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

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A prototype sampling system for measuring respirator workplace protection factors (WPFs) was developed. Methods for measuring the concentration of contaminants inside respirators have previously been described; however, these studies have typically involved continuous sampling of aerosols. Our work focuses on developing an intermittent sampling system designed to measure the concentration of gases and vapors during inspiration. This approach addresses two potential problems associated with continuous sampling: biased results due to lower contaminant concentrations and high humidity in exhaled air. The system consists of a pressure transducer circuit designed to activate a pair of personal sampling pumps during inspiration based on differential pressure inside the respirator. One pump draws air from inside the respirator while the second samples the ambient air. Solid granular adsorbent tubes are used to trap the contaminants, making the approach applicable to a large number of gases and vapors. Laboratory testing was performed using a respirator mounted on a headform connected to a breathing machine producing a sinusoidal flow pattern with an average flow rate of 20 L/min and a period of 3 seconds. The sampling system was adjusted to activate the pumps when the pressure inside the respirator was less than −0.1 inch H_2O. Quantitative fit-tests using human subjects were conducted to evaluate the effect of the sampling system on respirator performance. A total of 299 fit-tests were completed for two different types of respirators (half- and full-facepiece) from two different manufacturers (MSA and North). Statistical tests showed no significant differences between mean fit factors for respirators equipped with the sampling system versus unmodified respirators. Field testing of the prototype sampling system was performed in livestock production facilities and estimates of WPFs for ammonia were obtained. Results demonstrate the feasibility of this approach and will be used in developing improved instrumentation for measuring WPFs.

Keywords Respirators, Workplace Protection Factor, WPF, Assigned Protection Factor, APF, Sampling System

Occupational Safety and Health Administration (OSHA) estimates and the results of recent polls suggest that approximately 3–5 million workers, representing roughly 10–20 percent of all workplaces, wear respirators at some time.[1,2] Given such widespread use, it is obviously important to have sufficient data characterizing the performance of respirators so that workers can be adequately protected from chemical hazards in the workplace. However, one of the points raised in the Final Rule for OSHA's Respiratory Protection Standard is the limited amount of data available for evaluating the performance of respiratory protection under actual workplace conditions.

The workplace protection factor (WPF) is defined as 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.[3,4] Specifically, the WPF is equal to the ratio of the ambient contaminant concentration (C_o) to the concentration inside the respirator facepiece (C_i) or C_o/C_i. A relatively small number of studies have been published describing the measurement of WPFs for powered air purifying respirators,[5–10] non-powered air purifying half- and full-facepiece respirators,[11–17] and disposable half-facepiece respirators.[18–20] The lack of data may be due at least in part to the difficulty associated with collecting and interpreting the field measurements needed to calculate WPFs: samples must be collected from inside the respirator facepiece under conditions of high humidity;[21–23] concentrations inside the respirator are typically quite low, thus requiring sufficiently sensitive analytical methods;[22–24] samples collected continuously (during both inhalation and exhalation) from inside the facepiece may need to be corrected for dead volume and pulmonary retention to minimize bias in the resulting WPF;[25–27] sample probe location may significantly bias estimates of in-mask concentrations;[28–30] and sampling equipment can be cumbersome and may change the characteristics of the respirator being examined and/or the work practices of the worker.

There is a need to address the challenges associated with measuring WPFs in order to assure that the millions of employees using respiratory protection receive adequate protection. Although OSHA regulations stipulate that fit-testing be performed prior to the use of respirators, no correlation between fit factors (FFs) measured with quantitative fit-testing methods (QNFT) and WPFs has been demonstrated in studies making the comparison.[7,23,27] More recently, correlations between FFs and biological measures of exposure to Freon-113 in a study of simulated healthcare environments has been demonstrated.[31–33] The authors suggested that one of the reasons that FFs do not correlate with WPFs is the fact that WPF studies do not include workers with FFs less than 100, whereas in the simulated healthcare study, the inclusion of these data largely influenced the establishment of a correlation between FF and exposure to Freon-113.[32,33]

The lack of a correlation between FFs and WPFs and the previously cited paucity of WPF data also complicates the process of setting assigned protection factors (APFs) for different types of respirators. Although ANSI has assigned APF values of 10 and 100 to half- and full-facepiece respirators, respectively,[34] in the Final Rule of the Respiratory Protection Standard, OSHA has reserved the sections on the definition and actual values of APFs so that these can be promulgated at a later date. This delay is likely due to uncertainty regarding the relationship between QNFT results and WPFs, as well as the limited amount of WPF data currently available to use as the basis for APFs.[1] This situation demonstrates the need for better techniques for evaluating the levels of protection afforded by respirators under real working conditions.

Another issue raised in the Final Rule is the almost complete lack of WPF studies for gases and vapors. In reviewing the available literature, OSHA was only able to identify a single study that examined WPFs for a vapor[1] and this scarcity has been echoed by other reviewers as well.[24,27] The reasons for the lack of gas and vapor data are not clear—it may be that the previously cited difficulties in measuring WPFs are more pronounced for gases and vapors. Whatever the reasons, without adequate WPF data, the assignment of an APF value for respirators used for gases and vapors based on aerosol data is questionable.

Numerous studies have shown that fit factors for dusts are related to the size distribution of the contaminant particles due to the size-selective nature of respirator leaks.[35–38] This characteristic has the effect of increasing the magnitude of protection factors measured for dusts in comparison to a gas or vapor for the same leakage. Given that the APF is often defined as the minimum level of respiratory protection that would be provided by a properly functioning respirator,[34] a strong argument could be made that APFs should be based on gas and vapor WPF studies in order to derive a conservative estimate. Nicas identified this option in a report to OSHA,[27] but went on to point out that the vast majority of WPF data are based on aerosol studies. This scenario clearly demonstrates the specific need for additional gas and vapor WPF data and improved instrumentation and techniques for data collection.

This project focuses on the development and testing of a prototype personal sampling system for measuring WPFs for gases and vapors in order to address the research needs identified above. The system is designed to sample during inspiration to reduce potential problems associated with continuous in-mask sampling, that is, biases due to lower contaminant concentrations in exhaled air, and high humidity. WPF data 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. It is anticipated that the findings from the studies with the current prototype system will lead to the development of an integrated sampling instrument, thus providing an effective and convenient tool for health and safety professionals engaged in evaluating the effectiveness of respiratory protection.

MATERIALS AND METHODS

Prototype Sampling System

The prototype sampling system was based on two low-flow sampling pumps with stroke counters (Model SP-13, Anatole J. Sipin Co., New York, NY) modified such that the output from a pressure transducer could be used to turn the pumps on and off in relation to a reference voltage set-point. The complete sampling system consists of two low flow pumps, and an enclosure that contains the pressure transducer and comparator circuitry. The pumps are connected to solid granular adsorbent tubes selected for the contaminant of interest. One sorbent tube is connected to a sampling port installed on the respirator to be tested while a second sorbent tube is used to sample the ambient air. A second sampling port is connected to the pressure transducer to allow the differential pressure inside the respirator to be monitored.

A low-range differential pressure transducer (PX163, Omega Engineering, Stamford, CT) was initially used to develop the switching circuit for the prototype. This transducer requires a regulated excitation voltage between 6 and 12 VDC, provides a conditioned 1–6 VDC output signal that is proportional to pressure over the range of $+/-2.5$ in H_2O, and draws approximately 20 mA. Initial selection of the PX163 transducer was based on the availability of a high-level output (V-DC), which minimized the amount of additional circuitry that had to be developed for the prototype instrument. In later designs, a smaller pressure transducer was employed (PX70, Omega Engineering) based on a desire to minimize size and power requirements, the tradeoff being that there is no on-board power supply circuitry or output amplification in the PX70. The PX163 was used for initial development of the prototype and the PX70 was used in field testing of the sampling system.

Switching the pumps on and off was accomplished using an op-amp based comparator circuit and a switching transistor. The circuit was adjusted so that whenever the transducer output exceeded a reference voltage (i.e., during inspiration), the output from the comparator would activate the transistor switch, which then turned on the sampling pumps. The system was designed to activate both the ambient and in-mask sampling pumps for consistency. It is not necessary to turn the ambient pump on and off even when in-mask sampling is conducted only during inhalation. However, since it was a simple matter to simultaneously turn the ambient sample pump on and off, this approach was taken.

Sampling ports (Kynar) were added to half- and full-facepiece respirators from two different manufacturers (North and MSA). Selection of the types of respirators used in the study was based primarily on what had been donated by safety equipment vendors although it was also required that the respirators be commercially available and in use in industry. For the full-facepiece respirators (North 7600, North Safety Products, Cranston, RI) (Advantage 1000, Mine Safety Appliance Co., Pittsburgh, PA) the speech diaphragm was replaced with a Plexiglas "blank" of the same thickness and diameter. This blank was then equipped with two sample ports that were connected to the prototype sampling system pressure transducer and the sorbent tube/sampling 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. Sorbent tubes were connected to the sampling ports using short lengths of silicone tubing to minimize potential sample loss.

This approach worked well for both types of full-facepiece respirator and allowed for the sampling ports to be switched in and out without modifying the main respirator body. Sampling ports were added to half-facepiece respirators (North 7700, North Safety Products, Cranston, RI) (MSA Advantage 200, Mine Safety Appliance Co., Pittsburgh, PA) 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 fitting used for the half-facepiece respirators was located roughly halfway between the nose and mouth and extended approximately 0.25″ into the respirator.

The prototype sampling system was tested using a respirator mounted on a headform (PosiChek Test Head, Biosystems, Inc., Middletown, CT) in a sealed Plexiglas exposure chamber measuring approximately 22″ × 22″ × 20″. The headform was connected to a dog ventilator (Model 613 Respiration Pump, Harvard Apparatus Co., Holliston, MA) modified for use as a breathing machine. The breathing machine flow rate was measured using a calibrated in-line orifice meter equipped with a pressure transducer and the output was continuously recorded using a data logger. The breathing machine was set to yield an average flow rate of approximately 20 L/min and a period of 3 seconds, which is roughly equivalent to a sedentary "work rate."[39] The purpose of this preliminary testing was simply to determine if the pump switching system functioned properly, so the flow rate used was not critical.

The voltage outputs from the prototype sampling system pressure transducer and comparator were recorded using a portable data logger (Tattletale Model 5F-LCD, Onset Computer Corp., Pocasset, MA). This allowed both the pressure measured inside the respirator mask and the switching mechanism of the circuit to be monitored simultaneously. Data was recorded at a frequency of 10 samples/second and downloaded to a PC for storage and display.

Quantitative Fit-Testing

Quantitative fit-testing was performed to evaluate whether the prototype sampling system significantly altered respirator performance. Fit-tests were conducted for two subjects wearing unmodified respirators and while using modified respirators with the prototype sampling system running. Respirators were removed and then re-donned for each fit-test. Tests were performed with a TSI PortaCount Plus Fit Tester (TSI Incorporated, St. Paul, MN) using the default 29 CFR 1910.134 protocol included in the FitPlus for Windows fit-test software. Fit-testing of both unmodified and modified full-facepiece respirators was conducted over the same time frame since the ports required for using the sampling system were easily switched out with the speech diaphragm.

Alternatively, the modifications required to add sampling ports to the half-facepiece respirators were not reversible, meaning that all pre-modification fit tests had to be conducted first, followed by the addition of sampling ports and then the post-modification fit-testing. Pre- and post-modification fit-test experiments were conducted for two each of half- and full-facepiece respirators from the two different manufacturers for a total of four respirators.

Preliminary Field Testing

Upon completion of laboratory testing of the prototype sampling system, preliminary field tests were conducted to evaluate the performance of the system under actual workplace conditions. Three volunteers were fitted with sampling systems and a quantitative fit test was administered. Subjects traveled to hog, turkey, and chicken (egg-laying) production facilities where they simulated the work activities of the farmers while wearing full-facepiece respirators (Figure 1). Activities included tasks such as washing down and scraping the walkways and aisles between the chicken cages in the egg-laying facility. Ambient and in-mask samples for ammonia were collected on acid-treated silica-gel adsorbent tubes (Cat No. 226-10-06, SKC Inc., Eighty Four, PA) using flow rates of 220–250 ml/min for a period of approximately 2–3 hr. Samples were analyzed according to NIOSH Method 6016 using ion chromatography. Ambient ammonia concentrations were screened using a portable photoionization detector (ToxiRAE Pocket PID, PGM-30D, RAE Systems) calibrated for ammonia.

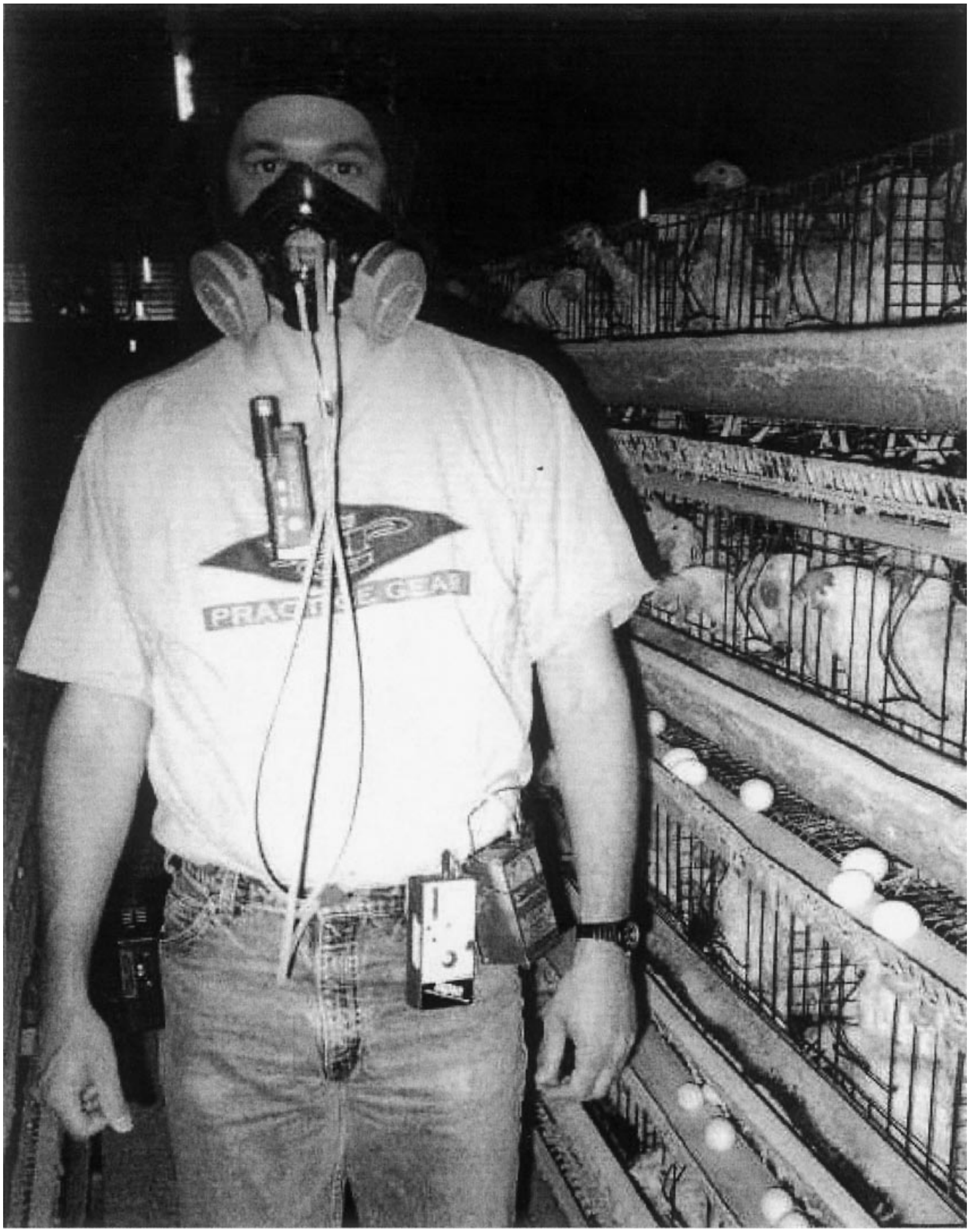


FIGURE 1
Subject wearing prototype personal sampling system for measuring ammonia WPFs.

RESULTS AND DISCUSSION

Prototype Sampling System

A photograph of the complete prototype sampling system is shown in Figure 2. Two low-flow pumps and an enclosure containing the pressure transducer/switching circuitry are worn on the belt of the subject and are attached to the appropriate samplers/ports via lengths of silicone rubber tubing. The pressure transducer enclosure is connected to each of the two pumps by short lengths of wiring that allow the pumps to be turned on and off during sampling. Although this arrangement was found to be functional in the field, the process of attaching three separate devices to the subject and connecting the associated wiring, tubing, and samplers was somewhat complicated. In addition, the

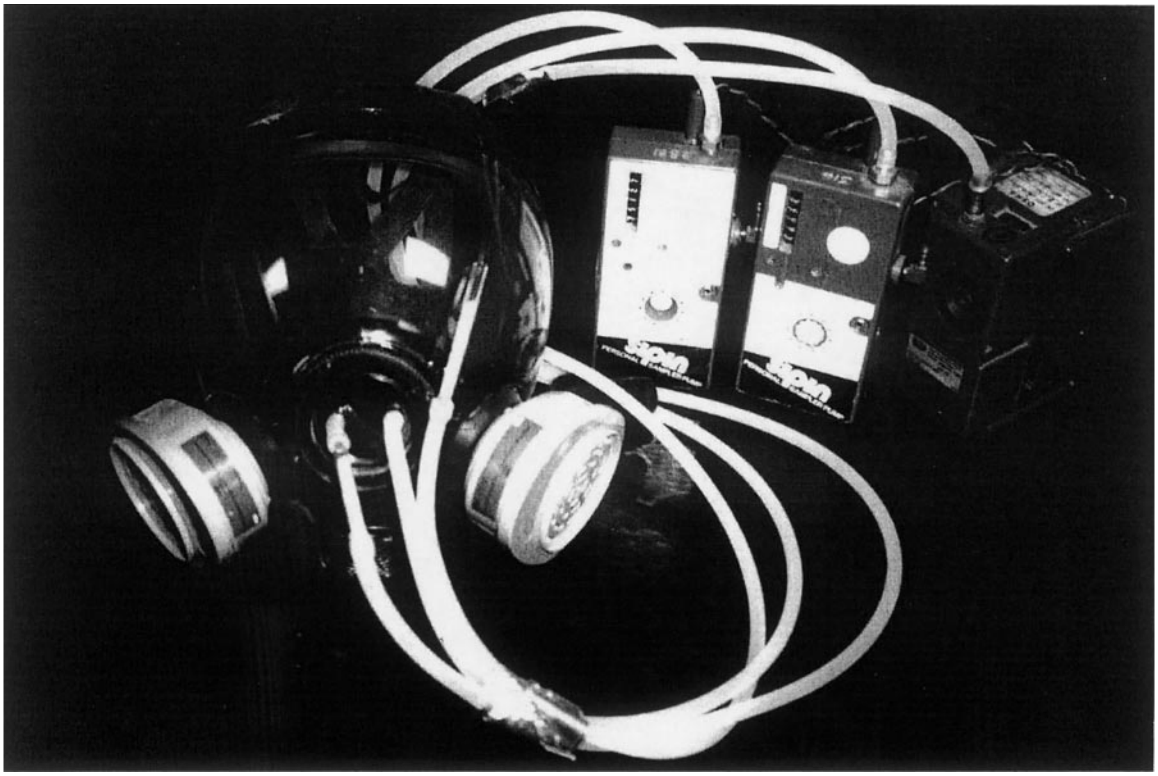
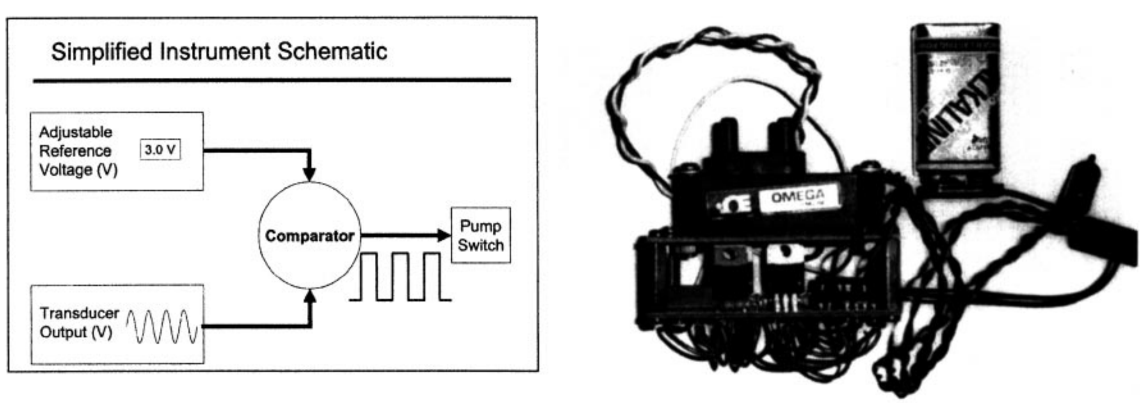


FIGURE 2
MSA advantage 1000 full-face respirator connected to prototype sampling system.

external wiring connecting the pumps and pressure transducers was prone to becoming entangled as the subjects simulated work activities. Integration of the various components into a single, slightly larger enclosure would greatly simplify use in the field and the development of such a prototype system is underway.

A simplified schematic for the pressure transducer/pump-switching circuitry and a photograph of the first prototype circuit board are shown in Figure 3. Figure 3a shows a reference voltage (set via a potentiometer) compared electronically to the output of the pressure transducer. Whenever the output of the transducer falls below the reference voltage a comparator circuit sends a 5-volt signal to a transistor switch used to turn on the sampling pumps. The process is illustrated in Figure 4, which shows a plot of the output voltage for the pressure transducer (light line)



a) b)

FIGURE 3
a) Simplified schematic for the pressure transducer comparator circuit. b) Actual prototype circuit.

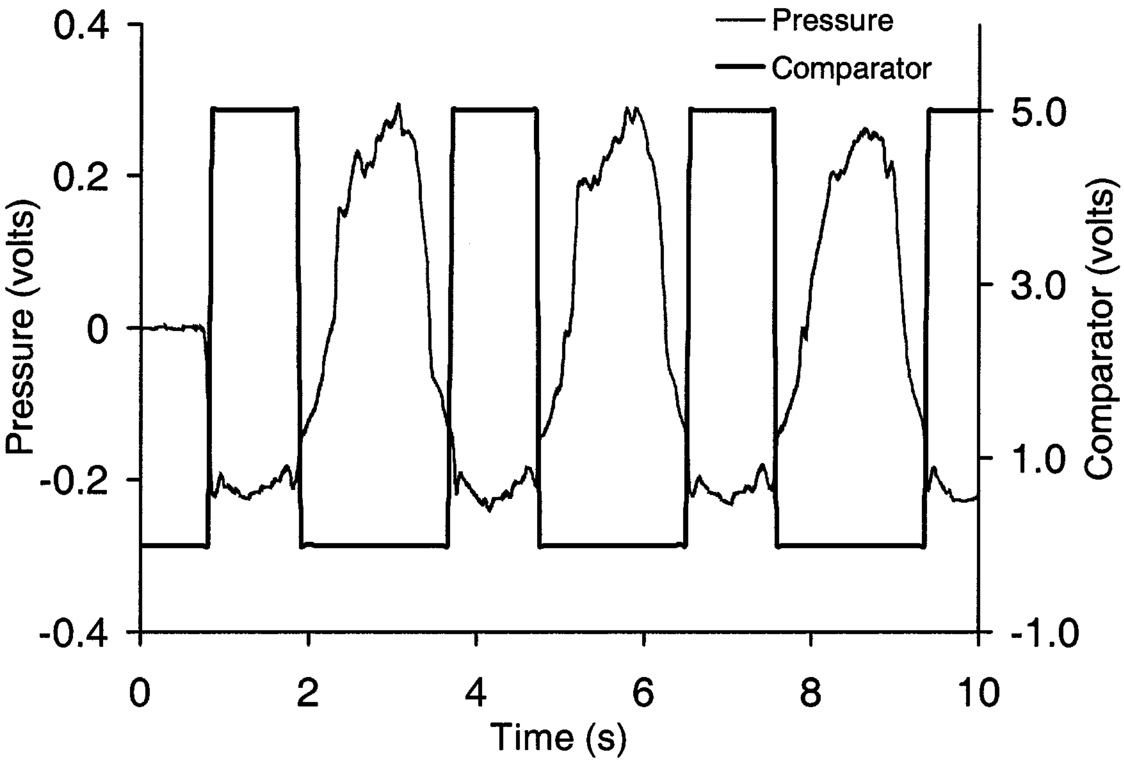


FIGURE 4
Pressure transducer output and pump switching voltage.

and the comparator circuit output (heavy line) used to switch on the sampling pumps while the system was connected to the breathing machine. As the pressure becomes negative within the respirator during inspiration, the output from the transducer falls below the reference voltage and the comparator output swings high (5V) to activate sampling pumps. When the pressure within the respirator begins to increase at the start of exhalation, the output of the pressure transducer rises above the reference voltage and the output of the comparator returns to zero, which in turn stops the sampling pumps.

During preliminary tests it was found that when the pumps were switched off, they typically continued to cycle for several strokes before coming to a complete stop. Although not critical for the ambient air sample, this potentially allowed in-mask sampling to continue past the end of inspiration. An examination of the pump switching circuit showed that the original design allowed the electrical input to the pump motor to "float" when in the "off" position, which in turn caused the additional strokes to occur after the pump was switched off. The switch circuit was redesigned to ensure that the input to the pump motor was grounded when in the off position, which has the effect of bringing the motor to an immediate stop. The function of the redesigned switch was tested by donning the sampling system and producing a series of quick inhalations—the activation of the pumps is audible and one can easily verify that the pumps are in fact starting and stopping immediately at the beginning and end of an inspiration. No other problems were encountered with the pressure transducer circuitry and both laboratory and field testing showed that the system reliably and consistently activated the pumps only during inhalation.

Quantitative Fit-Testing

Results for the respirator pre- and post-modification quantitative fit-testing are presented in Table I. A total of 299 fit-tests were completed for the two different types of respirators (full- and half-facepiece) from two manufacturers (MSA and North). A t-test (SigmaStat) was used to compare the mean pre- and post-modification fit factors with a null hypothesis that the difference between the means was equal to zero. Preliminary sample size calculations indicated that approximately 27 fit-tests per respirator were required to detect a 25 percent difference in mean fit factor with a power of 0.8 ($\alpha = 0.05$); however, actual sample sizes were adjusted according to the fit-test variability encountered for the different subject/respirator combinations. Tests of normality and equal variance were performed prior to conducting the t-test and were positive for both North respirators and the MSA full-facepiece respirator, that is, the distribution of pre- and post-modification fit factors was consistent with a normal distribution and variances were similar. The subsequent t-test indicated that the null hypothesis could not be rejected, meaning that there was not a statistically significant difference between mean pre- and post-modification fit factors. A retrospective power analysis showed that the power of the t-test was

TABLE I
Results for pre- and post-modification quantitative respirator fit testing

Respirator (subject)	n[1]	Ave FF[2]	s	CV%	t-test p	t-test t	Power[3]	% Diff.	CV%
North									
Pre-full (1)	32	27,928	9121	33	0.651	−0.455	0.803	25	35
Post-full (1)	32	29,019	10,046	35					
Pre-half (1)	33	7532	1972	26	0.196	1.306	0.936	25	28
Post-half (1)	30	6890	1925	28					
MSA									
Pre-full (1)	28	16,829	4,393	26	0.990	−0.013	0.942	25	26
Post-full (1)	28	16,844	4163	25					
Pre-half (2)	58	7229	4270	59	0.134[4]	—	0.619	25	59
Post-half (2)	58	8480	4302	51					

[1]Number of tests conducted (TSI PortaCount® default 29 CFR 1910.134 protocol, respirator re-donned for each test).
[2]Average fit factor (FF) for n measurements.
[3]Results of retrospective power analysis for indicated % difference in means and CV% ($\alpha = 0.05$).
[4]Failed normality test—Mann-Whitney rank sum test performed.

greater than 0.8 ($\alpha = 0.05$) for detecting a 25 percent difference in the mean fit factor for all three comparisons.

Fit factors for the MSA half-facepiece respirator were found to be much more variable than for the other respirators and the normality test failed. The data still did not pass a normality test after a log-transformation of the fit-factors, so a non-parametric Mann-Whitney rank sum test was employed to compare the pre- and post-modification mean fit factors. Results showed that there was no significant difference between pre- and post-modification fit factors. Retrospective power analysis indicates a power of 0.61 ($\alpha = 0.05$) for detecting a difference in means of 25 percent; however, this is only an approximation since the data failed the test for normality. A two-tailed test was used for comparing means of the pre- and post-modification fit tests; however, a decrease in mean fit factor for the post-modification tests would be the greatest concern since it would suggest the sampling system has decreased the performance of the respirator. Although the results for the MSA half-facepiece respirator indicate a power of less than 0.8 for detecting a 25 percent difference in pre- and post-modification fit factors, the post-modification mean is actually higher than the pre-modification mean, which suggests that the performance of the respirator was not decreased by the sampling system.

Two subjects were used for the quantitative fit-tests—one subject was used for both the North fit tests (full-and half-facepiece) and the MSA full-facepiece tests while a second subject completed the MSA half-facepiece testing. The variability of the fit-test results for the MSA half-facepiece could be due to the facial features of the subject or differences in the way the subject donned the respirator for the tests compared to another subject.

The results for the pre- and post-modification quantitative fit-tests are important for the project since a fundamental concern regarding any measurement system is whether its use alters the characteristic being examined. These results indicate that the use of the prototype sampling system did not significantly alter the fit-tests of the respirators. This comparison is limited by the fact that it is based on fit factors that can be subject to biases related to the location of sampling probes;[(28–30)] however, given the establishment of correlations between fit factors and exposure[(31–33)] and the lack of an alternative technique for assessing the effect of the sampling system on respirator performance, it can be reasonably inferred from these results that the sampling system is not likely to significantly alter the performance of respirators when used to measure workplace protection factors (WPFs).

Preliminary Field Testing

Results for three individuals wearing full-facepiece respirators for preliminary field tests of the prototype WPF sampling system are presented in Table II. Sampling was conducted in several different livestock production facilities including chicken egg-laying (Figure 1), turkey, and hog operations. WPFs ranged from 80–253 for the three samples yielding measurable ammonia

TABLE II
Preliminary field-testing results for ammonia WPF measurements (full-facepiece respirators)

Operation	Ambient concentration (ppm)	In-mask concentration (ppm)	WPF	Ratio of in-mask sample mass to LOD
Hog	14	0.16	90	1.4
Chicken	8.7	0.12	80	1.2
Turkey	76	0.30	253	4.5

concentrations on the in-mask samples. However, the values were only slightly above the LOD as indicated by the ratio of sample mass to LOD in the last column. Given the proximity of these sample results to the LOD, the accuracy of the results is questionable and the estimates of WPF should be considered semi-quantitative.

The purpose of these initial field tests was to allow a functional evaluation of the sampling system rather than to provide a rigorous study of WPFs for ammonia. In addition to demonstrating the field performance of the sampling system these results reinforce the importance of the sensitivity of the analytical method used when performing WPF studies.[22,23] PID readings were not listed in Table II but were generally in close agreement with the average measured value for ambient concentrations. The PID proved to be very useful in screening ambient concentrations and could be used in future studies to estimate sample times needed to ensure that the in-mask sample loading is adequate based on the expected protection for a particular type of respirator.

Preliminary testing yielded important information to be used in the further development of the prototype sampling system. Results showed that the transducer circuitry functioned well and that the use of such a device in the field is feasible. However, the current prototype system is somewhat awkward to use as a result of the number of separate components, electrical connections, and tubing. Future work will focus on the integration of the components of the sampling system into a single more compact unit. In addition, the use of a single pump for the collection of both ambient and in-mask samples will be examined in order to obtain significant reductions in the size and power requirements of the instrument. Finally, the addition of a datalogger and heart rate transducer system will be considered so that a more detailed characterization of the working conditions associated with a given measurement of a WPF can be provided.

CONCLUSIONS AND RECOMMENDATIONS

A prototype sampling system for measuring workplace protection factors has been developed and tested. The system employs a pressure transducer and switching circuitry to allow intermittent respirator sampling during inhalation only. It is expected that this approach will reduce the effects of high sample humidity and potentially biased results associated with in-mask samples collected continuously. The system does not address the problem of biased results due to the location of the sampling probe inside the respirator, and further work needs to be conducted to evaluate strategies for controlling this phenomenon. A series of quantitative fit-tests conducted for full- and half-facepiece respirators from two different manufacturers showed that there was not a statistically significant difference between mean pre- and post-modification fit factors for any of the respirators examined. Although the results are based on fit factors, the establishment of correlations between fit factors and the actual exposure of respirator users makes it reasonable to infer that the system would not significantly alter respirator performance during actual use. The prototype sampling system was used to measure WPFs for ammonia in several livestock production facilities. While not intended to represent a rigorous and comprehensive WPF study, results of field testing demonstrated the feasibility of using such a system. It was found that the current system design made its use in the field cumbersome and future work will focus on integrating the separate components into a single, more compact package.

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