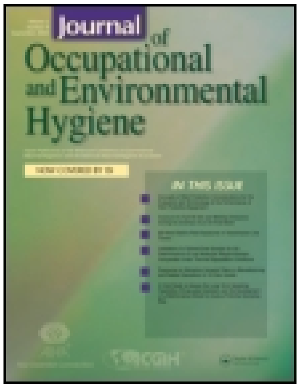

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Characterizing Inward Leakage in a Pressure-Demand, Self-Contained Breathing Apparatus

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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 the facepiece of a self-contained breathing apparatus (SCBA) during a steady below-ambient facepiece pressure. The model was used to estimate leakage rates with respect to the size of the leak and for below-ambient (negative) pressure conditions reflective of measured occurrences. 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 mounted on a headform. Negative facepiece pressure measured in the presence of a leak correlated with the measured particle concentration ratio. 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 capability to predict a momentary compromise in respirator protection during momentary negative facepiece pressure conditions.

Keywords firefighter, inward leakage, leak, respirator, SCBA

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INTRODUCTION

The prevailing assumption surrounding the protection offered by pressure-demand breathing systems such as the self-contained breathing apparatus (SCBA) 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. There is evidence from laboratory studies that at high work rates a SCBA may be overbreathed, meaning that the user requires more air than is being supplied. Therefore, below-ambient or negative pressure conditions may exist inside the facepiece during the inhalation phase of the breathing cycle. Early evidence of overbreathing the pressure-demand SCBA was reported by Myhre et al.(1) who conducted a study of the respiratory stresses imposed on firefighters wearing a SCBA while working.

Negative pressure inside the facepiece was frequently observed. The firefighters were required to walk on a treadmill to reach specific work rates; the lowest work rate being 50% of the subject's maximum achievable work rate. Negative facepiece pressure was observed even at the lowest work rate. Held and Harder(2) conducted a study to evaluate the performance of SCBAs from different manufacturers for the purpose of selecting models that gave the best protection to firefighters. A breathing machine was used to simulate breathing during a moderate-to-heavy work rate while exposing the SCBA units to temperature extremes. An environmental chamber was used to create conditions similar to the actual fire environment.

Investigators reported that many of the pressure-demand SCBA units exhibited negative facepiece pressure when exposed to excessive environmental temperatures. Researchers in Sweden used a tracer gas to investigate the effect of negative facepiece pressure in pressure-demand SCBAs by measuring the leak rates during inhalation.(3) Experiments were conducted using a breathing machine as well as human subjects. When the inhalation volume flow rate exceeded 300 L/min, negative pressure occurred in the facepiece, and leakage of the ambient atmosphere into the facepiece was detected. Unfortunately, the leak rate was greater than the measurement range of the tracer gas detection instrument.

In response to the previous studies, Stengel and Rodrigues(4) tested a group of SCBAs from different manufacturers to investigate the reports of negative facepiece pressure during high work rates. Their experiments were conducted using a breathing machine to simulate high work rates. The results confirmed the frequent occurrence of negative pressure inside the facepiece, even for an air cylinder at full capacity. When the air cylinder pressure was reduced, the magnitude of negative pressure inside the facepiece increased. Bentley et al.[5] also investigated the occurrence of negative pressure inside the facepiece and the resulting protection of a pressure-demand SCBA. Firefighters exercised on a treadmill while wearing a SCBA and performing prescribed tasks, such as head movements and talking. Negative pressures were measured inside the facepiece, especially during talking. Simultaneous measurements of leakage were conducted using a tracer gas. The occurrence of inward leakage was shown to coincide with negative pressure inside the facepiece.

Campbell et al.[6] conducted an investigation to provide more insight concerning the significance of momentary negative-pressure events on the level of protection offered by the SCBA. An analytical model to estimate the protection of an SCBA relative to the protection offered by a negative-pressure respirator using the SCBA facepiece was presented. Using actual facepiece pressure traces from miniature pressure transducers worn by firefighters working at a fire scene, workplace protection factors, defined as "*the ratio of the contaminant concentration that would be inspired by a worker without a respirator to that inspired by the worker when wearing a respirator,*"[6,p. 323] were estimated for the case of momentary negative facepiece pressure. Estimated protection factors were consistent with the NIOSH (National Institute for Occupational Safety and Health)-assigned protection factor for a properly functioning and properly fitted SCBA-type respirator.[7] The usefulness of such a model was demonstrated while its limitations were also discussed.

The 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) is aware of the aforementioned evidence and has recommended that quantitative fit testing be performed to help firefighters achieve the best face-to-facepiece seal.[8] A quantitative fit test is "*an assessment of the adequacy of respirator fit by numerically measuring the amount of leakage into the respirator.*"[7,p. 422]

The occurrence of negative pressure inside the facepiece of a pressure-demand SCBA is the cause for questioning the protection of the SCBA. As noted in the previous studies, reproducing the actual conditions of firefighter use of an SCBA to conduct the measurements necessary to characterize SCBA performance is a formidable challenge.

However, much can be learned from simulating the most important conditions instead of re-creating actual scenarios. The most important conditions that result in inward leakage in a pressure-demand SCBA can be generalized as (1) a negative pressure differential exists between the facepiece and the ambient environment; (2) a break or opening exists somewhere in the facepiece or at the 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 sec. The flexibility of the facepiece and the wearer's face will cause the geometry of the break to change due to the wearer's actions and the dynamics of the flow. The condition for negative pressure also depends on the wearer's peak inspiration flow 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 to view the problem with more clarity.

The purpose of this investigation was to characterize inward leakage in a pressure-demand SCBA and explore the use of an analytical model that could predict leaks in a SCBA facepiece during a steady negative facepiece pressure. The model considered flow across resistive flow paths, such as orifices and pipes, to estimate leakage rates for a representative range of pressures and geometric sizes of the leak. Results of the model were used to demonstrate predictions of the protection offered by the respirator during the leak for given inspiration flow rates of a wearer.

Experiments were conducted to confirm whether or not the model predictions were reasonable. Prescribed leaks in a well-controlled environment and under repeatable conditions were created using an SCBA mounted on a test headform. Leaks under constant flow conditions were used to simplify the problem to one of constant pressure instead of the variable pressure that results during breathing. The leak points or breaks were rigid to control the geometry of the leak. Quantitative fit measurements were conducted, and the results were compared with the leak predictions. Descriptions of the model equations, experimental procedures, and a discussion of the results are presented in the following sections.

ANALYTICAL MODEL

Leak Flow Rate

The volume flow rate, Q (m^3/s), through a resistive flow path such as a leak, can be expressed as a function of the pressure drop, Δp (Pa), along the path.

$$Q = C\,|\Delta p|^{\lambda} \tag{1}$$

Here, Δp is defined as the facepiece pressure relative to ambient pressure and therefore can be negative. The constants C (m$^{(\lambda+3)}$s$^{(2\lambda-1)}$/kg$^{\lambda}$) and λ (dimensionless) 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.[6,9,10] The constant C will contain details about the area of the leak as well as the fluid density and the flow resistance. 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. If more details of the leak geometry are known, it is possible to improve upon the relation written in Eq. 1. The illustrative example of this study is a leak across a SCBA facepiece defined

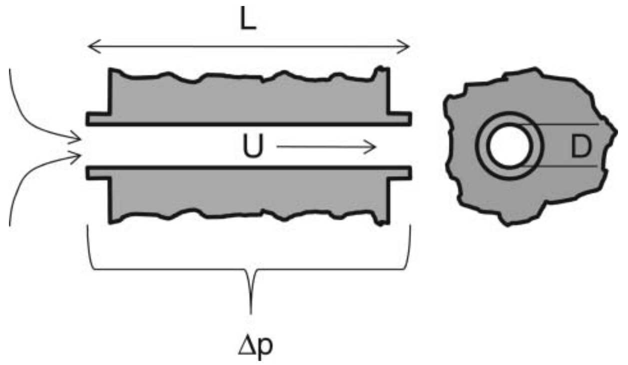

FIGURE 1. Schematic of flow across a leak with a circular cross-section, with leak length, *L*, leak inner diameter, *D*, fluid velocity, *U*, and pressure drop, Δp

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.(11)

$$\Delta p = \frac{\rho U^2}{2}\left(1 + K + f\frac{L}{D}\right) \quad \textbf{(2)}$$

where $K = 1.2 + \dfrac{38}{\text{Re}}$ **(3)**

and $f = \dfrac{64}{\text{Re}}$ **(4)**

An increase in average fluid velocity, U (m/s), along the tube results in an increased loss in fluid pressure, assuming a constant fluid density, ρ (1.17 kg/m^3, air). 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 Eq. 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 in meters, and D is the hydraulic diameter of the tube in meters (equivalent to the inner diameter for circular cross-sections). The loss constants, K and f, are functions of Reynolds number, Re, where $\text{Re} = \rho UD/\mu$, with fluid density, ρ, and dynamic viscosity of the fluid, μ (kg/m-s). For a tube of known cross-sectional area, A (m^2), and length, the volume flow rate of the leak, $Q_{leak} = UA$, in a pressure-demand SCBA can be determined by rearranging Eq. 2 for U, resulting in the following relation.

$$Q_{leak} = A\left(\frac{2\left|\Delta p\right|}{\rho\left(1 + K + f\frac{L}{D}\right)}\right)^{1/2} \quad \textbf{(5)}$$

Therefore, in the case of the pressure-demand SCBA, an inward leak occurs only when the facepiece pressure is below ambient ($\Delta p < 0$). In the case that the facepiece pressure is above ambient ($\Delta p > 0$), flow is directed out of the facepiece and the assumption that inward leakage does not occur is applied. Comparing Eqs. 1 and 5, it is apparent that the empirical constant, C, is a function of several factors that include the irreversible losses due to flow resistance and the geometry of the leak. Equations 3, 4, and 5 can be solved iteratively for U from an initial estimate that excludes the irreversible losses for a given Δp. 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.

Quantitative Fit—Concentration Ratio

The adequacy of the seal of a respirator to the wearer's face can be assessed by measuring 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 (kg/m^3), and that agent's concentration inside the respirator, C_i (kg/m^3), provides a quantitative measure of how well the respirator seals out the ambient environment or protects the wearer. This ratio is termed the quantitative fit factor, FF in Eq. 6,(9) and it is the parameter frequently measured in a fit test to evaluate the protection given by a particular respirator to a particular person.(7)

$$FF = \frac{C_o}{C_i} \quad \textbf{(6)}$$

Following the analysis by Campbell et al.(6) and by Williams,(9) it can be shown that negative facepiece pressure correlates with fit factor. For a given leak, the mass flow rate of the agent leaking into the respirator, $\dot{m}_{leak}$, can be expressed as:

$$\dot{m}_{leak} = C_{leak} Q_{leak} \quad \textbf{(7)}$$

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_{leak}, is equal to the agent concentration in the ambient air, C_o.

$$C_{leak} = C_o \quad \textbf{(8)}$$

Once the agent penetrates the inside of the facepiece it will be diluted by the supplied air flowing into the facepiece. During positive-pressure conditions the flow of air inside the facepiece is equal to the flow of supplied air, which is greater than the flow of air being inspired. When the flow of inspired air exceeds the flow of the supplied air, a negative-pressure condition results and the volume flow rate of the air inside the facepiece is equal to the inspiration volume flow rate, Q_{insp}. Given that mass is conserved and assuming that the agent is perfectly mixed once inside the facepiece, Eqs. 7 and 8 can be used to define the concentration of the agent inside the facepiece.

$$C_i = \frac{C_o Q_{leak}}{Q_{insp}} \quad \textbf{(9)}$$

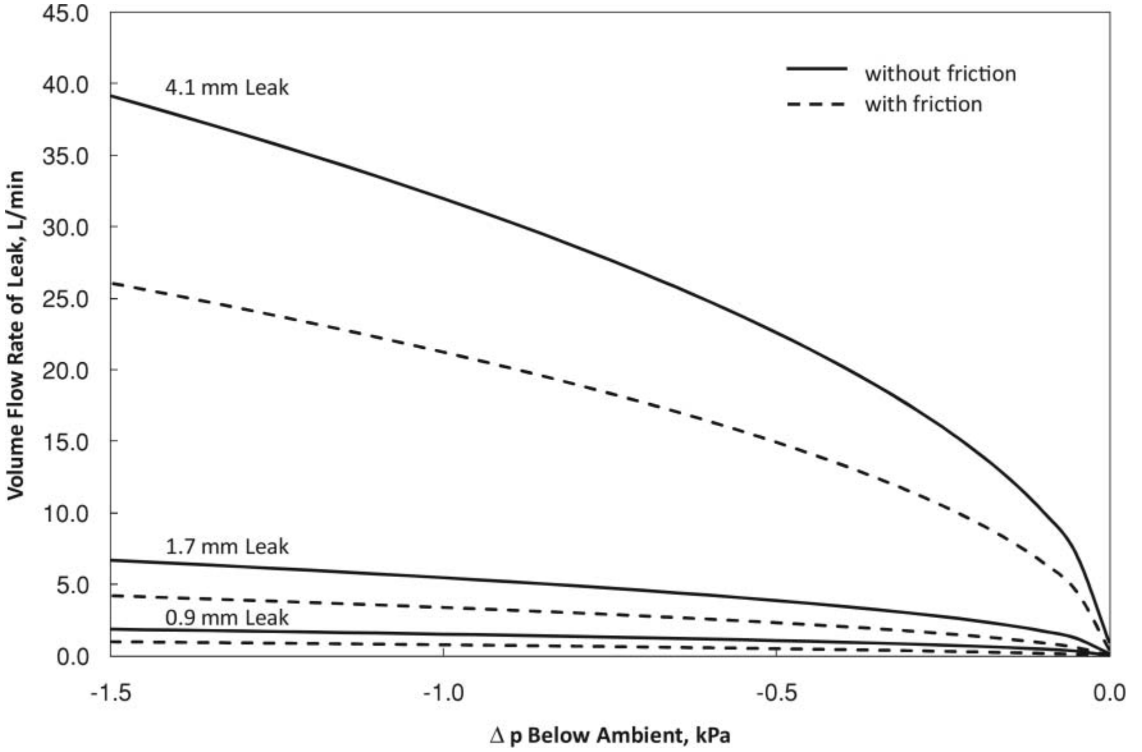

FIGURE 2. Predicted leakage in SCBA facepiece due to a facepiece pressure below ambient for leak diameters of 0.9 mm, 1.7 mm, and 4.1 mm.

Rearranging Eq. 9 it is apparent that FF as defined by the agent concentration ratio in Eq. 6 can be approximated by the ratio of the volume flow rate of the inspired breath and the volume flow rate of the leak.

$$\frac{C_o}{C_i} = \frac{Q_{insp}}{Q_{leak}} \tag{10}$$

Equation 10 is built on 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,(6,9,10) and
(3) the agent is perfectly distributed inside the facepiece.

Negative facepiece pressure is the major requirement for inward leakage. The leak rate is a function of negative facepiece pressure, and Eq. 10 combined with Eq. 5 leads to the correlation between quantitative fit and negative facepiece pressure. The following section will show how negative pressure can be used to predict the magnitude of the leak.

Model Predictions

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 overbreathing.(1,3,5,6) They were momentary spikes of below-ambient pressure and were typically less than 0.5 sec in duration. By assuming steady flow, therefore a constant facepiece pressure below ambient, the results of Eq. 5 can be examined for instantaneous 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 respirator that requires significant adjustment to eliminate a leak. 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 barrier that is most vulnerable to leaks is the interface of the wearer's face and the SCBA facepiece. This interface 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 Eq. 5, the volume flow rate of the leak was computed for a range of pressure conditions and leak diameters, shown in Figure 2. Equation 5 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 an ill-fitting respirator, the amount of the leak will be significantly greater. Removing the resistance (friction), K and f, from Eq. 5 demonstrates an upper limit for possible worst-case scenarios. In the absence of resistance across the leak, the volume flow rate would be increased by almost a factor of 2. For the range of leak diameters considered here, the predicted flow from a leak should not exceed 40 L/min.

The evidence for overbreathing an SCBA shows that it occurs during the peak of an inspiration breath. In a study

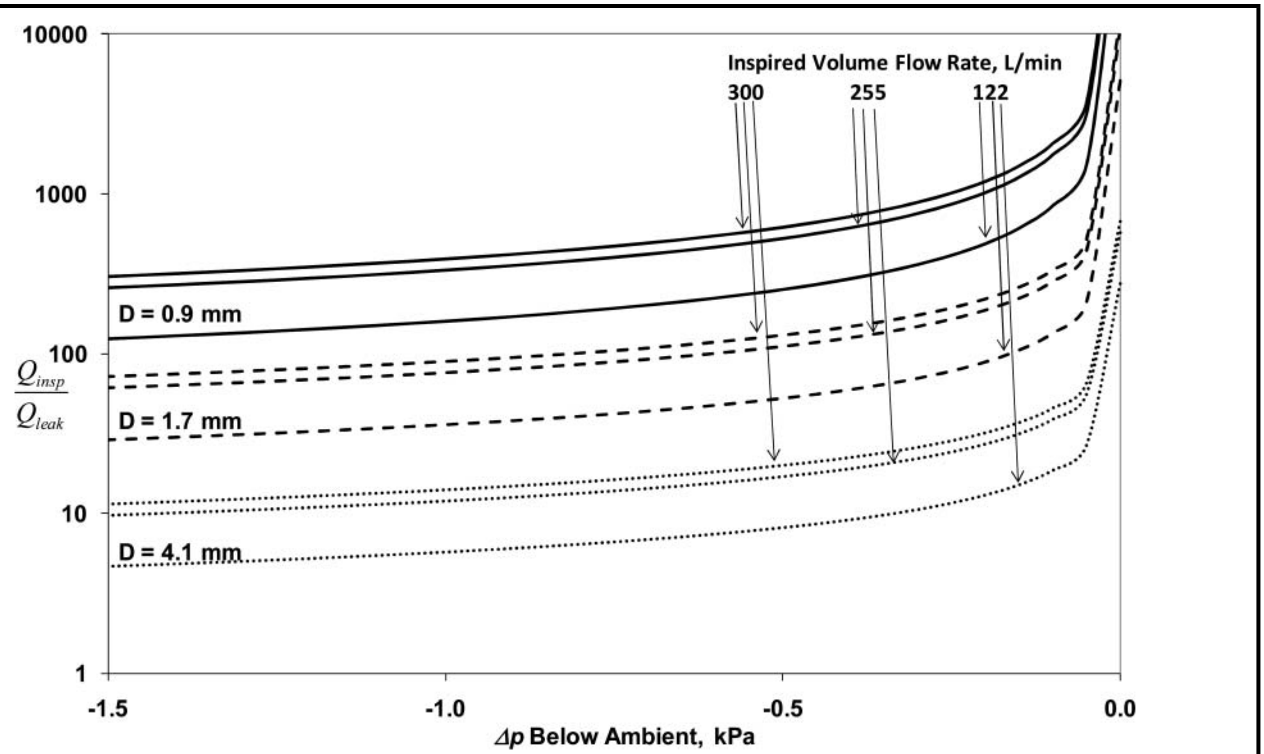

FIGURE 3. Predicted flow rate ratio of a SCBA respirator during a below-ambient facepiece pressure. Flow resistance is included in the prediction.

of human subjects exercising on a treadmill, peak inspiration flow rates as high as 450 L/min were observed in one test subject, and these conditions induced negative facepiece pressures.(3) The study defined 300 L/min as a critical value for the potential of overbreathing an SCBA. Peak inspiration may induce a leak; but as demonstrated by Eq. 9, a leak at a given pressure condition becomes more diluted as inspiration flow rate increases. Equation 5 does not attempt to couple the magnitude of the leak with the inspiration flow rate, only to predict it for given conditions of leak geometry and below-ambient facepiece pressure. However, the effect of the inspiration flow rate on the resulting agent concentration ratio in the presence of a leak can be examined with Eq. 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. Peak inspiration flow rates produced by these breathing waveforms are 122 L/min and 255 L/min, respectively, and provide other reference values for peak inspiration flow rates.

The ratio of inspired airflow rate to estimated leak flow rate for an SCBA with a circular cross-section leak is plotted in Figure 3 for different assumed inspiration flow rates. As shown in Eq. 10, this flow rate ratio is equivalent to the agent concentration ratio, which is used for measuring fit factor. The leak flow rate has been evaluated from Eq. 5, which includes flow resistance. For a given leak geometry, the flow rate ratio will increase if the inspiration flow rate is increased without changes in the deflection of the facepiece pressure below ambient. It is predicted that a flow rate ratio on the order of 1000 or less will result for leaks with hydraulic diameter greater than 1 mm and facepiece pressure more than 0.1 kPa below ambient.

The NIOSH assigned protection factor (APF), defined as "*the workplace level of respiratory protection that a respirator or class of respirators is expected to provide,*" for a positive pressure SCBA is 10,000.(7,p. 421) 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 three orders of magnitude in the case of an ill-fitting respirator.

EXPERIMENTAL METHOD

To evaluate the analytical results, experiments were conducted to induce a continuous negative pressure inside the facepiece of an SCBA donned on a test headform. Leak sites were prescribed using brass tubes of different diameter. Measurements of facepiece pressure, particulate concentration inside and outside the facepiece, and inspired volume flow rate were conducted.

Materials

An SCBA facepiece (Scott AV-2000; Scott Safety, Monroe, N.C.; see disclaimer) was donned on a test headform (Biosystems PosiChek3; Sperian Protection, Smithfield, R. I.) used

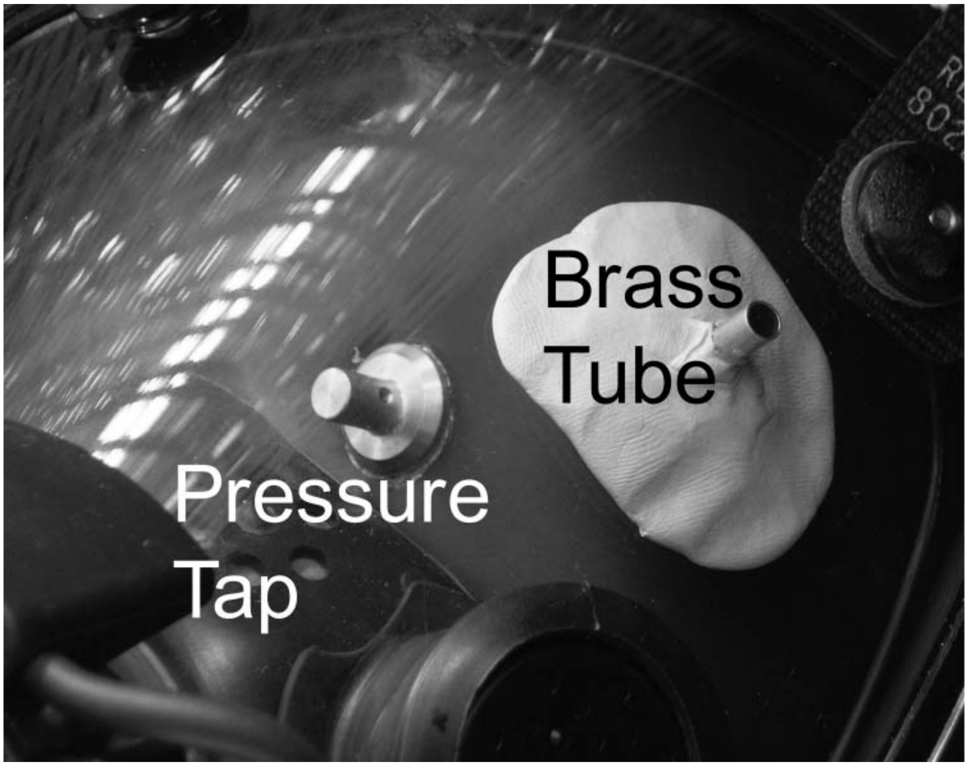

FIGURE 4. Photograph of leak site on the facepiece and facepiece pressure tap on the headform inside the facepiece.

for SCBA airflow performance testing. A 12.7 mm hole was cut into one side of the plastic visor of the facepiece at eye level. The hole was plugged with a flexible adhesive putty, and brass tubes were inserted through the putty to establish the leak sites (Figure 4). Tube inner diameters (equivalent to hydraulic diameter for circular cross-sections) were 0.9 mm, 1.7 mm, and 4.1 mm, with tube length to diameter ratios, *L/D*, of 30, 16, and 7, respectively. The facepiece visor was chosen for the leak sites because the putty could be sealed around the perimeter of the brass tube and then sealed to the outside of the facepiece visor. The common method of producing leak sites between the surface of the test headform and the facepiece seal, using tubes, wires, or putty and tubes,(10) was not employed to separate the process of donning the facepiece and preparing the leak site. Placing the leak site in the facepiece visor also allowed the geometry of the leak to be changed without having to remove and re-don the facepiece.

The SCBA unit and regulator (Scott Air-Pak 4.5) that attached to the facepiece were 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 an SCBA bottle is nearing empty caused the facepiece pressure to go negative during a reasonable inspiration flow rate. A high-efficiency particulate air filter (HEPA) 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.

Facepiece pressure, the differential pressure between the inside of the facepiece and the ambient environment, was measured using a differential pressure transducer (Baratron 698A11TRA; MKS Instruments, Andover, Mass.) attached to a pressure tap located at the left eye of the test headform (Figures 4 and 5). A vane pump (1023-V131Q-SG608X; Gast Manufacturing Inc., Benton Harbor, Mich.) pulled air at a constant flow rate from the mouth through the neck of the test headform. The airflow rate, Q_{insp}, was monitored by an electronic flow meter (4045; TSI, Shoreview, Minn.) placed in the flow line. A large baffle was also placed in the flow line to dampen the oscillations caused by the pump. The experimental setup is illustrated in Figure 5.

The concentration of particulates entering the SCBA facepiece due to the leak was measured by sampling the flow from two different locations in different experiments to check for a sampling bias: after the flow had left the test headform, and inside the facepiece lens. Particulate concentrations were measured using a PORTACOUNT (TSI 8010), a particle counting device commonly used for quantitative fit testing of respirators. The device measures the ambient concentration of particulates and compares it with the concentration of particulates measured inside the respirator to compute a fit factor. The particle counter samples the air at a flow rate of 0.7 L/min.

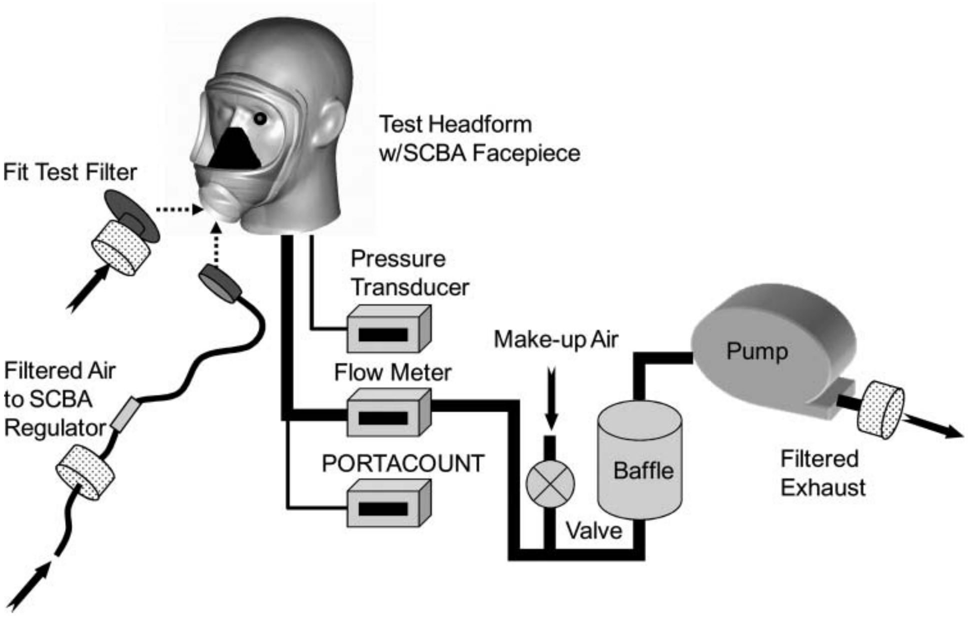

FIGURE 5. Schematic of the experimental setup to study SCBA leaks under constant flow conditions.

Procedures

The SCBA facepiece was donned on the test headform and secured to ensure a good fit. A standard fit test filter assembly was attached to the SCBA, instead of the SCBA supply air regulator, to perform an initial fit test. The pump was turned on and the flow conditions were set by adjusting a metering valve for the make-up air. In this configuration, ambient air flowed through the system and was filtered at the fit test filter assembly. The leak site was plugged with the adhesive putty, and an initial fit test was performed to check for leaks. Particulates were generated in the laboratory to bring the ambient particulate concentration up to the levels recommended for the particle counter to operate properly—greater than 1000 particles/cm^3. This was accomplished by burning a tapered candle during the experiments. Ambient concentrations were on the order of 17,000 particles/cm^3 to 66,000 particles/cm^3. Concentration ratios measured during the initial leak check ranged from 11,700 to 1,400,000. These values would represent very high fit factors, confirming the absence of leaks in the setup.

The fit test filter assembly was replaced by the SCBA regulator, and the leak site was unplugged (Figure 5). By adjusting the air supply pressure and the metering valve for the make-up air, negative-pressure conditions inside the facepiece were achieved for the desired volume flow rate of inspired air. Flow conditions were allowed to settle for at least 3 to 4 min before measurements were recorded. Facepiece pressure and inspired volume flow rate were measured at a sampling rate of 100 Hz and 10 Hz, respectively.

Preliminary experiments revealed that small concentrations of particulates were present inside the respirator mask during positive pressure conditions. This implied that the filter in the air supply line failed to remove all of the particulates and therefore a background particulate concentration would exist. This background particulate concentration was measured for each experimental run and was subtracted from the mask concentration measurements. The average background was 5 particles/cm^3. This had a negligible effect on the measured concentration ratio due to the large concentration of particulates leaking into the mask.

RESULTS AND DISCUSSION

The sequence of sampling by the particle counter was to first draw a sample from the ambient environment, draw a sample from inside the mask, and, finally, draw a sample from the ambient again, as shown in Figure 6. This sequence was repeated for a minimum of three cycles to record the particle concentrations in the ambient air and inside the mask. An overall particle concentration ratio and an average facepiece pressure were computed for the given number of cycles. Since the facepiece pressure becomes more negative during the mask sampling period, only pressure measurements acquired during the mask samples were used to compute the average facepiece pressure. The particle counter 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.

In the present study, a constant inspiration flow rate was simulated with flow induced by a pump. The vane pump used for this study was run at maximum capacity. Combining the flow rate of the vane pump and the sample flow rate of the particle counter (0.7 L/min) resulted in an average inspiration flow rate of 125 L/min. This was slightly greater than the peak inspiration flow rate produced by the 40 L/min NFPA breathing waveform, but it was adequate for the purpose of

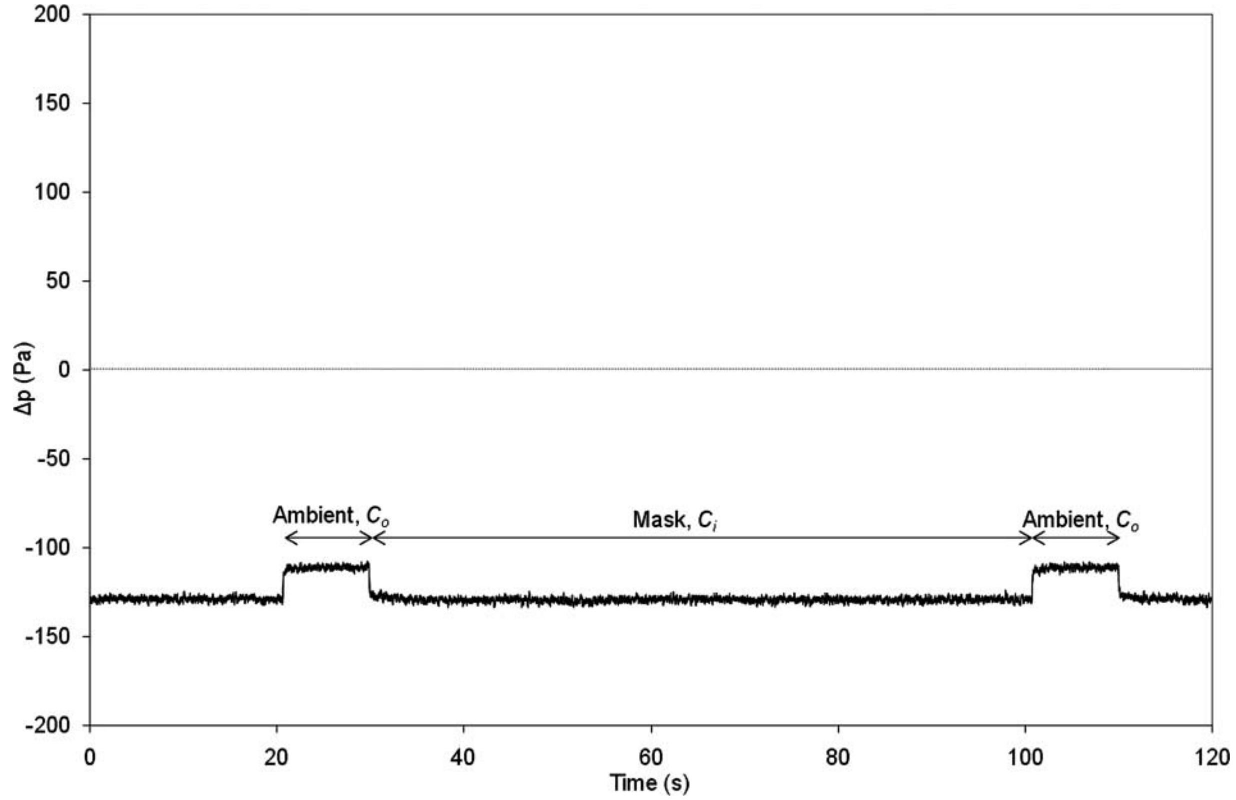

FIGURE 6. Facepiece pressure during the particle counter sampling sequence.

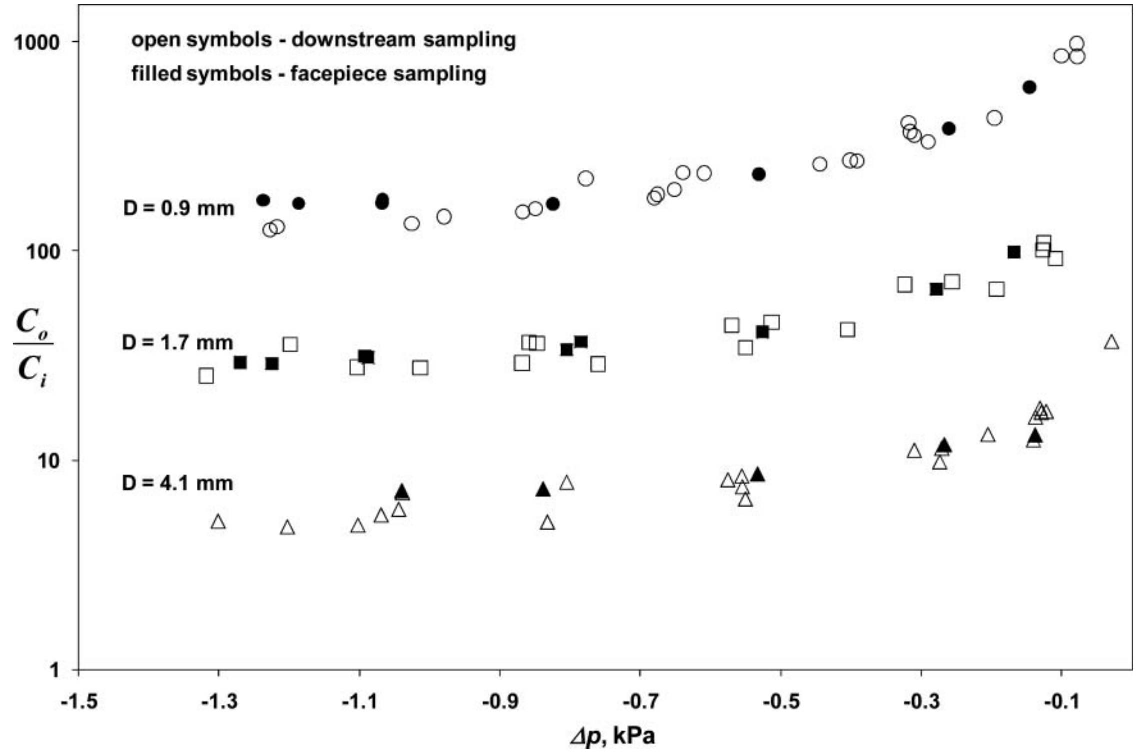

FIGURE 7. Relationship between negative facepiece pressure and particle concentration ratio, C_o/C_i, from downstream sampling (open symbols) and from facepiece sampling (filled symbols) at an average inspiration flow rate of 125 L/min.

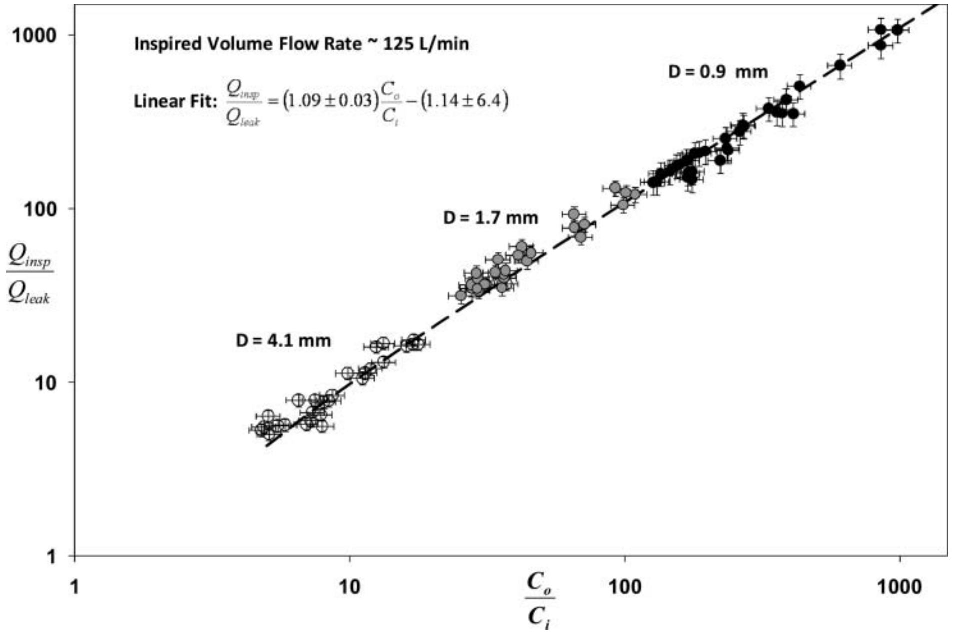

FIGURE 8. Agreement between flow rate ratio computed from below-ambient facepiece pressure measurements and concentration ratio computed from particle counter measurements.

this study. Previous studies$^{(1,3,5,6)}$ provided a baseline set of facepiece pressure conditions for the present study that ranged from 0 kPa to 1.3 kPa. The relationship of concentration ratios measured by the particle counter to facepiece negative pressure is shown in Figure 7.

Significant sampling biases have been reported by Myers et al.$^{(12–14)}$ for half-facepiece and full-facepiece negative-pressure respirators. Facepiece design, which influences airflow patterns, and sample probe insertion depth, were the major parameters linked to the observed sampling bias. Their study of full-facepiece respirators provided the insight that during the inhalation breath flow mixing was incomplete, especially when the purified air was directed across the facepiece lens to reduce fogging.

In the present study, sampling was performed at the facepiece to check for a sample bias in the positive pressure SCBA. The open circles in Figure 7 represent the experiments performed with the sampling port downstream of the flow leaving the headform. The filled circles represent the experiments performed when the sampling port was moved to a location in the facepiece lens, at the same height but opposite side as the leak. If a sampling bias existed, it would be expected that the facepiece sampling location would result in discernible differences in concentration ratios because of its proximity to the leak and because of a potential for inhomogeneity in the particle concentration in the facepiece. However, as seen by comparing the open and filled circles in Figure 7, no bias was detected for the selected facepiece sample location. The absence of a sampling bias can be explained by the source of the airflow.

Like some of the full-facepiece respirators investigated by Myers and Allender,$^{(14)}$ the SCBA facepiece directed the clean air across the lens to reduce condensation from the moisture contained in the exhaled breath. However, most of the airflow in the SCBA facepiece is forced flow from the SCBA regulator, which can be remarkably different from the clean airflow induced solely by an inhaled breath for a negative-pressure respirator. The forced flow of the SCBA had the added benefit of increasing the flow mixing inside the facepiece and therefore reducing any sampling bias.

The volume flow rate of the leak was computed from the average measured pressure differential using Eqs. 3, 4, and 5. Equation 10 suggests that the ratio of the inspired volume flow rate and the volume flow rate of the leak should equal the concentration ratio measured by the particle counter. These ratios are plotted against each other in Figure 8 to demonstrate their agreement as predicted in Eq. 10. A propagation of uncertainty was performed to estimate the measurement uncertainty of the volume flow ratio. Estimates of relative expanded uncertainty (coverage factor of 2 defines an interval having a level of confidence of approximately 95%) ranged from ±0.07 to ±0.08 for the 4.1 mm leak, ±0.09 to ±0.10 for the 1.7 mm leak, and ±0.16 to ±0.19 for the 0.9 mm leak. A least-squares regression of all the data using Microsoft Excel 2007 gives a linear fit of:

$$\frac{Q_{insp}}{Q_{leak}} = (1.09 \pm 0.03)\frac{C_o}{C_i} - (1.14 \pm 6.4) \qquad \textbf{(11)}$$

with the error limits for the slope and intercept given as the 95% confidence interval. The quantitative fit and the qualitative distribution of the data demonstrate very good agreement between the fit factor estimated from facepiece pressure measurements and the traditional measurement of fit factor computed from concentration measurements. The volume flow rate ratio tends to overpredict the fit factor by 6% to 12%. With the exception of the 1.7 mm data, most of the measurements are distributed about the fit.

It appears there is a bias associated with the 1.7 mm data, since all the flow rate ratios seem to be higher than the measured concentration ratios, instead of distributed on both sides of the line. Because the bias is most obvious for the 1.7 mm data, it is likely due to an experimental discrepancy associated with that leak tube, such as the dimensions of the leak. Overall, the predictions of fit factor for conditions of facepiece pressure below ambient and in the presence of a breach are quite reasonable for the range of leak geometries and facepiece pressures considered in the present study.

The good agreement between the experimental results demonstrated that the model is capable of predicting a compromise in respirator protection to within a few orders of magnitude if negative-pressure conditions are known to exist inside the facepiece and reasonable estimates of the leak geometry are available. This simplified steady-state model is the first step to quantifying the resulting reduction in respiratory protection from a measurement of below-ambient facepiece pressure in a pressure-demand SCBA. Future steps will consist of generating pressure traces from simulated breathing and using the model to predict overall respiratory protection during breathing.

Recent studies have generated digital three-dimensional headforms of the general population of respirator users(15) and have used the digital headforms to simulate the interaction between respirator and headform.(16) Both demonstrate the trend toward the computer-aided design of respirators. Leak geometry is unknown during actual respirator use, and it is a significant parameter of the analytical model presented here. It is anticipated that the digital headforms and the interaction simulation can be used to predict leak geometries during actual use. Therefore, the analytical model and the previously mentioned studies can be used together as tools for respirator design and testing.

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 gathered from the literature. For a range of known inspiration flow rates, the model predicted the potential for a momentary reduction in protection level during below-ambient pressure events. Constant flow experiments were conducted to test the ability of the model to predict leakage from negative facepiece pressure measurements. The ratio of inspired air volume flow rate to the leak volume flow rate, computed from measurements of facepiece pressure, correlated well with particle concentration ratios measured from the particle counter, the conventional quantitative measure of respirator protection and fit. The results were 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. Without knowing the leak geometry, accurate predictions of leakage rates will remain a challenge. However, the good agreement with the experimental results demonstrated that the model is capable of predicting a compromise in respirator protection to within a few orders of magnitude if negative-pressure conditions are known to exist inside the facepiece.

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