

USAARL Report No. 2007-14

A Physiological and Human Factors Evaluation of a Novel Personal Helicopter Oxygen Delivery System

By Ian P. Curry
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Warfighter Protection Division

September 2007

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REPORT DOCUMENTATION PAGE

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|---|-------------|-------------------------|----------------------------|--|---|
| 1. REPORT DATE (DD-MM-YYYY) September 2007 | | 2. REPORT TYPE Final | | 3. DATES COVERED (From - To) | |
| 4. TITLE AND SUBTITLE A Physiological and Human Factors Evaluation of a Novel Personal Helicopter Oxygen Delivery System | | | | 5a. CONTRACT NUMBER | |
| | | | | 5b. GRANT NUMBER | |
| | | | | 5c. PROGRAM ELEMENT NUMBER | |
| | | | | 5d. PROJECT NUMBER | |
| 6. AUTHOR(S) Ian P. Curry Richard A. Roller | | | | 5e. TASK NUMBER | |
| | | | | 5f. WORK UNIT NUMBER | |
| | | | | | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Aeromedical Research Laboratory P.O. Box 620577 Fort Rucker, AL 36362-0577 | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER USAARL 2007-14 | |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Product Manager Air Warrior Air Warrior Program Office Redstone Arsenal Huntsville, AL | | | | 10. SPONSOR/MONITOR'S ACRONYM(S) | |
| | | | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) | |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. | | | | | |
| 13. SUPPLEMENTARY NOTES | | | | | |
| 14. ABSTRACT In current U.S. Army operations, rotary-wing aircrew can be repeatedly exposed to moderately high altitude (up to 18,000 feet pressure altitude), making hypoxia, and its performance effects, a real hazard. The United States Army Aeromedical Research Laboratory (USAARL) was tasked by the Product Manager Air Warrior to evaluate a portable oxygen system for potential use by U.S. Army helicopter aircrew. The system described below provided capability for oxygen production, charging of the portable system, as well as in-flight use by aircrew. The system was tested for its compatibility with current Aircrew Assemblies, Night Vision Goggles, aircrew duties, and emergency egress. The system was also tested on pilot volunteers at altitude to determine efficacy. The Personal Helicopter Oxygen Delivery System (PHODS) was able to maintain aircrew blood oxygen at acceptable levels up to and including 18,000 feet. | | | | | |
| 15. SUBJECT TERMS Helicopter Oxygen system Hypoxia Altitude | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | 19b. TELEPHONE NUMBER (Include area code) |
| UNCLAS | UNCLAS | UNCLAS | SAR | 51 | |

Acknowledgements

The Authors would like to express their sincere gratitude to the following people for their contributions to this project. This was a complex effort requiring much coordination and teamwork all done to a challenging time frame. Without the participation of the following people this project would not have succeeded.

- Mr. Joseph R. Licina, Chief ALSE Branch, for coordinating all of the compatibility testing.
- SGTs Harvey and Pieper, SPCs Sumner and Booms, for working long hours at unfamiliar tasks enabling the project to flow smoothly.
- COL Monica Gorbandt, for facilitating the use of the USASAM altitude chamber for this research.
- The USASAM chamber team, for their flexibility in operating the altitude runs.
- Ms. Victoria Mando, for her invaluable work in recording and then presenting the data in a manageable form.

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Introduction

In current U.S. Army operations, rotary-wing aircrew can be repeatedly exposed to moderately high altitude (up to 18,000 feet pressure altitude), making hypoxia, and its performance effects, a real hazard. The United States Army Aeromedical Research Laboratory (USAARL) was tasked by the Product Manager Air Warrior to evaluate a portable oxygen system for potential use by U.S. Army helicopter aircrew. The system, described below, provided capability for oxygen production, charging of the portable system, as well as in-flight use by aircrew.

The objectives of this investigation were to determine if the system can adequately protect aircrew from hypoxia at altitude, to assess the integration of the device into existing Aviation Life Support Equipment (ALSE), and to verify ease of use. It was performed in two main phases which will be reflected in this report; firstly the physiological performance of the PHODS was tested in an altitude chamber (phase I) and secondly the integration, and other human factors issues were studied in the aircraft types in which the PHODS might be employed (phase II).

Background

Military personnel are routinely required to transition quickly to and operate in a wide range of altitude. With air transport, personnel can be moved from sea level to over ten thousand feet in a few minutes, a far shorter time than required for acclimatization. In a recent survey of Australian helicopter aircrew, a substantial number (~75% of the returned surveys or 46) reported experiencing at least one hypoxic symptom during flight between 8,000 and 10,000 feet (Smith, 2005). A follow-up study demonstrated that hypoxia experienced at about 10,000 feet may be exacerbated greatly by physical exertion typical of the duties of aircrew personnel. (Smith, 2006) Another recent study demonstrated slight but statistically significant decrements in the cognitive performance of resting individuals for 20 minute exposures at 12,000 feet (Balladin et al, 2006). These studies have demonstrated the effects of hypoxia at altitudes previously thought to be too low to be of significant concern, thus leading to a potential impact on operational effectiveness at these moderate altitudes.

The crews of U.S. Army rotary wing aircraft on operations around the world are exposing to repeated incidences of moderate altitude (up to 18,000 feet). The current flight regulations (AR 95-1) list the following requirements for flight at altitude:

“Approved oxygen systems will be used as follows:

Unpressurized aircraft

Oxygen will be used by aircraft crews and occupants for flights as shown below:

a. Aircraft crews.

(1) On flights above 10,000 feet pressure altitude for more than one hour.

- (2) *On flights above 12,000 feet pressure altitude for more than 30 minutes.*
b. *Aircraft crews and all other occupants.*

(1) *On flights above 14,000 feet pressure altitude for any period of time.*

(2) *For flights above 18,000 feet pressure altitude, oxygen pre-breathing will be accomplished by aircrew members. Pre-breathing may utilize either 100 percent gaseous aviator's oxygen from a high pressure source, or an onboard oxygen generating system (OBOGS) that supplies at least 90 percent oxygen in the inspired gas. Pre-breathing will be for not less than 30 minutes at ground level and will continue while en route to altitude. In those extraordinary cases where mission requirements dictate rapid ascent, commanders may authorize shorter pre-breathing times on a case-by-case basis, with the realization that such practice increases the risk for developing altitude decompression illness. Return to normal oxygen (pressure demand regulator, gaseous oxygen-equipped aircraft) is authorized on descent below 18,000 feet pressure altitude, provided continued flight will not exceed this altitude."*

In-theater operations involving U.S. Army rotary wing aircraft are currently utilizing a constant flow portable oxygen system, which has not been fully tested or validated for safety and/or efficacy thereby potentially exposing aircrew to hypoxia. The purpose of this study is to assess the AquaLung[®] Portable Helicopter Oxygen Delivery System (PHODS) for its efficacy in preventing hypoxia at moderate altitude, and its compatibility with the human factors and engineering section of the Airworthiness Requirements (AWRs) for the various aircraft. This system is designed for use in aircraft types that have significant weight and space issues in which the use of an oxygen concentrator or heavy cylinder system is impracticable. The Helicopter Oxygen System (HOS) is currently the only system approved for use aboard U.S. Army aircraft, but it imposes significant weight, space, and operational restrictions on the aircraft and crew. It can be seen therefore, that it is likely that operational capability can be adversely affected by hypoxia in helicopter crews and the system under test is one potential method of reversing that effect.

Phase I methods

The AquaLung[®] PHODS is man-mounted (figure 1) and delivers oxygen from a standard portable Survival Egress Air (SEA) bottle (located on the survival vest) via nasal cannula. Detailed photographs of the man-mounting can be seen at Appendix A.

This apparatus includes an MH EDS 02D1 Pulse Demand Oxygen Unit (figure 2) which, according to the manufacturer (Mountain High[®] Corp.), automatically provides "on-demand" oxygen regulated to altitude based on detected barometric pressure (pressure altitude). Other novel features of the regulator include algorithms to detect and react to the aviator's breathing patterns.

Oxygen used in the tests was produced by the Breathing Air Systems Mobile Oxygen Concentrator (Mobile O₂) and the portable bottles were charged with the Deployable Oxygen Charging System – Oxygen (DCS-O), also by Breathing Air Systems (figure 4). These systems are FDA-certified and are currently deployed with U.S. Forces.



Figure 1. Aqualung PHODS in typical aviation configuration.



Figure 2. Pulse Oxygen Demand Unit.



Figure 3. PHODS components.



Figure 4. Deployable Oxygen Concentrator and Charging System Study population.

The testing was performed on volunteer aircrew members. The primary advantage of using aircrew was that these individuals perform chamber runs at altitude as part of their regular duties and training. They also experience significant altitude changes during the course of their normal operational duties. In fact the testing was performed at significantly lower altitudes (10,000 ft, 15,000 ft, & 18,000 ft) than they normally experience (up to and including 25,000 ft) during their Altitude Chamber training. Additionally, these subjects were from the same population who use the portable O₂ system during actual combat missions. Only subjects who had been previously certified in a chamber at altitude were included in the study. No females or past or present tobacco users volunteered for this phase of the study.

Procedures

Eighteen subjects were exposed to altitudes of 10, 15 and 18 thousand feet in four conditions as outlined in table 1, all subjects experienced all conditions. Throughout the study the subject's SpO₂ (peripheral hemoglobin-oxygen saturation) was continuously monitored. Two criterion values were selected: 91%, above which no cognitive deficit was expected, and 80%, below which significant cognitive deficits are more frequent (Pickard 2002).

The objective measurements of efficacy included cardiac function (pulse rate), pulse oximetry (as an indication of peripheral oxygenation) using an Onyx II[®] portable pulse oximeter (Yamaya et al., 2002) and color vision testing (as an indication of central oxygenation / hypoxia) (Vingrys and Garner, 1987). Below 10,000 ft very few normal individuals notice any symptoms from hypoxia, even though measurable deficiencies in color and night vision exist (Pickard, 2002). Additionally, Vingrys and Garner (1987) showed a reliable and reproducible decrement in color vision performance using the Farnsworth-Munsell 15 Hue desaturation test at the

moderate altitude of 12,000'. Pulse oximetry is also a widely used and validated clinical tool used throughout medical facilities.

During the testing period, there were a total of four separate ascents (altitude profiles) each involving six subjects at a time due to space considerations in the chamber, with two PIs/AIs monitoring inside the chamber. A total of 18 subjects were utilized. The basic schematic for the altitude exposures is at table 1 and the altitude profiles used at figures 5 and 6.

Table 1.
Outline of the four experimental test conditions used to evaluate the AquaLung® Portable Helicopter Oxygen Delivery System (PHODS).

| Experimental Condition/ Ascent | Verbal Task | Exercise | Inspired Gas | Breathing Device |
|-----------------------------------|----------------------|------------------------------|--------------------------|-------------------|
| 1 | Simulated Radio Call | None | Ambient Air [†] | None [†] |
| 2 | Simulated Radio Call | None | Oxygen | Nasal Cannula |
| 3 | None | Cycle Ergometer [‡] | Oxygen | Nasal Cannula |
| 4 | None | Cycle Ergometer | Oxygen | Face Mask |

[†] Aircrew were on chamber O₂ during ascent phase and then removed from O₂ at altitude.

[‡] Aircrew were exercised to 150% of their resting heart rate at altitude.

a. During the first two ascents the subjects were at rest and were not exercised.

(1) During Ascent 1 (table 1 & figure 5) the subjects were on chamber oxygen via the standard chamber face mask during the actual ascent portion. Once each discrete target altitude (10,000 ft, 15,000 ft and 18,000 ft) was reached the subjects went off oxygen while their pulse oximetry, pulse rate and color vision was measured for signs of hypoxia. Based on prior studies (Pickard, 2002; Stepanek, 2002) it was estimated that hemoglobin desaturation of each subject would occur fairly rapidly (1-2 minutes) once off oxygen at altitude; and each would equilibrate with the ambient air. This technique of “going off oxygen” at altitude is routinely employed during altitude chamber training to allow aircrew to experience and recognize the symptoms of hypoxia to prevent unconsciousness if this should happen during an actual mission. In fact during training, aircrew may go off oxygen for periods up to five minutes to adequately experience the effects of hypoxia. There have been no lasting effects shown in doing this

(Pickard, 2002; Stepanek, 2002; Webb and Pilmanis, 2005; Webb et al., 2005). Since the altitudes used in this study were considerably lower than those used in actual altitude chamber training (25,000 ft) any risks associated with subjects going off oxygen for 2-3 minutes was minimal. There was no requirement to pre-breathe oxygen during this study to minimize the likelihood of decompression illness as this is unknown at altitudes below 18,000 feet (Webb 1998). Additionally, each subject was closely monitored, and if their hemoglobin saturation (PaO₂) dropped to 91% he was immediately placed back on oxygen via the standard face mask. This ascent profile allowed the establishment of a “baseline” and control from which data from the other three ascents was compared.

(2) During Ascent 2 (table 1 & figure 5) each subject remained on oxygen using the experimental equipment being tested. Each subject inspired oxygen via nasal cannula during the entire altitude profile exposure. All subjects were monitored for signs and symptoms of hypoxia continuously. This exposure allowed evaluation of the efficacy of the experimental system in providing oxygen at altitude for the prevention of hypoxia.

b. During Ascents 3 and 4 (table 1 and figure 6) the subjects were exercised to 150% of their resting heart rate utilizing a cycle ergometer, this was judged to be roughly equivalent to a crew chief during normal duties moving about the aircraft cabin. The subjects ascended at rest and then exercised once at each target altitude (10,000 ft, 15,000 ft and 18,000 ft). All subjects were on oxygen at all times during these two ascents. Once the target heart rate was reached the exercise was stopped and immediately the heart rate and hemoglobin saturation (PaO₂) and color vision were measured and used to estimate the efficacy of O₂ delivery.

(1) Ascent 3 involved subjects using the PHODS and receiving oxygen via nasal cannula (figures 1 and 3). Use of the nasal cannula reflects the system proposed for the pilots of U.S. Army helicopters. The data from this profile was compared to that from Ascents 1 and 2.

(2) Ascent 4 involved subjects using the PHODS and receiving oxygen via an experimental face mask system that Aqualung[®] proposed for use by crew chiefs who do a considerable amount of physical work in the back of helicopters. These data allowed the comparison of the efficacy of the mask to the nasal cannula (Ascent 3) during exercise.

The time spent at each experimental altitude (figures 5 and 6) reflected an assessment as to how long it would take each subject to “desaturate” added to how long it would take to record the data at each altitude. The times illustrated in figures 5 and 6 were fixed times for the altitude profile and agreed in advance with the USASAM Altitude Chamber staff. Each time at altitude was longer than that we felt necessary for the actual data recording however, this allowed flexibility in time at altitude for any unforeseen delay in data collection.

The ascent and descent rate was set at 2000 fpm which is conservative and slower than the standard rate (2500 fpm) for most altitude chambers. The ascent/descent profiles are illustrated in figures 5 and 6.

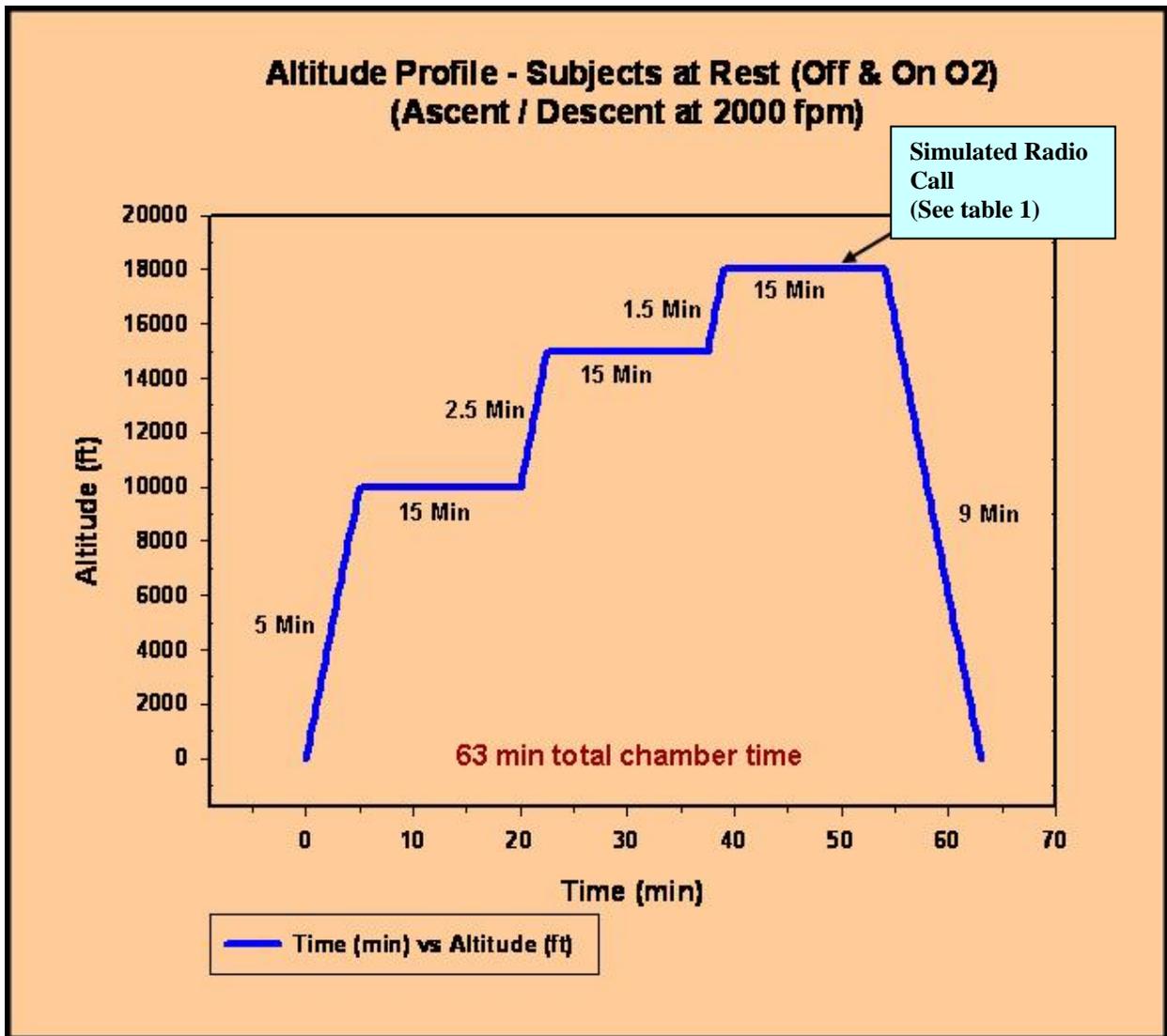


Figure 5. Altitude profile (time vs. altitude) for “at rest” ascent on and off oxygen (two separate profiles).

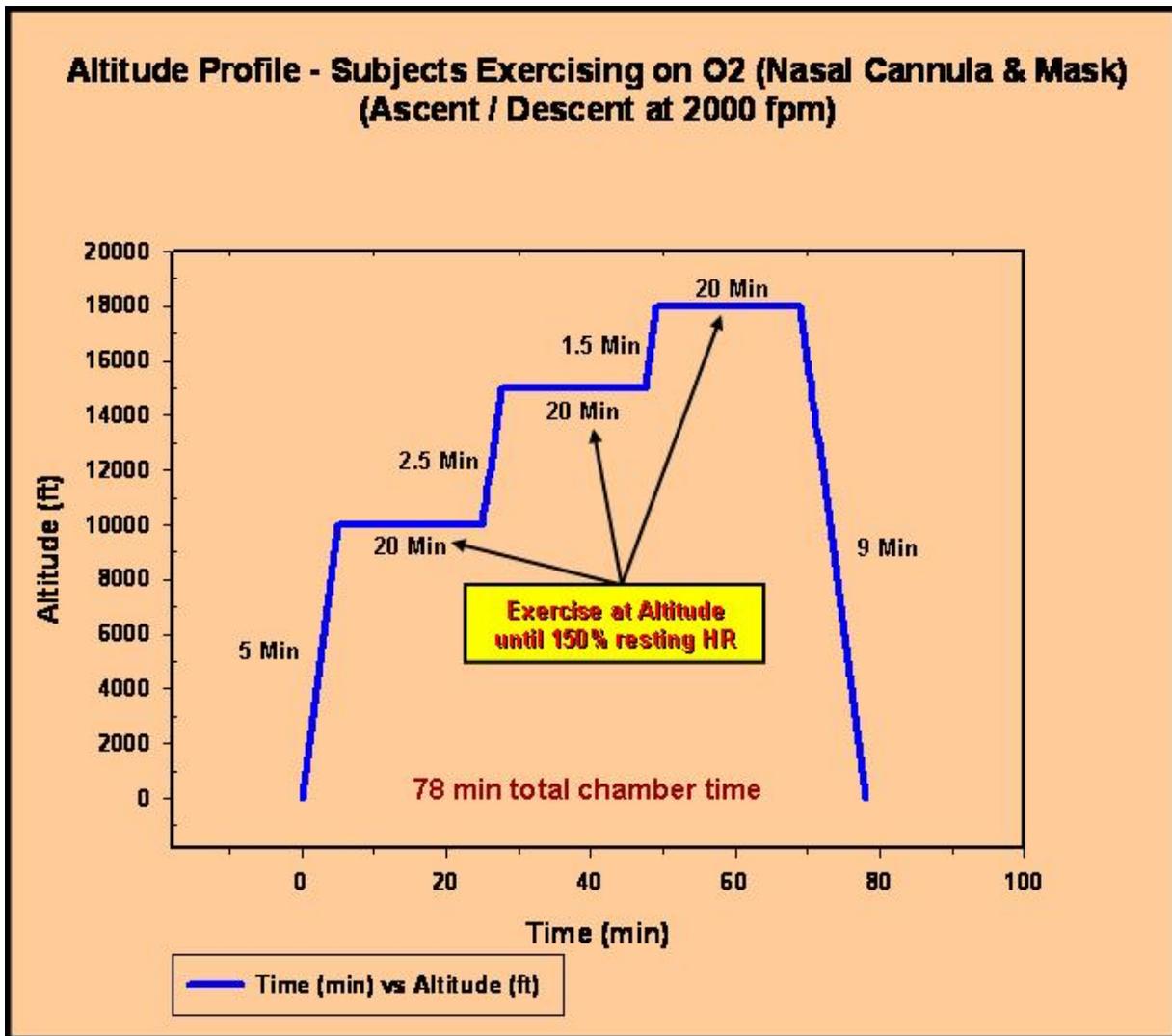


Figure 6. Altitude profile (time vs. altitude) for “exercise” ascent on oxygen.

As stated above, the test procedure outlined in table 1 was followed both off and then on oxygen at rest (two separate but identical ascents – figure 5) with the subjects acting as their own controls. For the “on-oxygen” ascent, subjects utilized the Aqualung® Portable Helicopter Oxygen Delivery System. The chamber changed pressure both up and down at a slow rate of 2000 fpm, which allowed for both gradual equilibration and for subjects to indicate any problems to the medical monitor. During the “on-oxygen” profile the oxygen delivery system was evaluated by both subjects and observers in the chamber in terms of operating efficiency, and ease of use. The ‘at rest’ profiles were followed by two exercise profiles, one with PHODS cannula delivery and the other using PHODS face-mask delivery. Exercise was accomplished by having each subject use a cycle ergometer during a different ascent profile (figure 6). Again, to standardize, each subject had his resting heart rate (HR) measured, and then was exercised to 150% of resting HR (figure 7 and 9). Subjects were asked to fill out a written survey at the conclusion of the experiment concerning their experience of the oxygen delivery system.



Figure 7. Subject exercising in the altitude chamber.

Measurements at rest were made while the subjects were sitting quietly in the altitude chamber after equilibration at each discrete altitude (10,000 ft, 15,000 ft, and 18,000 ft)

Phase I results

Mean SpO₂ declined significantly ($p < 0.01$ on paired t-testing) with increasing altitude whether the subjects were on or off oxygen. When subjects were off oxygen this decrease reached the criterion value of 91% (figure 8). With the oxygen system in use (nasal cannula), mean SpO₂ levels were above 91%, significantly ($p < 0.01$ on paired t-testing) better than without supplemental oxygen. One subject's SpO₂ dropped below 91% but never below 84%. There were no significant changes ($p < 0.49$ on paired t-testing) in color vision with increasing altitude.

Post exercise SpO₂ was significantly lower ($p < 0.001$, paired t-test) than pre-exercise for both mask and cannula conditions (figure 9). There was no significant difference ($p > 0.05$, t-test) in SpO₂ between mask and cannula after exercise (figure 9). Exercise had no significant effect on color vision in any test configuration.

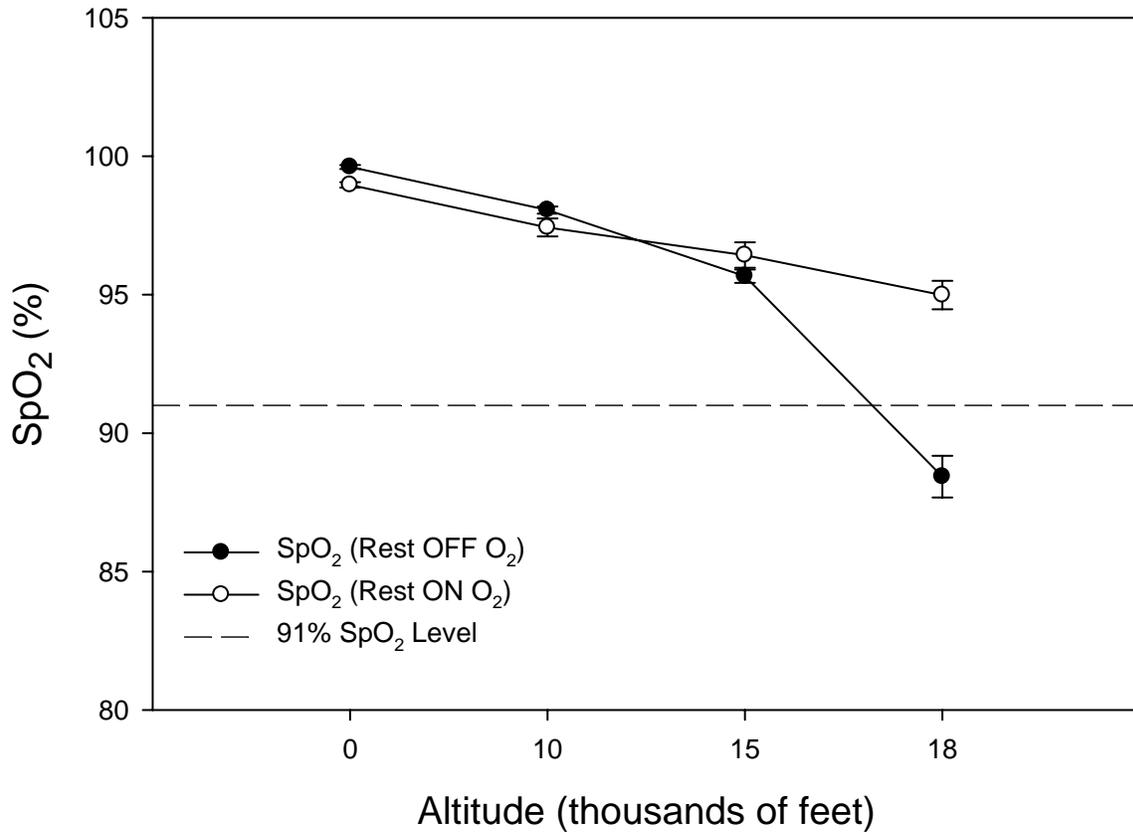


Figure 8. SpO₂ vs Altitude for subjects at rest on and off oxygen, using the AquaLung[®] PHODS with nasal cannula.

Measurements were taken after 10 minutes equilibration at each altitude. Data are expressed as Mean ± S.E. N=18.

Figure 8 shows that without oxygen the subject population maintained their SpO₂ at rest without any supplementary oxygen. This is contrary to expectation and is likely to be due to the youth and very high levels of physical fitness in the study population and should not be viewed as a result that is applicable to the more general population.

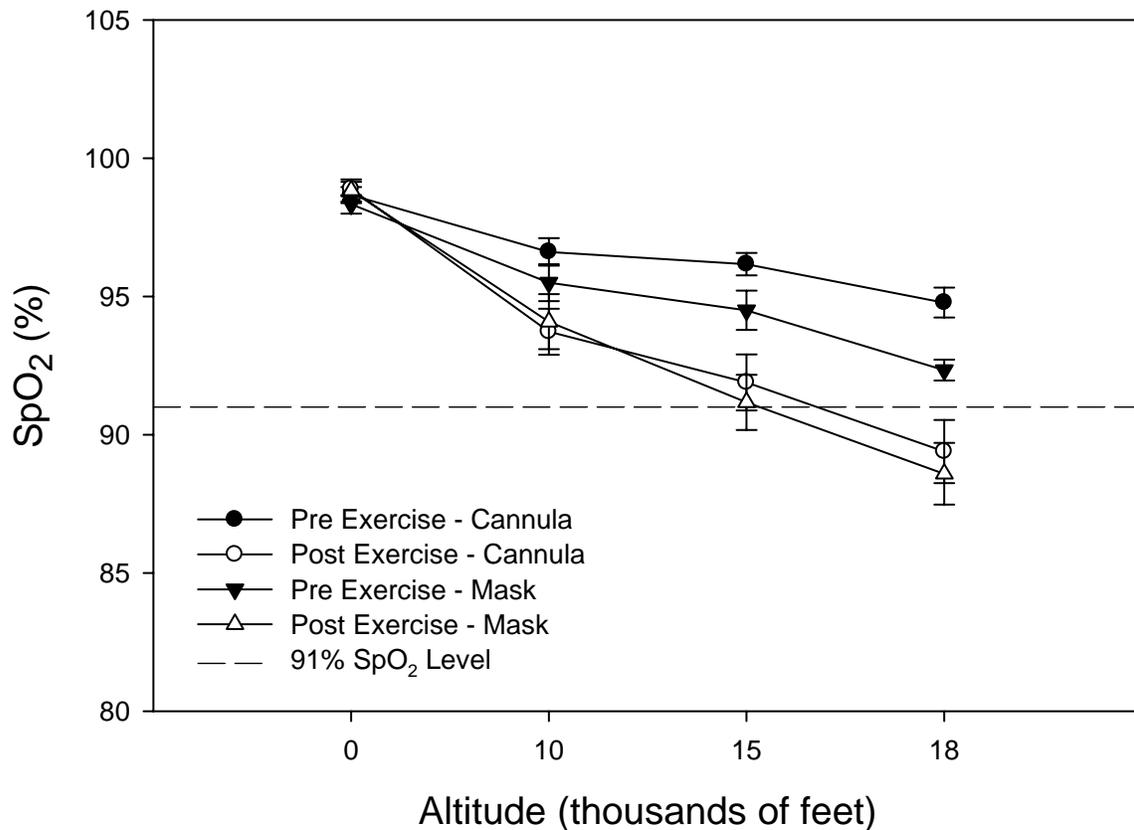


Figure 9. SpO₂ vs Altitude before and after exercising on oxygen via cannula or mask.

Measurements were taken after 10 minutes equilibration at each altitude and immediately after exercise to 150% of resting heart rate. Data are expressed as Mean \pm S.E. N=18.

Subject opinions on the usability of the system were generally positive with some reservations regarding both the mask and nasal cannula. These were not consistent across the subjects and the detail has been passed back to the manufacturers.

Phase I integration

Examination of the PHODS integration revealed that the nasal cannula required a bracket to be attached to the right hand side of the HGU-56/P helmet (figure 1) and the mask (figure 7) was designed to utilize the mounting brackets for the maxillo-facial shield. The oxygen supply bottle was designed to fit the pouch that is normally occupied by the survival egress air (SEA) bottle; if there is a requirement for both bottles then a further compatible pouch has been produced. The routing of the oxygen tubing was designed by Aviation Life Support Equipment experts at USAARL to pose minimal risk of snagging and a low risk of kinking of oxygen tubing.

While a formal evaluation of the Breathing Air Systems Mobile Oxygen Concentrator (Mobile O₂) was beyond the scope of this study, the system appeared to perform well, in terms of rapid and safe filling of the SEA bottles used in this study.

Phase II introduction

During this phase of the study the main effort was to assess the human factors engineering section of the Airworthiness Requirements (AWRs) for the AquaLung[®] Portable Helicopter Oxygen Delivery System (PHODS). The areas of particular interest were its use by the full anthropometric range of aircrew, any effects on ingress and egress from aircraft, the full use of all aircraft controls, compatibility with existing flight gear including NVGs and a thorough operator workload assessment. The PHODS should be regarded as an integral part of the Air Warrior Ensemble (AWE) once it has been attached to the vest, the only difference from any other mounted item is the oxygen line from the regulator to the boom cannula mounted on the helmet. This intimate integration into the AWE proved to be the main problem in this phase of the study in that separating out the minimal effects of the PHODS as opposed to those of the heavy, bulky and restrictive AWE proved to be challenging.

Phase II anthropometry and compatibility

Methods

The anthropometry standards utilized for the study were the Army Aviation tables based on the 1982 survey. The measuring was performed according to US Army Aviation Life Support Equipment protocols. The measurements chosen represent the gross anatomy of an individual; height, weight, chest and waist circumference and two measurements critical to operation of the full range of controls in any cockpit; sitting height and thumb-tip reach. On the systems under test, all oxygen lines were cut to a length to accommodate the full range of test subjects and might have represented a snagging hazard on smaller individuals if they had not been correctly fitted. This emphasizes the need for custom fitting of the system to each individual by an ALSE technician. The appropriate ALSE was worn by subjects given their normal crew position and aircraft type, thus the HGU-56P helmet (figure 1) was worn by all except the AH-64 pilots who were fitted with the IHADSS helmet (figures 10 and 11). Both helmet types were modified with mountings for the PHODS cannula.

During the compatibility testing all crews were requested to don the AWE with the PHODS attached as they would do in a normal pre-flight. They then moved out to the aircraft and performed their aircraft walk-round before entering the aircraft. The normal sequence of pre-flight checks was then undergone including turning the PHODS on by operating the on/off switch on the OPC. The crews included all of their full and free movement checks for all controls and the adjustable components; the seats and pedals. They were then asked to reach and simulate operation of all the switch-gear in the cockpit and egress the aircraft in a normal

fashion. They were observed throughout by at least one standardization pilot and a flight surgeon and were immediately asked to fill out the questionnaire at appendix A.



Figure 10. Mounting bracket for PHODS cannula on IHADSS helmet.



Figure 11. PHODS configuration with Air Warrior ensemble and IHADSS helmet.

The major difference from the HGU 56-P helmet was the locating of the nasal cannula on the left hand side of the helmet to avoid interaction with the HMD.

Results

The range of aircrew measured can be seen in table 3 and although they did not completely cover the full range of body sizes that could possibly utilize the PHODS the bias was towards larger aircrew and no issues were reported. As an integral part of the Air Warrior vest, the PHODS did not represent a significant addition in weight or fit restriction. The AWE provided some problems for aircrew in the smaller cockpits such as the AH-64 and those comments may be seen in full at appendix A.

Table 2. Anthropometric data sheet.

All measurements are presented in appropriate gender specific percentiles.

| Aircraft | Height | Weight | Chest Circumference | Waist Circumference | Sitting Height | Thumb-tip Reach |
|----------|--------|--------|---------------------|---------------------|----------------|-----------------|
| CH-47 | | | | | | |
| PC | 47 | 94 | 87 | 98 | 57 | 73 |
| P | 97 | 43 | 40 | 24 | 98 | 99 |
| FE | 69 | 83 | 87 | 75 | 67 | 65 |
| CE | 69 | 8 | 8 | 13 | 89 | 29 |
| | | | | | | |
| UH-60 | | | | | | |
| PC | 67 | 88 | 99 | 99 | 97.5 | 79 |
| P | 98 | 81 | 98.5 | 84 | 36.5 | 90 |
| CE (F) | 1 | 37 | 87 | 34 | 34 | 1 |
| FM (F) | 64 | 57 | 54 | 54 | 35.5 | 60 |
| | | | | | | |
| AH-64 | | | | | | |
| PC | 69 | 99 | 98.4 | 99 | 10 | 63 |
| CPG | 73 | 59 | 64 | 69 | 5 | 60 |
| PC | 35 | 65 | 86 | 94 | 62 | 22 |
| CPG | 89 | 60 | 74 | 87 | 90 | 51 |

PC - Pilot in command
 FE - Flight Engineer
 F - Female data

P - Pilot
 CE - Crew Chief

CPG - Copilot Gunner
 FM - Flight Medic

Compatibility was tested by questionnaire (appendix A). There were relatively few areas of concern with the PHODS. Because the pilots were issued Air Warrior equipment for this

evaluation, and did not use their current flight gear, they had to be reminded that they were assessing the oxygen system rather than the AWE which they all found bulky, heavy, and restrictive. There were few adverse comments from crew in either the UH-60 or the CH-47, but there were areas of concern expressed in the more confined AH-64 cockpits:

- The AH-64 crew were fitted with the IHADSS helmet which to avoid interference with the HMD had the PHODS cannula mounted on the left side. The configuration chosen for the other aircraft types was to mount the bottle and OPC on the crew's right front side as the bottle uses the same housing as the SEA bottle for underwater egress. In the AH-64 the crews thought that the hose from bottle to regulator might interfere with the IHADSS wiring, and they recommended that the bottle and OPC be moved to the left side of the vest to prevent this.
- Both pilot and gunner had to adjust the bottle up between one and two inches to clear the seat. The bottles were initially mounted near the bottom of the vest as can be seen in figure 10.
- The gunner noted that the CPG cyclic was very close to the regulator when pulled hard into the right aft position.
- The cannula was noted to be too long by one of the smaller individuals and too short by one of the larger. In both cases this caused problems keeping the cannula in the nose during head movement. This suggests that one size does not fit all and a mechanism for adjusting cannula length is necessary, particularly in the NVD flight environment where the scanning requirement produces a lot of side to side head movement.
- One UH-60 pilot noted that the portion of the walk-round involving getting up on top of the aircraft was a challenge wearing the AWE, this would only really be an issue where the walk-round was occurring at altitude and oxygen delivery via the PHODS was necessary. This is probably a rare circumstance but would require some thought as the walk-round is a mission critical function.

Ingress/egress

Methods

The AR 95-1 standard time for emergency egress from any aircraft is thirty seconds. The method for assessing this and any effects the PHODS had was observational. At the start of the trial aircrew were sat at their respective crew stations, strapped in and wearing normal flight gear with the full AWE including the PHODS. The crews were then given a countdown and then all performed an emergency egress simultaneously. Each crewmember was separately timed on three iterations of the egress. The only exception to this procedure was the AH-64 where it was deemed to be an excessive risk to have the pilots jump the six feet from the side pontoons to the ground as they would in a real emergency egress. The procedures were observed throughout by at least one standardization pilot and one flight surgeon.

Results

With one exception, this standard was successfully met in all trials. The emergency egress from UH-60 and CH-47 from all crew positions was at most 12.5 seconds, averaged over three

iterations. In the AH-64, the pilots did not perform a standard emergency egress because of safety considerations. In a real emergency both pilot and gunner would jump from the side of the aircraft to the ground. In this case that was deemed too risky, and they both climbed down as they would normally exit the aircraft. This resulted in one of the three times for the gunner being 33 seconds. The average of three runs was still under the 30 second mark and would have been considerably under had the pilots been jumping from their aircraft. All the timings can be seen in tabular form in appendix B. There was only one other incident worthy of note in that the UH-60 commander felt a snag to his helmet on one egress, and on examination on the ground, the oxygen line was noted to have detached from the helmet at the press fitting. There was no way to determine what had snagged the line, but as it detached without damage to the aircraft or the PHODS, it was considered incidental and unlikely to occur in normal use. This fitting has subsequently been re-designed as a snap-fit and had no further inadvertent releases on further testing.

Workload

Methods

The workload portion of the testing was designed to determine if the PHODS added significantly to the difficulty of the aircrew task. Throughout the PHODS was mounted on the AWE and crew were reminded not to assess the AWE but the PHODS only. The method used was to test fly the system in UH-60 and AH-64 simulators and perform a real test flight in the USAARL UH-60 helicopter. All crewmembers wore their standard ALSE issue plus the AWE with PHODS mounted. The testing began with the donning of the equipment through pre-flight and into the sortie. The flight tasks and profiles can be seen in detail at appendix C, essentially the simulator sorties were designed to be very taxing to provide the maximum possibility for PHODS interference with the flying task. The flight in the real UH-60 was less involved but did contain an ascent to altitude to allow the crew to assess the PHODS in operation. The assessment method utilized the Modified Cooper-Harper Scale and the Bedford Workload Scale (appendix D), both standard tools for measuring workload in the flight environment. Both the scales produce a numerical value related to task difficulty, and also a reference to capacity for other activities with 1 being the lowest difficulty and 5 the highest. Crew were administered these scales immediately after flight by an investigator familiar in their use.

Results

The numerical values resulting from the workload scales can be seen in detail at appendix C, from these it can be seen that the PHODS did not significantly impact workload in any meaningful way. The only activity that rated anything other than insignificant was switching on the regulator because the pilots opted to turn the system on in flight rather than as part of the pre-flight checks to simulate maximum difficulty. The slightly increased workload was due to having a relatively small on/off button on a small OPC mounted on a fairly cluttered AW vest. The pilots also noted that they had to use both hands to manipulate equipment if they wanted to observe the light on top of the OPC flashing to indicate function.



Figure 12. Configuration used for the simulator and aircraft workload testing

Figure 12 shows the aircraft commander who represented a 75th percentile male and a crew member representing a 5th percentile female.

During the flight tests, a PHODS attached to the AW ensemble was worn by a flight surgeon who simulated all the movement that would be expected of a rear crew member wearing the AWE with the PHODS, through getting into the aircraft, strapping in, un-strapping, and moving freely around while bending, kneeling, and reaching. One issue that was noted was the difficulty of turning on the bottle in its position to the rear on the left side of the AW vest. To remedy this, the bottle should be turned on before donning the AW vest, or have it turned on before flight by another crew member.

Another issue noted was that the nasal cannula tended to pull away from the nose when the head was turned to the extreme left. It was also noted that when mounted on the extra large HGU-56P helmet, the cannula as supplied was approximately one inch too short and was difficult to position correctly at the nose. These same issues had been noted in the compatibility portion of the study and again emphasize the necessity of custom fitting the PHODS.

In summary therefore, the workload portion of the study provided no areas of major concern. The assessment was that the PHODS did not add to the workload of conducting crew operations in the aircraft or of conducting a very challenging simulated flight.

An additional finding in the flight portion of the study was that the two systems under test started to deliver oxygen appropriately at 10,000 feet but then continued to deliver small boluses of on demand oxygen down to ground level after a descent at 1000 feet per minute from 14,000 feet to ground level. This was pointed out to the manufacturer and the software in the OPC was modified. On a subsequent flight to 15,000 feet the OPC started and stopped delivering oxygen at 8500 feet.

NVD compatibility

Methods

The requirement from PM Air Warrior was to evaluate the PHODS from two NVD perspectives. The first was the visibility of the OPC warning light from outside the cockpit with the observer using infantry NVDs, and the second was the possibility of interference of pilots NVD performance. The first test was performed on an open HLS under a three-quarter moon, and the OPC light was filmed from outside the cockpit using an infantry NVD and from inside the cockpit using ANVIS. Subsequently, the ANVIS visibility and compatibility of the warning light on the OPC was subjectively evaluated in the USAARL UH-60 simulator under overcast starlight conditions. The ANVIS versions were the OMNI V, which have approximately the same gain as the latest fielded OMNI VI ANVIS. The PHODS equipped pilot was in the right seat with the regulator mounted on the left side of the AW vest, this mounting location maximized the view by the copilot in the left seat. The cockpit lighting was turned down to the lowest usable level.

Results

The test of the infantry NVD showed that the OPC light is barely visible from outside the cockpit even at close (6 foot) range. Inside the cockpit activation of the warning light on the OPC was not detectable by either the pilot or copilot unless they were looking directly at the warning light. Any other lighting conditions from either outside or inside the aircraft would make the visibility of the warning light more difficult. All photographs are attached to this report as appendix E.

Based on this test result, it appears that the PHODS light is highly NVD compatible and if the pilots are expected to notice any warning of loss of function then the light should be increased in visible and ANVIS radiance intensity. Test results also suggest that the color be changed from green to a red LED to increase the probability of detection when using goggles. If a small red LED is identified that would replace the green one, USAARL could evaluate just the light and quantify the ANVIS radiance.

Discussion

Although hypoxia unquestionably developed in these subjects when unprotected at higher altitudes (figure 8), oxygen saturation never dipped below the lower criterion value of 80%. This

observation is corroborated by the lack of any change in color vision at any altitude in the present study.

The PHODS maintained hemoglobin saturation above 91% at rest performing simulated pilot tasks (radio calls) (figure 8). This would provide protection from the negative effects of altitudes up to 18,000'. However, the system did not maintain 91% oxygen saturation during moderate exercise above 15,000' (figure 9) using either mask or nasal cannula. This study population maintained a high level of oxygen saturation at the 15,000 feet level when sedentary. This may have been due to the low age and high physical fitness of the subjects and should not be used as a benchmark for gauging operational oxygen requirements. Indeed the same subjects did de-saturate appreciably when under very moderate exercise stress and this is probably a more reasonable simulation of the stresses of operational flying. Contrary to the authors' expectations, there was no perceptible difference in effectiveness of oxygen delivery between the mask and nasal cannula during exercise, indeed the mask appeared to be worse but this was not significant ($p < 0.23$ on paired t-testing).

Although not specifically studied, it was noted by chamber staff that mouth-breathing resulted in poorer oxygenation than nose-breathing. Although this may seem obvious, it had to be reinforced during the course of the study especially when exercise was performed. This is an example of why specific training for PHODS users should be developed, and underscores the potential advantage of a mask system over a nasal delivery route.

The warning light for operation and loss of function is not visible enough under NVDs and is difficult to see under bright light conditions. A reliable and noticeable indication of failure is a vital component of the system. The oxygen pulses provide an obvious indication of flow and therefore an indication of function. However, under high workload conditions, noticing the absence of a subtle tactile stimulus to the inside of the nose is probably unrealistic and therefore a more noticeable indication of malfunction is strongly recommended.

The cramped cockpit of the AH-64 provides a challenge for integration of the PHODS and the major concerns of aviators were the siting of the various PHODS components on the AWE, this emphasizes the need for individual fitting of the PHODS onto the ensemble by a trained ALSE technician. The various aircraft types have very different cockpits and the AH-64 with very little space and the added concern of the HMD wiring will need particular care when integrating the PHODS into the pilot/cockpit system.

Problems with the length of the nasal cannula were mentioned several times, being too long for one subject and too short for another. These findings would suggest that there should be some form of adjustment in the cannula mount in all helmet types to allow pilots and ALSE personnel to tailor the cannula length to each user.

The alteration of the OPC software to start and stop oxygen delivery at 8500 feet is of little inherent significance unless the operational circumstances dictate maximum endurance at high altitude, and therefore maximum oxygen conservation, is a priority. The phase I study of the PHODS in the altitude chamber indicated that the probable endurance for a fully charged system would be in the order of 2.5 hrs at a consistent 15,000 feet.

The contents gauge of the pre-modification bottles read line pressure rather than bottle pressure, therefore they read empty unless connected to the system and turned on. The post-modification gauges read bottle pressure and thus read true throughout. This modification does not affect any of the previous testing but will be a useful improvement for field use.

Conclusion

The PHODS system provided adequate oxygenation (defined as $SpO_2 > 91\%$) at low levels of exertion up to 18,000 ft, but oxygenation dropped with exercise at the higher altitudes. Given the necessary compromise between optimal oxygenation and operational suitability, we believe that the system is suitable for use by properly trained and physically fit Soldiers at the altitudes tested. However, crews and leaders must be cautious and vigilant when PHODS users exercise at or above 15,000' PA.

The system as currently configured showed no advantage of facial mask over nasal cannula during exercise. This seems counterintuitive and may indicate that more development work is required by the manufacturer.

The PHODS was shown to be fully compatible with the full anthropometric range of U.S. Army Aviators, with a small caveat on the cannula length and adjustability, to not materially affect ingress or egress and to have a negligible effect on workload in any condition. The warning light on the PHODS that indicates both function and failure was shown to be difficult to see with NVDs and a remediation was suggested. Overall the PHODS tested was suitable for purpose and with a few minor modifications the recommendation of the authors would be for its acceptance into service.

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Appendix A.

Cockpit Compatibility Questionnaire/Responses.

1. Donning /Doffing of the PHODS, and the compatibility with other items in the Air Warrior System (includes fit adjustments):

UH-60

CE (F): Very adjustable to accommodate.
FM (F): Couldn't even tell I was wearing it.
PC: Good.
P: No difficulties.

CH-47

PC: Would like to feel a "click" to ensure hose is seated securely.
CE: No problems / issue.
FE: No problems donning, no problems doffing. System seems very friendly.
P: No problems / issues.

AH-64

PC: Possible feeder tube snag with HDU friction knob.
CPG: Possible interference with HDU.

2. Fit of the PHODS:

UH-60

CE (F): Good.
FM (F): Good.
PC: Good.
P: Good.

CH-47

PC: Fit was good, but will not fit all.
CE: Excellent fit.
FE: Excellent.
P: Excellent.

AH-64

PC: Adjusted bottle one notch upward.
CPG: Bottle was adjusted up approx 1 inch from initial position to clear seat.

3. Weight of the PHODS:

UH-60

CE (F): Negligible. Couldn't tell the PHODS was on with weight of vest and armor.
FM (F): Negligible.
PC: No problem.
P: Negligible.

CH-47

PC: Not able to notice.
CE: Very comfortable / light weight without ballistic vests.
FE: Minimal.
P: Good.

AH-64

PC: None.
CPG: No problem.

4. Overall comfort of the PHODS:

UH-60

CE(F): Vest and armor heavy after awhile; hot; glad I fly instead of walk with it.
Couldn't feel the actual PHODS device on vest.
FM(F): Good.
PC: Good.
P: Good.

CH-47

PC: No overall difference with system installed.
CE: From a scale of 1 to 10 with ten being the best, I would score this as a 9.
FE: Excellent.
P: Good.

AH-64

PC: None.
CPG: No problem.

5. Placement of the PHODS/pockets on the Air Warrior ensemble:

UH-60

CE(F): Good.
FM(F): Good, good view of on/off switch.
P: Good.
CP: Good.

CH-47

PC: Perfect.
CE: Excellent.
FE: Good.
P: Good.

AH-64

PC: Change location of bottle to left side of vest due to possible snag of tube with HDU.
CPG: Bottle was adjusted up approx 1 inch from initial position to clear seat.

6. Accessibility of the PHODS (in and out of the aircraft):

UH-60

CE(F): Very accessible. No restrictions.
FM(F): Good; alarm audible or light? NVG compatible?
P: Good.
CP: Good, no problems.

CH-47

PC: Good.
CE: Good.
FE: Not noticeable at all.
P: Good.

AH-64

PC: None.
CPG: No problem.

7. Compatibility with other ALSE items (gloves, helmets, etc.):

UH-60

CE(F): Did not interfere.
FM(F): Good.
P: Good.
CP: Good, no problems.

CH-47

PC: Good.
CE: Excellent.
FE: Fully compatible.
P: Good.

AH-64

PC: Change location of bottle to left side of vest due to possible snag of tube with HDU.
CPG: Bottle was adjusted up approx 1 inch from initial position to clear seat.

8. Compatibility during preflight inspection:

UH-60

CE(F): N/A.
FM(F): N/A.
P: Good.
CP: Good.

CH-47

PC: N/A.
CE: Good.
FE: N/A.
P: N/A.

AH-64

PC: None.
CPG: Good.

9. Head / body movement restrictions in the aircraft caused by PHODS:

UH-60

CE(F): Had to keep adjusting the nasal piece. It moved away from my nose when I moved my head.
FM(F): None, no restrictions.
P: None.
CP: None, No restriction of crash worthy seat / performance.

CH-47

PC: None.
CE: Excellent.
FE: None.
P: None.

AH-64

PC: Change location of bottle to left side of vest due to possible snag of tube with HDU.
CPG: None.

10. Internal field-of-view restrictions caused by the PHODS:

UH-60

CE(F): None, but hard to fit mouth piece and nasal piece in the right places.
FM(F): None, no sight restrictions.
P: None.
CP: None.

CH-47

PC: None.
CE: Good. None or very limited.
FE: None.
P: None.

AH-64

PC: N/A.
CPG: N/A.

11. External field-of-view restrictions caused by the PHODS:

UH-60

CE(F): None.
FM(F): No internal restrictions.
P: None.
CP: None.

CH-47

PC: None.
CE: None.
FE: (No answer).
P: None.

AH-64

PC: No answer
CPG: N/A

12. Flight control restrictions caused by the PHODS:

UH-60

CE(F): N/A I was in the crew (left side) seat.
FM(F): N/A.
P: None.
CP: None.

CH-47

PC: None.
CE: N/A.
FE: N/A.
P: None.

AH-64

PC: None.
CPG: CPG Cyclic was very close to control unit when cyclic was right and aft.

13. Crew station reach restrictions caused by the PHODS:

UH-60

CE(F): No restrictions that inhibited ingress and egress. I wouldn't want to climb on top of an aircraft with all of that equipment that could get caught on the aircraft.
FM(F): None, I couldn't even tell I had the system on, other than a little nostril tickle.
P: None.
CP: None.

CH-47

PC: None.
CE: None.
FE: None.
P: None.

AH-64

PC: None.
CPG: Reaching the CPG cyclic to stow / un-stow was difficult (not due to PHODS, but to vest / armor configuration).

SEAT STROKE

UH-60

P: PHODS will not, in my opinion, cause any interference with the seat stroke capability.
CP: No restriction of crash worthy seat / performance.

CH-47

Seat Stroke N/A.

AH-64

No issues front or rear seat.

Appendix B.

All times in seconds.

UH-60 Ingress and Egress Time

| | Ingress | | | |
|---------|------------------|--------------|-------------|-------------|
| | Pilot Side 1 | Pilot Side 2 | Crew side 1 | Crew side 2 |
| Run 1 | 43 | 46 | <i>27</i> | <i>49</i> |
| Run 2 | 38 | 38 | <i>23</i> | <i>23</i> |
| Run 3 | 35 | 38 | <i>22</i> | 21 |
| Average | 38.7 | 40.7 | 24.0 | 31.0 |
| | | 39.7 | | 27.5 |
| | Emergency Egress | | | |
| | Pilot Side 1 | Pilot Side 2 | Crew side 1 | Crew side 2 |
| Run 1 | 11 | 11 | <i>10</i> | <i>5</i> |
| Run 2 | 12 | 11 | <i>8</i> | <i>5</i> |
| Run 3 | 14 | 16 | <i>7</i> | 6 |
| Average | 12.3 | 12.7 | 8.3 | 5.3 |

** Individuals wearing body armor are indicated in bold and italicized font.

** Run #3 was conducted with extended armor panels on the pilot seats.

** Run #3 was conducted with pilot #2 using gloves.

CH-47 Ingress and Egress Time

| | Ingress | | | |
|---------|------------------|------------------|-----------|-----------|
| | Pilot Side 1 | Pilot Side 2 | Crew Rear | Crew Side |
| Run 1 | 44 | <i>56</i> | 35 | 31 |
| Run 2 | 38 | <i>38</i> | 16 | 16 |
| Run 3 | 34 | <i>42</i> | 12 | 18 |
| Average | 38.7 | 45.3 | 21.0 | 21.7 |
| | | 42.0 | | 21.3 |
| | | | | |
| | Emergency Egress | | | |
| | Pilot Side 1 | Pilot Side 2 | Crew Rear | Crew Side |
| Run 1 | 12 | <i>9</i> | 6 | 10 |
| Run 2 | 13 | <i>10</i> | 12 | 15 |
| Run 3 | 11 | <i>8</i> | 8 | 10 |
| Average | 12.0 | 9.0 | 8.7 | 11.7 |
| | | | | |

** The individual wearing body armor is indicated by bold and italicized font.

AH-64 Ingress and Egress Time

| | | |
|---------|-------------------|------------|
| AH-64 | | |
| | Ingress | |
| | Pilot Front | Pilot Rear |
| Run 1 | <i>105</i> | 88 |
| Run 2 | <i>80</i> | 80 |
| Run 3 | <i>76</i> | 78 |
| Average | 87.0 | 82.0 |
| | | 84.5 |
| | Standard Egress | |
| | Pilot Front | Pilot Rear |
| Run 1 | <i>25</i> | 16 |
| Run 2 | <i>27</i> | 33 |
| Run 3 | <i>23</i> | 15 |
| Average | 25.0 | 21.3 |

** The individual wearing body armor is indicated by bold and italicized font.

** For safety, the front gunner did not jump from the aircraft, instead the gunner climbed out.

** The pilot and gunner alternated who climbed down the aircraft first.

Appendix C.

1. Aircraft: Aeromedical Flight Simulator 2B24 Device No. 85-00009
2. Aircraft Commander: Research Helicopter Pilot, SP/IE/ASO
3. Co-pilot: UH-60 qualified pilot
4. Performed 24 October 2006, 1430-1600hrs
5. ALSE worn: HGU 56-P helmets modified with PHODS cannula and Air Warrior vest with body armor worn by the aircraft commander and PHODS attached (see photographs below)
6. Risk Level: Low

* MC-H: Modified Cooper-Harper Scale (appendix D)

* Bed: Bedford Workload Scale (appendix D)

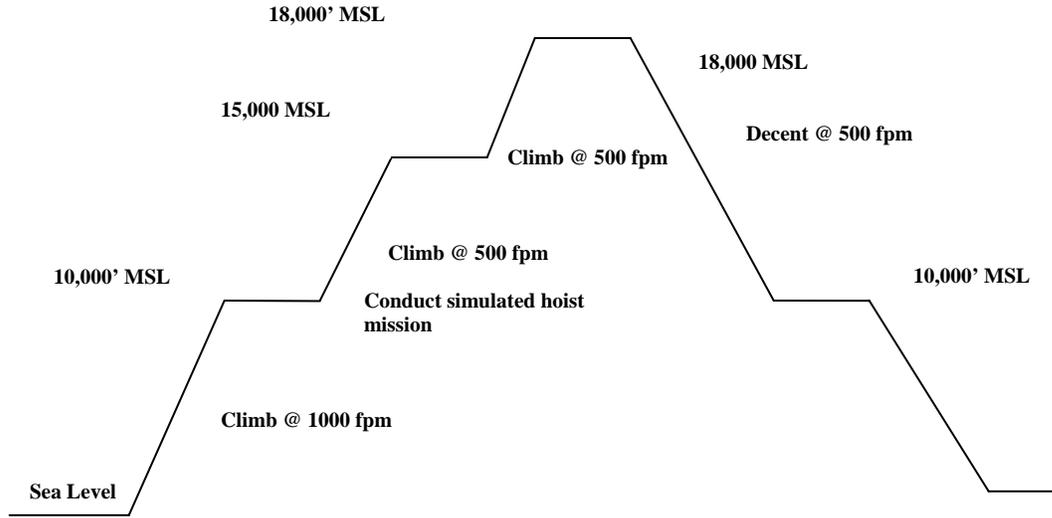
* All maneuvers were completed to standard in accordance with the UH-60 Aircrew Training Manual (TC 1-237)

| Task | Description | Profile Standards | Start & Stop Points | Best Measures | AC CDR | | Pilot | |
|------|--------------------------------------|---|--|--|--------|-----|-------|-----|
| | | | | | MC-H | Bed | MC-H | Bed |
| 1 | Depart Alaska Army Airfield database | Take-off checks complete, level climb to 10,000' MSL. | Pilots perform equipment checks level 10,000' MSL. | Oxygen delivery equipment checks ON and operational. | 2 | 3 | 2 | 3 |
| 2 | Straight and Level Flight | Maintaining a constant heading @ 10,000' MSL straight and level flight. Maintain 120 KIAS. Maintain aircraft in trim. | Start- Collective adjusted for level off. Stop- Collective reduction for descent. | Equipment checks, systems operational. | 1 | 1 | 1 | 1 |
| 3 | Hoist Mission | Maintain a 100' above ground level (AGL) hover with minimum drift for five minutes. | Start- Hover achieved. Stop- Maneuver completed commencing forward flight. | Oxygen delivery equipment checks ON and operational. Pilot interface with equipment. | 1 | 1 | 1 | 1 |
| 4 | VMC Climb | Standard level climb @ 500 fpm to | N/A | Equipment status observed, | 1 | 1 | 1 | 1 |

| Task | Description | Profile Standards | Start & Stop Points | Best Measures | AC CDR | | Pilot | |
|------|---------------------------|---|---|--|--------|-----|-------|-----|
| | | | | | MC-H | Bed | MC-H | Bed |
| | | 15,000' MSI. Maintain 120 KIAS. Maintain aircraft in trim. | | Aqua-Lung subject observed. | | | | |
| 5 | Straight and Level Flight | Maintaining a constant heading @ 15,000' MSL straight and level flight. | Start-Collective adjusted for level off. Stop-Collective reduction for descent. | Equipment status observed, Aqua-Lung subject observed. | 1 | 1 | 1 | 1 |
| 6 | VMC Climb | Standard level climb @ 500 fpm to 18,000' MSI. Maintain 120 KIAS. Maintain aircraft in trim. | N/A | Equipment status observed, Aqua-Lung subject observed. | 1 | 1 | 1 | 1 |
| 7 | Straight and Level Flight | Maintaining a constant heading @ 18,000' MSL straight and level flight. Maintain 120 KIAS. Maintain aircraft in trim. | Start-Collective adjusted for level off. Stop – Collective reduction for descent. | Equipment status observed, Aqua-Lung subject observed. | 1 | 1 | 1 | 1 |
| 8 | VMC Descent | Standard level descent @ 500 fpm to 10,000' MSL. Maintain 120 KIAS. Maintain aircraft in trim. | N/A | Equipment status observed, Aqua-Lung subject observed. | 1 | 1 | 1 | 1 |

| Task | Description | Profile Standards | Start & Stop Points | Best Measures | AC CDR | | Pilot | |
|------|--|---|--|--|--------|-----|-------|-----|
| | | | | | MC-H | Bed | MC-H | Bed |
| 9 | Straight and Level Flight | Straight and Level Flight Maintain 10,000' MSL. Maintain 120 KIAS. Maintain aircraft in trim. | Start- Collective adjusted for level off. Stop – Collective reduction for descent. | Equipment status observed, Aqua-Lung subject observed. | 1 | 1 | 1 | 1 |
| 10 | Emergency Procedures | Respond to single engine failure. | Pilot identifies and responds correctly to emergency procedure. | Any interference with pilot actions during high workload; equipment operational. | 1 | 1 | 1 | 1 |
| 11 | Emergency Procedures | Respond to dual engine failure- autorotate. | Pilot identifies dual-engine failure and correctly responds with entering autorotation. | Interference with pilot actions during high workload; equipment operational checks. | 1 | 1 | 1 | 1 |
| 12 | VMC Descent while encountering an emergency procedure | Level descent @ 500 - 1000 fpm to Sea Level. Maintain 120 KIAS. Maintain aircraft in trim. | Emergency Procedure: #2 Hydraulic Pump failure resulting on Boost Off flight. | Pilot workload during emergency, effects on Aqua-Lung. | 1 | 1 | 1 | 1 |
| 13 | Termination of flight to nearest suitable landing area | Aircraft control during emergency. Radio communications procedures. Respond to Emergency Procedures. VMC Approach. | Respond to Emergency Procedures. Situational Awareness. Effects of Aqua-Lung usage during contingency. | Aircraft control. Cognitive workload and physical workload while boost assist is off. | 1 | 1 | 1 | 1 |

Aqua Lung PHODS Simulator test plan profile



In-Flight Equipment Workload Assessment Test Plan for AquaLung® PHODS

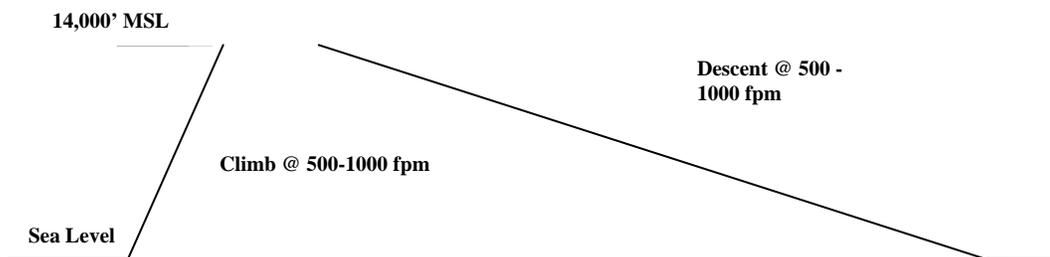
1. Aircraft: JUH-60A Serial Number: 88-26069
2. Aircraft Commander: Research Helicopter Pilot, SP/IE/ASO
3. Weather minimums: IAW USAARL Aviation Research Protocol SOP
4. Risk Level: Low

Pilot responses on in-flight workload.

| Task | Description | Profile Standards | Start & Stop Points | Best Measures | MC-H | Bed |
|------|---|---|---|--|------|-----|
| 1 | Depart USAARL helipad and VMC Climb | Hovering flight VMC Take-off Standard level climb to 1000' MSI | Preflight checks completed and system is ON. | Vibration effects, Gz effects, comfort | 1 | 1 |
| 2 | Straight and Level Flight to stagefield for closed traffic pattern maneuvers. | VMC Flight maneuvers: Roll-On landing Banking flight (30 degrees) VMC Approach (high vibration profile) Boost-Off flight (degraded automatic flight control system scenario) Rolling take-off. | System operational (check for failure indications or system irregularities) | Vibration effects, Gz effects, comfort, Viewing system indications during vibration. On/Off feasibility. | 1 | 1 |
| 3 | VMC Climb | Standard level climb @ 500 – 1000 fpm to 14,000' MSI Maintain 120 KIAS Maintain aircraft in trim (parameters within AR 95-1 oxygen usage requirements) | System regulator function, auto-On, delivery flow. | Equipment status observed | 1 | 1 |
| 4 | Straight and Level Flight | Maintaining a constant heading @ 14,000' MSL straight and level flight Maintain 120 | Start-Collective adjusted for level off Stop – Collective reduction for | Equipment status observed, AquaLung functioning as designed | 1 | 1 |

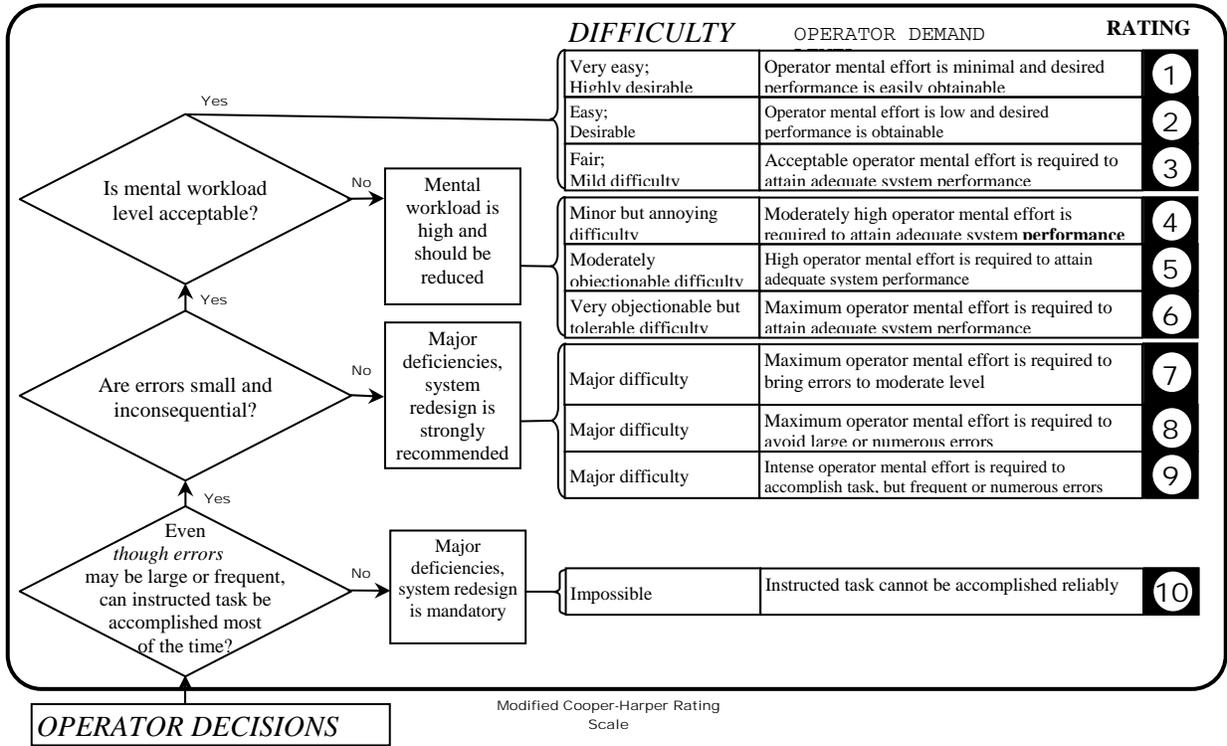
| Task | Description | Profile Standards | Start & Stop Points | Best Measures | MC-H | Bed |
|------|---|---|--|--|------|-----|
| | | KIAS Maintain aircraft in trim (parameters within AR 95-1 oxygen usage requirements) | descent (5 minutes @ 14,000) | | | |
| 5 | VMC Descent | Standard level descent @ 500 fpm to 1000' MSI Maintain 120 KIAS Maintain aircraft in trim | System regulator function, auto-On, delivery flow | Equipment status observed, Aqua-Lung functioning as designed | 1 | 1 |
| 6 | Instrument Approach Procedures | Conduct ILS Rwy 6 to Cairns | Observe system and determine workload effects, if any, during ILS Approach | Equipment status observed | 1 | 1 |
| 7 | Straight and Level Flight to USAARL helipad | VMC Approach to landing and termination | Observe system and determine workload effects, if any, during VMC Approach | Equipment status observed. | 1 | 1 |
| 8 | Termination of flight to USAARL helipad | | | | 1 | 1 |

Aqua Lung PHODS In-Flight Test Plan

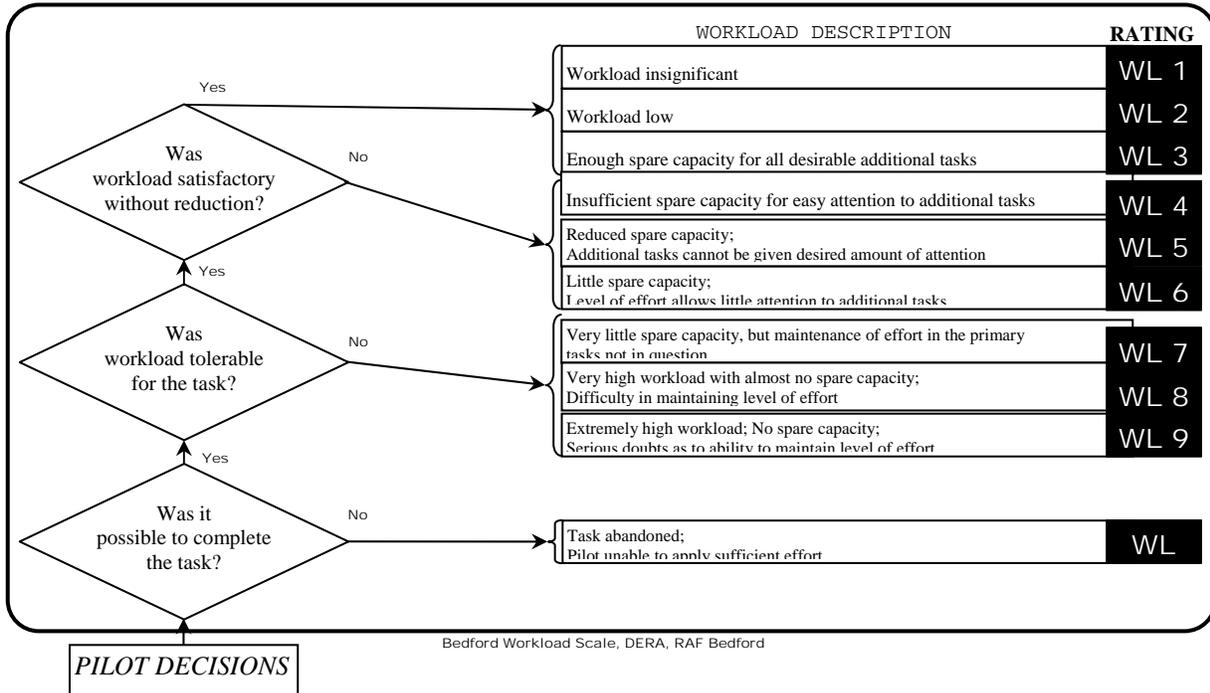


Appendix D.

Modified Cooper-Harper Rating Scale



BEDFORD WORKLOAD SCALE



Appendix E.



Infantry NVG images of pilot with ANVIS and PHODS 1 Nov 2006, Lowe AAF, Ft. Rucker, AL. Moon illumination 75%, Sunset 16:54 local, pictures taken at approximately 17:50 local.

Appendix F.

Pictures of the revised system with anti-snag pigtail lead and snap fittings rather than push fits for the oxygen leads.



