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Comparison of Portable Crewmember Protective Breathing Equipment (CPBE) Designs

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16. Abstract CPBE presently certified for transport category aircraft employ 3 types of oxygen production systems: chlorate candle, potassium superoxide, and compressed oxygen. CPBE performance was evaluated to expose significant differences based on this distinction. CPBE tests employing humans were conducted in accordance with FAA Technical Standard Order C-116. All CPBE were tested for oxygen production, carbon dioxide concentration, internal temperature, moisture, and breathing resistance for 15 minutes at ground level (1,300 ft) and cabin altitude (8,000 ft), while subjects exercised. All CPBE produced a mean oxygen level of at least 59% and maintained carbon dioxide level below 5% at ground level. Differences in internal temperature and humidity were found. Performance at altitude generally paralleled these findings. Oxygen and carbon dioxide levels provide little discrimination about the relative merits of particular CPBE. However, differences in the wearability of CPBE, based on internal temperature, humidity, and weight, were dependent on the type of CPBE oxygen production system.			
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COMPARISON OF PORTABLE CREWMEMBER PROTECTIVE BREATHING EQUIPMENT (CPBE) DESIGNS

INTRODUCTION

Federal Aviation Regulation (FAR) 25.1439 establishes the requirement for crewmember protective breathing equipment (CPBE) aboard transport category aircraft equipped with Class A, B, or E cargo compartments. This equipment is to be used by crewmembers who must locate and fight onboard fires. The regulation also provides minimum design and operational standards, as codified in Technical Standard Order (TSO)-C116. The minimum performance standards include: 1) an oxygen (O_2) partial pressure of 149 mm Hg measured at the trachea, 2) an overall test mean limit on carbon dioxide (CO_2) of 4%, or 5% for any 2-minute period, at sea level, 3) a maximum internal temperature of 40° Celsius (C) *wet bulb* at an ambient temperature of 21°, or 50° C at an ambient temperature of 100° C, 4) a maximum inward contaminant leakage of 5% of the challenge gas level in the ambient atmosphere, and 5) a maximum breathing resistance of 3.5 inches of water from sea level to 8,000 feet above sea level (ASL). TSO-C116 also prescribes a test protocol to evaluate candidate CPBE. This protocol includes a 15-minute physical exercise profile to determine whether the system can provide the required breathable atmosphere during the anticipated fire-fighting workload.

Three American-made CPBE have been certified to meet the requirements of FAR 25.1439. All these CPBE provide adequate oxygen, and all incorporate means to eliminate CO_2 from the breathable gas supply. Elimination of CO_2 is required to prevent decreases in the pH of the blood, which is a component of a detrimental respiratory acidosis. This condition could induce a reflex action by the wearer to remove the CPBE, even in a dangerous, smoke-filled environment. Each CPBE design uses a different technique to remove the unwanted CO_2 . These 3 CPBE can be categorized 2 ways: 1) the type of oxygen production system, and 2) the type of hood design. Two of these CPBE use chemically-generated sources of oxygen; of these, one employs potassium superoxide (KO_2) and the other uses a chlorate candle ($KClO_3$). The other CPBE uses compressed oxygen

cylinders (COC) for the storage and delivery of the O_2 . The CPBE that use $KClO_3$ and COC are designed as closed systems, in which the exhaled breath mixes freely within the CPBE hood with the newly-generated O_2 . Thus, there is no partitioning of the supplied oxygen and exhaled gases within the CPBE. The other CPBE, which provides O_2 via the KO_2 system, has an open loop design, in which the exhaled breath is shunted outside the hood to provide a breathable atmosphere essentially free of exhaled gases. Each type of CPBE is described below:

- 1) The CPBE employing an open-loop design utilizes KO_2 to produce oxygen. Its structure consists of a hood with an oral/nasal mask located on the front visor inside the hood. The KO_2 canister is mounted externally on the lower posterior portion of the hood. One-way valves in the oral/nasal mask connect with the KO_2 canister through plastic tubing; exhaled gases are directed to the KO_2 canister, which converts the wearer's exhaled water vapor and CO_2 to O_2 . These are the balanced equations to this reaction, $[4KO_2 + 3H_2O = 4KOH + 3O_2]$ and $[4KO_2 + 2CO_2 = 3O_2 + 2K_2CO_3]$. The newly released O_2 is then scrubbed to remove any remaining water vapor and CO_2 before the O_2 is discharged into the hood. A small chlorate candle is also included to provide the O_2 required immediately after donning, before the KO_2 system reaches full activation. This CPBE weighs 4.0 pounds.
- 2) The CPBE utilizing COC is a closed-loop system. This CPBE incorporates two such COC to provide the O_2 ; one releases its oxygen within 20 seconds to quickly fill the CPBE very quickly, and the other releases its O_2 more slowly to replenish the O_2 within the CPBE and maintain the required duration of function. Packets of lithium hydroxide are attached around the lower inside lining of the CPBE to suppress the buildup of CO_2 . This CPBE weighs 3.2 pounds.

- 3) The CPBE utilizing the chlorate candle is also a closed-loop system. The KClO_3 is housed outside the CPBE on the lower posterior portion of the hood, as is the lithium hydroxide CO_2 scrubber. The CPBE is activated by pulling a pin on the housing; the KClO_3 is heated, releasing O_2 which is emitted continuously into the hood through a venturi nozzle. The venturi effect causes the atmosphere inside the hood to be drawn across the CO_2 scrubber, which emits its effluent back into the CPBE. This CPBE weighs 3.5 pounds.

While all these CPBE systems have proven effective in providing a breathable atmosphere for use in a hostile environment, the differences in design and mode of operation combine to produce a unique opportunity to evaluate the relative merits of specific CPBE technology. Such a comparison should include all the performance factors specified in TSO-C116, as well as more subtle considerations such as crewmember acceptance and CPBE wearability.

Subjects

A total of 18 males and 9 females participated in the CPBE tests. Prior to each study, every subject was fully informed about the test procedure and objectives of the research. After this briefing, each subject executed informed written consent to proceed with the study. All subjects were in excellent health and generally well conditioned physically, as verified by a medical history questionnaire, a physical examination and an exercise stress test conducted using the workload profile for compliance with TSO C-116. The stress testing was conducted using a Jaeger EOS Sprint Pulmonary Function Monitor. Neck circumferences were measured to insure that the test subject sample ranged from the 5th percentile female to the 95th percentile male.

METHODS

Equipment: The ground level tests were conducted in the Civil Aeromedical Institute (CAMI) challenge-gas test chamber and the 8,000 feet ASL tests were conducted in the CAMI research altitude chamber. A Bosch bicycle ergometer equipped with a medical monitoring system was used to effect the required subject workload. Two *Perkin-Elmer* medical gas analyzers were used to measure the levels of O_2 , CO_2 and Sulfur Hexafluoride (SF_6) challenge-gas. CPBE hood/mask internal pressure measurements were made with a Stathem pressure transducer, and internal CPBE temperature was monitored via a copper-constantin thermocouple. Acquired data were stored on microcomputer.

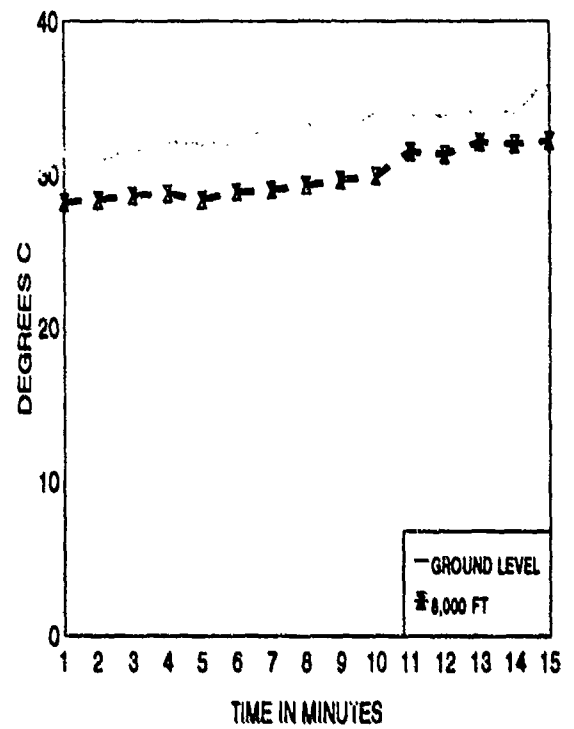
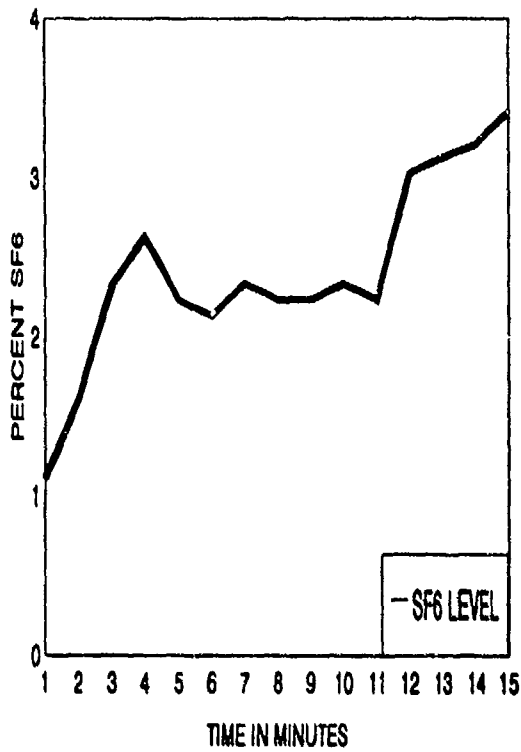
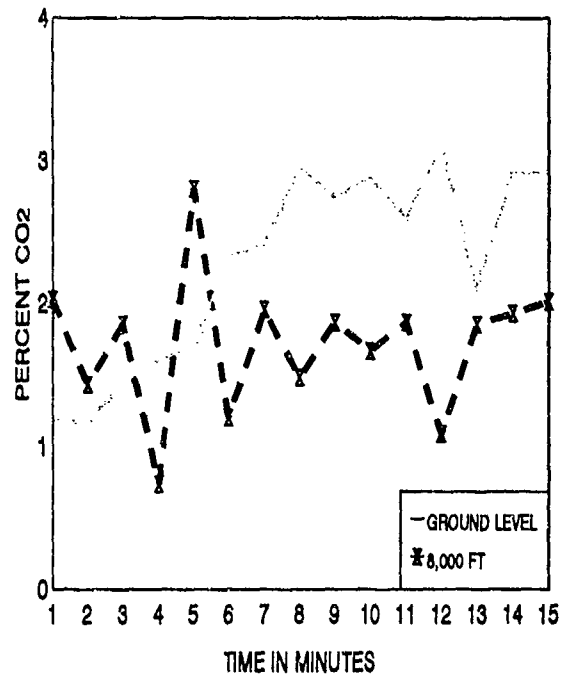
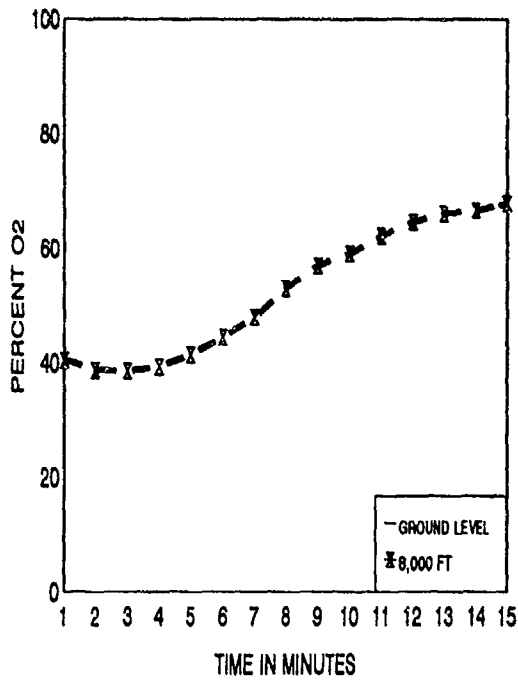
Ground Level Tests: The CPBE tests at ground level (1,300 feet at CAMI) were conducted on days subsequent to each subject's physical exam and exercise stress test. After electrocardiogram (EKG) electrodes used for medical monitoring during the test were applied, each subject was escorted to the test chamber, connected to the EKG monitor, and fitted with a blood pressure cuff. The subject was then seated on the bicycle ergometer and provided with the CPBE, which he/she then donned and activated. The chamber door was closed immediately, and the SF_6 challenge gas was introduced into the chamber. Upon reaching a 1% SF_6 level in the chamber, the subject was instructed to begin pedaling the bicycle ergometer at the workload prescribed in TSO-C116 (see Table 1). To stress the CPBE neck seal to expose potential leaks, the subject had to move his/her head slowly from side-to-side and up/down; the subject was also instructed to recite the English alphabet aloud to simulate the effects of verbal communications on respiratory

Table 1

TSO-C116 Exercise Profile

00 to 05 minutes - workload = .33 watts/Lb body weight
05 to 07 minutes - workload = .66 watts/Lb body weight
07 to 12 minutes - workload = .50 watts/Lb body weight
12 to 14 minutes - workload = .66 watts/Lb body weight
14 to 15 minutes - workload = .33 watts/Lb body weight

Figure 1
Potassium Superoxide System Results



functions. The gas levels in the challenge gas chamber were measured continuously during the test, while the level of SF₆ in the CPBE was measured at one-minute intervals. Temperature and breathing resistance were also measured continuously.

At the conclusion of the test, the subject completed a post-test questionnaire that surveyed his/her acceptance and perceived wearability of the device. Appendix I provides a sample questionnaire.

Altitude Chamber Tests: The CPBE altitude chamber tests employed the same subjects and were conducted on a day following completion of the ground level tests. The tests were conducted at a simulated aircraft cabin altitude of 8,000 feet ASL. The bicycle ergometer, medical monitoring equipment, and medical gas analyzers were relocated to the altitude chamber control room, and the tests were again conducted in accordance with TSO-C116, except for the measurement of inward contaminant leakage using SF₆, which could only be employed in the dedicated SF₆ test chamber. All other measurements were consistent with the ground level tests.

RESULTS

All three types of CPBE performed in accordance with TSO-C116. For all CPBE, O₂ concentrations ranged well above physiological requirements at 40% to 90%, indicating that the required O₂ partial pressures at the trachea would easily be met. Carbon dioxide levels also remained well below the 5% limit for all CPBE. Inward contaminant leakage of the SF₆ challenge-gas remained within limits, indicating that the TSO requirements for limiting noxious gases produced by a fire would also be met. Among the different CPBE, internal temperatures proved more variable than any other measure; this circumstance can be traced to the design and operational differences in CPBE oxygen production systems. Similarly, the relative humidities present in each type of CPBE were dependent on the O₂ production system. Internal breathing resistances were minimal in both closed-loop systems; the open-loop system also performed easily within the 3.5 inches-of-water requirement. Data specific to each type of CPBE are provided below:

Potassium Superoxide

This system produced excellent amounts of O₂, showing increases in the absolute oxygen values maintained within the CPBE during all tests at both ground level and at 8,000 feet ASL. The highest amount of O₂ was found at ground level with an overall increase of about 10% above the measured amount at altitude. The CO₂ levels also remained below a mean of 4% for both the hood and the oral-nasal mask for the duration of all tests. The mean inward leakage of the SF₆ challenge gas inside the CPBE was 3.1%, and the SF₆ never exceeded the 5% maximum value during any test. The mean internal temperature of the CPBE for the ground level tests was 32.5° C *dry bulb*, and the mean *dry bulb* temperature for the altitude chamber tests was 30° C. These values easily met the 40° C *wet bulb* criterion. The breathing resistance of the device was well within the required 3.5 inches of water from sea level to 8,000 ft ASL. Figure 1 displays these results.

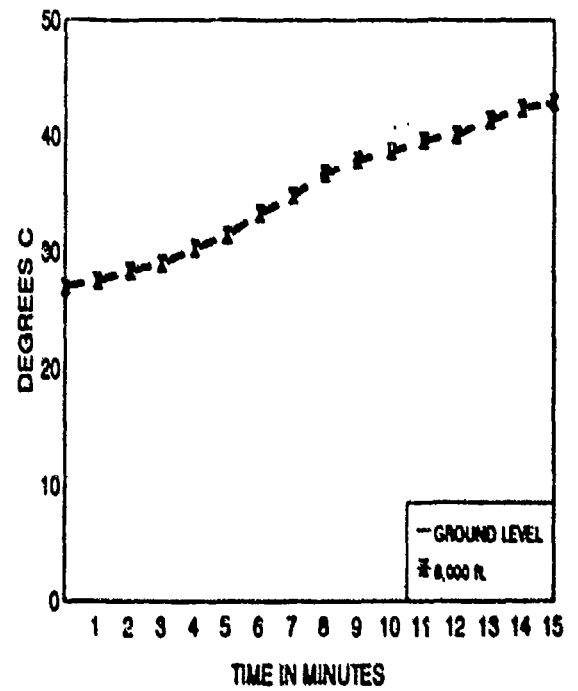
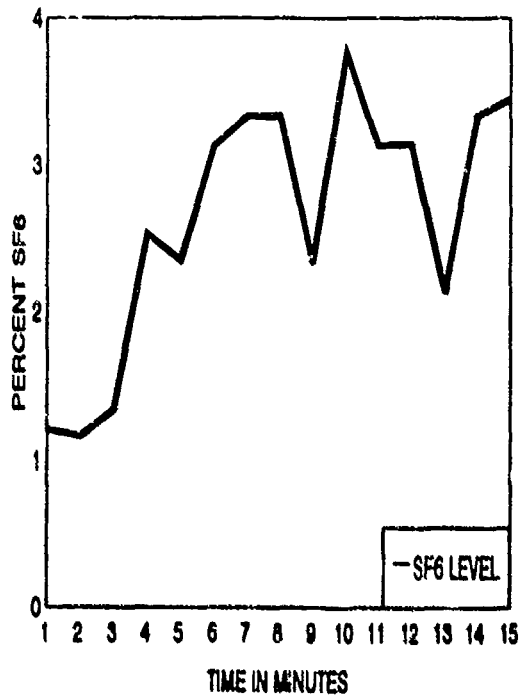
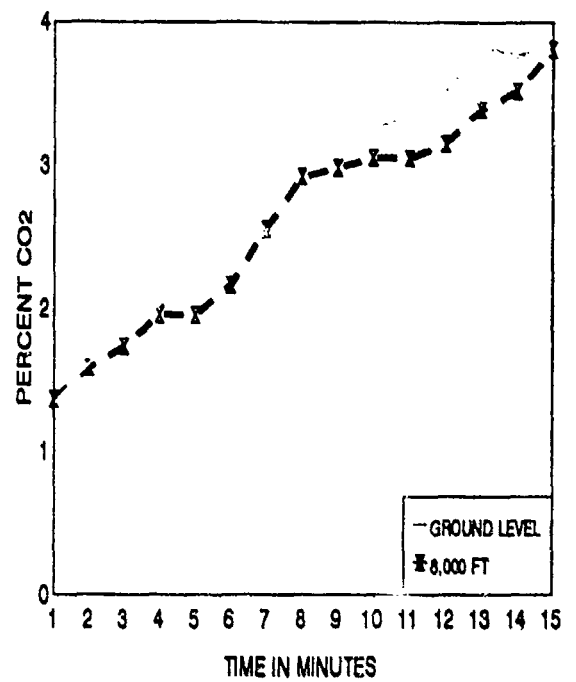
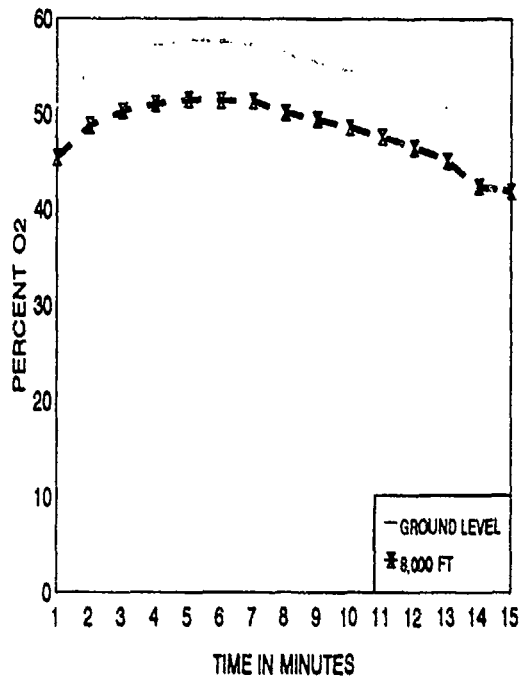
Compressed Oxygen Cylinders

This system produced appropriate levels of O₂ throughout all tests. The mean O₂ value for the tests conducted at ground level was 55%; the mean for the altitude chamber tests was 45%. The levels of O₂ tended to rise quickly for the first minute of each testing period and then leveled off for the duration of the test. The CO₂ levels for these tests were higher than for the other CPBE tested, reaching a mean of 3.5% (still well within limits). The levels of CO₂ increased steadily during both the ground level and 8,000 feet test runs. The inward contaminant leakage of SF₆ was well within the acceptable limits; the mean SF₆ level inside the CPBE was 3.1%. The mean internal *dry bulb* temperature at ground level was 38° C and the mean temperature at 8,000 ft ASL was 37° C. This difference was not statistically significant. The limit on breathing resistance was never approached at either ground level or 8,000 feet ASL; in fact, the highest pressures were attained initially because of the large amount of air within the hood. Figure 2 displays these results.

Chlorate Candle

This system also produced appropriate levels of O₂ for the duration of all tests. The mean value for O₂ at ground level was 55%, and the mean level at 8,000 feet ASL was

Figure 2
Compressed Oxygen Cylinder System Results



45%. The levels of O_2 tended to rise steadily through the duration of the testing period. The amount of CO_2 measured at both ground level and 8,000 feet ASL was within limits, although during one particular test the CO_2 increased to about 4% during the highest exercise workload. The inward contaminant leakage of SF_6 reached a mean of 2.12%, but at no time did the inward contaminant leakage exceed the 5% maximum. The mean *dry bulb* temperature at ground level was 38.5° C, and 35° C was the recorded mean temperature at 8,000 feet ASL. Figure 3 displays these results.

DISCUSSION

All three CPBE systems performed in accordance with TSO-C116. As such, there is little in the way of primary function to differentiate them. The ability of all three CPBE to deliver a breathable atmosphere during fire-fighting requirements is demonstrated. However, there are differences in the design of each system that contribute to the acceptance and wearability of the CPBE, depending on the physical characteristics, strength, and stamina of the intended crewmember. Although we do not formally present this data in this report, these relative advantages and disadvantages were indicated by evaluating each subject's post test questionnaire. These differences make the selection of any particular CPBE for potential use by crewmembers dependent on the design and operational characteristics of the CPBE.

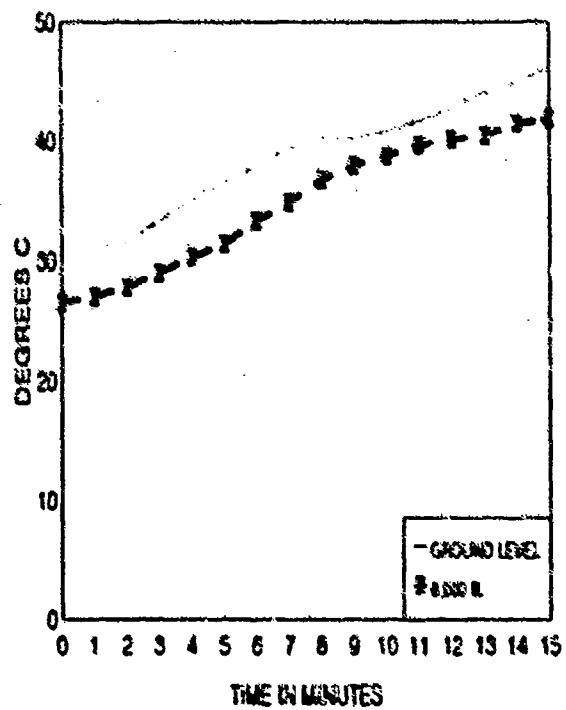
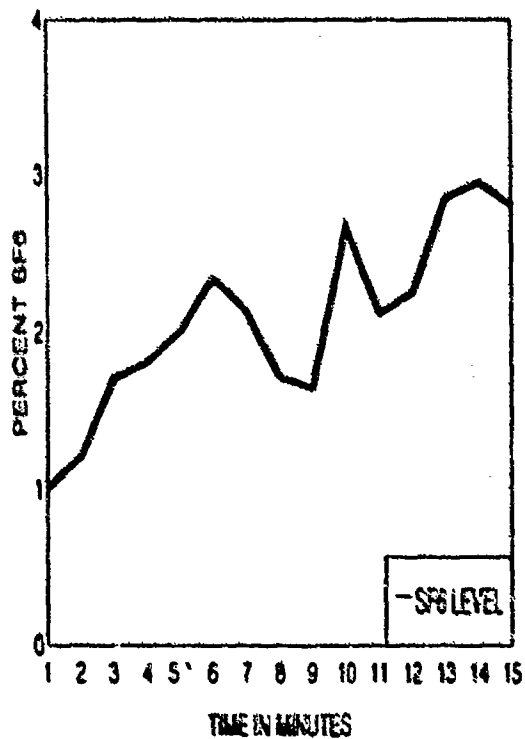
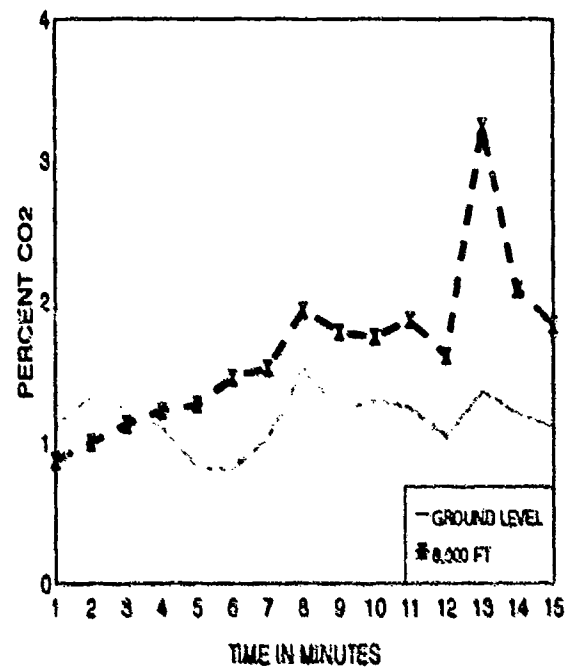
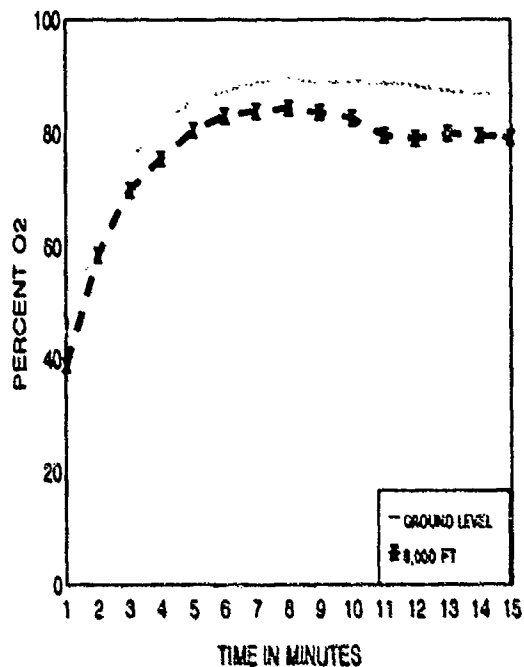
For example, the way a CPBE creates or controls its internal temperature is an important consideration. All of the CPBE tested had increasing temperatures over the course of all the test periods, and although no CPBE exceeded the temperature limit, the internal temperatures of the two closed-loop CPBE were found to be more uncomfortable. The higher internal temperatures were caused by several factors related to CPBE design and function. These include the method of oxygen production, the method used to eliminate CO_2 , and the fact that the closed-loop CPBE retains the exhaled breath of the wearer. The CPBE that provide O_2 by chemical reaction create heat as a by-product of those processes. The CPBE that uses COC does not have this problem. This gives the CPBE with storage cylinders an initial

advantage, allowing very short-term users of CPBE to benefit from this design.

As the respiratory rate of the wearer increases with exercise large quantities of hot, humidified air are produced. In the CPBE with closed-loop designs this creates a larger heat load than that in the CPBE with the open-loop design which vents the exhaled breath outside the CPBE. This problem is exacerbated in the CPBE that eliminate CO_2 by an exothermic reaction with lithium hydroxide, as more CO_2 is created and exhaled by persons who are exercising. Thus, the satisfactory performance of the closed-loop CPBE under resting conditions is degraded as the hot, humidified air raises the temperature above that of the open-loop design. As the moist hot air condenses on the inner surface of the CPBE, a problem with fogging is also created that could be detrimental to a crewmember trying to locate and fight an onboard fire. This effect occurred more readily in both closed-loop systems. Consequently, the open-loop system which vents the exhaled breath to the outside has a decided advantage in regard to heat management and its related effects on visibility.

Another factor which should be considered is the effects that CPBE size and weight have on movement and dexterity of the wearer. Although all the CPBE are fairly bulky, the closed-loop CPBE with oxygen cylinders is the largest. However, it is also the lightest. This combination provides an opportunity to equip small frame crewmembers with less burdensome fire-fighting protection. This CPBE might not allow activities in as cramped a space as one of the heavier, but more compact, CPBE. The other CPBE also have their oxygen generators located on the exterior rear surface of the CPBE hoods, and this feature tends to elicit CPBE rotation when the wearer bends over. To mitigate this tendency, the closed-loop CPBE with the $KClO_3$ system has a headband inside that restricts movement and the open-loop CPBE with the KO_2 system and the oral-nasal mask has exterior straps that bind the mask to the wearer's face when the CPBE is donned and activated. These features allow these CPBE to be worn in almost any attitude, although the weight of the oxygen generators on the back of the wearer's neck can produce the perception of being unbalanced.

Figure 3
Chlorate Candle System Results



REFERENCES

Use of these CPBE appears best suited to more large frame crewmembers. Thus, in certain aircraft, or with a certain crewmember compliment, proper CPBE selection could depend on these distinctions.

In conclusion, the ability to provide a high-quality breathable atmosphere for the wearer is the one factor that all three CPBE share. The tests have shown that all the CPBE perform this primary function very well, and that the main differences in CPBE acceptability and wearability depend more on comfort and utility. These essential properties are highly influenced by the design of the respective CPBE oxygen production systems, which result in significant differences in such CPBE operational characteristics as internal temperature, humidity, outward visibility, weight penalty, and effective ergonomic size of the CPBE. These variables interact with the specific wearer, the duration of usage, and the environment to make selection of any particular CPBE a process that must consider all these variables to obtain the best operational outcome.

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APPENDIX A

Post-Test Questionnaire Subj.# _____ Name _____ Date _____

VISION

- | | | | |
|----|------------------------|-----|----|
| 1. | Distortion? | yes | no |
| 2. | Fogged? | yes | no |
| 3. | Able to see ergometer? | yes | no |

HEAT

- | | | | |
|----|--|-------|----|
| 1. | Discomfort Level: 1 to 10 value (10 = worstcase) | _____ | |
| 2. | When? Minute: 1 to 15. | _____ | |
| 3. | Hot Spots? | yes | no |

BREATHING

- | | | | |
|----|---|-----|----|
| 1. | Feel as if you had enough air to breathe? | yes | no |
| 2. | Any difficulty breathing? | yes | no |
| 3. | Rapid breathing? | yes | no |
| 4. | Deep breathing? | yes | no |
| 5. | Lightheaded? | yes | no |
| 6. | Headache? | yes | no |

FIT

- | | | | |
|----|---|-----|----|
| 1. | Head harness fit problem? | yes | no |
| 2. | Neck fit or comfort problem? | yes | no |
| 3. | Weight of canister pull head forward or backward? | yes | no |
| 4. | Feel any heat on back where canister sits? | yes | no |

Comments: _____

