SYSTEM FOR MEASURING WORKPLACE PROTECTION FACTORS

FINAL REPORT

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Introduction

The purpose of this final report is to present results for this Special Emphasis Research Career Award (SERCA) entitled "Sampling System for Measuring Workplace Protection Factors". There have been no significant changes to Other Support of key personnel, nor was there significant re-budgeting of funds from what was approved for the project. In addition, there was not any change in the level of effort by key personnel. Finally, there was no unobligated balance exceeding 25% of the current budget year's total. The remainder of this report will be devoted to describing progress toward accomplishing the specific aims of the project.

a. Specific Aims

The overall goal of this project was to develop and test a personal sampling system for measuring workplace protection factors (WPF) for gases and vapors. The system consists of a low-flow sampling pump with stroke counter, 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 the pressure transducer as well as a transducer for measuring heart rate. The pressure transducer and solenoid valve are designed to allow sampling of the air inside the respirator face-piece during the inhalation portion of respiration, while the ambient environment is sampled during the exhalation phase. The system is relatively small and light-weight, allowing the unit to be worn easily on a worker's belt, and has adequate battery power to operate for at least a full 8-hour shift. The resulting personal sampling system should be a valuable tool for researchers interested in measuring WPFs for gases and vapors for the purpose of developing or evaluating Assigned Protection Factors (APF), or in exposure assessment for specific applications of respiratory protective equipment.

The specific aims for the project were to:

1. Integrate the following main components of the personal sampling system into a single enclosure measuring approximately 5"x5"x2.5" and weighing less than 2.5 lb. including the battery:

   A low-flow sampling pump with stroke counter
   Solenoid valve for switching between sampling in-mask and ambient atmospheres
   Pressure and heart rate monitoring transducer circuitry
   Multi-channel data-logging unit for recording transducer outputs
   Sampling ports and electrical connectors

2. Add sampling ports to 2 full- and 2 half-face respirators from 2 different manufacturers (4 respirators total) for use with the sampling system. Conduct quantitative fit-testing using a TSI Portacount before and after the modification to determine the nature of any effect on respirator fit-test performance.

3. Calibrate the sampling system pressure transducer to allow estimation of respiratory flow rates based on differential pressure inside the face-piece of the different respirators. Evaluate the general applicability and reproducibility of the relationship between in-mask pressure and flow rates.

4. Conduct laboratory testing of the sampling system using an exposure chamber containing a headform connected to a breathing machine modified to produce a humidified "exhaled" air stream. Compare results obtained using intermittent and continuous sampling approaches for evaluation of both in-mask and ambient concentrations for three different test vapors.

5. Fabricate 3 prototype sampling systems and conduct field-tests using volunteers in actual workplace settings.

A project timeline is presented in Table I in the form of a schedule of activities associated with accomplishing the specific aims of the project.

b. Studies and Results

Preliminary Tasks

Referring to Table I, it can be seen that the first scheduled activities were the identification of graduate students (Task 1) and procurement of equipment and supplies (Task 2). Graduate research assistants have been employed through wage payroll and assistantships. Although it would have been preferred that a graduate student in Industrial Health and Safety use this work as a thesis project, the IHS MS degree program was not formally approved until Fall of 2002 and so graduate students from related programs (e.g. Industrial Engineering (I.E.)) were recruited for the project. This did not significantly slow progress and the practice of hiring graduate students through wage payroll continued until appropriate I.E. M.S. candidates were identified. Purchasing of equipment and supplies was on schedule / completed.

Development of Prototype Instrument

Task 3 focused on the development of the prototype instrument including the development of transducer power and pump switching circuitry, selection and design of heart rate monitoring transducer circuitry, packaging of the prototype system components, and laboratory testing of the assembled system. Transducer power and pump switching circuitry has been completed and a commercially available chest-band type heart rate transmitter and receiver module (Polar) has been tested and incorporated into the prototype instrument. All components have been assembled and packaged in a case measuring approximately 8.5" x 4" x 2" (Figure 1a-c). Laboratory testing of the instrument and development of the user interface has been completed. The instrument has the capability to log and download several parameters into an Excel Spreadsheet, including the in-mask pressure, heart-rate, cumulative volume of air inhaled through the respirator cartridges, and the respiratory rates as a function of time over the course of the sampling period. Buttons on the front of the instrument allow the user to start and stop the recording of data and can also be programmed to initiate special "events" such

as sampling pressure and heart rate at higher frequencies over time periods of interest. The LCD display has been designed to display the run time, current in-mask pressure, and cumulative inhaled air volume, but is capable of displaying other parameters of interest such as the number of times the heart rate exceeded some pre-set value, or the breathing rate when the heart rate exceeds some target level. Two of the three prototype instruments have also been modified to allow the output from heart rate and pressure transducers to be displayed in real time (Figure 2). The capabilities of the instrument are extremely broad and flexible due to the use of the programmable TFX-11 data logger/microprocessor (Onset Computer, Cape Cod, MA).

Modification and Performance Testing of Respirators

Task 4 relates to the modification of respirators for use with the prototype instrument and includes pre- and post-modification respirator 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 manufactures for a total of four respirators.

Results for the respirator pre- and post-modification quantitative fit testing are presented in Table II. 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% difference in mean fit factor with a power of 0.8 (α =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, i.e., 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 greater than 0.8 (α=0.05) for detecting a 25% 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 (α =0.05) for detecting a difference in means of 25%, 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% 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.

It should be noted that 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 other 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 test results for the respirators. This comparison is limited by the fact that it is based on fit factors which can be subject to biases related to the location of sampling probes (1-3);however, given the establishment of correlations between fit factors and exposure (4-6) 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).

In-Mask Differential Pressure Measurements

Task 5 focused on the use of differential pressure measurements to predict flow rate and ultimately the volume of air passing through the respirator cartridges. This task included calibration of pressure transducers against a manometer to yield output voltage as a function of pressure and to then measure the flow rate through head-form mounted respirators as a function of differential pressure. The first phase of this task involved calibration of the pressure transducers for two different pressure ranges: 0-1 "H_2O and 0-5 "H_2O. Five transducers of each type were calibrated over the applicable pressure range. The results for 5 individual 0-5 "H_2O transducers were highly linear and reproducible across transducers as indicated by the superposition of the data points in Figure 3. Note that 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 sampling solenoid valve. Figure 4 shows the combined results for the five transducers and the results of a linear regression. The transducer outputs were highly linear (R^2 = 0.999) and the resulting regression equation can be used to estimate differential pressure inside the respirator as a function of transducer output (voltage) with minimal error.

Task 5 also includes an examination of the relationship between respirator differential pressure and flow rates through different types of cartridges and for different types of respirators. These experiments included an examination of flow rate versus pressure drop for three sets of two different types of respirator cartridge (ammonia and organic vapor) for different types of respirators - results are presented in Figure 5. 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 (Model 25 Mark II, Dwyer, Michigan City, IN). Figure 5 shows that plots of respirator flow rate versus differential pressure are linear for flow rates up to 80 L/min and reproducible. Additional tests using flow rates up to 160 L/min showed similar reproducibility but with signs of curvature in the relationship between vacuum pressure and flow rate. Excellent fits were obtained using a quadratic model with zero-intercept. This result demonstrates the feasibility of using respirator differential pressure measurements to estimate respirator flow rates and integrated exhalation volumes.

The emphasis in these studies is on the inhalation portion of the respiratory cycle since it is during this phase that contaminants are filtered by the respirator and leaks can result in infiltration into the face-piece. Calibrations of flow rate versus differential pressure have been performed for the exhalation phase of respiration as well – a combined plot of inhalation and exhalation flow rates is presented in Figure 6 (North 7600 Full-Facepiece, P100 cartridges). It can be seen that the relationship between flow rate and differential pressure is not a simple linear one for exhalation, most likely due to the characteristics of the exhalation valve which behaves much differently than a packed bed- or filter-type respirator cartridge. It would be possible to fit a more complicated expression to describe the exhalation data; however, the inhalation portion of the respiratory cycle is typically of most interest and can be relatively simply and accurately described.

Laboratory Testing of Sampling System

The integrated system was tested in the laboratory using a respirator headform mounted in a sealed exposure chamber and connected to a breathing machine (see Figure 7). Test-atmospheres were used to evaluate the performance of the sampling system using the appropriate adsorbent tubes. 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 (ammonia was dropped from the test set due to problems with the analytical method sensitivity – these problems were subsequently resolved through the development of a fluorometric method of analysis but time did not allow for including ammonia as a test contaminant). 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 ~37°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 7, the exhaust 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 exhaust stream could have on the chamber concentration.

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 2500 assuming an ambient concentration equal to 5 times an Occupational Exposure Limit (OEL) of 25 ppm. This level of protection (WPF=2500), although extreme for a half-mask respirator, has been documented as demonstrated by Galvin et al when they measured WPFs on the order of 1000 for styrene (7). This demonstrates the importance of adequate analytical sensitivity so that the distribution of WPFs can be fully characterized.

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 cartridges. In-mask samples were collected both intermittently using the personal sampling system (S3), and continuously using low flow pump (S4). Samples were also collected in the exposure chamber using both the intermittent personal sampling system (S1) and a continuous low-flow pump (S2). Samples were analyzed according to the appropriate NIOSH analytical method using GC-FID. Table III outlines several chemical and physical properties of test vapors, as well as the ACGIH TLVs, the applicable analytical method, estimated limit of detection for the method (LOD), average flow rate, and an estimated sample time. The latter value is calculated assuming a chamber concentration of 50 ppb, with the specified sample flowrates and LODs. Chemicals were analyzed using an activated carbon sorbent-tube based method. Backup sorbent sections were analyzed to determine whether breakthrough occurred.

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 a 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, and exposure chamber samples. Ideally

these results should not be significantly different. However, if some loss of contaminant occurs as a result of flow through the non-filtering restrictive element, 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 intermittent exposure chamber sample. Comparisons can also be made between the intermittent and continuous exposure chamber samples (S1 & S2) in order to confirm that the intermittent sampling approach yields results comparable to continuous sampling.

Results of the exposure chamber tests are summarized in Table IV. 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. This is an important result for the development of the prototype system since a single sampling pump is relied upon to intermittently sample from inside and outside the respirator.

Results for continuous (S3) and intermittent (S4) in-mask samples are also displayed in Table IV 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). A likely explanation for the negative bias of the intermittent in-mask sample to the chamber samples is the effect of respirator dead volume – the concentration inside the respirator is cycling from a high value during inhalation that should be approximately equal to the chamber concentration, to a low value which is close to the exhalation concentration which should be zero for these experiments. 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 it may accurately represent the actual concentration of the air inhaled by someone wearing a respirator.

Main effects plots were examined to evaluate the influence of the three factors: Manufacturer (MSA, North), Respirator Type (Full-Facepiece, Half-Facepiece), and Solvent (Perchloroethylene, Acetone), on the ratio of the in-mask concentrations to the chamber concentrations and each other (Figure 8). Results show minimal influence on the measured quantities. The only statistically significant effect detected was that of Solvent on the ratio of intermittent in-mask sample to the chamber concentration (Ci/Co); however, the magnitude of this effect was less than 10%. This apparent decrease in the relative in-mask concentration of acetone versus perchloroethylene may reflect the much greater water solubility of acetone - the humidified exhalation stream produces a significant quantity of condensed water within the respirator (similar to actual use) which may serve as a "sink" for acetone. A larger study examining more solvents with a range of water solubility would be needed to confirm this hypothesis but, in any case, the

magnitude of the effect was less than 10% for acetone which is very water soluble so it is not anticipated that significantly larger decreases in in-mask concentrations would be encountered.

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 used to calculate the WPF. Additional studies would be required to fully determine whether continuous sampling or intermittent sampling yields results that are more representative of the actual inhaled concentrations. However, the current work clearly demonstrates the reproducibility of measurements taken using an intermittent sampling protocol and 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 also reduces the amount of water that has to be accounted for in the sample matrix during analysis.

The remaining work on the prototype sampling system focused on developing the software used for data logging, downloading, display, and storage. The 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 binary data file to an ordinary text file which can then be loaded as a spreadsheet (comma delimited). A sample of an offloaded data text file is shown in Figure 9. The data can then be processed and displayed allowing for an examination of the quantities of interest such as in-mask pressures, and instantaneous flow rates (Figures 10, 11). Models developed for correlating physical work rates with heart rate and individual characteristics can be used to prepare plots such as those in Figure 10b depicting heart rate, work rate, and minute volume over the course of the sampling run. The interrelationship of heart rate, minute volume, and work rate 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 the workplace protection factor. The data can also be used to examine peak inhalation flow rates (Figure 11) and the distribution of flow rates (Figure 12) for different levels of activity.

Field Testing of Prototype Instrument

The primary functional components of the sampling system have been tested extensively both in the laboratory and in the field. However, due to the time spent on the development of the fluorometric method for ammonia analysis and a much more extensive examination of the relationship between workload, heart rate, and individual characteristics than was originally planned, the final field testing of the prototype sampling system could not be completed within the project period. While the field demonstration portion of the project is important and unfunded work will continue to complete this phase, due to the comprehensive nature of the preliminary field testing and the thorough laboratory testing, the decision was made to focus efforts on the unplanned, but equally important aspects of the project.

Fluorometric Method for Analysis of Ammonia in Air

A fluorometric method for analysis of ammonia in ambient air was developed and tested. The approach is based on modifications to an existing method for analysis of ammonium in marine and freshwater samples to enable measurement of low concentrations of ammonia in ambient air. Optimal results for the new method were obtained using a tube containing 100 mg of acid-treated silica-gel for sample collection, and an analytical protocol which entailed a 30 minute desorption of samples in 80 mL of DI water, addition of 20 mL of fluorometric working reagent, and 2 hr room temperature incubation. Samples were quantified using a digital filter fluorometer with excitation and emission wavelengths of 365 and 420 nm, respectively. A dynamic test-atmosphere generation system was used to prepare atmospheres containing 1.01 ppm of ammonia and side-by-side samples were collected so that results for the fluorometric method could be compared to those obtained from an outside laboratory using NIOSH Method S-347. Sample time and flow rate were adjusted to account for different method sensitivities – samples for analysis by the NIOSH method were collected at 200 mL/min for 240 minutes while two samples for fluorometric analysis were collected sequentially at 50 mL/min for 120 minutes to span the 240 minute sample period. A total of 13 runs was conducted over a period of one week resulting in 26 samples for fluorometric analysis and 13 for the NIOSH method. The average ammonia concentration for samples analyzed using the fluorometric method was 1.06 + 0.03 ppm versus 0.978 + 0.09 ppm for samples analyzed using NIOSH S-347. Average percent errors relative to the expected concentration were 4.7% and –11% for the fluorometric and NIOSH methods, respectively. Results demonstrate excellent accuracy and precision for the new method which should be useful for measuring low concentrations of ammonia.

Predicting Work Rate from Heart Rate Measurements

It has been recognized that a number of factors influence the determination of WPFs including particle size, work time, environmental conditions, analytical method, sensitivity of the analytical method, and work rate (8). In particular, work rate has been found to be critically important in evaluating respirator performance and so is frequently evaluated in WPF studies or used as a reference for breathing rates in laboratory studies designed to evaluate respirators, or in the development of fit-testing instrumentation (8-17). One would expect that work rate would significantly impact the extent of contaminant penetration in a respirator as a result of the associated increased respiration rate and level of activity. If a WPF study involves a population of workers whose job entails a relatively low level of activity, it is possible that the resulting WPFs may be high compared to a population using the same class of respirator but in a job requiring much more strenuous exertions and frequent activity. Without some measurement of work rate it would not be possible to examine any potential relationship between level of activity and WPFs. Although subjective evaluations of work rates can be made based on observation of workers, it would be very useful to have measurements of physiological parameters correlated with work rate to be used along with observation data to better characterize the conditions under which WPF data are collected. Heart rate and body temperature are two such parameters that are relatively easy to measure and evaluate (18). Both can be recorded during actual work activities and then compared to results from a standardized activity used as a reference for each

subject. Alternatively, predictive models can be developed for estimating work rates based upon heart rate and individual characteristics. The prototype WPF instrument was equipped with appropriate transducers and signal conditioning circuitry so that the measurement of heart rate could be implemented thus allowing a WPF measurement to be more fully characterized by providing the associated estimate of work rate.

A model for predicting physical workload (PWL) using heart rate and individual characteristics was developed and tested. Data were collected from 13 subjects performing a step-test for three levels of exertion spanning a range of physical work load of approximately 15-85 watts (W). Metabolic workload was measured using a metabolic monitor and physical workload was estimated from the known step height, weight of the subject, and step frequency. Stepwise regression was performed to obtain the significant variables and a predictive equation was developed:

$$PWL = -253 + 0.0370*HR*H - 0.0368*HR*RH + 0.0417*HR*A - 0.0424*RH*A + 0.137*W*B*G - 0.0227*W*H*G - 0.126*A*W*G - 0.000499*A*W*B + 0.293*A*H*G + 0.177*RH*W - 0.00125*RH*W*H - 0.00162*RH*W*B - 12.7*B*G - 3.68*RH$$

where HR = heart rate, bpm
H = height, in
A = age, yr
RH = resting heart rate, bpm
W = weight, lb
B = body mass index (BMI)
G = gender, M = 0, F = 1

The resulting model included 14 significant variables resulting in an R^2 value of 0.9605 (Figure 13) This equation was used to predict the physical workload (PWL). The average percentage error between the actual and predicted PWL was 1.37% and the average absolute percentage error was calculated to be 9.3%. This expression was subsequently used to predict PWL from recorded heart rate and individual characteristics (see Figure 10b). A similar expression was developed for predicting metabolic work load (MWL).

c. Significance

The research conducted as part of this project has lead to the development of a valuable instrument for use in gathering WPF data for gases and vapors. The sampling system developed is small and light-weight, allowing the unit to be worn easily on a worker's belt, and has adequate battery power to operate for a full 8-hour shift. This technology should help to address research needs identified in the Final Rule of the Respiratory Protection Standard. 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. The importance of this type of research is recognized in the National Occupational Research Agenda (NORA) as demonstrated by designation of the category "Control Technology

and Personal Protective Equipment" as a priority research area. This project is consistent with the research needs identified in the NORA documents (19,20) and should lead to the development of an important tool for researchers engaged in characterizing and evaluating respiratory protective equipment.

d. Plans

It is intended that this research will serve as a starting point for a series of related projects following a logical progression that expands on the original work. The current proposal has lead to the development of a thoroughly characterized tool that is designed for evaluating respirators used in the workplace for protection from gases and vapors. The logical next step would be the use of the personal sampling system in a larger, carefully designed WPF study focusing on the protection afforded by different types of respirators for various gases and vapors. To that end, one of the goals of this SERCA project was to lay the ground work for this next study by providing adequate preliminary data to support a subsequent R01-type proposal. Important logistical information has already been gathered during preliminary field tests and laboratory testing of the prototype instrument thus allowing the framework for a larger study to be refined.

This SERCA project and a subsequent three year WPF study based on the proposed personal sampling system would allow a foothold to be gained in this important and exciting area of research and would serve as a springboard for numerous related projects. The use of calibrated pressure transducers to measure respiratory flow rates and cumulative filtered air volumes could find use as an aid to estimating service lives and for indicating scheduled cartridge replacements. Another opportunity for further development of this technology could involve modification of the system to sample exhaled breath as a means of biological monitoring. The system could be modified to sample only during exhalation and when combined with respiration and heart rate data may provide a way to thoroughly characterize the pharmacokinetics for many volatile organic compounds. These are just a few examples of some of the exciting new lines of research that may be spawned by this project.

e. Publications / Presentations / Theses / Projects

Publications

Groves WA, Reynolds SJ, "Prototype Sampling System For Measuring Workplace Protection Factors For Gases And Vapors", Appl Occup Environ Hyg 2003 18(5); 394-402.

Manuscripts In Progress

Groves WA, Reynolds SJ, "An Integrated Personal Sampling System for Measuring Workplace Protection Factors – Development and Evaluation".

Groves WA, Agarwal D, Chandra MJ, Reynolds SJ, "A Fluorometric Method for Ammonia Analysis".

Kamalakannan B, Groves WA, Freivalds A, Reynolds SJ, "A Protocol for Estimating Employee Work Rate During Respirator Use Based Upon Individual Characteristics and Recorded Heart Rate".

Presentations

Groves WA, Reynolds SJ. Preliminary development and testing of a personal sampling system for measuring respirator workplace protection factors for gases and vapors. American Industrial Hygiene Conference and Exposition; 1998 May 14; Atlanta, GA.

Groves WA, Conrad C, Reynolds SJ. Development of a personal sampling system for measuring respirator workplace protection factors for ammonia in livestock production facilities. Fourth International Symposium: "Rural Health and Safety in a Changing World"; 1998 Oct 20; Saskatoon, Saskatchewan, Canada

Groves WA, Conrad C, Reynolds SJ. Sampling system for measuring respirator workplace protection factors for gases and vapors. Iowa-Illinois local section meeting of the American Industrial Hygiene Association, 1999 Feb 11; Iowa City, IA

Groves W, Reynolds S. An integrated sampling system for measuring workplace protection factors for gases and vapors. American Industrial Hygiene Conference and Exposition; 2002 June 5; San Diego, CA.

Agarwal DR, Chandra MJ, Reynolds SJ, Groves WA. A fluorometric method for ammonia analysis in ambient air. Graduate Student Poster Session (505). American Industrial Hygiene Conference and Exposition; 2002 June 5; San Diego, CA.

Groves WA, Agarwal D, Chandra M, Reynolds J. Evaluation of a new fluorometric method for ammonia analysis in ambient air. American Industrial Hygiene Conference and Exposition; 2003 May 12; Dallas, TX.

MS Theses In Progress

Divya Agarwal, "A Fluorometric Method for Ammonia Analysis".
Admitted to the Industrial Engineering MS Degree program in Fall 2001. Co-Advising with Dr. M. Jeya Chandra, Professor of Industrial and Manufacturing Engineering, Penn State University

Balaji Kamalakannan, "A Protocol for Estimating Employee Work Rate Based on Recorded Heart Rate for Employees Wearing Respirators". Admitted to the Industrial Engineering MS Degree program in Fall 2002. Co-Advising with Dr. Andris Freivalds, Professor of Industrial and Manufacturing Engineering, Penn State University

Independent Research Projects

William Raab, Industrial Health and Safety Program, IHS 496 Independent Study (3 credits), "Calibration of Pressure Transducers and Correlation of Flow Rate with In-Mask Pressure", 2002.

Michael Pinkerton, Environmental Resource Management Program, IHS 496 Independent Study (3 credits), "Effect of a Prototype WPF Sampling System on Quantitative Fit-Test Results", 2001.

f. Project Generated Resources

none

g. Literature Cited

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Table I. Schedule of Activities by Quarter, November 1999 to October 2002

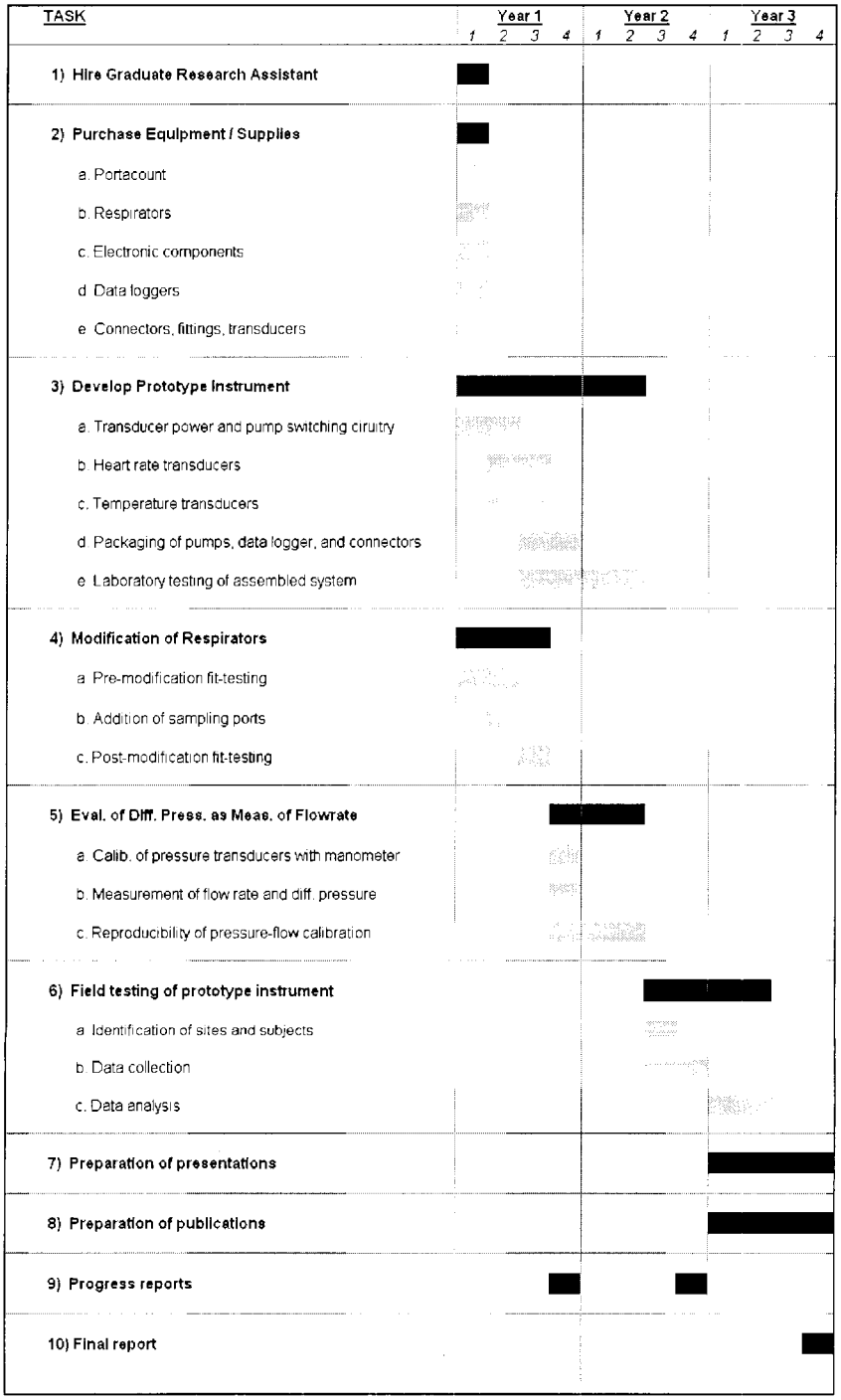

Table II. Results for Pre- and Post-Modification Respirator Fit Testing

Respirator (subject)		n[3]	Ave FF [1]	s	CV%	t-test		Power [2]	% Diff.	CV%
						p	*t*			
North	Pre-Full (1)	32	27,928	9,121	33	0.651	-0.455	0.803	25	35
	Post-Full (1)	32	29,019	10,046	35					
	Pre-Half (1)	33	7,532	1,972	26	0.196	1.306	0.936	25	28
	Post-Half (1)	30	6,890	1,925	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	4,163	25					
	Pre-Half (2)	58	7,229	4,270	59	0.134 [4]	-	0.619	25	59
	Post-Half (2)	58	8,480	4,302	51					

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

Table III. Chemical and physical properties for test chemicals

Chemical	*MW*	*VP, mm Hg*	*Dipole Moment, debye*	*1998 TLV, ppm*	*Analytical Method*	*Est. LOD, µg/sample*	*Ave. flow rate[1], mL/min*	*Time to detect 50 ppb, min*
Acetone	58.1	230	2.9	500	NIOSH 1300 GC/FID	1	100	84
Ammonia	17.0	>760	1.5	25	NIOSH 6016 IC	2	250	230
Perchloroethylene	166	14	0.0	25	NIOSH 1003 GC/FID	1	100	29

[1] Average flow rate is equal to one half the actual flow rate for intermittent sampling pumps

TABLE IV. Laboratory testing results for intermittent and continuous sampling (conc. in PPB)

Chamber Concentration, C^o		Respirator Concentration, C^R		Concentration Ratios		
C^o_{cont} (S1)	C^o_{int} (S2)	C^R_{cont} (S3)	C^R_{int} (S4)	C^R_{cont}/C^o	C^R_{int}/C^o	C^R_{int}/C^R_{cont}
MSA Half-Facepiece[1], Perchloroethylene						
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
				0.50(0.02)	**0.78(0.04)**	**1.56(0.09)**
North Half-Facepiece[2], Perchloroethylene						
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
				0.53(0.05)	**0.76(0.07)**	**1.44(0.04)**
MSA Full-Facepiece[3], Perchloroethylene						
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
				0.49(0.04)	**0.77(0.06)**	**1.57(0.07)**
North Full-Facepiece[4], Perchloroethylene						
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
				0.48(0.03)	**0.78(0.02)**	**1.62(0.11)**
MSA Full-Facepiece[3], Acetone						
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
				0.50(0.04)	**0.70(0.05)**	**1.40(0.06)**
North Full-Facepiece[4], Acetone						
48	45	19	34	0.41	0.73	1.8
41	45	21	33	0.49	0.77	1.6
				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

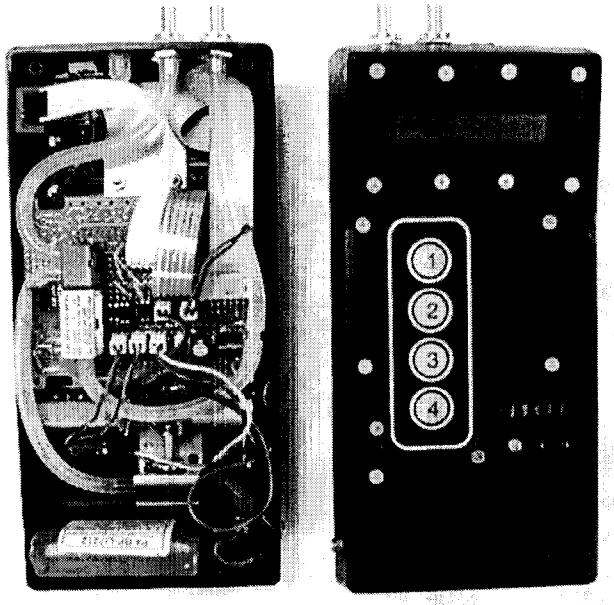

Figure 1a. Packaged prototype instrument.

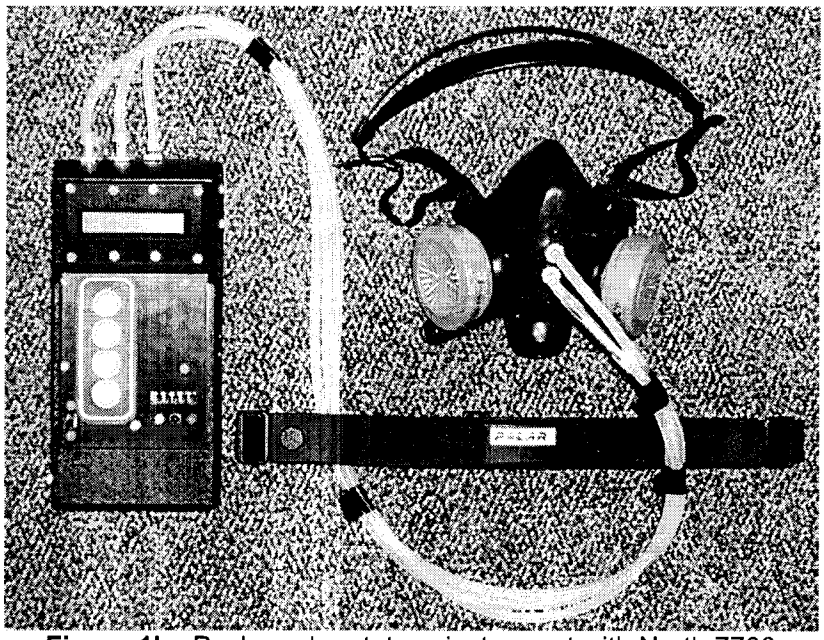

Figure 1b. Packaged prototype instrument with North 7700 respirator and Polar heart rate monitor (transmitting chest-band transducer)

Figure 1c. Subject wearing prototype WPF sampling system with North 7700 respirator (heart-rate transducer under shirt)

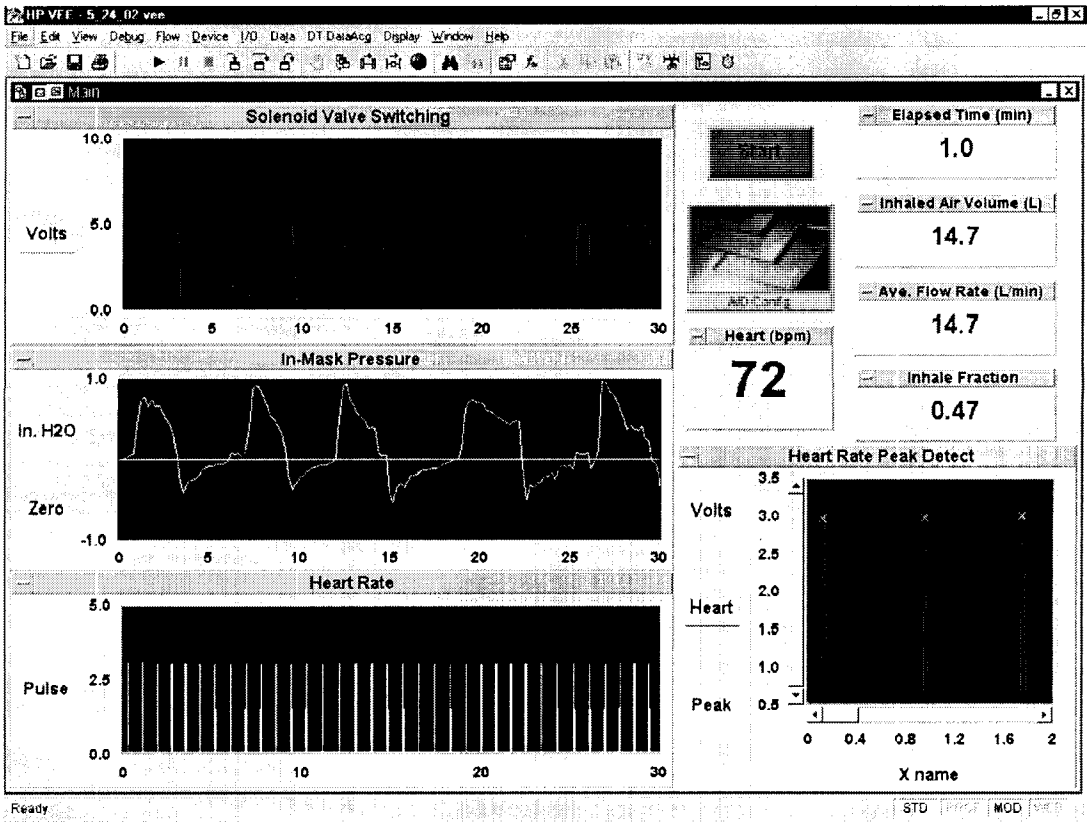

Figure 2. Real time display of transducer outputs and calculated values for minute volume, cumulative filtered air volume, inhalation portion of sample time, and elapsed time.

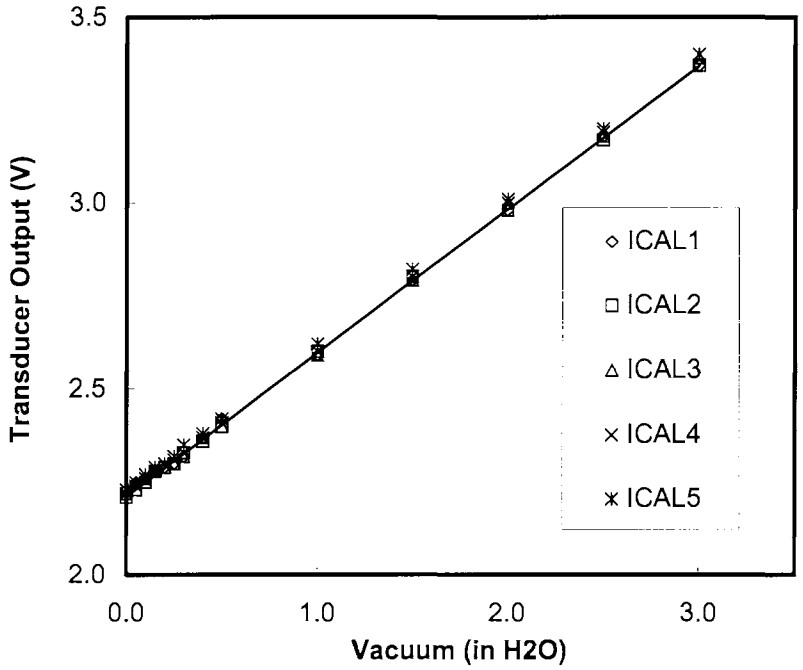

Figure 3. Individual pressure transducer calibrations – 5 "H_2O range

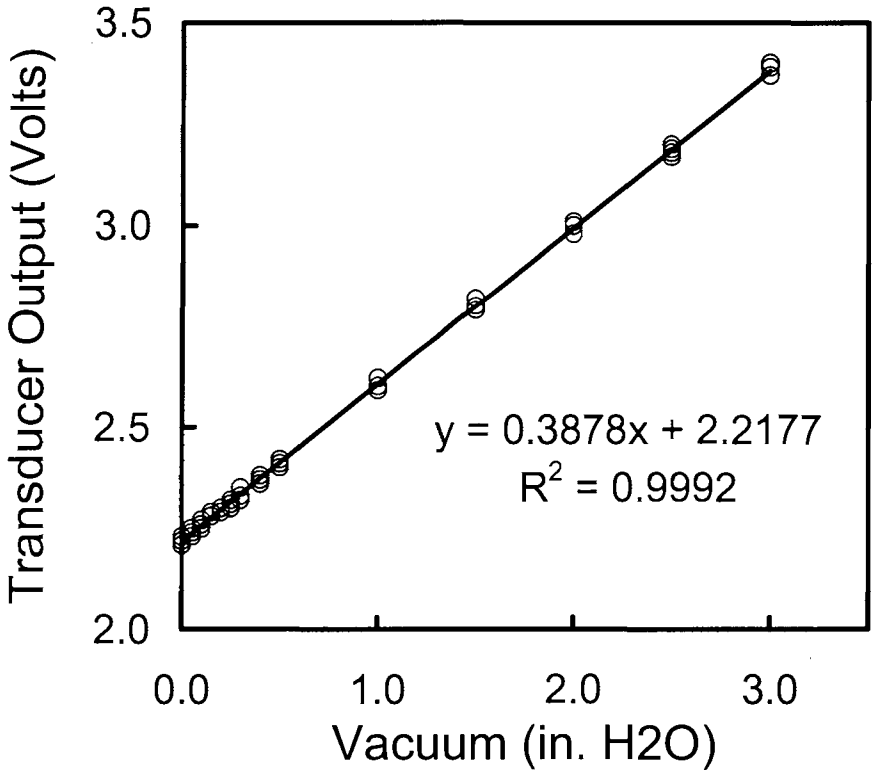

Figure 4. Combined pressure transducer calibration – 5 "H_2O range

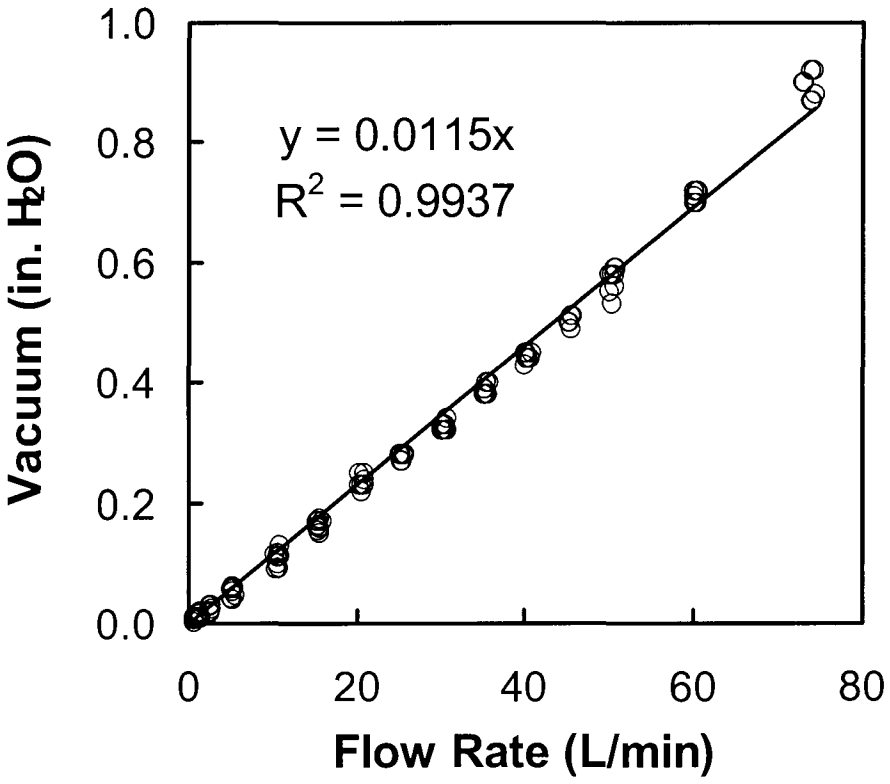

Figure 5. Combined results for three different North 7600 full-face respirators using three different sets of AM / MA cartridges

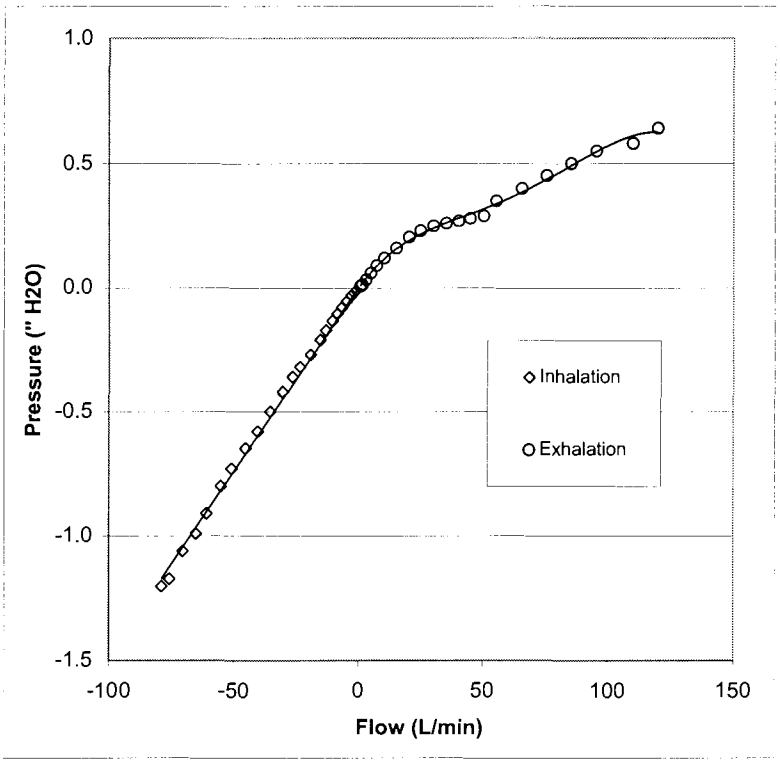

Figure 6. Pressure drop versus flow rate for inhalation and exhalation cycles (North 7600 Full-Facepiece Respirator, P100 Cartridges)

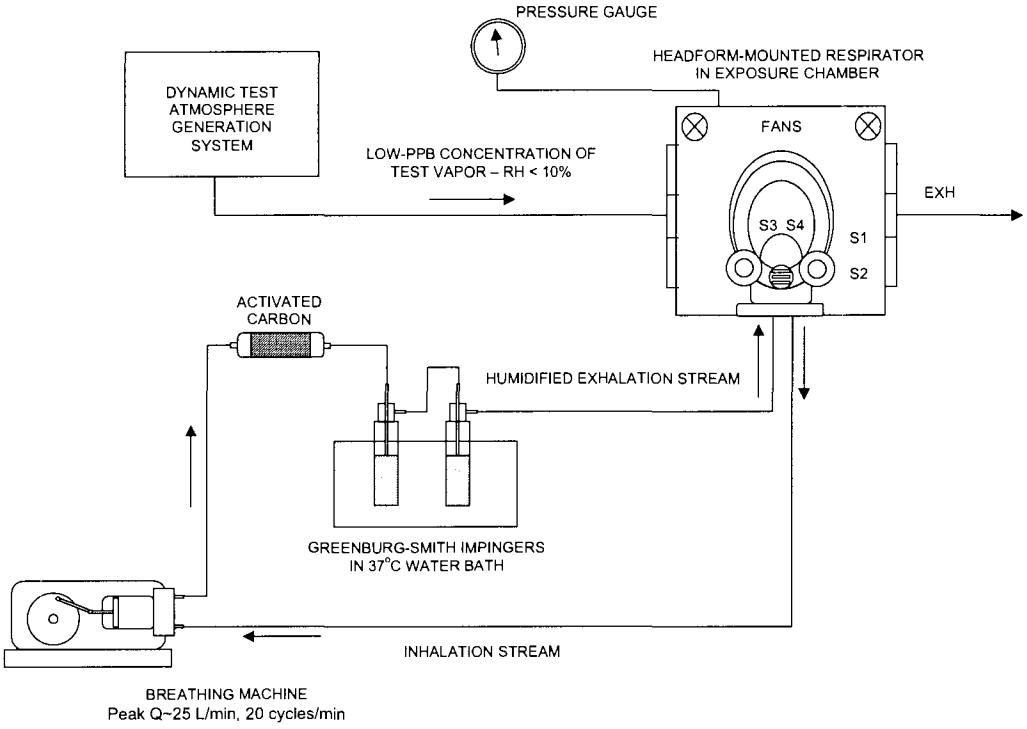

Figure 7. Exposure chamber diagram and sample description for exposure chamber tests; S1 – continuous chamber sample, S2 – intermittent chamber sample, S3 – intermittent in-mask (respirator) sample, S4 - continuous in-mask (respirator) sample

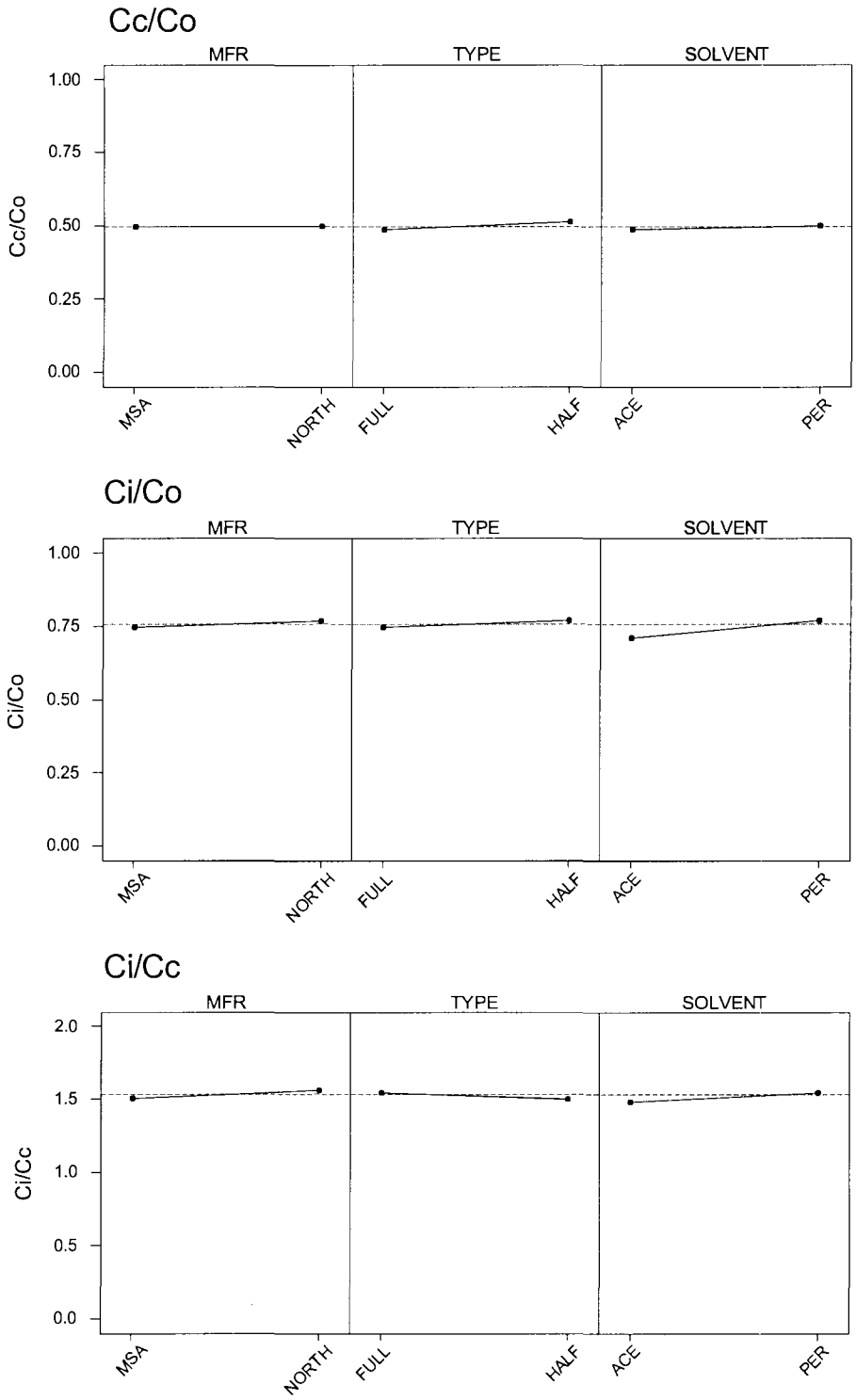

Figure 8. Main-effects plots for ratio of in-mask concentrations measured continuously (Cc) and intermittently (Ci) to chamber concentration (Co), and to each other.

```
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"13:25:08:15,002,000,000000,000002,0.00, 0.0831,0000.0"
"13:25:08:35,003,000,000000,000003,0.00, 0.0831,0000.0"
"13:25:08:55,004,000,000000,000004,0.00, 0.0635,0000.0"
"13:25:08:75,005,000,000000,000005,0.00, 0.0439,0000.0"
"13:25:08:95,001,000,000001,000006,0.17,-0.2698,0000.0"
"13:25:09:15,002,000,000002,000007,0.28,-0.4855,0000.0"
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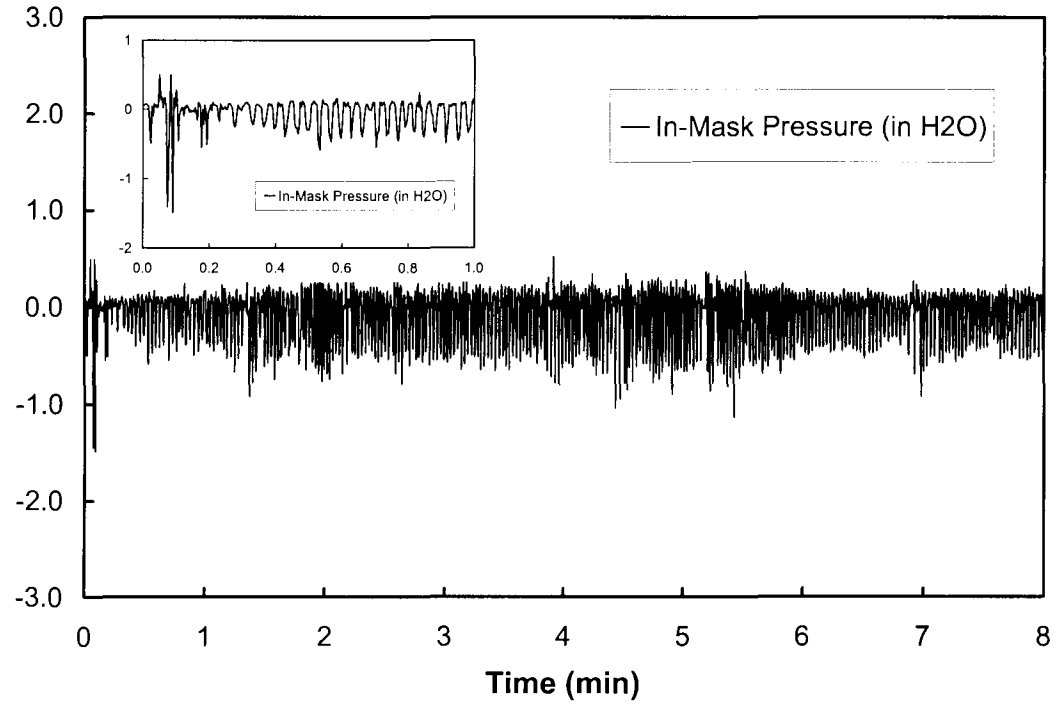
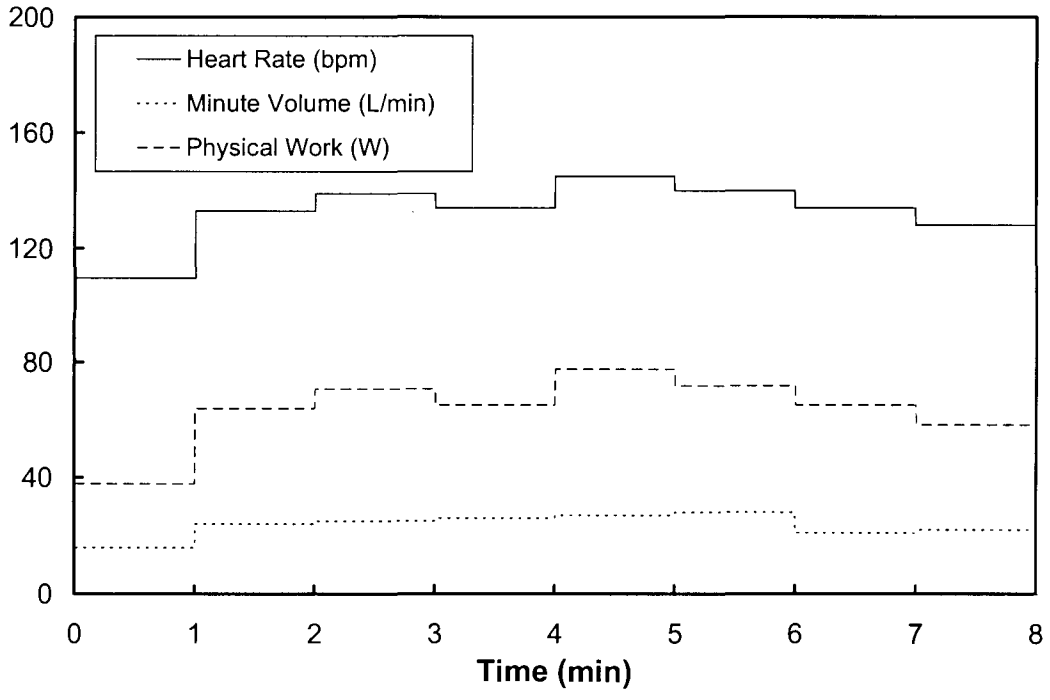
Figure 9. Sample data log file downloaded from personal sampling system.

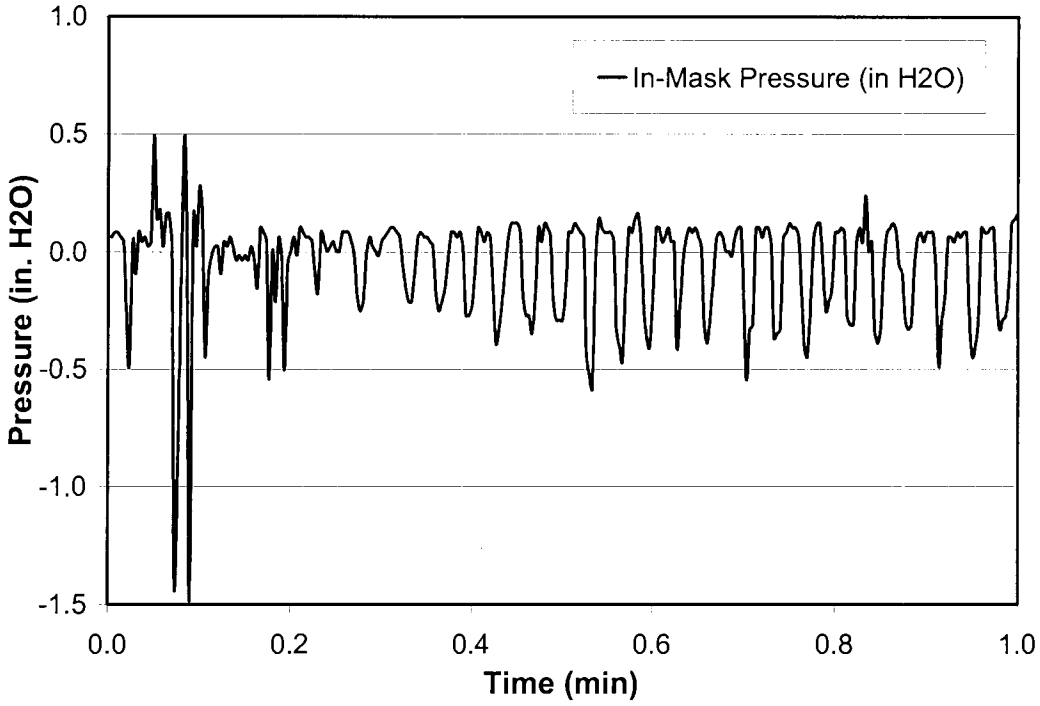


a)

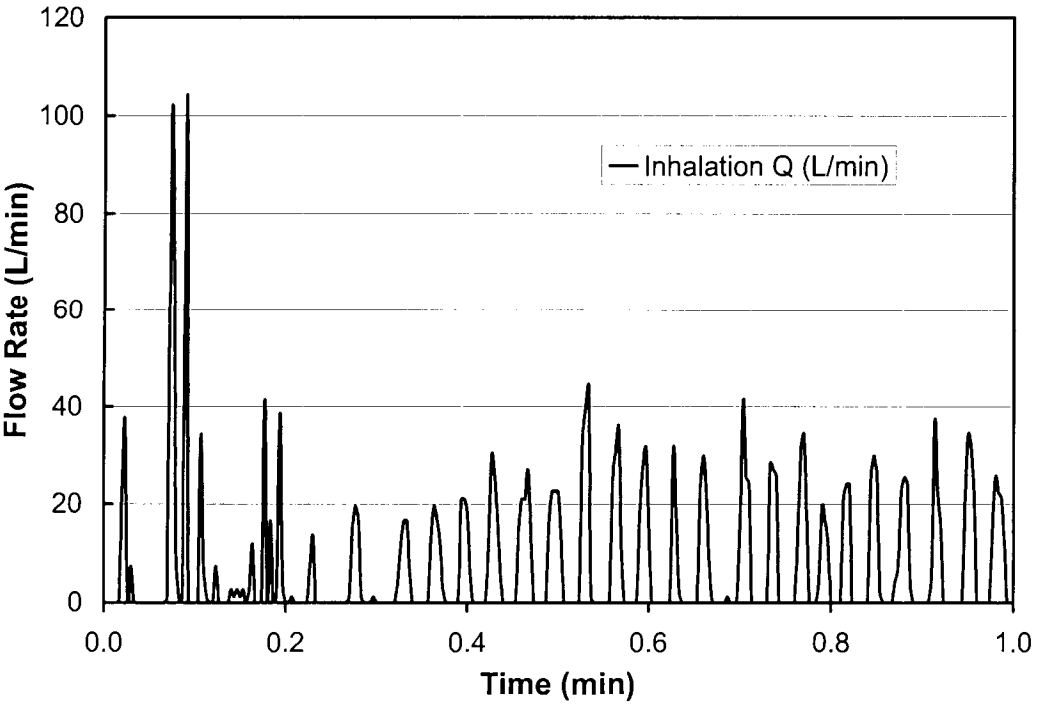


b)

Figure 10. Recorded data for a) in-mask pressure and b) heart rate, minute volume, and estimated physical work rate, for an eight minute period.



a)



b)

Figure 11. Display of logged a) in-mask pressure and b) resulting instantaneous inhalation flow rate for the first minute recorded (sampling rate = 5 Hz, 300 data points)

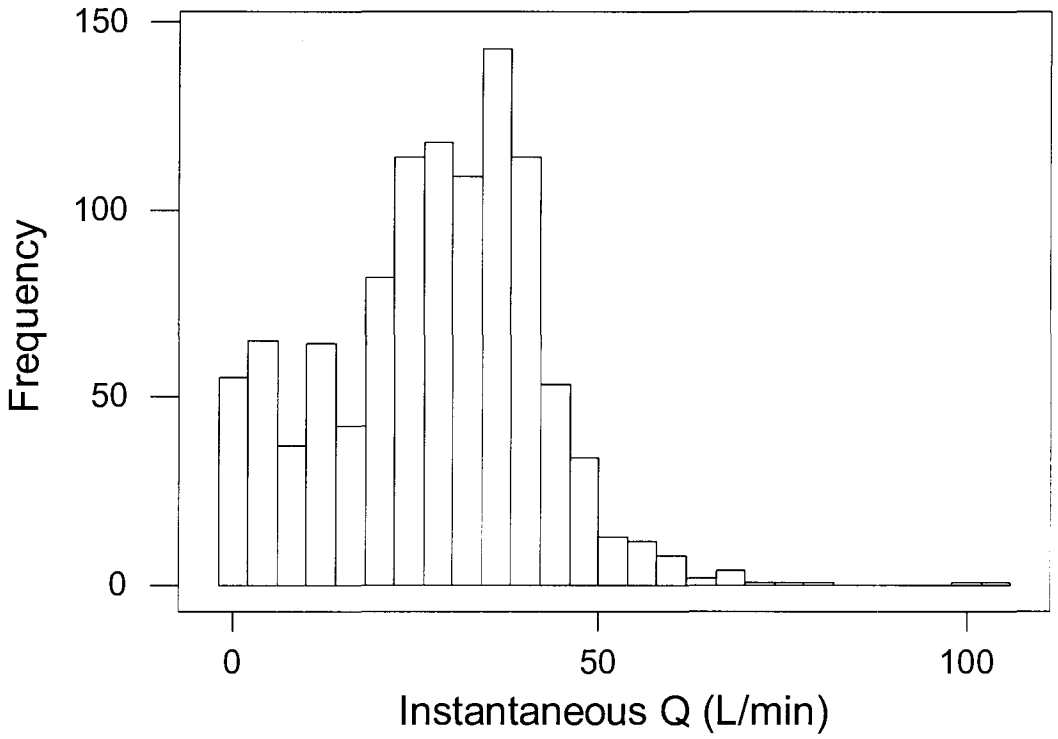


Figure 12. Histogram for inhalation flow rate.

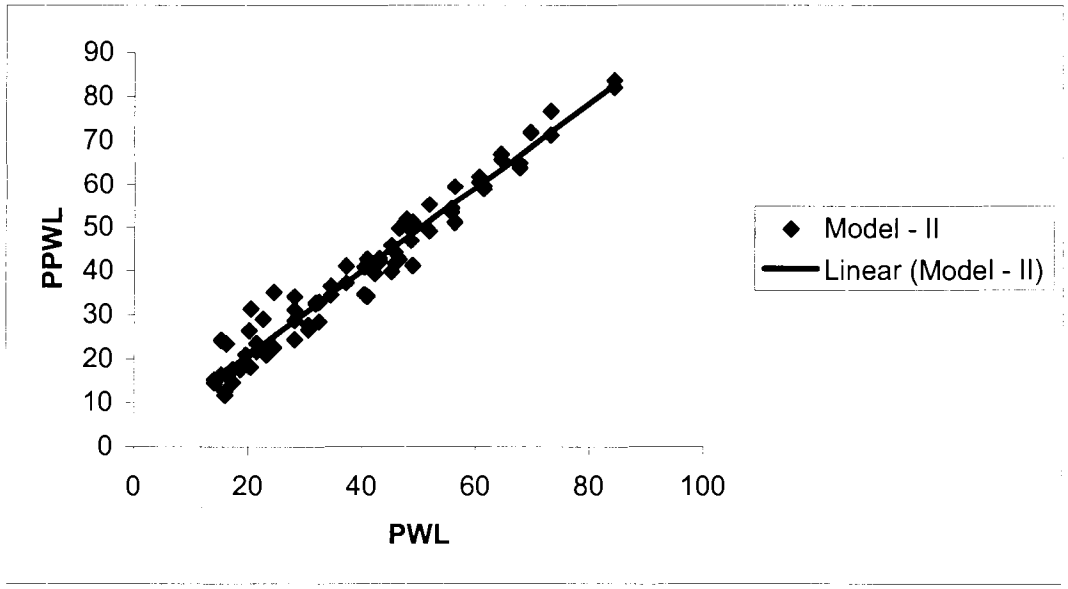


Figure 13. Predicted physical workload versus actual physical workload (Watts)

DEPARTMENT OF HEALTH AND HUMAN SERVICES

Public Health Service
Centers for Disease Control
and Prevention (CDC)

Memorandum

Date: January 26, 2004

From: Michael J. Galvin, Ph.D., Program Official
Office of Extramural Programs, NIOSH, E-74

Subject: Final Report Submitted for Entry into NTIS for Grant 5K01OH000177-04.

To: William D. Bennett
Data Systems Team, Information Resources Branch, EID, NIOSH, P03/C18

The attached final report has been received from the principal investigator on the subject NIOSH grant. If this document is forwarded to the National Technical Information Service, please let us know when a document number is known so that we can inform anyone who inquires about this final report.

Any publications that are included with this report are highlighted on the list below.

Attachment
cc: Sherri Diana, EID, P03/C13

List of Publications

Groves WA, Reynolds SJ, "Prototype Sampling System For Measuring Workplace Protection Factors For Gases And Vapors", Appl Occup Environ Hyg 2003 18(5); 394- 402.

Title:	System For Measuring Workplace Protection Factors
Investigator:	William A. Groves
Affiliation:	Pennsylvania State University
City & State:	University Park, PA
Telephone:	
Award Number:	5K01OH000177-04
Start & End Date:	9/30/1999-9/29/2003
Total Project Cost:	108000
Program Area:	
Key Words:	protective equipment, respirators, toxic fumes

Final Report Abstract:

The overall goal of this project was to develop and test a personal sampling system for measuring workplace protection factors (WPF) for gases and vapors. The system consists of a low-flow sampling pump with stroke counter, 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 the pressure transducer as well as a transducer for measuring heart rate. The pressure transducer and solenoid valve are designed to allow sampling of the air inside the respirator face-piece during the inhalation portion of respiration, while the ambient environment is sampled during the exhalation phase. The system is relatively small and light-weight, allowing the unit to be worn easily on a worker's belt, and has adequate battery power to operate for at least a full 8-hour shift. The resulting personal sampling system should be a valuable tool for researchers interested in measuring WPFs for gases and vapors for the purpose of developing or evaluating Assigned Protection Factors (APF), or in exposure assessment for specific applications of respiratory protective equipment.

The research conducted as part of this project has lead to the development of a valuable instrument for use in gathering WPF data for gases and vapors. The sampling system developed is small and light-weight, allowing the unit to be worn easily on a worker's belt, and has adequate battery power to operate for a full 8-hour shift. This technology should help to address research needs identified in the Final Rule of the Respiratory Protection Standard. Data gathered using the instrument could be used in developing and evaluating APFs for different types of respirators, or as an exposure tool for specific applications of respiratory protective equipment.

It is intended that this research will serve as a strating point for a series of related projects following a logical progression that expands on the original work. The current proposal has lead to the development of a thoroughly characterized tool that is designed for evaluating respirators used in the workplace for protection from gases and vapors.

Publications:

Groves WA, Reynolds SJ, "Prototype Sampling System For Measuring Workplace Protection Factors For Gases And Vapors", Appl Occup Environ Hyg 2003 18(5); 394- 402.