside the facepiece cavity and a decrease in the WPF over time was found for people with three or four measurements. This indicates either a change in performance of the respirator over time or a bias from low-level exposures during the day or skin absorption.

Keywords: air-purifying respirator, styrene, workplace protection factor

A workplace protection factor (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 when it is correctly worn and used.[1] It is defined as the workplace contaminant concentration the user would inhale if he or she were not wearing the respirator (C_o) divided by the workplace concentration inside the respirator facepiece (C_i). Both C_o and C_i are determined from samples taken simultaneously, only while the respirator is worn and used during normal work activities.

Collecting and analyzing gases and vapors inside a hot and humid respirator cavity pose some unique and different challenges compared with collecting and analyzing particles. The collection efficiency of most gases and vapors on charcoal is affected by high temperatures and humidity, whereas particle sampling is typically more reliable under similar conditions. Analysis techniques for charcoal sorbents typically do not have the sensitivity to show the extremely low concentrations usually found in the respirator; in contrast, a relatively new analysis for particulate mass (or material) called proton induced X-ray emission has detection limits down to the nanogram level. Another challenge unique to gas and vapor WPF studies is dealing with the potential bias of pulmonary and dermal absorption.

The purpose of this WPF investigation was to design and evaluate a study that addresses these challenges and to compare results and challenges found in particle WPF studies.

MATERIALS AND METHODS

A protocol was developed that outlined the sampling method, handling procedure, and analytical techniques. This initial protocol was evaluated in a small pilot study, and factors that would affect the outcome of the final WPF study were identified. The factors identified in the pilot study as important will be discussed later in this article. The working protocol was modified accordingly and implemented. For this WPF study, measurements were made while employees of a fiber glass boat manufacturing facility performed their normal work duties. Styrene was the contaminant measured. The employees wore 3M model 5000 (TC-23C–860) half-mask elastomeric facepiece respirators equipped with organic vapor and dust/mist filters. Special care was taken to control the biases that may have been present in the WPF measurement.

The National Institute for Occupational Safety and Health (NIOSH) analytical method for styrene has a detection limit of about 10 μg.[2] Workplace concentrations of up to 200 ppm

(860 μg/L) styrene were expected to occur during the study. Based on the detection limit of the NIOSH method and anticipated sample times, inadequate amounts of styrene would be found inside the respirator to reliably determine WPFs. An analytical method with a limit of quantification of 0.1 to 1 μg was required to measure the expected WPFs reliably. Limit of quantification is defined as the lowest mass that can be detected that yields acceptable precision.

In this study, styrene was collected by Carbotrap™ sorbent (Supelco Inc., Bellefont, Pa.). Carbotrap is a graphized carbon black that is more hydrophobic than Tenax® GC, or Amberlite® XAD®, two widely used adsorbants for thermal desorption analysis; therefore, the effect of humidity is less, an advantage for this study.(3) Since commercial sampling tubes were not available, stainless steel 6.35 mm (¼ inch) diameter sorbent tubes were hand loaded with 200 mg of the Carbotrap.

A Perkin Elmer ATD 50 thermal desorber (Norwalk, Conn.) equipped with a Hewlett-Packard (Avondale, Pa.) 5890 gas chromatograph and a Hewlett-Packard 5970 mass spectrometer were used to quantify the amount of styrene collected. Desorption time was set for 8 min, at an oven temperature of 250°C. The lower limit of quantification by this method was 0.1 μg.

Each test respirator was probed with a ¼-inch stainless steel elbow. The probe was positioned between the nose and mouth and extended into the respirator cavity 5–7 mm to minimize sample bias.(4,5) Inside facepiece samples were collected by attaching a ¼-inch sorbent tube to the elbow fitting and connecting a sampling pump to the other end.

The air was drawn through the sorbent tubes by MSA Heavy Duty Flow Lite pumps (Pittsburgh, Pa.). The pumps were calibrated before and after each sample with a TSI 67 Mass Flow Meter (Minneapolis, Minn.). The sampling flow rates were from 40 to 135 mL/min.

Samples were collected during distinct time periods as described in following paragraphs. Sample times ranged from 23 to 88 min. The same respirator cartridges and filters were used for the entire day. Previous measurements of cartridge efficiency in a pilot study showed that their capacity was adequate for a full day's use at the expected C_o concentrations.

Field blanks were taken to identify potential contamination due to handling, field storage, and shipment. The blanks were treated in the same manner as the C_o and C_i samples, except no air was drawn through the tubes.

Once the sample period was completed, the sorbent tubes were immediately capped with a metal fitting and transported to a styrene-free environment within 1 hour after the sample period. During the pilot study, field blanks showed the presence of styrene. Apparently, if sample tubes were left in an environment containing styrene, the styrene vapor penetrated plastic caps that were used to seal the sample tubes. This was confirmed with a laboratory experiment. Open sample tubes that were capped and wrapped in plastic, as during the pilot study, were placed in a container with a low concentration of styrene. Analysis of these tubes showed that styrene permeated into the tubes.

Work Site and Participant Considerations

The employees participating in the study were regular users of respirators. To participate, each had to pass a qualitative fit-test. The saccharin fit-test as described in the Occupational Safety and Health Administration lead standard was used.(6)

Each study participant wore flock-lined natural rubber protective gloves (Best, Model 702) and Tyvek® coveralls. Workers wore all their protective clothing, including gloves, while performing job tasks; however, it was observed that participants routinely took off their protective gloves while cleaning their tools in an acetone bath. The breakthrough time for styrene with these specific gloves is 0.17 hours, and the permeation rate is 348 μg/cm³ per minute.(7)

TABLE I. Typical Workday by Time Period

Time Period	Respirator Worn	Duration in Area (min)	Exposure Concentration Range (ppm)
A	no	1–5	1–5
B	yes	~120	40–200
C	no	5–20	5–50
D	yes	~120	40–200
E	no	~30	5–50
F	yes	~120	40–200
G	no	5–20	5–50
H	yes	~120	40–200
I	no	5–10	1–200

Job titles held by participants included gunner and laminator. The gunner's job was to coat the mold by spraying a layer of chopped fiber glass mixed with the styrene-containing polymer system. The laminators used rollers to spread and compress the sprayed mixture evenly over the mold. The work rate was judged to be moderate.(8) The tasks performed required walking about, bending over, and moderate lifting and pushing.

During sample collection, the participants were watched by a study team member. This individual was responsible for observing and noting any sampler problems during the collection period. For example, if the sample pump malfunctioned, sorbent tube was dislodged, or the respirator was removed from the face, the observer noted the problem and the sample was voided.

Pulmonary Background Correction

Vapors can be absorbed readily in the lungs. For styrene the estimated pulmonary absorption is 65%.(9) Once absorbed, vapors can be found in exhaled breath after exposure ceases.(10) Absorption of material through the skin can result in the material being found in the breath, since material in the blood is eliminated partly in exhaled air. For styrene the dermal absorption rate is estimated at 60 μg/cm²/hour.(11) These factors can lead to an under- or overestimation of the concentration inside the respirator and an over- or underestimation of the WPF.

Styrene is eliminated from the body by the breath at several exponential rates. The two main components are a relatively fast half-life of 13–52 min and a longer half-life of 4–20 hours.(12) Estimating the rate of pulmonary elimination is difficult. Leung predicted that an end-of-shift breath sample (8 hour exposure at 50 ppm) would contain 25 ppm styrene.(13) This is a mixed sample in that it contains some of the 50 ppm that was inhaled immediately prior to the collection of the breath sample. At the beginning of the next shift, after a 16-hour period with no exposure, 0.33 ppm was found. At the end of a work week prior to last work shift, 0.74 ppm was found. This indicates that styrene can bioaccumulate.

For this study the workday was broken up into distinct time periods. At this work site, eight periods were identified, A through I. "A" is the period at the start of the workday when employees prepared for the workday; respirators were not worn during this period. Periods C, E, and G represent the times that employees

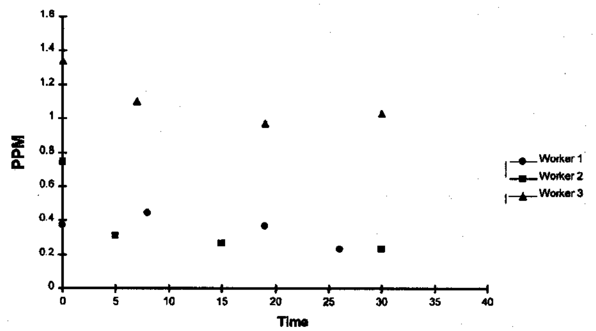

FIGURE 1. Pulmonary elimination

took breaks and ate lunch; therefore, respirators were not worn during these periods. Respirators were worn during Periods B, D, F, and H. The final period at the end of the day, I is similar to Period A, when employees clean up and leave. Time Periods A and I were not continuously monitored as part of this study; however, periodic detector tube samples for styrene were taken. Table I shows the relative times each period lasted and the approximate amount of styrene that was measured for the other periods.

Styrene in the C_i measurement was the result of two sources, pulmonary elimination and leakage into the respirator. Pulmonary elimination is the sum of the styrene concentration in the exhaled breath from exposure to low levels of styrene inhaled during the nonrespirator exposure times A, C, E, and G, plus any contribution from skin absorption and previous day's exposure, both inhaled and dermal.

As part of a pilot study, the pulmonary elimination for several workers was determined to estimate the magnitude of bias that may come from the uncontrolled inhalation exposures in the lunch room and from the previous inhalation and dermal exposures. At different intervals during the day, workers were taken to the lunchroom for approximately 30 min; the workers were placed in a styrene-free environment while wearing a respirator. Several 2–4 min samples were collected from inside the respirator during the next 30 min. The respirator served as a collection chamber and duplicated the measurement of styrene in a WPF study. To produce a styrene-free environment, the worker wore a hooded powered air-purifying respirator (PAPR) equipped with fresh charcoal canisters. Samples collected inside the PAPR hood were found to be free of styrene. Thus, any styrene detected was from the exhaled breath. Figure 1 is a plot of the pulmonary elimination samples. As shown, there is a bias present due to nonwork area exposures.

To correct for this bias would require that the contribution of nonwork exposure be determined for each individual, during individual wear time. This would require that the elimination rate for each individual be determined and the concentration for Exposure Periods A, C, E, and G be measured.

An alternative would be to lessen the contribution from lunchroom exposures by providing a styrene-free atmosphere prior to any WPF measurement. This was the method chosen for this study. Prior to a WPF measurement, the person wore the respirator while working for a 30-min time period before the pumps were started to collect the samples for the WPF measurement. This time would allow for some of the body burden to be eliminated, providing faceseal leakage was not significant. The time chosen was a practical compromise; longer sample times would have lowered the amount of bias, but would have shortened the length of a possible WPF measurement. Therefore, the total time available for a WPF measurement was about 90 min.

TABLE II. Comparison of Amount of Styrene Spiked to Amount Recovered

Spike Level	Spiked Weight (μg)	Styrene Found (μg)	Styrene Recovery (%)	ppm Level for 3L Sample
Very Low	0.0338	0.0339	100.3	0.0026
	0.0676	0.0675	99.9	0.0053
Low	0.203	0.203	100.1	0.016
	0.338	0.335	99.1	0.026
	0.676	0.693	102.5	0.053
	2.028	2.111	104.1	0.159
	3.380	3.498	103.5	0.265
	6.756	6.235	92.3	0.529
High	218.27	254.86	116.8	17.08
	436.55	408.09	93.5	34.16
	1309.65	1124.72	85.9	102.5
	3055.85	2590.85	84.8	239.1
Mean			98.6	
Standard deviation			8.66	

Note: t-test: $p = 0.58$ (accept H_0 = 100% recovery)

TABLE III. Comparison of Charcoal Tube and Carbotrap Measuring a 10-ppm Atmosphere

	Charcoal Sorbent Tube (Styrene ppm)	Carbotrap Sorbent Tube (Styrene ppm)
	9.3	10.48
	8.88	9.06
	9.59	10.26
	9.53	10.01
	9.53	9.92
	9.89	10.6
Mean	9.45	10.06
Standard deviation	0.39	0.55

Note: t-test: $p = 0.046$

TABLE IV. Field Comparison of Three Sample Methods

Set	Charcoal Tubes (Styrene ppm)	Organic Vapor Diffusion Monitors (Styrene ppm)	Carbotrap Sorbent Tubes (Styrene ppm)	Sampling Time (min)
1	48	51	30	115
2	72	79	54	64
3	59	64	33	180
4	64	66	65	90
5	64	62	65	60
6	50	52	51	180
7	69	69	68	90
8	47	51	49	56
Average concentration	59	62	54	95
ANOVA		$p = 0.39$		

TABLE V. Summary of WPF Data

Employee	Job	Time Period	Sample Time (min)	Inside ppm	Inside Corrected for Lung Retention	Outside ppm	Uncorrected WPF	WPF Corrected for Lung Retention
1	LAMINATOR	D	41	1.3	1.8	90.2	70.3	50.2
2	LAMINATOR	D	34	0.8	1.1	74.0	91.6	65.4
2	LAMINATOR	F	54	0.7	1.0	47.3	66.0	47.1
2	LAMINATOR	H	55	1.6	2.3	61.2	37.4	26.7
3	GUNNER	F	72	1.9	2.7	39.7	20.8	14.9
3	GUNNER	H	77	1.3	1.8	40.2	32.0	22.8
4	LAMINATOR	B	65	0.7	0.9	71.2	107.6	76.8
4	LAMINATOR	D	65	0.8	1.1	71.8	92.3	65.9
4	LAMINATOR	F	25	0.9	1.3	154.5	171.5	122.5
5	LAMINATOR	D	57	0.9	1.2	47.3	54.4	38.9
5	LAMINATOR	H	72	2.1	2.9	39.1	18.8	13.4
6	GUNNER	B	60	0.3	0.4	68.3	247.8	177.0
6	GUNNER	D	65	1.2	1.7	65.6	55.3	39.5
6	GUNNER	F	78	1.4	1.9	52.2	37.6	26.8
6	GUNNER	H	46	1.1	1.6	134.9	117.9	84.2
7	LAMINATOR	D	64	0.9	1.2	70.6	81.8	58.4
7	LAMINATOR	H	82	0.8	1.1	27.8	35.5	25.4
8	LAMINATOR	B	65	0.4	0.6	51.8	130.0	92.9
8	LAMINATOR	F	75	1.6	2.3	63.5	38.6	27.5
8	LAMINATOR	H	40	1.1	1.6	56.2	49.0	35.0
9	LAMINATOR	B	57	0.6	0.8	89.7	159.7	114.1
10	LAMINATOR	F	23	5.4	7.6	118.2	21.7	15.5
10	LAMINATOR	H	50	3.2	4.5	54.3	17.0	12.1
11	LAMINATOR	B	56	2.1	2.9	74.7	35.9	25.6
11	LAMINATOR	D	88	0.8	1.2	50.4	61.1	43.6
12	GUNNER	D	60	1.8	2.5	63.3	35.5	25.3
12	GUNNER	F	48	3.3	4.6	64.3	19.5	13.9
13	LAMINATOR	B	70	5.6	7.9	64.8	11.6	8.3
13	LAMINATOR	F	75	6.3	8.8	69.9	11.1	7.9
14	LAMINATOR	B	56	0.4	0.5	75.8	196.9	140.7
14	LAMINATOR	F	60	1.3	1.9	74.9	55.7	39.8
14	LAMINATOR	H	60	1.1	1.5	75.4	68.2	48.7
15	LAMINATOR	B	45	0.6	0.8	62.1	108.6	77.6
15	LAMINATOR	F	67	0.7	1.0	48.0	66.8	47.7
15	LAMINATOR	H	35	0.7	1.0	91.2	124.7	89.1
16	LAMINATOR	F	65	1.9	2.6	43.2	23.3	16.6
16	LAMINATOR	H	50	2.4	3.3	55.3	23.5	16.8
17	GUNNER	B	82	0.3	0.4	52.6	187.3	133.8
17	GUNNER	D	61	1.0	1.4	68.3	66.5	47.5
17	GUNNER	F	67	1.1	1.6	56.5	49.7	35.5
17	GUNNER	H	62	1.7	2.3	70.7	42.4	30.3
18	LAMINATOR	B	61	0.9	1.3	87.4	93.0	66.4
18	LAMINATOR	D	53	1.5	2.1	93.2	61.3	43.8
18	LAMINATOR	H	67	1.2	1.7	67.1	56.1	40.0
19	GUNNER	B	70	0.7	0.9	64.3	96.4	68.9
19	GUNNER	D	70	0.8	1.1	56.7	73.6	52.5

RESULTS AND DISCUSSION

The minimum dynamic range required for a successful WPF study with a half-mask is from the detection limit of the analytical method to at least 10 times the mean blank mass.(14) This allows WPFs of at least 10 to be determined. A larger dynamic range is desirable, since many studies have reported WPFs much greater than 10. As shown in Table II, the dynamic range for recovery was five orders of magnitude. The collection and analysis techniques of this Carbotrap/thermal desorption has the ability to measure a large dynamic range. With sampling conditions at 100 cc/min for 1 hour, the 0.1 μg detection level could determine a WPF of up to 12,000 in a 50-ppm styrene environment.

To compare the Carbotrap/thermal desorption analytical method with the NIOSH method, a laboratory exposure system was designed that generated a 10-ppm atmosphere. Six side-by-side samples were collected with each method. The summary statistics are shown in Table III. A Student t-test indicates that the methods could be slightly different ($p = 0.046$).

A second series of tests were run in the work environment to determine if there were any differences between the charcoal tube, Carbotrap, and a 3M 3500 organic vapor monitor. The purpose of this sampling plan was to compare the Carbotrap sampling method against two tested and proven sampling and analytical

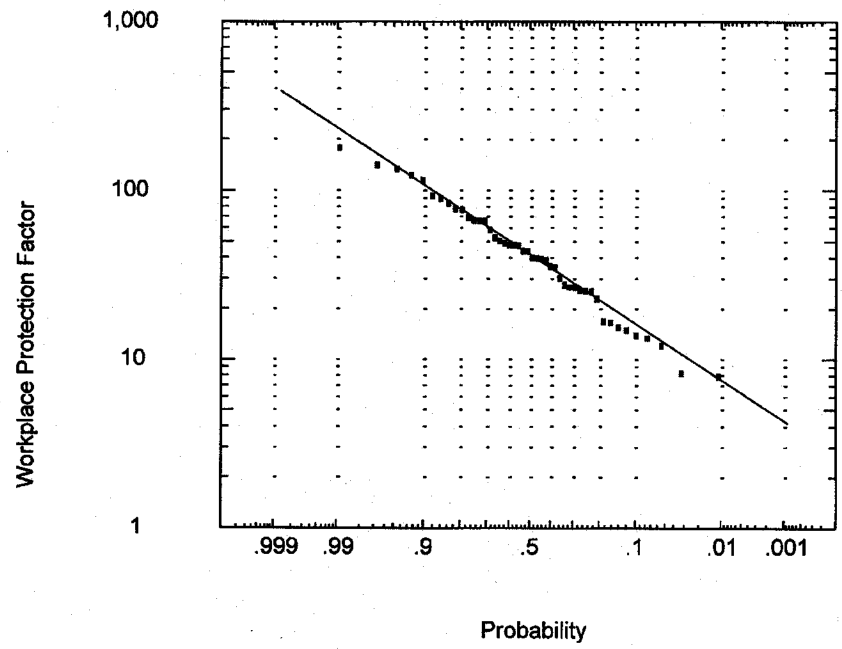

FIGURE 2. Log probability plot of corrected WPF values

techniques. Summary statistics are shown in Table IV. An analysis of variance showed there was no statistical difference among the three methods ($p = 0.39$).

Forty-six valid WPF measurements were acquired with the Carbotrap sorbent tubes. The field blanks averaged 0.09 μg, less than the limit of quantification, thus sample masses were not blank corrected. Table V is a listing of the results. WPFs are shown uncorrected and corrected for lung retention. To correct for pulmonary retention, the C_i concentration was multiplied by 1.4.[15] The geometric mean WPF measurement is 39.7 for the lung retention corrected. The GSD is 2.14, and the best estimate of the fifth percentile is 11. A log probability plot is shown in Figure 2.

An analysis of variance (ANOVA) shows that the geometric mean C_o concentrations for the four time periods (B, D, F, and H) are not significantly different ($p= 0.74$). An ANOVA by time period shows that the geometric mean C_i concentrations are significantly different ($p = 0.008$). Additionally, the geometric mean lung retention corrected WPF measurements are also significantly different ($p = 0.005$). The analysis for the C_o value, C_i value, and corrected WPF are shown in Table VI.

When data from people with three or four measurements is examined, a trend toward increasing C_i concentrations during the day is seen. This is shown in Figure 3. The geometric mean WPF measurements decreased from 103 for Period B to 51, 43, and 45 for the remaining periods.

The increase in penetration during the day could be due to a decrease in respirator performance during the day or to an increase in pulmonary elimination. This could be the result of an increase in the body burden from the nonwear times or a contribution from skin absorption. Myers has shown that the part of the workday a respirator is worn does not effect the measured WPF.[16] Whether the decrease in performance is the result of skin absorption or nonwear time exposure cannot be determined from the data available in this study.

This study points out some of the difficulties in sampling for vapors inside the respirator cavity. Sampling particles also has its challenges. For particles, losses may occur at the site of a leak. Hinds determined that particles larger than 10 μm are very unlikely to enter into the respirator cavity.[17] However, Myers has shown large particles are found inside the respirator.[16] Thus, the losses at a leak site are unknown and cannot be reliably estimated to correct the measured WPF. Particles are also lost by deposition in the lungs.[18] The amount of deposition will vary by a number of factors including particle size, breathing rate, and individual

TABLE VI. Analysis of C_o and C_i by Time Period

Time Period	Number of Samples	C_o Geometric Mean ppm Styrene	C_o GSD	C_i Geometric Mean ppm Styrene	WPF Geometric Mean ppm Styrene
B	11	68.4	1.24	0.70	460
D	12	67.0	1.24	1.02	170
E	12	63.7	1.50	1.72	34
F	12	59.5	1.54	1.39	52
		ANOVA $F = 0.412$, $F_{crit} = 2.83$, $P = 0.74$		ANOVA $F = 4.43$, $F_{crit} = 2.83$, $p = 0.008$	ANOVA $F = 4.92$, $F_{crit} = 2.83$, $P = 0.005$

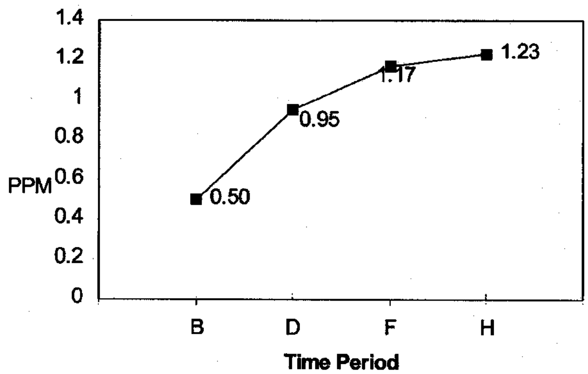

FIGURE 3. Concentration inside respirator (C_i by time period)

differences in breathing patterns and physiology. Both these factors (leak site losses and lung deposition) may lead to an underestimation of the true concentration inside the respirator and an overestimation of the true WPF.

CONCLUSIONS

Analysis of styrene by thermal desorption method provided similar results to the NIOSH method, but has a much lower limit of quantification. The thermal desorption method has several advantages that make it a good candidate for WPF measurements. The adsorbent is not affected by moisture and the dynamic range is wider.

In attempting a WPF study with a vapor or gas, the contribution from previous exposures needs to be understood. It may not be possible to determine the exact contribution of pulmonary elimination in cases in which the material is absorbed through the skin. Making measurements of the pulmonary elimination will enable an estimation of the magnitude of bias. Providing a contaminant-free environment with a PAPR is a simple method to measure pulmonary elimination.

The half-mask respirators used in this study provided a level of protection that is consistent with the assigned protection factor of 10.[19] Several measurement biases of C_i were not corrected. As discussed, there was a significant contribution in the measured C_i concentration from the exposure in the lunchroom. Even delaying the start of sampling for 30 min did not reduce this concentration significantly.

Another source of bias in C_i is the possible streamlining of airflow in the facepiece.[4,5] Extending the sampling inlet 5–7 mm into the facepiece cavity at a point midway between the nose and the mouth minimizes the bias, but it still underreports the C_i concentration by 20% on average.

The measured WPFs appear to be biased, since the mean C_i concentrations increased during the day for people with three or four measurements. The increasing trend in C_i from Period B to Period H averaged 40%. This increase in styrene concentration is an indication of the uncontrolled bias present in the WPF measurement.

A study by Galvin[15] also determined the performance of a half-facepiece elastomeric respirator in a styrene environment. In their study, several different techniques were used to measure WPFs. This included the use of an irritant smoke fit-test and a different sampling and analytical method. They also outlined some technical challenges regarding their sampling and analytical method and the need to better understand the contribution of prior exposures. This study attempted to address some of the more difficult challenges outlined by Galvin, such as sampling gases and vapors at low concentrations in high humidity environments and offering a technique that could be used to measure the effect of prior exposures. The Galvin study did not find an effect on WPF by time period, whereas this study did. Although these studies differed in technique and methodology, the resulting WPFs were similar.

This study has shown that a gas and vapor WPF study has some unique and different challenges when compared with a particulate WPF study. Skin absorption and exposure to gases and vapors during breaks were negative influences; therefore, the WPF can be underestimated. Although these biases were present, the study indicated that the respirator provided its appropriate protection level.

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