PREDICTING INWARD LEAKAGE FOR NEGATIVE PRESSURE CONDITIONS IN A FIREFIGHTER RESPIRATOR

Rodney A. Bryant
National Institute of Standards and Technology
Building and Fire Research Laboratory, USA

ABSTRACT

An analytical model of the flow across a resistive flow path such as an orifice or pipe was applied to predict the inward leakage in an SCBA facepiece during a steady negative facepiece pressure. Starting with a range of negative pressure conditions assembled from the literature, the model was used to estimate leakage rates with respect to the size of the leak. The results of the model were also used to make quantitative estimates of the protection level of the respirator. Experiments were designed to induce a continuous below-ambient pressure inside the facepiece of a pressure-demand SCBA attached to a head form. Negative facepiece pressure measured in the presence of a leak correlated with measured fit factor. The results show that the analytical model generated reasonable estimates of leakage rates during conditions of negative pressure inside the facepiece. Thus the analytical model performed well for constant flow conditions, demonstrating the potential to predict a momentary compromise in respirator protection during momentary negative facepiece pressure conditions.

INTRODUCTION

The prevailing assumption surrounding the protection offered by a firefighter's respirator is that inward leakage does not occur even in the event of a break of a sealing edge as long as positive pressure is maintained within the facepiece. The firefighter's respirator, the self-contained breathing apparatus (SCBA), is a pressure-demand breathing system. There is evidence from laboratory studies that an SCBA may be over-breathed at high work rates.[1-3] Over-breathed means that the user requires more air than is being supplied and therefore negative pressure conditions exist inside the facepiece during the inhalation phase of the breathing cycle.

A negative pressure condition inside the facepiece creates the potential for inward leakage. If there is a break in the face-to-facepiece seal or any component of the facepiece during the negative pressure event, contaminants from the ambient environment will penetrate the mask. These negative pressure events are momentary, on the order of a few milliseconds to hundreds of milliseconds. The effect of such momentary leaks on the overall protection to the firefighter has not been well quantified. The National Fire Protection Association (NFPA) has long been aware of the aforementioned evidence and as a result recommended that quantitative fit testing be performed to help firefighters achieve the best face-to-facepiece seal.[4]

Reproducing the actual conditions of firefighter use of an SCBA in order to conduct the measurements necessary to characterize SCBA performance is a formidable challenge. However, much can be learned from simulating the most important conditions: a negative pressure inside the facepiece and a breach in the facepiece or interface of the facepiece and the wearer's face. Both conditions must occur simultaneously. Actual negative pressure conditions will occur either periodically or intermittently and over short time intervals, typically less than 1 s. The flexibility of the facepiece and the wearer's face will cause the geometry of the break to change due to the wearer's physical movements and the dynamics of the flow (pressure). The condition for negative pressure also depends on the wearer's peak inspiration rate and the ability of the regulated air supply to provide enough air. These detailed characteristics of the leak conditions can be simplified or removed in order to view the problem with better clarity.

The present investigation explores the use of an analytical model of flow across resistive flow paths such as orifices and pipes to predict leaks in an SCBA facepiece during a steady negative facepiece pressure. The model was used to estimate leakage rates for a reasonable range of pressures and geometric sizes of the leak. The results of the model were also used to demonstrate predictions of the quantitative protection level of the respirator during the leak for given inspiration rates of a wearer. Finally, some preliminary experiments were conducted to confirm that the model predictions were reasonable.

MODEL EQUATIONS

Leak

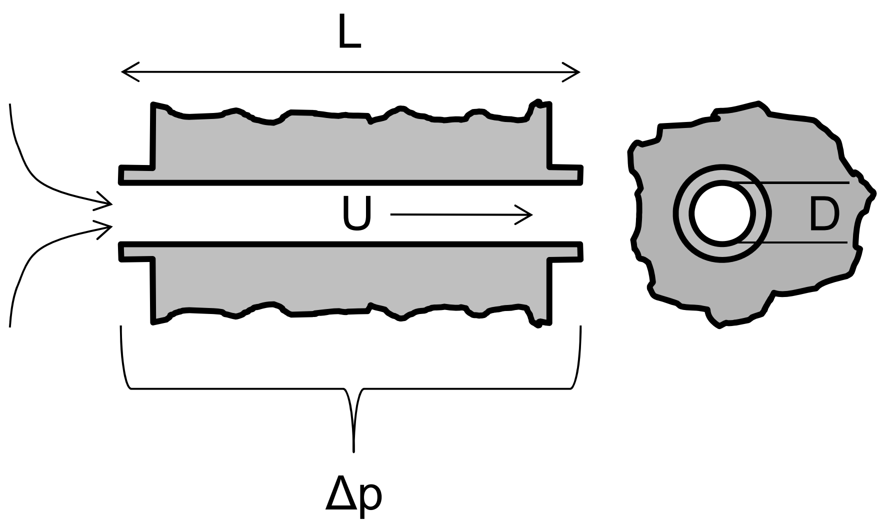
The volume flow rate, $\dot{Q}$, through a resistive flow path such as a leak can be expressed as a function of the pressure drop, Δp, along the path.

$$\dot{Q} = C \Delta p^{\lambda} \qquad [1]$$

The constants C and λ can be determined empirically. They will depend on the geometry of the leak and the characteristics of the flow. The exponential constant λ varies from 0.5 to 1.0 for pinholes and orifices to capillaries and pipes, respectively.[5-7] The constant C will contain details about the area of the leak as well as the unit conversions for the corresponding exponential, λ. Empirical relations describing the pressure drop induced by flow across a resistive path have been developed for a variety of path geometries and cross sections.[8] If more details of the leak geometry are known, it is possible to improve upon the relation expressing volume flow rate as a function of the pressure drop. The illustrative example of this study is a leak across a SCBA facepiece defined by a circular tube, Figure 1. This leak is analogous to the flow through an abrupt contraction with a circular cross section. The pressure drop due to the flow across this region can be expressed as follows.[8]

$$\Delta p = \frac{\rho U^2}{2}(1 + K + f\,\frac{L}{D}) \qquad [2]$$

Figure 1 Schematic of flow across a leak with a circular cross section.



An increase in kinetic energy or average fluid velocity, U, along the tube results in an increased loss in fluid pressure. Also contributing to the pressure loss is the flow resistance at the inlet and along the length of the tube. This is represented by the second and third terms of Eqn 2. The dimensionless constant K scales with the inlet resistance, and the frictional loss along the length of the tube is represented by the third term, where f is the dimensionless friction factor, L is the length of the tube, and D is the hydraulic diameter of the tube (equivalent to the inner diameter for circular cross sections). For a tube of known cross sectional area, A, and length, the volume flow rate of the leak, $\dot{Q}_l = UA$, in a pressure-demand SCBA can be determined from the following relation.

$$\dot{Q}_l = \begin{cases} A\left(\dfrac{2|\Delta p|}{\rho(1+K+f\,\dfrac{L}{D})}\right)^{1/2}, & \Delta p < 0 \\[2ex] 0, & \Delta p \geq 0 \end{cases} \qquad [3]$$

where

$$K = 1.2 + \frac{38}{\text{Re}} \qquad [4]$$

and

$$f = \frac{64}{\text{Re}} \qquad [5]$$

Therefore, in the case of the pressure-demand SCBA a leak occurs only when the facepiece pressure is below ambient (negative Δp). Comparing Eqn 1 and Eqn 3, it is apparent that the empirical constant, C, will contain the irreversible losses due to the resistance at the leak inlet and along its length, as well as the geometry of the leak. The loss constants, K and f, are functions of Reynolds number, Re. Eqns 3, 4, and 5 can therefore be solved iteratively from an initial estimate that excludes the irreversible losses. For flow starting at rest in a large reservoir (the ambient environment) and passing through an abrupt contraction (the tube), it is reasonable to assume a laminar flow regime to estimate the loss constants.

Respirator Fit Factor

The most quantitative means to assess the adequacy of the seal of a respirator to the wearer's face is to monitor the amount of the ambient atmosphere that leaks into the breathing zone inside the respirator. Instrumentation that monitors the ratio of the ambient concentration of a particular test agent outside the respirator, C_o, and that agent's concentration inside the respirator, C_i, provides a quantitative measure of how well the respirator seals out the ambient environment or protects the wearer. This ratio is termed the "fit factor," Eqn 6, and it is a frequently used parameter for rating the protection of a particular respirator to a particular person.

$$FF = \frac{C_o}{C_i} \qquad [6]$$

For a given leak, the mass flow rate of the agent leaking into the respirator can be expressed as:

$$\dot{m}_l = C_l \dot{Q}_l \qquad [7]$$

Assuming that the leak is only a result of a breach in the facepiece or facepiece-to-face seal and that there is no loss in the concentration of ambient agent as it passes through the breach, then the agent concentration of the leak, C_l, is equal to the agent concentration in the ambient air, C_o.

$$C_l = C_o \qquad [8]$$

Once the agent penetrates the inside of the facepiece, it will be diluted by the supplied air flowing into the facepiece. Since the negative pressure condition inside the facepiece is induced by the wearer inspiring at a rate greater than the rate of supplied air, the volume flow rate inside the facepiece is equal to the inspiration volume flow rate, $\dot{Q}_{insp}$. Given that mass is conserved and assuming that the agent is perfectly mixed once inside the facepiece, Eqns 7 and 8 can be used to define the concentration of the agent inside the facepiece.

$$C_i = \frac{C_o \dot{Q}_l}{\dot{Q}_{insp}} \qquad [9]$$

Rearranging Eqn 9 it is apparent that the fit factor as defined in Eqn 6 can be approximated by the ratio of the volume flow rate of the inspired breath and the volume flow rate of the leak.

$$\frac{C_o}{C_i} = \frac{\dot{Q}_{insp}}{\dot{Q}_l} \qquad [10]$$

Eqn 10 is built upon the following assumptions: 1) the only source of contamination of the breathing air by the agent is a breach at the facepiece, 2) there is not a loss of agent (or mass) as it travels through the leak, which is a reasonable assumption for gases and respirable particulates,[5-7] 3) the agent is perfectly distributed inside the facepiece. Negative facepiece pressure is the major requirement for inward leakage. The following section will show how it can be used to predict the magnitude of the leak.

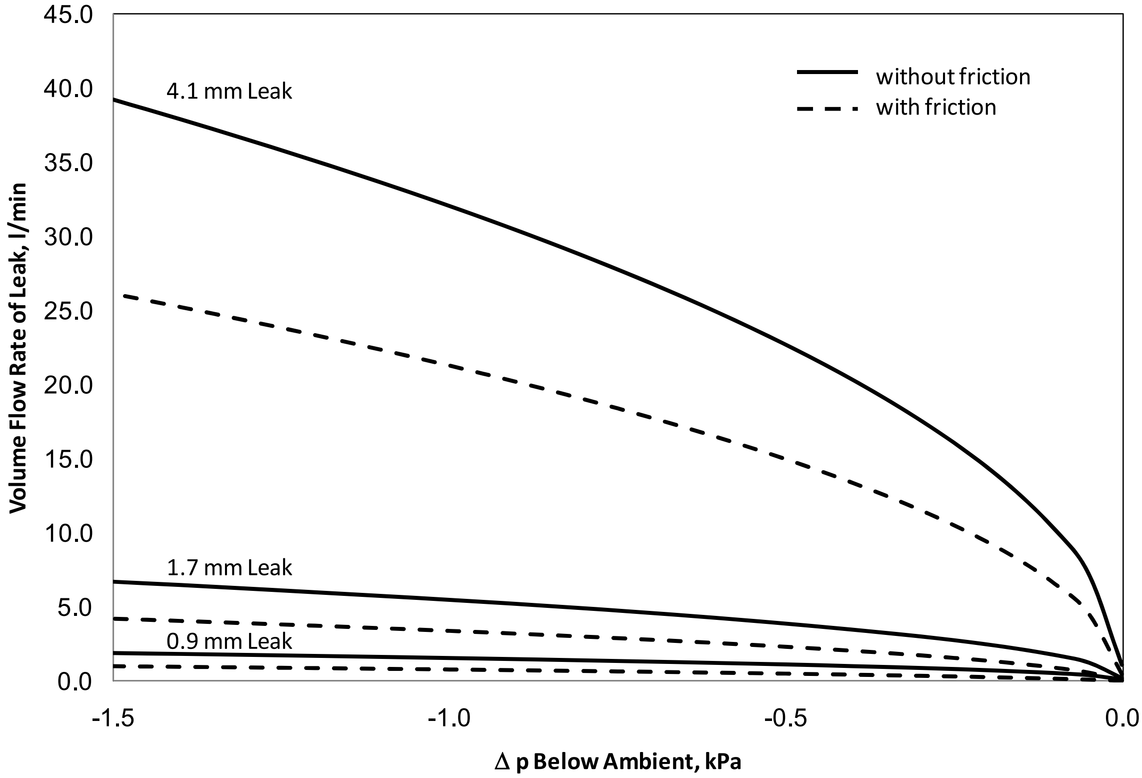
ANALYTICAL RESULTS

A survey of the literature reporting SCBA facepiece pressure measurements during work revealed that the pressures inside the facepiece were as much as -1.25 kPa below ambient pressure during over-breathing.[1, 3, 5, 9] These were momentary spikes and were typically less than 0.5 seconds in duration. By assuming steady flow, therefore a constant facepiece pressure below ambient, the results of Eqn 3 can be examined for conditions typical of a leak.

A leak with a circular cross section and a diameter on the order of 4 mm was applied to simulate a leak in a loose fitting respirator. A respirator requiring minimal adjustment to eliminate a leak was simulated by a circular cross section with a diameter on the order of 1 mm. The initial barrier between the ambient environment and wearer’s breathing zone is the interface of the wearer’s face and the SCBA facepiece. This flexible strip of material typically has a width on the order of 25 mm. Therefore the length chosen to simulate the circular leaks was also on the order of 25 mm.

Using Eqn 3, the volume flow rate of the leak was computed for a range of pressure conditions and leak diameters, Figure 2. Equation 3 predicts that the volume flow rate of the leak will increase with the square root of the facepiece differential pressure below ambient. For large geometry leaks, such as in a loose fitting respirator, the amount of the leak will be significantly greater. In the simple case of no resistance across the leak, such that K and f are equal to zero, the volume flow rate is increased by almost a factor of 2. Removing the resistance from Eqn 3 demonstrates an upper limit for possible worst case scenarios. For the conditions considered here, the predicted flow from a leak is less than 40 l/min.

Figure 2 Leakage in SCBA facepiece due to a facepiece pressure below ambient.

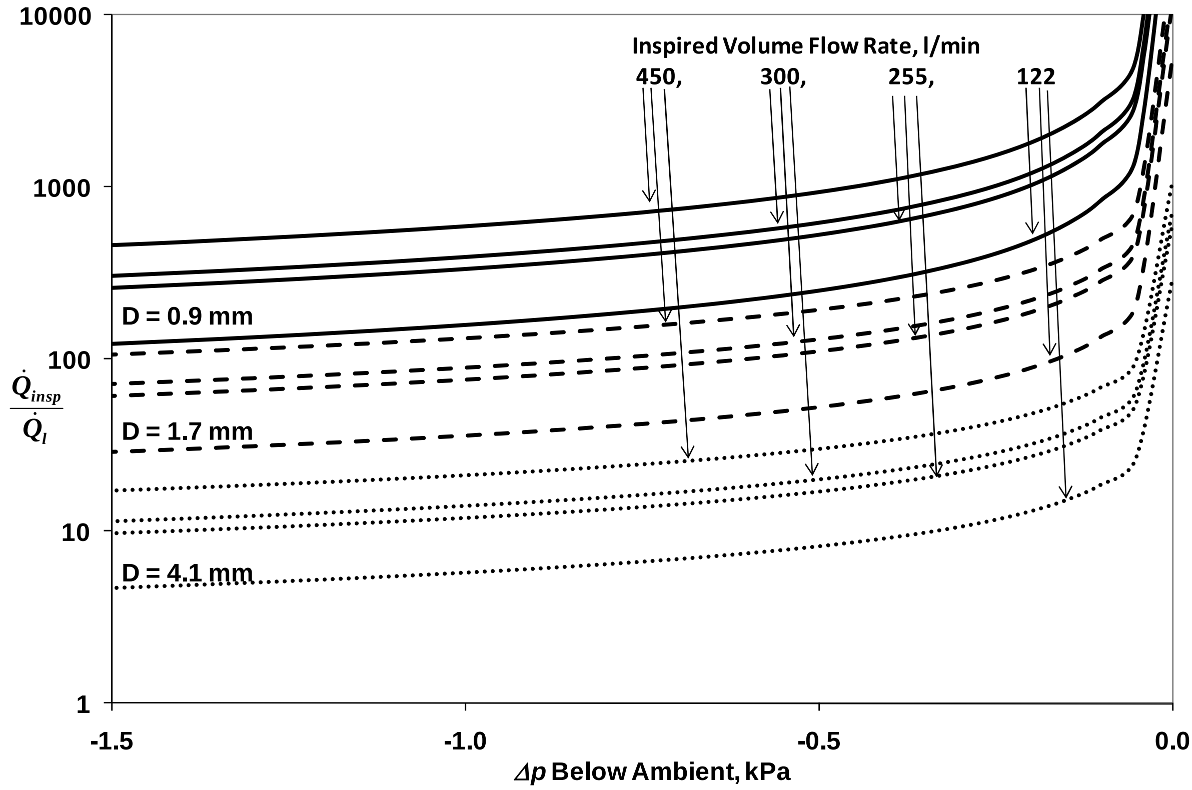


The evidence for over-breathing an SCBA shows that it occurs during the peak of an inspiration breath. In a study of human subjects exercising on a treadmill, peak inspiration flow rates as high as 450 l/min were observed to induce negative facepiece pressures.[3] The study defined 300 l/min as a critical value for the potential of over-breathing an SCBA. Peak inspiration may induce a leak; but as demonstrated by Eqn 9, a leak at a given pressure condition becomes more diluted for increases in inspiration rate.

Eqn 3 does not attempt to couple the magnitude of the leak with the inspiration rate, only to predict it for given conditions of leak geometry and below-ambient facepiece pressure. However, the effect of the inspiration rate on the resulting protection level in the presence of a leak can be examined with Eqn 10. The NFPA 1981 airflow performance test requires that an SCBA is tested with breathing waveforms having ventilation rates of 40 l/min and 103 l/min. The peak inspiration rates produced by these breathing waveforms are 122 l/min and 255 l/min, respectively, and provide other reference values for peak inspiration rates.

The estimated protection level for an SCBA with a circular cross section leak is plotted in Figure 3. The plots in Figure 3 are the result of evaluating Eqn 10 with resistance included in the estimation of the leak rate. For a given leak geometry, the protection level will increase if the inspiration rate is increased without inducing an increase in the deflection of the facepiece pressure below ambient. It is predicted that an absolute facepiece pressure of 0.1 kPa or more below ambient and occurring with a leak with a hydraulic diameter greater than 1 mm will result in a protection factor less than 1000.

Figure 3 Predicted momentary fit factor of a SCBA respirator during a below-ambient facepiece pressure. Flow resistance is included in the prediction.



A well maintained and properly fitted SCBA has a protection factor on the order of 10,000. From Figure 3, it is predicted that in the presence of a breach in the facepiece, a momentary period of negative facepiece pressure will result in a momentary reduction in protection. This momentary reduction in protection may be as much as 3 orders of magnitude.

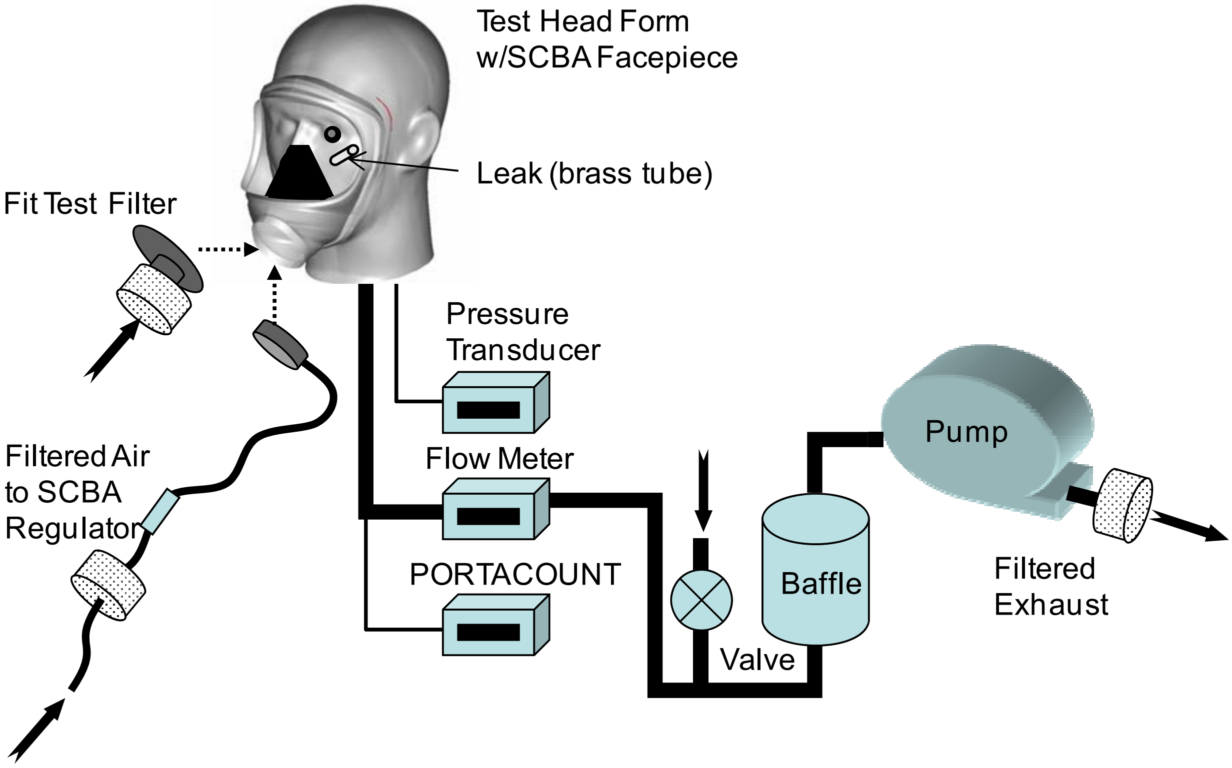
EXPERIMENTAL METHOD

The predictions of the analytical model were tested by conducting constant flow experiments to induce a continuous negative pressure inside the facepiece of an SCBA donned on a test head form. Using a prescribed leak geometry, measurements of facepiece pressure and inspired volume flow rate along with simultaneous determinations of the quantitative fit factor were conducted. Leak sites were prescribed using brass tubes of different diameters. The quantitative fit factor was determined from measurements of particulate concentration in the ambient environment and inside the facepiece.

An SCBA facepiece was donned on a test head form used for SCBA air flow performance testing. The leak site was formed by inserting the brass tube through the facepiece visor. The tubes had inner diameters of 0.88 mm ± 0.06 mm and 4.05 mm ± 0.06 mm. The SCBA regulator, which attached to the facepiece, was supplied with compressed air from the laboratory reservoir instead of from the standard SCBA compressed air bottle. This allowed the supply pressure and subsequently the facepiece pressure to be controlled and to remain constant over the duration of an experiment. Reducing the supply pressure to levels experienced when a SCBA bottle is nearing empty caused the facepiece pressure to go negative during a reasonable (steady) inspiration rate. A HEPA filter was installed just upstream of the SCBA pressure reducer assembly to remove particulates from the supply air. This was necessary to isolate the leak as the only source of particulates inside the mask.

The facepiece pressure relative to the ambient environment was measured using a differential pressure transducer (MKS Baratron 698A11TRA)* attached to a pressure tap located at the left eye of the test head form. The test head form was attached to a vane pump (GAST 1023-V131Q-SG608X) which pulled air at a constant flow through the test head form. The air flow rate, $\dot{Q}_{insp}$, was monitored by an electronic flow meter (TSI 4045) placed in the flow line. The experimental setup is illustrated in Figure 4.

Figure 4 Schematic of the experimental setup to study SCBA leaks under constant flow conditions.



The concentration of particulates entering the SCBA facepiece due to the leak was measured by sampling the flow after it had left the test head form to avoid sampling bias. Particulate concentrations were measured using a PORTACOUNT (TSI 8010), a device commonly used for quantitative fit testing of respirators. The device measures the ambient concentration of particulates and compares it to the concentration of particulates measured inside the respirator to compute the respirator fit factor.

EXPERIMENTAL RESULTS

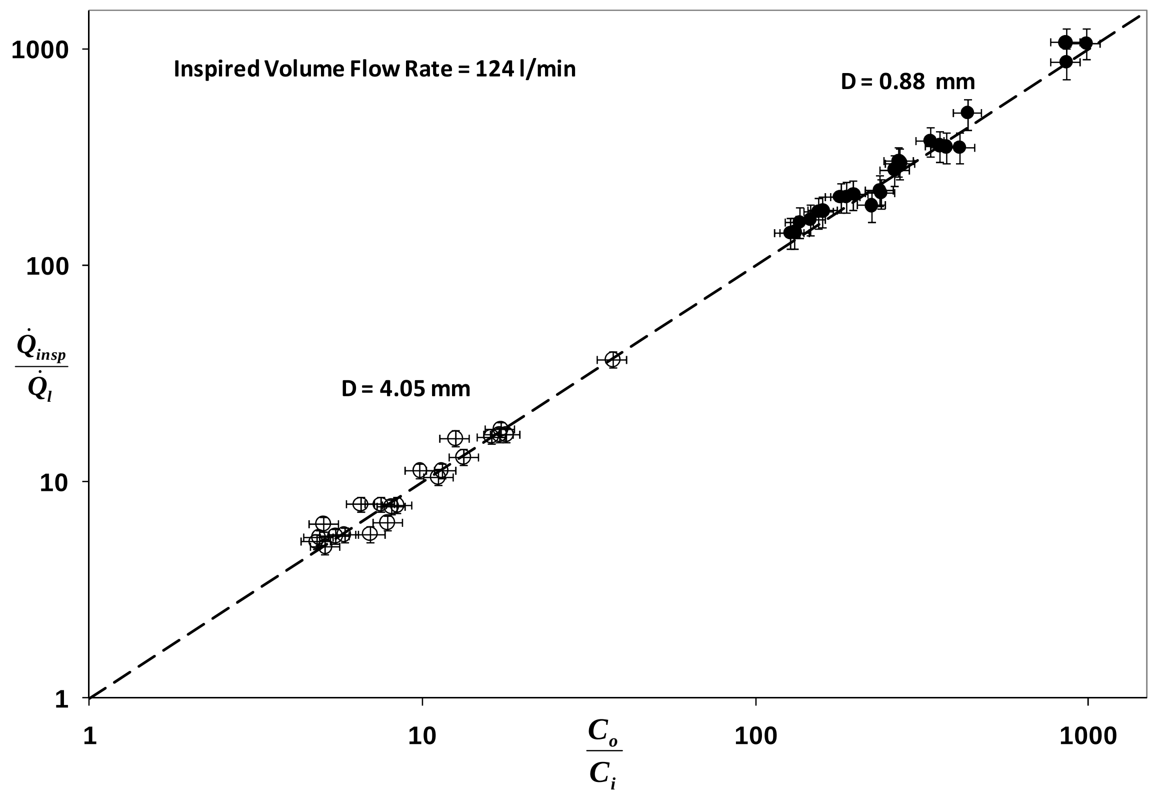
The sequence of sampling by the PORTACOUNT was to first draw a sample from the ambient environment, then draw a sample from inside the mask, and finally draw a sample from the ambient again. This sequence was repeated for a minimum of 3 cycles to record the particle concentrations in the ambient environment and inside the mask. An overall fit factor and an average facepiece pressure were computed for the given number of cycles. PORTACOUNT fit factor measurements had a relative expanded uncertainty of ± 0.10. The estimated relative expanded uncertainty of the average facepiece pressure measurement was ± 0.0025.

* Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

Negative pressure conditions in the SCBA occur during peak inhalation or peak inspiration rates. In the present study, a constant inspiration rate was simulated with flow induced by a pump. The vane pump used for this study was run at maximum capacity; resulting in an average inspiration rate of 124 l/min ± 2 l/min. This was slightly greater than the peak inspiration rate produced by the 40 l/min NFPA breathing waveform, but adequate for the purpose of this study.

Equation 10 predicts that the ratio of the inspired volume flow rate and the volume flow rate of the leak, $\dot{Q}_{insp}/\dot{Q}_l$, should provide an estimate of the fit factor measured by the PORTACOUNT. Using the average facepiece pressure measurement as an input, this ratio was computed and the result is plotted in Figure 5 with respect to the fit factor measured by the PORTACOUNT. A propagation of uncertainty was performed to estimate the measurement uncertainty of the volume flow ratio. Estimates of relative expanded uncertainty ranged from ± 0.07 to ± 0.08 for the 4.05 mm leak and ± 0.16 to ± 0.19 for the 0.88 mm leak. With the exception of a few data points, the measurements are distributed about the diagonal within the estimated measurement uncertainty. This demonstrates very good agreement between the estimated fit factor based on facepiece pressure measurements and the traditional measurement of fit factor. Therefore predictions of fit factor for conditions of facepiece pressure below ambient and in the presence of a breach are reasonable, for the range of leak geometries and facepiece pressures considered in the present study.

Figure 5 Comparison of fit factor predicted from below-ambient facepiece pressure measurements with fit factor computed from concentration measurements.



CONCLUSIONS

An analytical model of flow across a resistive path was applied to predict the flow through a leak in an SCBA facepiece during a steady negative facepiece pressure. Inputs to the model were generalized based on a range of negative pressure conditions assembled from the literature. For a range of known inspiration rates, the model predicted the potential for a momentary reduction in protection level during below-ambient pressure events. Some simple constant flow experiments were conducted to test the ability of the model to predict leakage from negative facepiece pressure measurements. Fit factors computed from measurements of facepiece pressure and inspired volume flow rate correlate well with fit factors from aerosol concentration measurements, the conventional quantitative measure of respirator protection and fit. The results are for the ideal conditions of constant flow and known leak geometries. Real leaks will occur over very short durations and it is highly unlikely that the geometry of the leak will be known, therefore making it difficult to accurately predict leakage rates. However, the results demonstrate that a momentary compromise in respirator protection and fit can be predicted from momentary negative pressure conditions.

REFERENCES

[1] Myhre, L.G., Holden, R.D., Baumgardner, F.W., Tucker, D., Physiological Limits of Firefighters, Air Force Engineering and Services Center, Tyndall Air Force Base, Florida, 1979.

[2] Held, B.J., Harder, C.A., Effectiveness of Self-Contained Breathing Apparatus in a Fire Environment, Journal of the International Society for Respiratory Protection, **1** (4), 1983, p.9 - p.27.

[3] Dahlback, G.O., Novak, L., Do Pressure-Demand Breathing Systems Safeguard Against Inward Leakage, American Industrial Hygiene Association Journal, **44** (5), 1983, p.336 - p.340.

[4] Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services, NFPA, Quincy MA, p.

[5] Campbell, D.L., Noonan, G.P., Merinar, T.R., Stobbe, J.A., Estimated Workplace Protection Factors for Positive-Pressure Self-Contained Breathing Apparatus, American Industrial Hygiene Association Journal, **55** (4), 1994, p.322 - p.329.

[6] Williams, F.T., An Analytical Method for Respirator Performance Prediction Utilizing the Quantitative Fit Test (QNFT), Journal of the International Society for Respiratory Protection, **1** , 1983, p.109 - p.125.

[7] Hinds, W.C., Kraske, G., Performance of Dust Respirators with Facial Seal Leaks .1. Experimental, American Industrial Hygiene Association Journal, **48** (10), 1987, p.836 - p.841.

[8] Blevins, R.D., Pipe and Duct Flow, Van Nostrand Reinhold Company, New York, p.38-123.

[9] Bentley, R.A., Bostock, G.J., Longson, D.J., Roff, M.W., Determination of the Quantitative Fit Factors of Various Types of Respiratory Protective Equipment, Journal of the International Society of Respiratory Protection, **2** (4), 1984, p.313 - p.337.