
Developing an Air Sampling System for Detecting Oxygen Leaks from the Facepiece of a Self-Contained Breathing Apparatus

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ABSTRACT

The goal of this work was to develop and validate an oxygen leak detection system for use with a closed circuit self-contained breathing apparatus (CC-SCBA). CC-SCBAs operate under a positive pressure closed loop, where carbon dioxide is removed from exhaled air while oxygen and other gases are recovered and recycled. There has been a long standing NIOSH prohibition against the use of such oxygen based closed circuit systems in the presence of high radiant heat or open flame due to concerns over possible user burn injury as a result of leaks in the vicinity of the facepiece. Past studies performed according to the NFPA 1981 standard have revealed that facepiece fit poses the biggest risk for a closed circuit respirator and will most likely be the location for a leak to occur. The system developed here was intended to detect leaks emanating from the facepiece seal using a plenum with sampling ports at intervals located along the periphery of the facepiece to pull air to an oxygen analyzer. Leaks were located at the neck, temple, and cheek of the facepiece and the changes in percent oxygen in the surrounding air were recorded for leak and no leak conditions. With this approach the oxygen leaks can be sensed directly and independently of size or location. It was found that the proposed system is capable of sampling from the vicinity of the facepiece; however its sensitivity in detecting leaks was not found to be adequate enough to definitively state if a leak had occurred due to large fluctuations in oxygen detected as a result of a low sample rate and a high dilution factor.

Keywords: closed circuit self-contained breathing apparatus, respirator fit, respiratory protection, oxygen leak

INTRODUCTION

Self-contained breathing apparatus (SCBA) that recycle exhaled air must remove carbon dioxide, but save oxygen and inert gases (nitrogen). Augmenting the portion of oxygen in the compressed gas cylinder would allow either extended service times with the same size cylinder or lighter weight with a smaller cylinder. It has been found that by breathing oxygen-enriched air (e.g. 40% oxygen by volume in nitrogen), firefighters can improve their physical performance and increase the operational time available from an SCBA (Williams, 1998). However, many SCBA are used in firefighting or other combustible atmospheres. Oxygen-rich air mixtures leaking from the positive-pressure facepiece could pose a burn hazard for the wearer during these situations.

The National Institute of Occupational Safety and Health (NIOSH) has issued a long standing prohibition against the use of any oxygen based SCBA in the presence of high heat based upon this concern (NIOSH, 1985). Flame engulfment testing tests conducted at Intertek ETL Laboratories in Cortland, New York according the NFPA 1981 standard have shown that the most likely cause of a leak is an inadequate seal of the facepiece against the face. This can be the result of any number of factors including old equipment, the presence of facial hair, or the unique structural composition of the face of the wearer (Rehak, 2008).

A typical closed-circuit respirator provides the user with three stages of oxygen supply into the breathing loop. There is: 1) a constant flow rate of air designed to accommodate a moderate rate of consumption, 2) a pressure demand flow designed to supplement oxygen supplies to users consuming oxygen above the constant rate, and 3) an emergency flow rate, designed to compensate for pressure regulator failure. The constant oxygen flow rate is usually in a range of 1.5 to 2.0 Liters per minute (Lpm) while pressure demand and emergency flows are in the range of 80 to 100 Lpm. Typical steady-state maximum oxygen consumptions for people are about 3.5 Lpm to 5.5 Lpm for highly-trained individuals.

There are only two situations that cause actuation of the pressure demand oxygen flow. When a user consumes oxygen at a rate higher than the constant add, the pressure demand supplements the oxygen feed with short duration 80 to 100 Lpm additions. Or, should a closed-circuit respirator develop a leak in any portion of the breathing loop, escaping oxygen decreases the amount of the constant add available to the user, and will initiate pressure demand additions.

With vigorous movements of the head or body, transient oxygen leaks are possible. Janssen (2000 a & b) has reported that face seal leaks detected during workplace monitoring are intermittent and vary greatly in size. Anecdotal testimonies from firefighters attest to the occurrences of leaks around the face seals of respirators as they are worn in action. These oxygen leaks in the presence of combustible atmospheric mixtures can ignite, not only the mixtures, but also the facepieces themselves. The danger of leak-caused combustion is exacerbated by oxygen enriched mixtures in the SCBA cylinders. For this reason, it is important to be able to detect oxygen leaks before oxygen-enrichment is legally permitted.

The approach taken here was intended to provide a means of directly sampling air from the immediate vicinity of the facepiece using a plenum located around the periphery of the facepiece with sampling ports along the entire length to draw in gas samples to be read by an oxygen detector. Previous work at the University of Maryland showed that surrounding combustible mixtures can be ignited from oxygen leaks with diameters on the order of 1 mm (Zhang, 2012). The goal of this effort was to determine the ability of a continuous sampling method to detect the minimum size leak resulting from compromised facepieces.

This approach could detect oxygen leaks directly and somewhat independently of the sizes or locations of multiple face seal leaks. If successful, this method could result in a sensor system that could be incorporated into new SCBA or added to existing SCBA. However, drawing gas simultaneously

through all sampling ports would dilute local oxygen concentrations, so the minimum average sample oxygen concentration able to be detected would have to be determined, and this minimum oxygen concentration may be too high to be useful. A second possible problem with this method is that oxygen leak detection must be made on a relative, rather than absolute, scale. Normal air contains 21% oxygen. Air in a fire may contain very little oxygen. Thus the system needs to be able to adjust its reference level to local ambient conditions. It is also possible that an oxygen detector could be fouled by combustion products during a fire.

METHODS

Design of Sampling System and Leak Induction

The sampling system consisted of a Biopak 240R CC-SCBA, a test chamber, breathing simulator, oxygen detector (Yokogawa OX400 Tokyo, Japan), and the plenum which was used for acquiring samples. The plenum was fabricated from Tygon (Saint Gobain Courbevoie, France) plastic tubing which had an inner diameter of 4.8 mm (0.1875 inch). Holes 1 mm (0.04 inch) in size were punched into one side of the tubing wall and spaced 2.5 cm (1 inch) apart. The plenum was wrapped and affixed around the facepiece with the holes oriented towards the edge of the mask where it formed a seal with the face (Figure 1a). Leaks were induced by inserting pieces of tubing 2.5 cm (1 inch) in length and of various diameters between the seal of the facepiece with the face as shown in Figure 1b. Any additional gaps in the seal caused by the insertion were covered as best as possible with modeling clay. The entire system setup is picture in Figure 1c.

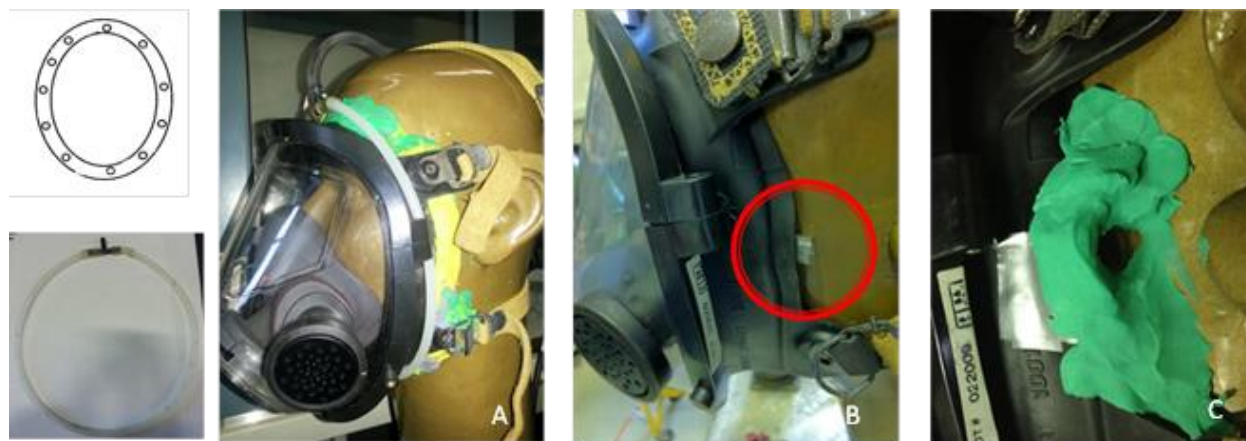


Figure 1 (a) Head form with attached plenum. Sampling ports are located facing the facepiece seal with the face. **(b)** Inserted tubing to simulate a leak **(c)** sealing of unintended gaps via clay.

Calibration of Leak Rates and Determination of What Constitutes a Leak

The CC-SCBA used in these tests was a positive pressure system and, as a result, the leak rate from an opening in the facepiece should be defined by two factors: size of the leak opening and breathing rate (assuming that this changes the pressure). A computational fluid dynamic study has found that increases in breathing rate can directly increase the leak rate (Butler, 2007). In order to determine the volume flow rate of air leaking through each diameter of inserted tube, it was necessary to first find the average pressure in the facepiece. Any leaks are the result of the pressure difference between the interior and the atmosphere. The facepiece was placed on a head form and connected to the CC-SCBA. The

head form was then sealed and made as air tight as possible. A 7.94 mm (0.3125 inch) tube was inserted into the facepiece with the free end attached to a manometer. The entire system was turned on and allowed to equilibrate. The pressure reading from the manometer was found to be 0.03 cm of H₂O and was accepted to be the pressure inside the facepiece. Determination of the leak volume flow rate for various tube sizes was then found based on this pressure value. The tubes used to induce leaks (various sizes from 7.94 mm (0.3125 inch) to 1.19 mm (0.046875 inch)) were attached to a "T" connection with one port of the "T" being attached to the manometer and the other to a hand operated syringe with a volume of 3 L. Air from the facepiece was then pulled through the tubes into the syringe, creating enough suction such that the manometer indicated the value found previously in the pressure determination study. The time taken to fill the 3 L syringe at the SCBA facepiece pressure was measured for each tube size and flow rates calculated. Three replications were conducted on each size tube. A diagram of the calibration setup is presented in Figure 2 and results are found in Table I.



Figure 2 Leak assessment setup. A hand operated syringe was pulled to match the pressure found in the facepiece of a CC-SCBA to determine the leak rate from various tube sizes which were inserted into the facepiece.

Table I. Average Rate of Flow from Various Size Tubes Inserted into Facepiece

Tube Diameter (mm)	Average Flow (L/sec)	Standard Deviation
7.94	0.075	0.002
4.76	0.069	0.002
3.18	0.036	0.001
1.59	0.005	0.0001
1.19	0.003	0.0001

The oxygen detector can report percent O₂ values with accuracy in the hundredths place. With the plenum attached the % O₂ value was very unlikely to remain constant and the inherent variability in the system was determined. Due to the continuous sampling method of the plenum, and the surrounding environment being very difficult to control precisely for O₂ concentration, it was clear that this assessment was necessary. The SCBA facepiece with plenum was mounted on a medium sized head form associated with a breathing machine (Krug Life Sciences; San Antonio, TX). Figure 3 shows a graph of the detector-plenum system and its variability for various breathing rate conditions (Table II). It was found that the system varied with a standard deviation of about 0.25%. In order to clearly define what is and isn't a leak, it was decided to use a change in percent O₂ of 1% or greater as a defined leak.

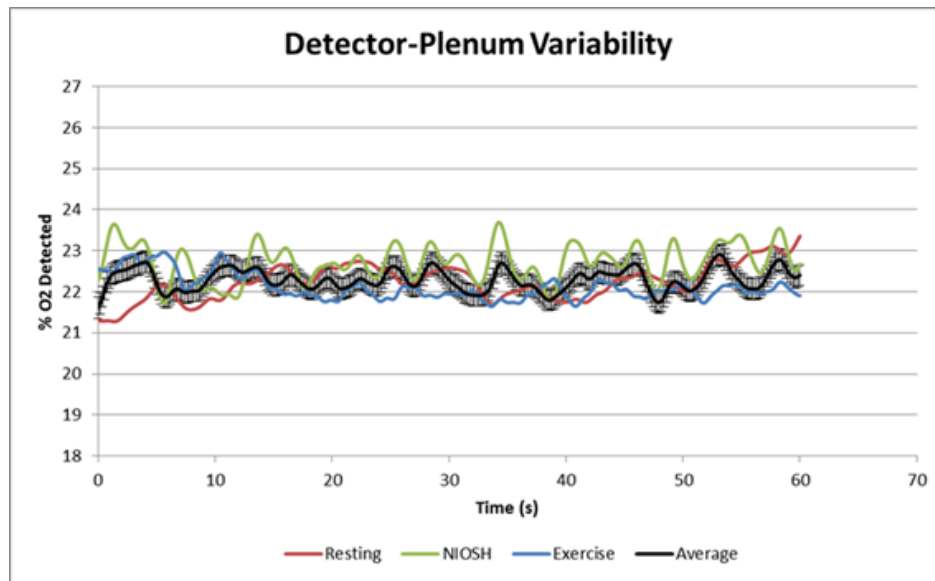


Figure 3 System variability was found to have a standard deviation of 0.25%.

Table II. Breathing Rate Settings and Associated Volumes per Breath

	Breaths per Minute (BPM)	Liters Per Breath (LPB)
Resting	15	0.5
NIOSH	24	1.67
Exercise	42	2.38

The three rates are intended to reproduce all possible user breathing rates. With resting representing low exertion, NIOSH the rate typically used for testing done to NIOSH standards and exercise being the level of maximum exertion. A breathing simulator was used for all tests.

Once the leak size was determined, the system was assembled and five trials for various leak and breathing rates were tested (Figure 4). Three leak locations were tested: Neck, cheek and temple of the head form and three breathing rates: Resting, NIOSH (Rehak 2008) and Exercise. It was found via computer models (Butler, 2007) that breathing rate may affect leak rate and these rates are representative of the full spectrum of rates possible.



Figure 4. Overall test setup with the SCBA facepiece mounted on the breathing machine head form.

Each test was conducted by first opening the oxygen tank of the CC-SCBA and turning on the breathing simulator to the desired rate. The tube causing the leak was initially plugged for the first 20 seconds of the test. At the 20 second mark the leak was opened and remained so for 10 seconds before being resealed as best as possible. The oxygen detector was allowed to run for an additional 30 seconds following this for a total duration of 60 seconds per test. All data was collected using a Yokogawa OX400 Oxygen Analyzer and a Labview (National Instruments, Austin, TX) program for plotting and saving results.

RESULTS AND DISCUSSION

Five trials for each breathing and leak rate at each location were conducted. Individual results from various trials are presented in Figure 5. Of the three leak locations tested only two produced results that indicated that a leak had occurred. The leak position at the neck (Figure 1) was most likely too far from the point of suction to obtain any successful samples. This can be adjusted in future tests by either reducing the number of sampling ports on the plenum or increasing the suction rate to the detector. In this case the detector sampling and analysis rate limited our ability to greatly increase the plenum sampling rate. Therefore no data from the neck is presented in this paper. Additionally no data to support a detected leak for a leak size less than 3.18 mm (0.125 inch) was found. The cheek and temple however provided favorable outcomes in some cases. Results from individual trials for 7.94mm, 4.76 mm, and 3.18mm leaks presented in Figure 5 clearly show that at the beginning of the induced leak (first red arrow) the plenum almost instantly retrieved a sample that reported a leak (change in %O₂ greater than 1%). However following this period the leak appears to linger in the surrounding atmosphere and the plenum repeatedly samples it. The actual leak was closed after the second red arrow and lingering changes in % O₂ were due to sampling of the remaining high environmental O₂ concentration. Additionally, while the plenum did appear to detect a leak at the 20 second mark in these individual trials,

averaging of 5 trials showed that the variability of plenum sampling was very high. Figure 6 shows that the standard deviation for the 60 second time scale was very large and in some cases the plenum was unable to detect a leak while in others it only detected the leak for the duration of the trial.

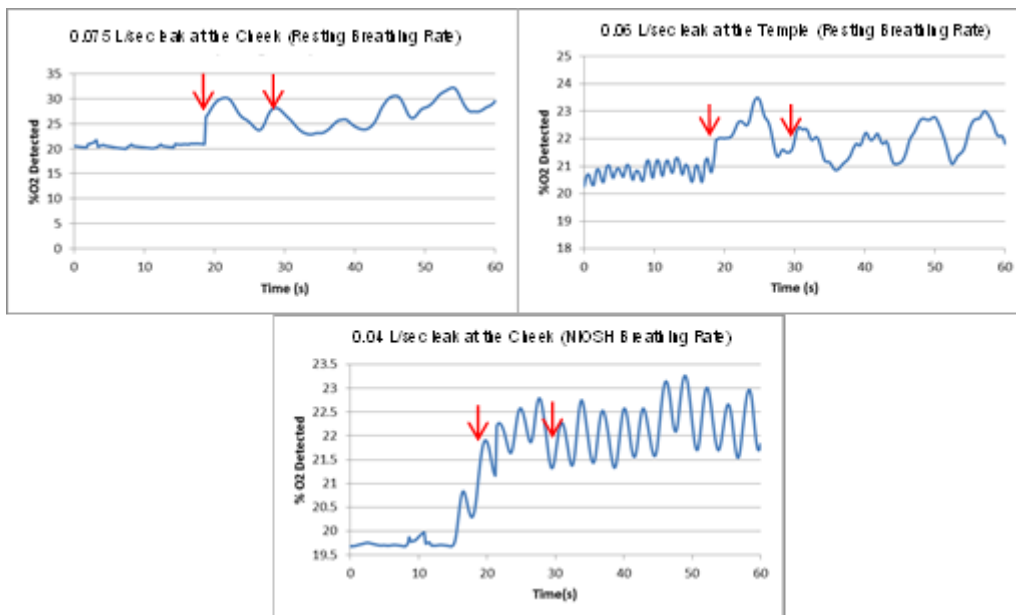


Figure 5 Results for various leaks from individual trials. Arrows indicate the time during a test when a leak was induced and subsequently closed.

Overall it was clear that while the sampling system detected leaks it was not consistent enough to do so reliably and would not provide a warning to a wearer of a CC-SCBA. When a leak was induced the plenum rapidly collected an air sample due to the continuous sampling and indicated changes in percent oxygen greater than 1% almost immediately. However it was clear from the high standard deviation from 5 trials that after this point the continuous sampling became a negative aspect of the approach. Regions of air remained in the vicinity of the facepiece where the plenum could retrieve samples containing high concentrations of oxygen, despite the leak being closed after the 30 second mark (Figure 6). Therefore, it was difficult to state that a leak was or was not present over a period of time with this method.

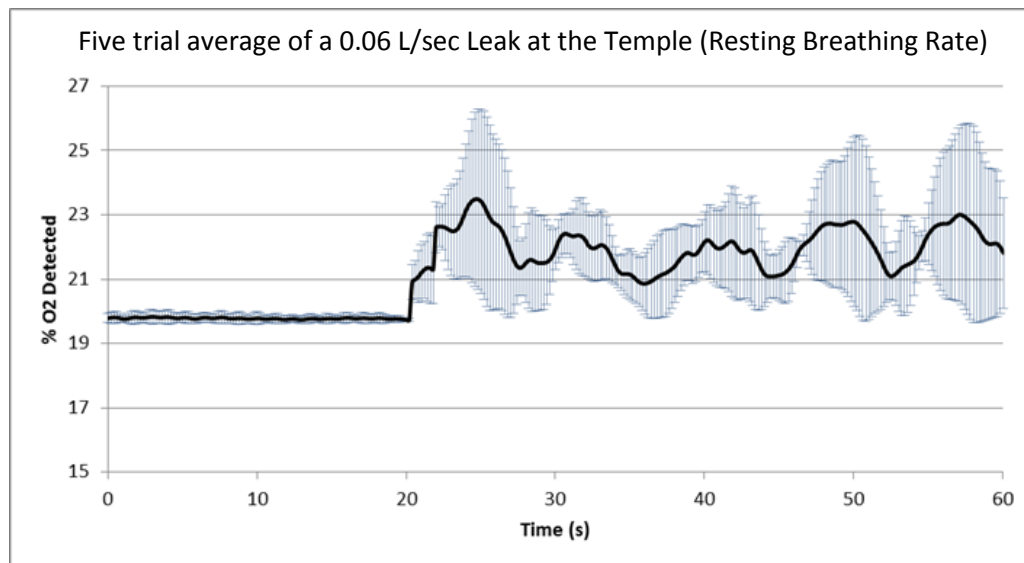


Figure 6. Average of five trials for a 0.06 L/sec leak located at the temple. The shaded portion is the standard deviation of the trials.

CONCLUSIONS

Development of a leak detection system for CC-SCBA is the first step in ensuring their safety if they are used with pure oxygen in open flame or high radiant heat environments. While effective in some trials, the concept of sampling the air surrounding the facepiece proved to be far too inconsistent to adequately address concerns related to CC-SCBA safety. The plenum was able to detect leaks; however confidently stating that a leak did or did not occur over a period of time was not possible with this method. Additionally, due to the continuous sampling method of the system the variability of samples collected over a 60 second period was very high, which reduced confidence in its leak detection capability.

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