

Personal Sampling System for Measuring Workplace Protection Factors for Gases and Vapors

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ABSTRACT

Existing methods for measuring workplace protection factors (WPFs) typically employ continuous sampling of ambient and in-mask environments using two personal sampling pumps. This project focused on development of an intermittent sampling system for measuring concentrations of gases and vapors inside respirators during inspiration, while sampling the ambient environment during exhalation. This approach eliminates the need for two pumps and mitigates humidity effects on sampling and analysis. The system is based on a pressure transducer circuit that activates a solenoid valve such that a single pump can be used to alternately sample in-mask and ambient environments. Adsorbent tubes are used to trap the contaminants making the approach applicable to numerous gases and vapors. A pressure transducer, sampling pump, solenoid valve, and data-logger are integrated into a single battery-powered unit measuring 20x10x6.4 cm and weighing < 1.1 kg. Interface circuitry was developed to log heart-rate and in-mask pressures allowing estimates of work/ventilation rates to be associated with the WPF measurement. Pressure transducer calibrations relating in-mask pressure to flow rate for different types of cartridges and respirators were performed. The resulting curves yield instantaneous flow rates which when integrated provide a measure of the cumulative filtered air volume. Laboratory evaluation of the sampling system was conducted for half- and full-face respirators from two different manufacturers using an exposure chamber containing a headform connected to a breathing machine. SWPFs were measured for a contact adhesive application with varying levels of physical exertion to evaluate performance of the system. Low ppb contaminant concentrations corresponding to WPFs on the order of 100-25,000 were successfully measured in the laboratory and during simulated work activities. The resulting integrated sampling system should be a valuable tool for evaluating the effectiveness of respirators for gases and vapors in the workplace.

Keywords: Workplace Protection Factor, Simulated Workplace Protection Factor, Assigned Protection Factor, APF, WPF, SWPF, Air Purifying Respirators

INTRODUCTION

The 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 while it is correctly worn and used (Janssen, 2002). The WPF is equal to the ratio of the ambient contaminant concentration to the concentration inside the respirator facepiece, C_o/C_i . A limited number of WPF

studies have been published for negative pressure air purifying half-and full-facepiece respirators (OSHA, 2003) which may be due in part to the difficulty in taking the measurement – very low concentrations must be collected inside the respirator facepiece under conditions of high humidity (Galvin, 1990; Johnston, 1992; Nelson, 1995; Revior, 1997). In addition, facepiece samples collected continuously (during both inhalation and exhalation) may need to be corrected for dead volume and pulmonary retention to minimize bias in the resulting WPF (Hewett, 1993; Hinds, 1993; Nicas, 1995). Finally, the sampling equipment is cumbersome and may change the characteristics of the respirator or the work practices of the worker.

It was noted in the Final Rule of the Respiratory Protection Standard that there were very few WPF studies for gases and vapors - only one study was identified (Code of Federal Regulations, 1998). While it is not clear why there are so few studies for gases and vapors, the designation of an assigned protection factor (APF) based on aerosol data for respirators used for gases is questionable. Fit factors for dusts are related to the size distribution of the contaminant particles due to the size-selective nature of respirator leaks (Hinds, 1987a; Hinds, 1987b; Holton, 1987a; Holton, 1987b) which can increase the magnitude of protection factors measured for dusts in comparison to a gas. If the APF is defined as the minimum level of respiratory protection that would be provided by a properly functioning respirator (Nelson, 1996), it could be reasoned that APFs based on gas and vapor studies would represent a conservative approach. Nicas (1995) identified this option, but noted that most WPF data is based on aerosol studies so the resulting WPFs could not be used for developing APFs. In addition, there are potential biases involved with measuring gases and vapors including background contaminant exposures and dermal absorption (Weber, 2000). These issues indicate the need for improved instrumentation and techniques for collection of additional WPF data.

The goal of this project was to develop and test an integrated personal sampling system for measuring workplace protection factors (WPF) for gases and vapors. A prototype system was previously described (Groves, 2003). The new system consists of a single sampling pump, a solenoid valve for directing the sampling flow stream, a pressure transducer designed to sense differential pressure inside the respirator, and a multi-channel data-logging unit for recording the output from pressure and heart rate transducers. The pressure transducer and solenoid valve are designed to allow sampling of the air inside the respirator face-piece during inhalation, while the ambient environment is sampled during exhalation. The specific goals for development of this second generation instrument were to integrate all components (pump, solenoid control valve, pressure and heart rate transducer circuitry, data logger, and sampling ports) into a single enclosure comparable in size to existing personal sampling equipment. Experiments were then conducted to characterize respiratory flow rates based on differential pressure inside the face-piece of different respirators. A comparison of concentration measurements obtained using intermittent and continuous sampling of low ppb concentrations of perchloroethylene and acetone was performed. Finally, the complete system was used to measure simulated workplace protection factors (SWPFs) for a contact adhesive application.

MATERIALS AND METHODS

Sampling System

Preliminary work on the sampling system focused on packaging the pressure transducer, sampling pump, solenoid valve, and data-logger into an OEM type plastic housing and installation of the sampling, data, and battery charging ports and connectors (Figure 1). The instrument is based on a single low flow sampling pump with stroke counter (Model 222, SKC Inc., Eighty Four, PA) which is connected to a three-way solenoid valve (Predyne Model MA345, Precision Dynamics, Inc., New Britain, CT). A low-range differential pressure transducer (ICAL05DN, SenSym ICT, Milpitas, CA) with an excitation voltage of 5V and a ratiometric output voltage of 4V (2.25 ± 2.0 V) was selected based on size, sensitivity, and power requirements. The output from the pressure transducer is monitored at a frequency of 5 Hz using the data-logger and onboard microprocessor (Tattletale TFX-11, Onset Computer, Bourne, MA). Firmware for the data-logger was developed to actuate the solenoid valve whenever the pressure inside the

respirator was negative to allow sampling from within the respirator during inhalation (Instrument Sampling Port 1) and from outside the respirator during exhalation (Instrument Sampling Port 2). One sorbent tube is connected to a sampling port installed on the respirator to be tested (Respirator Sampling Port 1) while a second sorbent tube is used to sample the ambient air. A third instrument port allows the pressure transducer to be connected to the respirator pressure sensing port (Respirator Sampling Port 2) so that differential pressure can be measured.

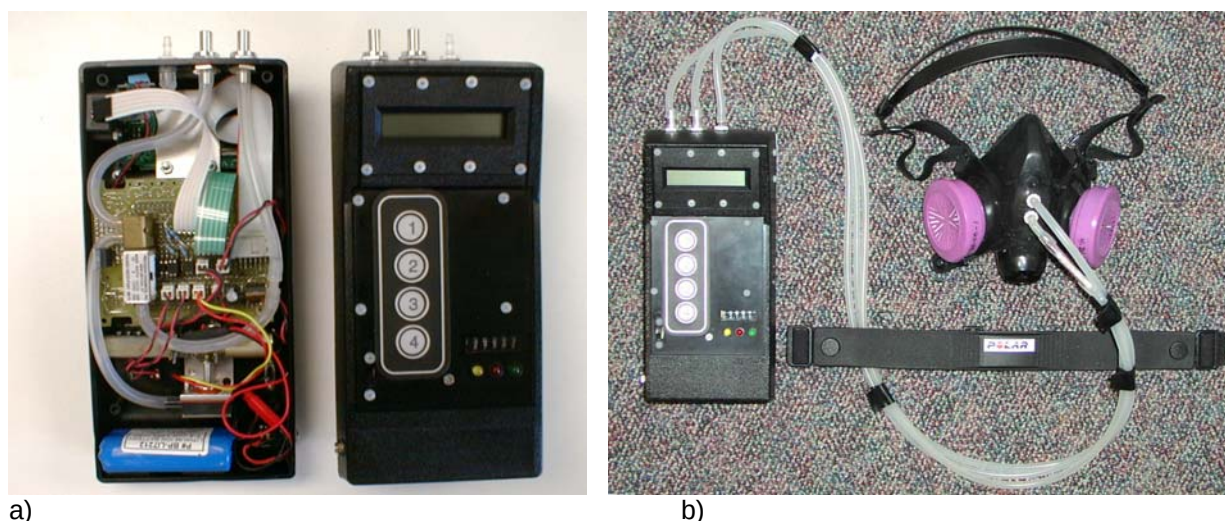


Figure 1. a) Interior of prototype instrument and b) prototype instrument with North 7700 respirator and Polar heart rate monitor (transmitting chest-band transducer).

An LCD and membrane button pad are used for interaction with the instrument which has calibration and sampling modes. Programs were written using TFBasic which is the data-logger manufacturer's programming environment (Onset Computing Corp., Bourne, MA). Data are stored in a binary format which has to be offloaded and converted to a text file for use. An Excel macro was created using Visual Basic to convert the offloaded binary data file to an ordinary text file which can then be loaded as a spreadsheet (comma delimited). The data can then be processed and displayed allowing for an examination of the quantities of interest such as in-mask pressures, instantaneous flow rates, and the fraction of the total sampling time that in-mask and ambient samples were collected. In calibration mode, the touch pad is used to activate the pump and solenoid valve so that flow rates for each instrument air sampling port can be calibrated. Sampling flow rates are approximately 275 mL/min which is the maximum obtained with the Series 222 pump and the regulated 3.6V supply available in the instrument. The air volume sampled by each port is calculated from the fraction of the total sample time for which the solenoid valve was actuated (inhale fraction) and the average of the pre-and post-sampling calibration results.

Calibration of Pressure Transducers for Respirators Examined

Pressure transducers (ICAL05DN, Sensym ICT, Milpitas, CA) were calibrated in order to use differential pressure measurements to predict flow rate and the volume of air passing through the respirator cartridges. This was accomplished by connecting a constant flow sampling pump to a needle valve used as an adjustable source of resistance. The pressure transducer sampling port was connected to the line with a T-fitting and the needle valve was adjusted to create a variable differential pressure spanning the range of operation for the transducer (0-5 in. water). Pressure was measured using an inclined manometer. The DC output voltage from the transducer was monitored using a digital multimeter and plots of vacuum pressure versus voltage output were prepared for five different transducers.

Once the pressure transducer calibration curve was established, the relationship between in-mask pressure and flow rate was examined for two brands each of half-facepiece (North 7700, North Safety Products, Cranston, RI) (MSA Advantage 200, Mine Safety Appliance Co., Pittsburgh, PA) and full-facepiece negative pressure elastomeric APR (North 7600, North Safety Products, Cranston, RI) (Advantage 1000, Mine Safety Appliance Co., Pittsburgh, PA). These experiments included an examination of two different types of respirator cartridge (ammonia and organic vapor). Flow rates were measured using an in-line mass flow meter (Model 4040, TSI, St. Paul, MN) and differential pressure was measured using an inclined manometer and the output from the pressure transducers (Figure 2). An adjustable valve was used to vary the flow rate through the headform-mounted respirator/cartridges to allow the measurement of pressure and flow rate for eight data points spanning 1-160 L/min for each calibration.

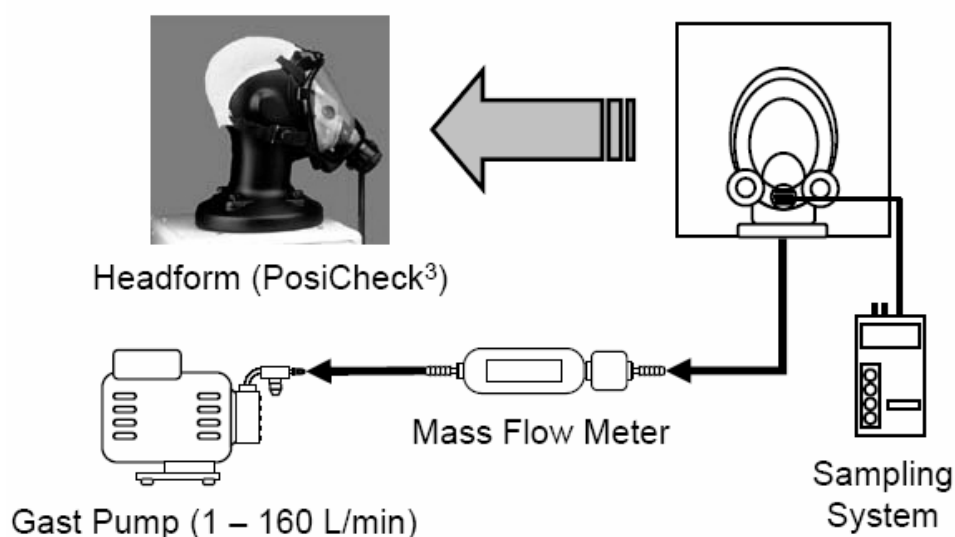


Figure 2. Schematic for measurement of flow rate through head-form mounted respirators as a function of differential pressure – sampling system records pressure versus varying flow rate for different combinations of respirator and cartridge.

Laboratory Testing of Intermittent Sampling System

Intermittent sampling was evaluated in the laboratory using a headform-mounted respirator equipped with HEPA filters in a sealed exposure chamber (Figure 3). The headform was connected to a modified dog ventilator (Model 613 Respiration Pump, Harvard Apparatus Co., Holliston, MA) which was used as a breathing machine. The breathing machine produced a sinusoidal flow pattern with an average flow rate of approximately 20 L/min and a period of 3 seconds which represents a low level of exertion. Test-atmospheres were used to evaluate the performance of an intermittent sampling system using the appropriate adsorbent tubes (226-01, SKC, Inc., Eighty Four, PA) and GC/FID analysis. Two different contaminants (acetone and perchloroethylene) were generated using certified calibration gas standards (Scott Specialty Gases, Inc.) mixed with dilution air using mass flow controllers to yield the desired test concentrations. These chemicals were selected to represent a range of chemical and physical properties. Conditions of high humidity during exhalation were simulated by routing the breathing machine exhalation stream through a series of Greenburg-Smith impingers placed in a water bath maintained at $\sim 37^{\circ}\text{C}$. The length of hose connecting the headform to the breathing machine was heated to a temperature slightly higher than 37°C using a thin film resistive heater and a temperature controller in order to minimize condensation. Although not shown in Figure 3, the exhalation valve of the respirator was vented to the outside of the chamber. This prevented the chamber relative humidity from increasing as a result of the

humid exhaled air stream and eliminated the potential dilution effect that the exhalation stream could have on the chamber concentration.

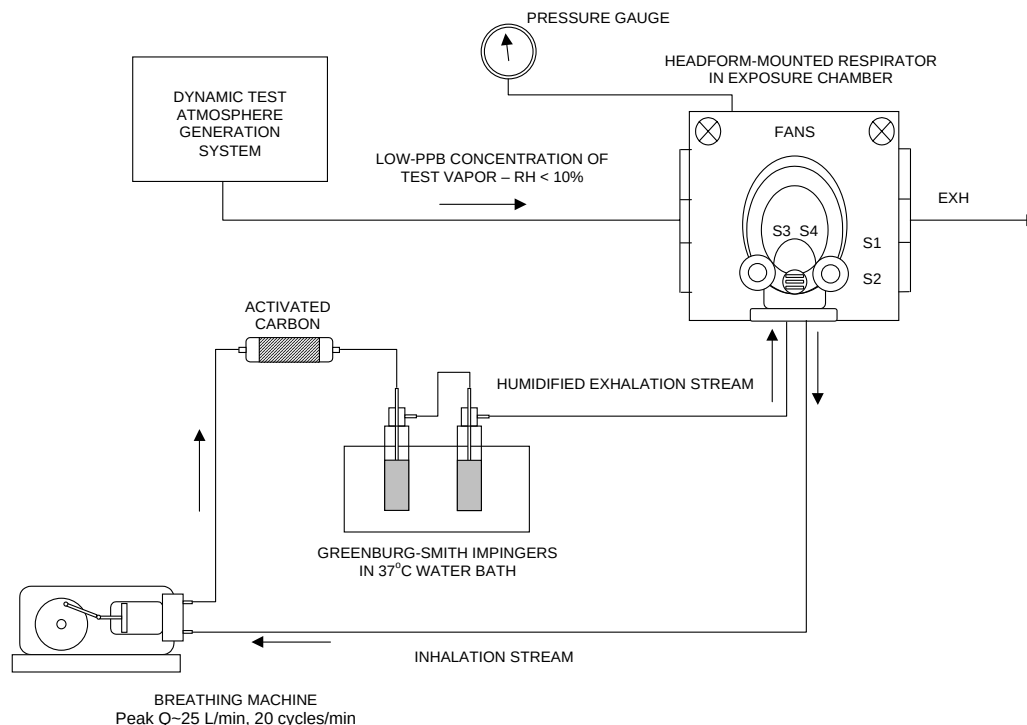


Figure 3. Exposure chamber diagram and sample description for exposure chamber tests; S1 – continuous chamber sample, S2 – intermittent chamber sample, S3 – intermittent in-mask (respirator) sample, S4 - continuous in-mask (respirator) sample.

A target test-atmosphere concentration of 50 ppb was prepared for the two chemicals examined. This level is somewhat arbitrary – it was selected based on the fact that it is estimated to be near the lower end of the range of concentrations that can be reproducibly generated using a dynamic test atmosphere generation system. The goal was to generate as low a chemical concentration as possible in order to simulate challenging in-mask sampling scenarios. By way of comparison, a 50 ppb in-mask concentration would represent a WPF of 2,500 assuming an ambient concentration equal to 5 times an Occupational Exposure Limit (OEL) of 25 ppm.

A HEPA filter was substituted for the organic vapor respirator cartridge resulting in 100% penetration of the chemical while establishing a resistance to flow comparable to typical OV cartridges. In-mask samples (C_i) were collected both intermittently using circuitry from the personal sampling system (S3), and continuously using a low flow pump (S4). Samples were also collected in the exposure chamber (C_o) using both intermittent sampling (S1) and a continuous low-flow pump (S2). Samples and backup sections were analyzed separately according to NIOSH analytical method 1003 using GC-FID. Limits of detection were approximately 1 ug/sample. Sample volumes were determined from the stroke count and the calibrated stroke volume for each pump.

Two Kynar[®] sampling ports were added to each of the respirators examined. For the full-facepiece respirators the speech diaphragm was replaced with a plexi-glass "blank" of the same thickness and diameter. The blank was equipped with two sample ports which were connected to the sampling system's pressure transducer and pump using silicone tubing. The sample port fittings provided a flush opening on the interior of the blank located directly in front of the mouth, approximately 0.64 cm to the right and left of centerline. A coconut shell charcoal sorbent tube (226-01, SKC Inc., Eighty Four, PA) was connected to the sampling port using a short length of silicone tubing to minimize potential sample

loss. Sampling ports were added to half-facepiece respirators by punching holes through the respirator facepiece and inserting a threaded sample-port fitting. Silicone sealant was used to ensure an airtight union between the sampling ports and the respirator facepiece. The sample port fittings used for the half-facepiece respirators were located on the centerline approximately half-way between the nose and mouth and extended 0.64 cm into the respirator.

Sampling System Evaluation – SWPFs for a Contact Cement Application

Two subjects were recruited to simulate work activities while wearing the workplace protection factor sampling system. Upon agreeing to participate, subjects were fitted with an air purifying respirator and given a quantitative fit-test using a TSI PortaCount[®] Plus Fit Tester (TSI Incorporated, St. Paul, MN) and the default 29 CFR 1910.134 protocol (Code of Federal Regulations, 1998). Respirators were probed for the fit test using the appropriate manufacturers' QNFT adapter with probes located on the facepiece near the right inhalation valve for full-facepiece respirators and at the centerline between the nose and mouth for half-facepiece respirators. After passing the fit-test, subjects donned respirators equipped with organic vapor cartridges and modified to allow air samples to be collected from inside the face-piece (Groves, 2003) as work activities are simulated in the laboratory. A Polar heart rate transducer was worn to transmit heart rate data for recording by the WPF sampling system. Subjects participated in a one-hour simulated work regimen consisting of the application of a commercially available contact adhesive (DAP Weldwood Contact Cement) to a 60x60 cm plywood panel using a 7.6 cm roller while wearing a respirator and the integrated WPF sampling system. The contact cement contains approximately 60% toluene, 20% aliphatic hydrocarbons, and 20% methyl ethyl ketone by weight.

The work regimen consisted of three stations: 1) application of contact adhesive on a table at waist height, 2) application of contact adhesive at floor level, and 3) a step-test conducted using a platform 32.5 cm in height. Subjects spent 10 minutes at each station before rotating to the next. The one hour regimen consisted of three 10-minute adhesive application tasks (two at waist height and one at floor level) and three 10-minute step-test tasks (three different levels of exertion – 5, 10, and 15 steps/min). Subjects alternated between adhesive application and step-test stations, e.g., a typical regimen would consist of a 10 min adhesive application at waist height, 10 min step test at 5 step/min, 10 min adhesive application at floor level, 10 min step test at 10 step/min, 10 min adhesive application at waist height, and a final step test at 15 steps/min for a total run time of 60 minutes. The level of exertion required is a function of the subject's weight and would be approximately 56 W for a 70 kg individual performing at the 15 step/min level.

A calibrated portable direct reading photo-ionization detector (PID) (MiniRAE 2000, RAE Systems, San Jose, CA) was used to monitor airborne concentrations of vapors generated by the contact adhesive application to ensure that excessive levels did not occur. Preliminary screening studies which employed the proposed work-step-test regimen showed that average ambient concentrations of contaminants were less than 100 ppm while in-mask concentrations were approximately 100-500 times lower (~0.1-0.7 ppm). The OSHA Permissible Exposure Limits (PELs) for toluene, MEK, and aliphatic hydrocarbons (Stoddard solvent) are 200 ppm, 200 ppm, and 500 ppm, respectively.

The sampling instruments were calibrated and placed on subjects in a separate laboratory area removed from the contact adhesive application location. Upon completion of the simulation, the subjects left the application area and walked to the laboratory for post-calibration and preparation of samples. In-mask sorbent tubes were removed first from the respirator sampling port (without removing the respirator), followed by the ambient sample tubes. Tubes were capped immediately and transported to the analytical laboratory along with blank sorbent tubes for desorption and GC analysis. Recorded data from the sampling system was then downloaded to a personal computer for display and storage.

RESULTS AND DISCUSSION

Calibration of Pressure Transducers

Pressure transducer calibration results are summarized in Figure 4. Results for five individual transducers (0-5 in. H₂O vacuum) were highly linear and reproducible ($R^2 = 0.999$). The transducer port used for the measurements was reversed so that negative pressures yield an increasingly positive output voltage – this simplifies the use of the transducer output for switching the solenoid control valve. The resulting regression equation can be used to estimate differential pressure inside the respirator as a function of transducer output (voltage) with minimal error.

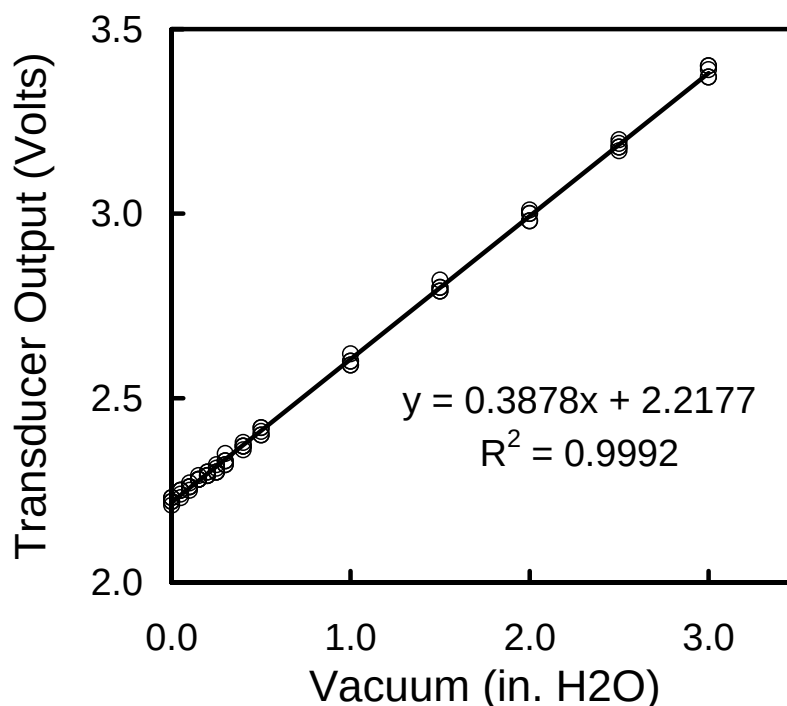


Figure 4. Combined pressure transducer calibration – 5 in. H₂O range.

A representative plot of the results for the comparison of in-mask pressure to inhalation flow rate is presented in Figure 5. The plot represents the combined results for three different sets of OV cartridges on two different respirators (North 7600, and 7700). Although the variability resulting from different respirators and cartridges is apparent, the use of a single regression equation introduces minimal error in the estimates of flow rate (<10%) and simplifies the use of the sampling system. Results were slightly more variable for the MSA respirators and cartridges examined but still yielded calibration equations considered to be adequately accurate. The resulting calibration equations can be stored in the programming of the sampling system and called up for use at the beginning of a run so that calculated instantaneous flow rates and integrated estimates of minute volume and cumulative filtered volume are accurately logged for the different types of respirator and cartridge in use (Figure 6).

Laboratory Testing of Sampling System

The exposure chamber tests yielded four measurements of the test-atmosphere concentration collected under different conditions, thus allowing several comparisons to be made. The samples collected inside the mask (S3 & S4) can be used to compare the intermittent sampling approach to the continuous method. Given the nature of the system it was initially expected that the continuous in-mask sample

would have a negative bias of approximately 50% relative to the intermittent sample since the exhaled air stream should be contaminant free. This scenario comprises one boundary condition for in-mask sampling that is representative of a contaminant that is completely absorbed by the body when inhaled. Possible deviations from this expected 50% bias may result from dilution/mixing effects from the respirator dead-space or from error introduced into the analytical method as a result of the elevated humidity in the mask. Comparisons can also be made between the intermittent in-mask (S3), and exposure chamber samples (S1, S2). Ideally these results should not be significantly different. However, if some loss of contaminant occurs as a result of flow through the HEPA filter, or if there is a dead-space related dilution effect on the in-mask intermittent sample, one would expect a negative bias relative to the exposure chamber samples. An assessment of the relationship between the intermittent and continuous exposure chamber samples (S1 & S2) can also be made to determine whether the intermittent sampling approach yields results comparable to continuous sampling.

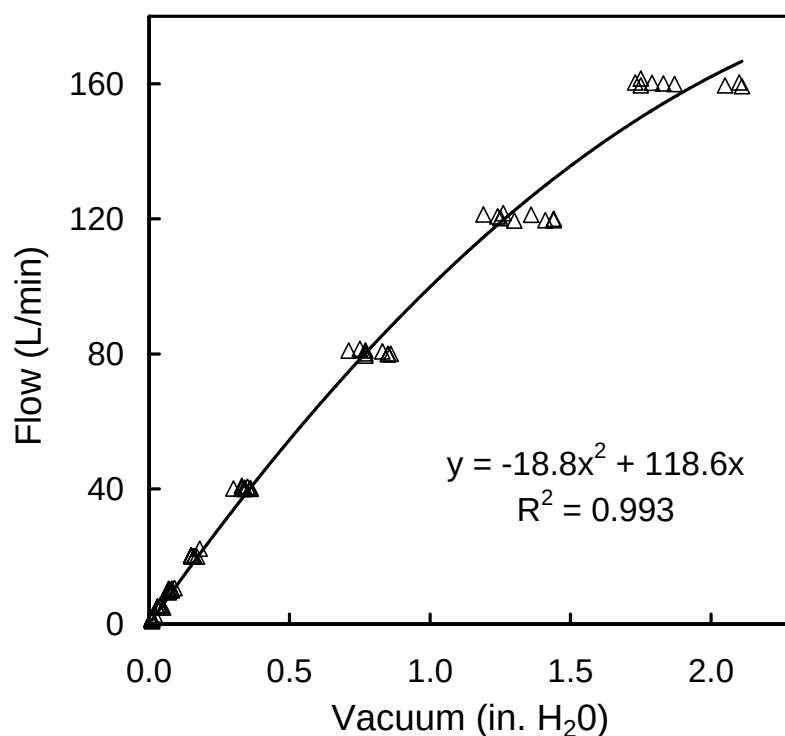


Figure 5. Combined calibration curve for North half- and full-facepiece respirators for organic vapor cartridge.

Results of the exposure chamber tests are summarized in Table I. Chamber concentrations measured continuously (S1) and intermittently (S2) are displayed in the first two columns for the two types of respirators and solvents examined. Agreement between S1 and S2 is excellent indicating that the intermittent sampling protocol yields results similar to the traditional continuous sampling technique. A paired t-test comparing S1 to S2 showed that the 95% C.I. for the mean difference was -0.359 to 1.914 ($p = 0.171$) thus the null hypothesis that the mean difference between the two methods was zero could not be rejected.

Results for continuous (S3) and intermittent (S4) in-mask samples are also displayed in Table I along with the ratio of the in-mask samples to the average chamber concentration (ave. of S1 and S2). As expected, the ratio of the continuous in-mask sample to the chamber concentration is approximately 0.5 (ave = 0.495, $s = 0.04$, $n = 27$) while the average ratio for the intermittent sample is 0.8 (ave = 0.756,

$s = 0.05$, $n=27$). One explanation for the negative bias of the intermittent in-mask samples relative to the chamber samples (-20%) is the effect of respirator dead volume (Hinds, 1993). The concentration inside the respirator is alternating between a higher value during inhalation (≤ 50 ppb) and a lower value during exhalation (≥ 0 ppb). The dynamic nature of the concentration inside the respirator should be a function of the dead volume of the respirator, the tidal volume of each respiratory cycle, and the effective mixing that occurs in the respirator. The fact that the ratio for intermittent in-mask sampling is less than one does not indicate a problem with this protocol – the result could merely reflect the dilution effect that occurs as a result of the dead space and therefore may accurately represent the actual concentration of the air inhaled by the respirator wearer.

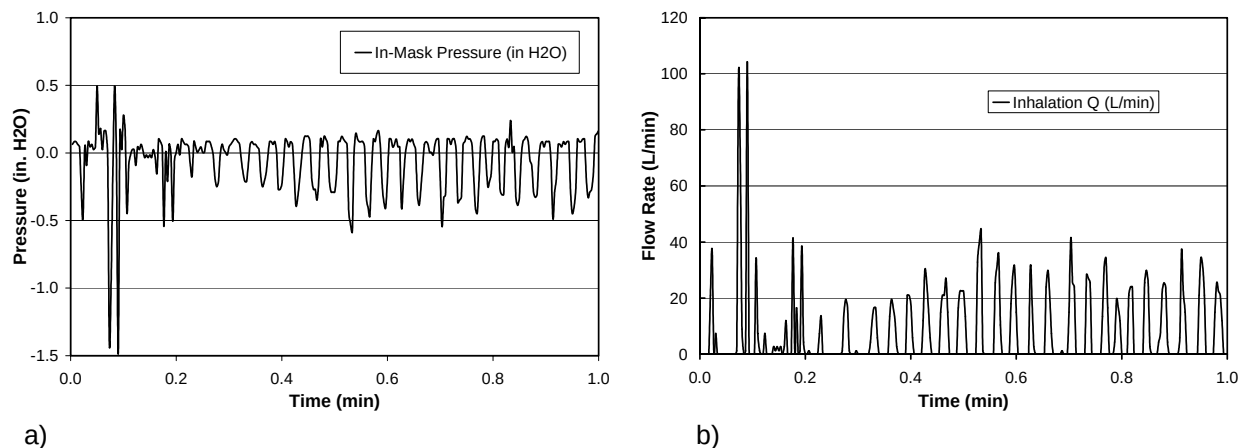


Figure 6. Display of logged a) in-mask pressure and b) resulting instantaneous inhalation flow rate for one minute recorded (sampling rate = 5 Hz, 300 data points).

The results of the laboratory testing of the sampling system demonstrate the feasibility of using intermittent sampling to measure the in-mask and ambient concentrations. Additional study is needed to fully determine whether continuous sampling or intermittent sampling yields results that better represent actual inhaled concentrations for gases and vapors in half- and full-facepiece respirators. In previous work, Myers et al. (1986) reported on the most important factors found to influence measurements of airborne concentrations within respirators including sample probe location, probe depth, leak site, breathing distribution (mouth vs nose), and measurement sample rate. The study also examined the question of whether to sample during inhalation only, or continuously (during inhalation and exhalation). It was reported that concentration measurements could be significantly biased even when sampling was conducted only during inhalation. This result was attributed to a streamlining effect as the contaminant entered through a leak and the lack of complete mixing in the respirator face piece. The authors reasoned that in this particular situation, continuous sampling actually provided a less biased estimate of the in-mask concentration. Unfortunately, no studies conducted to date can provide a definitive answer as to what actually occurs within a respirator given the dynamic nature of leaks and the work environment. Further, it is not clear how conclusions based on probes in half-facepiece respirators could be extended to other types of WPF sampling, e.g., full-facepiece respirators equipped with a nose-cup.

Table I. Laboratory Testing Results for Intermittent and Continuous Sampling (conc. in PPB)

Chamber Concentration, C^o		Respirator Concentration, C^R		Concentration Ratios		
C_{cont}^o (S1)	C_{int}^o (S2)	C_{cont}^R (S3)	C_{int}^R (S4)	C_{cont}^R/C^o	C_{int}^R/C^o	C_{int}^R/C_{cont}^R
<i>MSA Half-Facepiece¹, Perchloroethylene</i>						
48	47	23	36	0.48	0.76	1.6
47	39	21	31	0.49	0.72	1.5
41	40	20	32	0.49	0.79	1.6
40	40	21	31	0.53	0.78	1.5
39	40	19	32	0.50	0.84	1.7
Average (SD) =				0.50(0.02)	0.78(0.04)	1.56(0.09)
<i>North Half-Facepiece², Perchloroethylene</i>						
47	42	20	30	0.45	0.67	1.5
51	46	24	34	0.49	0.70	1.4
52	54	30	42	0.57	0.79	1.4
51	49	29	42	0.58	0.84	1.4
52	54	29	42	0.55	0.79	1.4
Average (SD) =				0.53(0.05)	0.76(0.07)	1.44(0.04)
<i>MSA Full-Facepiece³, Perchloroethylene</i>						
56	59	25	39	0.43	0.68	1.6
52	49	25	37	0.50	0.73	1.5
52	52	25	40	0.48	0.77	1.6
49	43	25	38	0.54	0.83	1.5
49	48	24	40	0.49	0.82	1.7
Average (SD) =				0.49(0.04)	0.77(0.06)	1.57(0.07)
<i>North Full-Facepiece⁴, Perchloroethylene</i>						
50	52	25	40	0.49	0.78	1.6
45	44	24	35	0.54	0.79	1.5
51	52	24	42	0.47	0.82	1.8
48	49	22	37	0.45	0.76	1.7
48	50	23	37	0.47	0.76	1.6
Average (SD) =				0.48(0.03)	0.78(0.02)	1.62(0.11)
<i>MSA Full-Facepiece³, Acetone</i>						
51	50	28	39	0.55	0.77	1.4
47	48	25	34	0.53	0.72	1.4
56	58	27	36	0.47	0.63	1.3
54	53	25	37	0.47	0.69	1.5
54	53	25	36	0.47	0.67	1.4
Average (SD) =				0.50(0.04)	0.70(0.05)	1.40(0.06)
<i>North Full-Facepiece⁴, Acetone</i>						
48	45	19	34	0.41	0.73	1.8
41	45	21	33	0.49	0.77	1.6
Average (SD) =				0.45(0.06)	0.75(0.03)	1.68(0.15)

¹ MSA Advantage 200; ² North 7700; ³ MSA Advantage 1000; ⁴ North 7600.

cont – continuous sampling; int – intermittent sampling, pump on during inhalation only.

Table II. Results for SWPFs

Date	Subject	Respirator	SWPF	Ambient Concentrations (toluene, ppm)	Work Rate (W)	V _{min} (L/min)
8/23/2004	1	A	92	61	25	22
8/24/2004	1	A	85	54	25	20
8/26/2004	1	A	98	39	25	19
3/30/2005	1	A	100	64	30	24
4/12/2005	1	A	150	24	30	30
5/3/2005	1	A	130	10	30	28
AVE (SD) =			108 (26)	42 (22)		
8/13/2004	1	B	280	60	20	15
8/19/2004	1	B	480	67	25	16
8/20/2004	1	B	290	73	25	15
3/30/2005	2	B	160	67	27	12
4/12/2005	2	B	210	20	27	*
5/3/2005	2	B	260	9	27	12
AVE (SD) =			280 (109)	49 (28)		

A – North Full-Facepiece (7600), B – North Half-Facepiece (7700)

* data lost during offload

SWPFs for a Contact Cement Application

The last phase of the sampling system evaluation involved measurement of SWPFs for subjects performing a contact adhesive application and step-test exercises. Results are presented in Table II. WPFs for the full-facepiece respirator (A) were measured on five separate occasions spanning a period of nine months. The average SWPF was 108 (sd = 26) with an average ambient concentration of 42 ppm toluene (sd = 22) and a range of 10-64 ppm. The average SWPF result for the half-facepiece respirator (B) was 280 (sd = 109) with an average ambient toluene concentration of 49 ppm (sd = 28) and a range of 9-73 ppm. The average work rate associated with the measurements is also listed in Table II and varies from 20-30W. These values vary depending on the weight of the subjects due to the step-tests used and are averages for the 60 minute period. Individual work rates varied from less than 10W during adhesive application at waist height to 75W for the 15 step/min exercise period. Estimated average minute volumes (V_{min}) are listed as well and generally show expected increases for higher work rates. One set of data were lost during download for subject 2 – the instrument was inadvertently turned off.

During the SWPF runs, subjects recorded their pulse rate every ten minutes for comparison to the sampling system data. Results showed that the sampling system heart rate was highly correlated with pulse rate ($r^2=0.84$) but consistently lower by approximately 10%. The instrument monitors heart rate by counting pulses transmitted by the chest band for each heart beat. It is likely that there is a source of interference from either the circuitry of the system itself or surrounding equipment, that causes some of the pulses to be missed. It was also noted that when two subjects worked in close proximity, the resulting recorded heart rates were more erratic indicating probable interference between the subjects' heart rate transmitters and the receiving modules in the instrument. Newer versions of the heart rate monitoring circuitry are equipped with data encoding to eliminate this interference.

Overall the personal sampling system performed very well. Collection of SWPF samples was simplified by the fact that there was a single unit to be calibrated and placed on each subject. Models developed for correlating work rates with heart rate (Kamalakaran, 2004) were used to prepare plots such as those in Figure 7 depicting heart rate, work rate, and minute volume over the course of the sampling run. The interrelationship of these parameters is clearly demonstrated and this type of information could be used for a thorough characterization of the activity levels associated with a given measurement of WPF. The need to wear the chest band heart-rate transducer could cause concern for some subjects – if $V_{\min}$ were considered to be an adequate indication of exertion, the heart rate monitor need not be used.

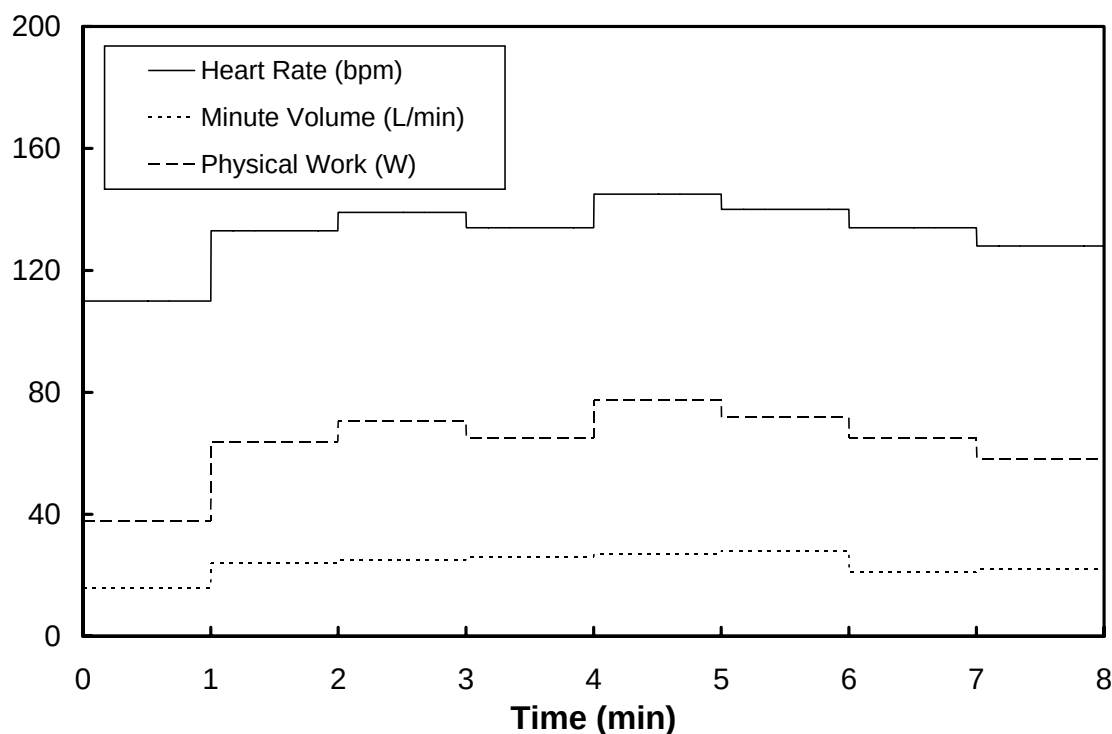


Figure 7. Recorded data for a) in-mask pressure and b) heart rate, minute volume, and estimated physical work rate, for an eight minute period.

Although these exercises served as a final functional test of the sampling system rather than a formal SWPF study, it was noted that the results for the full-face respirator were relatively low. After the first SWPF result of 92 was recorded on 8/23/04, all fittings on the respirator were checked for leaks and additional silicone sealant was added at the sampling port fitting threads. In the following test, a SWPF of 85 was determined. Following this run the respirator was disassembled and all valves were checked to ensure that there was no hair or other foreign objects causing leakage. The respirator was then re-assembled and quantitative fit-testing was performed for subject 1 using the same respirator and with the sampling system attached and operating. The subject passed the fit-test with an overall fit-factor of 10,600. The results of subsequent SWPF measurement were 98, 100, 150, and 130, suggesting that the protection achieved with this respirator was consistent, but lower than might be expected and apparently not due to any obvious leaks or malfunctions. Additional investigation is underway to determine whether these results indicate a problem with one particular respirator/subject combination, or a bias due to the sampling system itself.

CONCLUSIONS

An integrated personal sampling system for measuring WPFs for gases and vapors has been developed and tested in the laboratory. The system is small and light-weight, allowing it to be worn easily on a worker's belt, and has adequate battery power to operate for a full 8-hour shift. While important questions remain to be answered regarding sampling protocols for gases and vapors in different types of respirators, the integrated system and the additional capabilities offered for measuring work and ventilation rates should be useful in exploring these issues. This study clearly demonstrates the reproducibility of measurements taken using an intermittent sampling protocol. The additional logistical benefits that this approach affords for WPF sampling systems provide a strong argument for using this technique – intermittent sampling allows the use of a single sample pump thus reducing size and power requirements for the system, and simplifies the logistics of performing WPF studies. This technology should ultimately help address research needs identified in the Final Rule of the Respiratory Protection Standard (Code of Federal Regulations, 1998) including the limited amount of data available for WPFs for gases and vapors. Information gathered using the instrument could be used in developing and evaluating APFs for different types of respirators, or as an exposure assessment tool for specific applications of respiratory protective equipment.

Acknowledgements

NIOSH support for this work through SERCA Grant No. 5K01-OH00177 is gratefully acknowledged.

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