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Performance Criteria for Development of Extended Use Protective Breathing Equipment

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16. Abstract

The Federal Aviation Administration (FAA) requires under Federal Aviation Regulation (FAR) 121.337 that crew protective breathing equipment (PBE) for smoke and fume protection is installed aboard aircraft and that crewmembers be trained in the proper use of PBE (FAR 121.417). A variety of designs currently exist that meet the requirements of these regulations. However, the threat posed by atmospheric contamination in an environment that cannot be quickly escaped suggests that extending the protective capabilities of PBE devices beyond what is mandated by the FAA may be beneficial in aviation and other arenas. These experiments were conducted to evaluate the use of one style of PBE in terms of potential for long-term (>20 min) use and to identify issues critical to long-term use. A closed-circuit PBE device utilizing lithium hydroxide (LiOH) technology for carbon dioxide (CO_2) removal was tested. The capability to supply fresh oxygen to the user had been incorporated into the prototype design. Breathing simulator testing clearly demonstrated that CO_2 levels during use were consistent with theoretical values and represented the limiting factor for long-term wear when coupled with the "ad libitum" use of oxygen. As expected, metabolic CO_2 production rate was the primary factor limiting time of use in the prototype testing performed. From a practical standpoint, it was also clear that consistent and effective means of oxygen delivery and temperature control need to be developed. If these issues can be successfully addressed in terms of meeting a metabolic demand anticipated for a given operational environment, PBE capable of providing from 2 to 5 hours of protection to the user may be a viable possibility.

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Performance Criteria for Development of Extended Use Protective Breathing Equipment

INTRODUCTION

A variety of styles of protective breathing equipment (PBE) are available for use by passengers and crew in civil aviation. Historically, this type of equipment has been designated for relatively short-term use in emergency situations. PBE designed to protect the wearer from smoke and fumes are required on transport aircraft for crewmember use. These units are often referred to as "smoke hoods" and are required to provide protection for at least 15 minutes.

There are potential circumstances where longer duration protection would be desirable in this type of PBE. For example, a system failure aboard an aircraft could result in some type of contaminant being introduced into the cabin. A crewmember may have to work to remedy the situation and be in a noxious environment for the duration of the flight. Isolation and administration of first aid to an individual with a potentially infectious disease is also an application. Having an isolated, sustainable atmosphere to breath in would reduce the potential for infection. The possibility of a chemical or biological agent being released into the cabin environment is also a possibility. Even if confined to small area, those affected may need treatment and tasks in a contaminated area may still be necessary. These situations may require the user of the PBE to remain inside the unit until the untoward condition can be resolved.

Of the styles of PBE available, the closed circuit design seems well suited for extended wear. A closed-circuit design is one in which exhaled gas is processed to remove metabolic waste products and the oxygen consumed by the user is replaced. The breathable atmosphere for the user is isolated from the general environment. The potential of this type of device for long-term use needed to be examined in detail. The purpose of this study was to evaluate a current closed circuit design in terms of identifying modifications necessary to make it functionally viable for extended wear applications.

METHODS

Basic quantitative evaluations were performed to characterize performance. Testing included PBE activation on a metabolic simulator. The approach utilized is outlined below.

Equipment. The PBE utilized was a model manufactured by Essex PB & R, designated the victim rescue unit (VRU, Figure 1). The unit is not certified for crewmember use aboard aircraft because the design does not include features that meet the rigors of fire fighting. However, the materials and construction techniques are consistent with TSO-C116 models that have the more advanced features. Another difference was that the units used in these tests had been modified to allow additional gas inside the hood beyond the supply available from the

Figure 1. VRU in use under simulated emergency conditions in an aviation environment.

oxygen cylinder supplied. Of primary concern to this study was the fact that the VRU is a closed circuit device that uses carbon dioxide (CO_2) "scrubbers" based on lithium hydroxide (LiOH) chemistry. Gas concentrations in the VRU were measured using a mass spectrometer (Perkin-Elmer, MGA-1100).

The breathing simulator utilized is a model (Vacumed, 17050/51) designed for the precise calibration of metabolic gas analyzers and related equipment. The syringe was plumbed into a mannequin head (Figure 2). This configuration permitted the unit to be activated and internal volume displaced consistent with a user. The simulator was used because it allowed very specific quantities of CO_2 to be delivered so reaction in the hood could be studied.

LiOH is a commonly used CO_2 sorbent. It is used in a variety of models of PBE, aboard spacecraft, and in the extravehicular mobility unit worn by astronauts during extra vehicular activity in space. The capability of the scrubbers to adsorb CO_2 became a limiting factor since the VRU was modified to allow supplemental breathing gas, beyond that originally contained in the unit's oxygen cylinder, to be introduced into the hood.

The summary reaction of LiOH with CO_2 is:

$$2LiOH + CO_2(g) \rightarrow Li_2CO_3(s) + H_20(s) \qquad \text{Eq. 1}$$

A net total of 10.7 kcal of heat is released for each mole of LiOH utilized. The VRU has three CO_2 scrubbers installed, each containing approximately 30 grams of LiOH. Ideally, this would react with roughly 83 grams of CO_2 (~42 liters of gas, STPD).

Testing. Three tests were performed. The first analysis was to determine the relationship between theoretical and experimental adsorption of CO_2 in the VRU. The simulator was run at a CO_2 rate beyond the ability of the scrubbers to keep up with the volume of gas introduced. Once the CO_2 level inside the hood reached approximately 7%, the simulator was turned off and the concentration was allowed to return to a baseline level. Repeating this sequence allowed the adsorption rate over time to be estimated for the hood.

The second test was to let the simulator run for one hour at a manageable CO_2 production rate for the hood. The value chosen was equivalent to a workload of about 50 watts. At the end of the hour, the simulator was adjusted to produce a CO_2 flow consistent with about 160 watts until the concentration in the hood exceeded 7%. During this trial, oxygen was added to maintain a concentration in the hood above 21%.

The final test consisted of letting the simulator run at a rate consistent with a workload of roughly 40 watts and observing how long it took for the CO_2 level inside the hood to exceed 7%. Again, oxygen was added to keep the concentration in the hood above 21%.

Figure 2. Simulator setup and associated gases used in the testing.

RESULTS

The scrubber reaction with CO_2 inside the VRU was not linear. It followed an exponential decay of the following form:

$$Y = 1.3671e^{-0.0267X} \qquad \text{Eq. 2}$$

For practical applications, the reaction had stopped at 55 minutes. This represented a CO_2 volume of approximately 40 liters. Data collected after this point indicated that the reaction eventually would have exhausted all of the available LiOH, but the rate of adsorption is below the CO_2 buffering capacity needed for continued use.

Data from the second test is presented in Figure 3. CO_2 levels remained fairly steady for the first 30 minutes when introducing CO_2 into the VRU at a rate of 0.70 l/min. After this there was a discernable increase in the rate of CO_2 accumulation in the hood. At 60 minutes, the delivery rate of the simulator was increased to 2.24 l CO_2/min. It only took a little over a minute (1:22) for the concentration to exceed 7%. These two periods represent delivery of 42 and 2.9 liters of CO_2, respectively.

In the third test the simulator was allowed to run at 0.56 l CO_2/min (Figure 4). It took nearly 86 (85:50) minutes for the CO_2 concentration to reach 7%. A total of 47 liters of CO_2 was delivered to the hood during this time. Again, the CO_2 concentration remained relatively constant during the first 30 minutes of the test with a steady increase thereafter. The rate of this increase actually exceeds that observed in the previous test.

DISCUSSION

Based on equation 1, 90 grams of LiOH will react with 82.7 grams of CO_2. Theoretically this represents 42.1 liters of CO_2. The tests run are remarkably consistent with the theoretical value in light of the inherent variability in the experimental protocol. The amount of LiOH contained by any given scrubber is going to vary due to manufacturing tolerances. Placing the VRU on the mannequin, the rate and concentration of oxygen introduced followed general guidelines but did differ from test to test. All these factors could potentially influence the scrubber reaction.

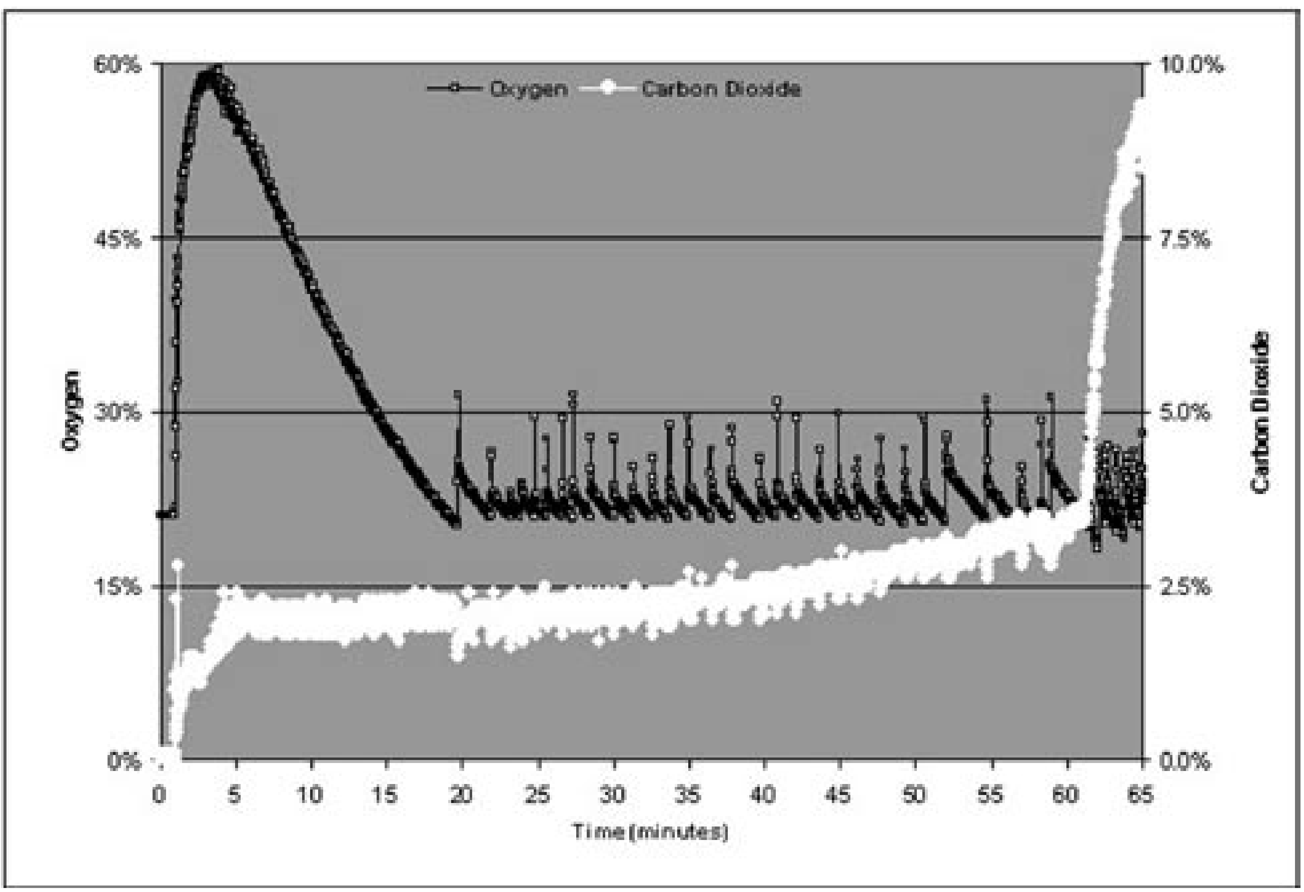

Figure 3. Carbon dioxide concentration changes inside the VRU at a delivery rate of 0.76 l/min.

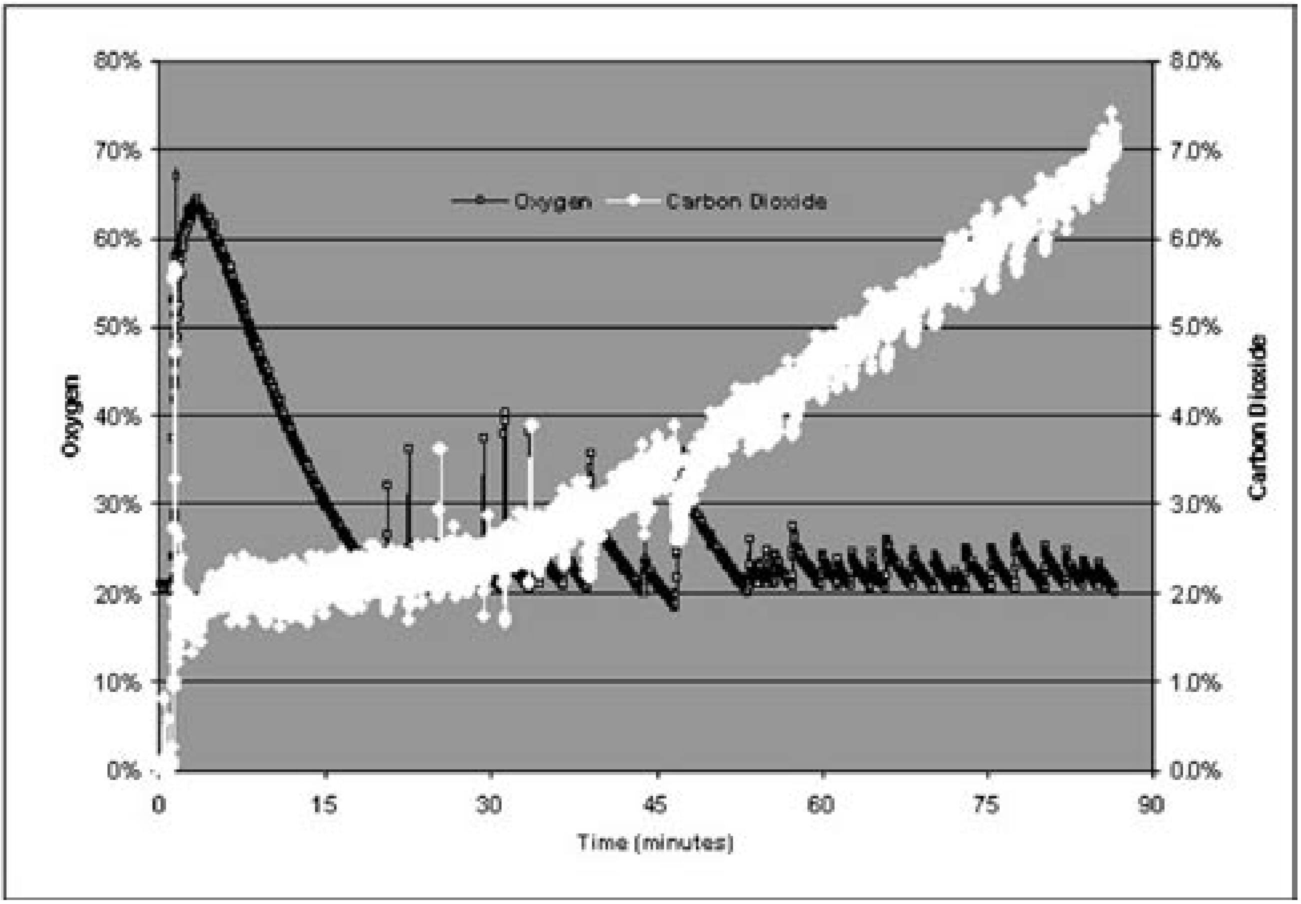

Figure 4. The rate of adsorption to 7% in the VRU is presented for a delivery rate of 0.56 l CO_2/min.

The test situation was idealized. Undoubtedly, this contributed to the overall efficiency of the reaction in terms of CO_2 adsorption. It is known that factors such as humidity levels and the way the LiOH is deposited on the scrubber media generally detract from the overall efficiency of the reaction. However, the current data still provides insight into long-term use potential for equipment of this type.

In the first test, the rate of CO_2 delivery was consistent with an estimated workload of 160 watts and the gas was quickly accumulating in the VRU. Therefore, it is clear that even moderate metabolic rates limit the application of the current technology in a number of situations. To cover higher metabolic rates and extend the useful life of a device at lower rates, additional LiOH could be used. Since the "scrubbing" is based on a relatively straightforward chemical reaction, the only potential improvement would be in how the LiOH is associated with the support matrix used for the scrubber. At best, this would only provide improvements in terms of adsorption rates. Total CO_2 buffering capacity would still be limited to the mass of LiOH present.

At low levels of work or at rest, the technology does offer a significant period of protection, assuming a sufficient breathable gas supply is available. One inherent advantage of being able to replenish the breathing gas is that a variety of supplemental sources can be tailored to specific applications or environments. In this study, aviators breathing oxygen from a large cylinder was used because it was readily available. A smaller cylinder, a number of small cylinders, or an oxygen concentrating device might also meet the demand. Filtering does become an issue for breathing gas generation if the immediate environment is used as a source. The ability to design a system customized for the need anticipated is a valuable characteristic of this particular technological approach. Managing the heat inside a hood is a more difficult challenge.

The reaction itself results in a net release of heat energy. Assuming 90 grams of LiOH, 40.7 kcal of heat will be released if all the reactant is consumed. The gas that an individual exhales is at body temperature, and the fact that the head is enclosed retards heat dissipation, adding to the heat load. Previous tests have indicated that individuals using this type of device find the temperature inside the device relatively uncomfortable during short-term use. It is likely that extending the time in a device would reemphasize this point. It should be noted that if the alternative to wearing a device were death or injury, the comfort level might be less of a priority. That should not preclude attempts to develop equipment that actively addresses user comfort.

Currently, transport category aircraft are required to have hood type devices installed for crew use in fire fighting and similar emergencies. Many companies have installed the VRU or similar devices aboard their private aircraft as a means to protect passengers from any contamination situation. Based on this data, it would appear that development of a device that could be used for periods up to two hours or more is possible if proper amounts of LiOH are available. The next step would be to determine if human test data is consistent with the simulator findings in terms of CO_2 adsorption. Anticipating that no great discrepancies exist, it would appear that optimizing the reaction for both CO_2 production rate and volume is indeed the primary limiting factor. Issues related to the breathable gas supply and heat buildup have to be addressed but certainly appear manageable for the protective needs envisioned in aviation and other environments.