

Increased System Fidelity for Navy Aviation Hypoxia Training

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ABSTRACT

In 2009, the Naval Aviation Survival Training Program (NASTP) Trainer Management Team (TMT) identified a need for a next-generation normobaric mask-on hypoxia trainer with enhanced capabilities due to the lack of positive air pressure provided by existing capabilities. The lack of a positive pressure-on-demand airflow delivery for current mask-on hypoxia training has been cited as a potential training gap wherein 44% of students experience air hunger (Artino, Folga, & Vacchiano, 2009). As a result, it is unclear whether students are able to recognize more subtle symptoms of hypoxia or if they are masked by air hunger. To address this, researchers have investigated an innovative technology solution to deliver representative pressure-on-demand flow rates, thereby increasing training fidelity by replicating the air delivery method of aircraft systems. This research also provided an opportunity to seek additional novel advances. Reducing the logistical footprint and increasing portability by removing the need for compressed gases was a goal to ease implementation within higher fidelity training simulators with limited space to increase immersive training opportunities. This paper will provide an overview of the training need and the technical approach to the training device development. Additionally, the authors will discuss the engineering and human subjects testing conducted to evaluate the system. The results will include how symptoms experienced using this novel device compare to historical data from other training systems, in addition to whether the system reduces or eliminates air hunger issues.

ABOUT THE AUTHORS

Beth F. Wheeler Atkinson is a Senior Research Psychologist at NAWCTSD and a NAVAIR Associate Fellow. She has led research and development efforts to increase fidelity of safety training for hypoxia, spatial disorientation and emergency parachute procedures since 2008. Other research interests include instructional systems to facilitate human performance assessment and post mission trend analysis, as well as human computer interaction. She holds an M.A. in Psychology, Applied Experimental Concentration, from the University of West Florida.

Jonathan Reeh is an Engineering Lead at Lynntech, Inc. He has led the design, manufacture and testing of a prototype electrochemical hypoxia device system, as well as its sub-systems and components. He has over 10 years of experience developing electrochemical systems, which provide the basis for the technology's technical approach. He has been the lead engineer on efforts including hybrid fuel cells, flexible power management systems, and oxygen concentrators. He holds a B.S. in Engineering Technology (minor in business) from Texas A&M University.

John Zbranek is a Lead Engineer at Lynntech, and he currently leads the Electrical Engineering and Cyber-Physical Systems group. His 12+ years of hardware, software, and system engineering has involved all aspects of technology development from concept to product for numerous embedded systems ranging from simple data logging applications to complex fully autonomous unmanned applications. He holds a B.S. in Electronics Engineering Technology from Texas A&M University.

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INTRODUCTION

There is a well-established understanding of the threat posed by hypoxia in aviation (Denison, Ledwith & Poulton, 1966; Green & Morgan, 1985; Hoffler, Turner, Wick, & Billings, 1974; Legg et al., 1989). Hypoxia, or oxygen deprivation at high altitudes, can cause rapid loss of mental, physical, and/or psychomotor abilities by the pilot and crew. Such symptoms have been—and continue to be—a costly problem. Recent years have brought increased national visibility to the phenomena due to spikes in reporting that have resulted in the grounding of aircraft by both the United States (U.S.) Air Force and U.S. Navy (Barber, 2012; Butler, 2012; Cenciotti, 2014; Freedberg, 2016, 2017; Ostrander, 2005). The latest significant events involved the grounding of the U.S. Navy's T-45 Goshawk training jet due to safety concerns with the oxygen system (Tomlinson, 2017). While operational solutions for oxygen systems were introduced to supply aviators with the ability to breathe in high altitude situations (Carey, n.d.), an aviator's last line of defense is their ability to recognize that they are experiencing symptoms. In this situation, the effectiveness of current aircrew safety solutions is dependent on the aviator's implementation of emergency procedures to mitigate the situation and avoid catastrophic outcomes.

As a means to mitigate the risks associated with hypoxia, current Navy instruction (Department of the Navy, 2016, CNAF M-3710.7) outlines annual hypoxia awareness training as well as a biennial dynamic hypoxia training requirement. Many units with access to dynamic hypoxia trainers have incorporated an annual DHT requirement into their respective Standard Operating Procedures (SOPs). Due to the effectiveness of dynamic hypoxia training (Artino, Folgo, & Swan, 2006; Smith, 2008; Westerman, 2004), the technologies currently supporting initial and refresher hypoxia training have remained the primary demonstration platforms (Department of the Navy, 2004). Further, a review of hazard reports from FY2002 to FY2012 indicated that approximately 16% of aviators who reported an episode cited existing training solutions as a factor in their ability to identify and react appropriately to symptoms when experienced (Scheeler, Atkinson, & Tindall, 2014). However, several factors are leading the U.S. Navy to investigate alternative training solutions. The authors of the paper provide an overview of the history of aviation hypoxia training within the U.S. Navy, highlighting the training gaps that exist with fielded training solutions. Finally, the authors will provide an overview of a technical approach to the development of a novel training solution, including the engineering tests and human subject research conducted to evaluate the system.

HISTORY OF AVIATION HYPOXIA TRAINING

Under the mission of the Navy Medicine Operational Training Center (NMOTC), the Naval Survival Training Institute (NSTI) is responsible for providing safe, effective, and relevant human performance and survival training for the entire Department of Defense (DoD) as the execution arm of the Chief of Naval Operations-mandated Naval Aviation Survival Training Program (NASTP; Welcome to NMOTC, n.d.). At the eight Aviation Survival Training Centers (ASTCs), the personnel of NSTI deliver aviation survival training that emphasizes mishap and accident prevention, enhancing and sustaining performance, and mishap survival (Welcome to NSTI, n.d.). Historically, Navy curriculum used several approaches to training including annual, biennial, and quadrennial classroom-based and experiential training through the Dynamic Hypoxia Training (DHT), hypobaric chamber or normobaric training devices (Naval Aerospace Medical Institute, 1991; Department of the Navy, 2004; West, Every, & Parker, 1972). Regardless of the training platform, the goal of the training is to mitigate the risks associated with the experience of hypoxia incidents that occur each year by creating a situation where the trainee can experience their individual symptoms for recognition. After recognition, trainees are expected to initiate their emergency procedures to resume the flow of concentrated oxygen to recover from the induced hypoxia condition.

The importance of symptom identification is due to the variance in symptoms experienced. That is, while there are a set of expected indicators (e.g., personality changes, euphoria, fatigue, cognitive deficits, memory loss, rapid breathing, nausea, loss of consciousness; Cable, 2003; Malle, Quinette, Laisney, Bourrilhon, Boissin, Desgranges, Eustache, & Piérard, 2013; Smith, 2008; Pickard, 2002), each individual's experience is somewhat unique (Johnston, Iremonger, Hunt, & Beattie, 2012; Smith, 2008; Westerman, 2004). Further, there have been mixed reports regarding symptom consistency within an individual. Some anecdotal reports and initial research studies have indicated that physiological symptoms and experiences may change day-to-day or flight-to-flight based on environmental and human factors (Alagha, Ahmadbeigy, Moosavi, & Jalali, 2012; W. T. Scheeler, E. Knock, personal communication, December 3, 2015), while other reports indicate that symptoms may remain consistent for an individual who experiences repeated exposure (Harding, 1999; Pickard, 2002).

Hypobaric Chamber Training

Hypobaric training provides a dynamic training opportunity within a pressurized chamber, exposing students to an environment of reduced pressure and oxygen partial pressure to experience the symptoms of acute altitude-induced hypoxia (Matthews, 1999). During this exposure, trainees participate in activities that allow for the recognition of the cognitive impairment associated with hypoxia (West et al., 1972). While effective for demonstrating the symptomology associated with hypoxia for future recognition, the system lacks the fidelity for higher-level cognitive tasks and decision-making encountered in flight by aircrew. Additionally, the inclusion of a pressurized environment increases the safety risks associated with the training including decompression sickness and barotrauma (Brandt, Morrison, & Butler, 2009; Dully, 1992; Ohri, et al., 2002; Smart & Gable, 2004; Snyder, 2006), and in extreme cases risks death (Neubauer, Dixon, & Herndon, 1988). These safety risks resulted in policies that required time delays between exposures, impacting flight time of students and availability of instructors (e.g., Department of the Navy, 2004, OPNAV Instruction 3710.7U). During the 1990s, researchers questioned the requirements of chamber training due to these safety risks (Dully, 1992). This type of research, accompanied by statements that chamber training was outdated (Stansel, 2013) and the increased sustainment issues due to obsolescence and significant maintenance costs were considerations when determining the future of hypoxia training. Based on these factors, the U.S. Navy made determination to decommission these trainers (Clutter, 2016; Mabeus, 2016).

Normobaric Hypoxia Training (NHT)

Normobaric Hypoxia Training (NHT) involves the use of a device that increases the ratio of nitrogen to oxygen in the air breathed by trainees, without the pressurized environment. While a review of existing literature suggests there may be true physiological differences in the experiences between the hypobaric chamber and NHT environments (Coppel, Hennis, Gilbert-Kawai, & Grocott, 2015; Neuhaus & Hinkelbein, 2014), studies indicate that the subjective experience of symptoms is similar (Artino et al., 2006; Naval Operational Medicine Institute, 2004). The U.S. Navy has considered two types of NHT devices. The first training solution is a room structure that allows for various training simulator configurations to be setup in an area where instructors can adjust the oxygen concentration levels (e.g., Circelli, 2012; Harmon, 2010). This training environment eliminates the risk of decompression sickness and barotraumas for aircrew, observers, and instructors by eliminating the pressurized

aspects of the historic training devices. This training device provides increased training fidelity due to the ability to introduce various flight simulator configurations and potential for encouraging typical aircrew coordination with the multi-crew capacity. However, the solution is only relevant to *mask off* aircrew.

The second NHT option is a mask on device, which provides a realistic training environment for aviators that typically wear a helmet and mask during flight (Artino et al., 2006; Artino et al., 2009). The current device, which began transitioning to Navy training in 2004 (Bureau of Medicine and Surgery Public Affairs, 2003; McVicar, 2007; Newell, 2006), adjusts the concentration of medical grade air and nitrogen from compressed gas tanks and delivers the airflow at a constant pressure through an oxygen mask (Reduced Oxygen Breathing Device 2, n.d.). The device setup at the ASTCs enables instructors to train hypoxia awareness and mitigation strategies while the student interacts with a simulated flight environment. While this greatly improves the fidelity of hypoxia training beyond the historical hypobaric chamber (e.g., Artino et al., 2006; Deussing, Artino, & Folga, 2011; Sausen, Bower, Stiney, Feigl, Wartman, & Clark, 2003; Sausen, Wallick, Slobodnik, et al., 2001; Vacchiano, Vagedes, & Gonzalez, 2004), there remains room for improvement due to training gaps (Cable, 2003) and the device footprint.

INCREASING HYPOXIA TRAINING FIDELITY

In 2009, the NASTP Trainer Management Team identified a need for a next-generation normobaric mask-on hypoxia trainer with enhanced capabilities, due to the lack of positive air pressure provided by existing capabilities (TMT 41-09). To date, training devices have provided a constant air pressure experience. Aviators who fly platforms that rely on oxygen masks to deliver air required to breathe are accustomed to pressure-on-demand airflow through a regulator such as the CRU-103 (CRU-103 Chest Mounted Oxygen Regulator, 2009). Previous research investigating the constant pressure systems, which at the time was only capable of providing continuous pressure airflow at a limited max 50 standard liters per minute (Artino et al., 2006; Artino et al., 2009; Deussing et al., 2011), indicated that up to 44% of students experience air hunger when using this device (Artino et al., 2009). The expected reason for this symptom is the lack of a positive pressure-on-demand airflow delivery method. The negative training that results from this limitation is the potential inability to recognize more subtle symptoms of hypoxia because they are masked by air hunger. Since the purpose of hypoxia training is to ensure aircrew are able to recognize and mitigate symptoms, the NASTP TMT identified the criticality of identifying an alternative training device capable of replicating the pressure-on-demand airflow experienced on the Navy's current aircraft to overcome existing training gaps. As a part of this effort, the technical team also sought to provide a means to reduce the logistic requirements and footprint associated with the reliance on compressed gas tanks.

The following sections describe the development and testing of a novel technology that strives to meet these objectives to deliver next-generation, hypoxia training. The underlying technology relies on electrochemical cells that utilize highly efficient oxygen evolution reaction catalysts in a Membrane Electrode Assembly (MEA) to separate the oxygen from nitrogen present in ambient air (Figure 1); Table 1 details the corresponding electrochemical half cell reactions that facilitate the operation of the device. Liquid water is fed to the anode compartment and water molecules are dissociated into protons and oxygen via electrolysis reaction over the anode electrocatalyst (see anode half cell reaction in Table 1). Atmospheric air is fed into the cathode compartment of the electrochemical cell. Protons generated at the anode are transported to the cathode side due to the electrical field gradient and react with the oxygen in the air to generate both water and reduced-oxygen air (this reaction is also known as electrochemical cathode depolarization). The electrochemical cathode depolarization phenomenon lowers the electrochemical device's electrical potential and hence, reduces its power consumption. The reduced-oxygen air

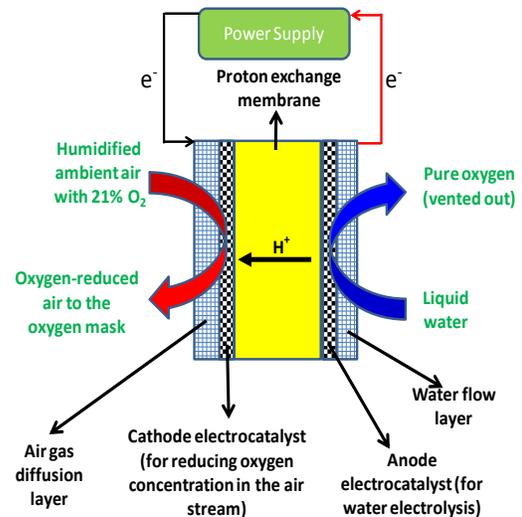


Figure 1. Schematic of the Electrochemical Oxygen Separation (EOS) Approach

stream at the cathode outlet is then transferred to the trainee via an oxygen mask (hypoxic air). The pure oxygen generated at the anode is vented out during normal operation. However, the pure oxygen anode stream can be made available for mask delivery in the event of a medical emergency.

Table 1. Electrochemical Half Cell Reactions for Electrochemical Oxygen Separator Technology

Cathode	$4 \text{H}^+ + 4 \text{e}^- + \text{Ambient air with 21\% O}_2 \rightarrow 2 \text{H}_2\text{O} + \text{Reduced-oxygen air stream}$
Anode	$2 \text{H}_2\text{O} \rightarrow \text{Pure O}_2 + 4 \text{H}^+ + 4 \text{e}^-$
Overall	Reduced-oxygen air stream (cathode outlet to oxygen mask) \rightarrow Pure O ₂ (anode outlet vented out)

The electrochemical oxygen separator device discussed in this paper utilizes an advanced Oxygen Evolution Reaction (OER) electrocatalyst. The efficiency and power consumption of the electrochemical oxygen separator device are mainly governed by the anode electrocatalyst and how the liquid water is fed. Since the anode side of the electrochemical oxygen separator uses the water electrolysis reaction, the OER electrocatalyst can provide high electrochemical efficiencies, which facilitates the reduction of power consumption of the device. In addition, to further improve the efficiency of the electrochemical oxygen separator device, liquid water is fed directly to the anode side. Flowing water directly onto the anode electrocatalyst eliminates the reactant mass transfer issues and allows the device to operate at high current densities, which drastically reduces the mass and volume of the final system.

The flow rate of ambient air that can be processed by the system is limited by the number of cells that can be stacked together in an electrochemical stack. The cells in the stack are electrically in series, and fluidically in parallel. It is important to maintain uniform water and gas flow through each MEA of each individual electrochemical cell, in order to maintain overall stability of the stack, and reduce system fluctuations. By changing the current input to the electrochemical cell, the amount of oxygen separated from the ambient air is controlled. This in turn controls the percentage of oxygen delivered to the pilot trainee via a mask, thus simulating the varying altitudes representative of hypoxia.

On-Demand Hypoxia Training (ODHT) Device System Description

The overall system consists of four primary subsystems including the Electrochemical Oxygen Separation (EOS) subsystem, the Balance-of-Plant (BOP) subsystem, the System Control (SC) subsystem, and the Hybrid Power Distribution (HPD) subsystem as shown in Figure 2.

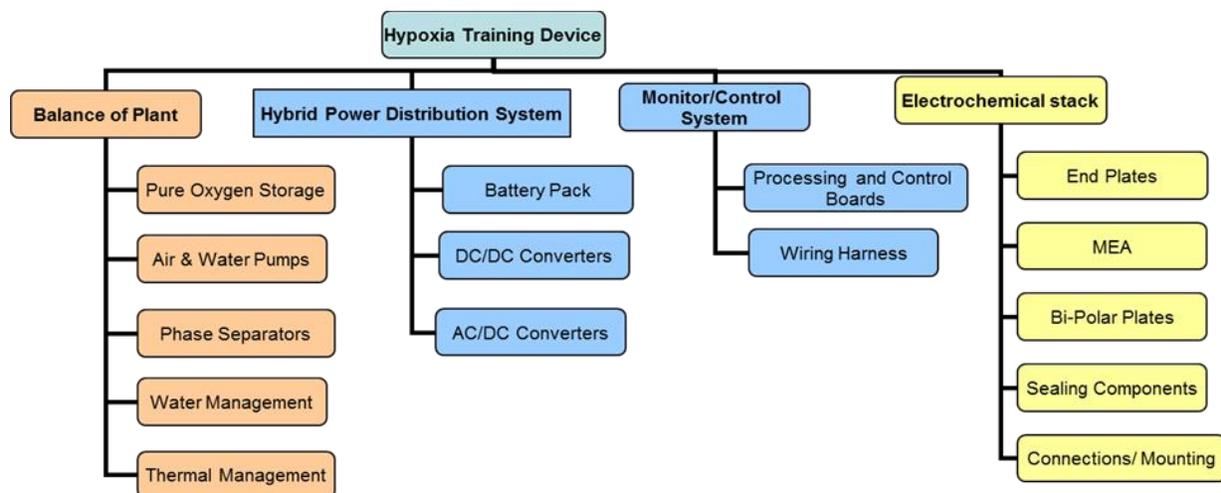


Figure 2. Subsystems of the ODHT Device with Critical Components for Operation

The EOS subsystem consists of the electrochemical stack (Figure 3) that performs the oxygen removal from ambient air to supply hypoxic air to the trainee. The four critical components of the stack are the MEAs, bipolar plates, end plates and seals. The MEAs facilitate the electrochemical reaction for oxygen separation, the bipolar plates assist in fluid and air delivery to the stack, while the end plates and seals provide overall rigidity and compression to the stack respectively.



Figure 3. Fully Assembled Electrochemical Stack

The BOP subsystem consists of three major fluidic loops including the air loop, oxygen loop, and liquid water loop and the associated Commercial-Off-The-Shelf (COTS) components necessary for operation of these fluidic loops. In the air loop, the ambient air is pulled in by a piston pump through an air filter that also behaves as a muffler. A flow meter ensures that the right amount of air enters the electrochemical stack. The reduced air oxygen is then fed to a condenser that condenses out water vapor. The condenser is critical to overall water management and temperature control of the gas supplied to the trainee. Condensed water is then collected in the phase separator. The reduced-oxygen air then passes through a forward pressure regulator following which it is delivered at a positive pressure to the trainee via a mask. In the coolant loop, the coolant fluid, that is used for temperature control of the stack, leaves the electrochemical stack and flows through a liquid to air heat exchanger dropping its temperature by 5 to 10°C. The water is collected in the reservoir from where it goes through a coolant heater. The coolant heater enables shorter start-up times by allowing the stack to reach the operating temperature quicker. In the oxygen loop, the humid pure oxygen then goes through a condenser that reduces the gas temperature and condenses out more water. This water is collected in a different phase separator from the one used for the reduced-oxygen fluidic line. The water collected in these phase separators is pumped into the coolant reservoir. The pure oxygen is collected in a bag to be used for trainee recovery.

The SC subsystem consists of the electronics boards and associated software necessary to control the various balance of plant components and electrochemical stack. It also performs data processing in order to display altitude as a function of the partial pressure of oxygen, and real time flow rate measurements. The HPD subsystem consists of the electronic boards and modules necessary for power conditioning and distribution to ensure that the correct voltage range of power is supplied to each individual subsystem. Additionally, the HPD subsystem consists of a rechargeable battery that limits the overall power, and hence current draw from the wall.

A top-level simplified block diagram showing the process flow of how ambient air is converted to reduced oxygen air and delivered to the trainee via a mask is shown in Figure 4. This demonstrates how the flow of ambient air is fed to the electrochemical stack using air pumps, following which current control to the stack facilitates the reduction of oxygen concentration in the hypoxic air delivered to the trainee via a mask.

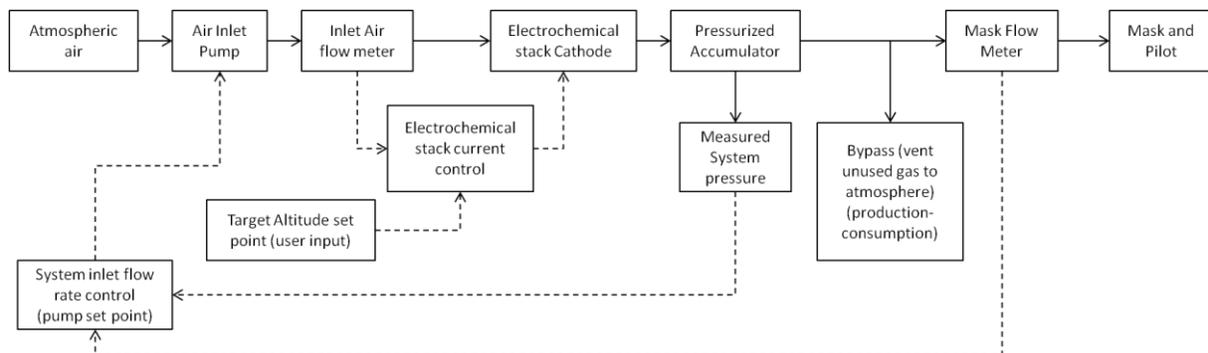


Figure 4. Top-Level Simplified Block Diagram of Air Flow Process

Engineering Testing of ODHT Device

The overall packaging of the various subsystems in the ODHT device and the 3-D CAD models of the completed enclosure with the packaged components inside the enclosure are shown in Figure 5 (Left – Details of packaged components inside the enclosure, Right – external operator interfaces identified).

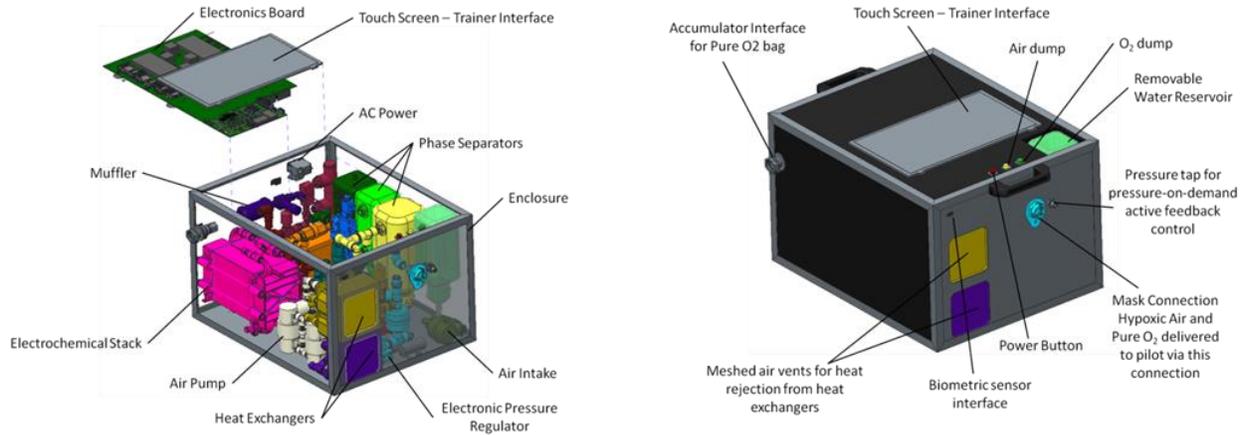


Figure 5. 3D CAD Model and Assembly Layout of the ODHT

The current packaged prototype device has undergone extensive benchtop testing in the lab to demonstrate its functionality and performance. Specifically, laboratory testing of the system response time to achieve altitude for both slow (Figure 6, left) and rapid training profiles (Figure 6, right) were successfully completed to minimize elapsed time to achieve altitude oxygen concentration and ensure accuracy of system. These figures demonstrate the start-up time with the system, once it was tuned was approximately 10 to 15 minutes (one sample is approximately equal to 1 second). The stack start-up time is highly dependent on the coolant heater since it determines how fast the stack can be brought up to operating temperature. Another factor that determines the start-up time is the total volume of the system; for a given operating pressure, the larger the volume the more time it will take a given pump to reach that pressure threshold.

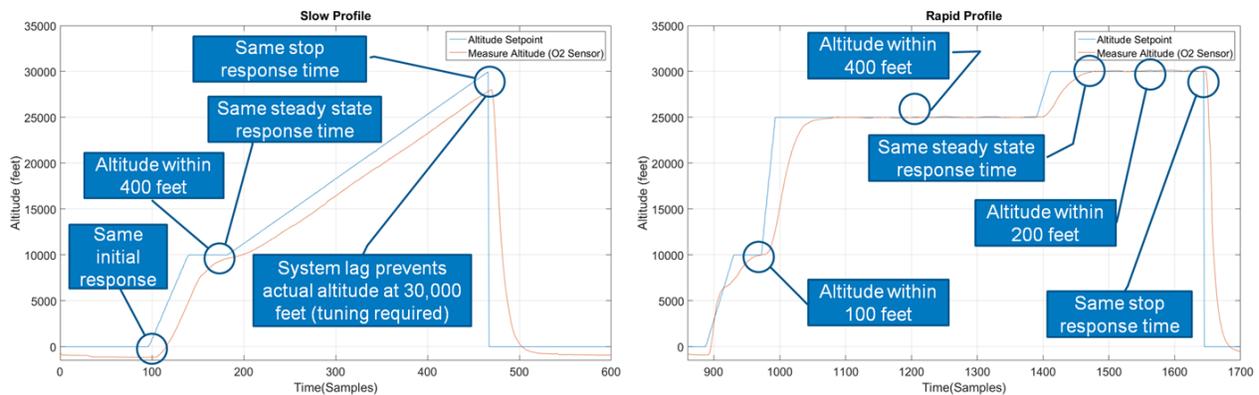


Figure 6. Testing Results of Altitude Accuracy and Response Time for Slow Profile (Left) and Rapid Profile (Right)

The data from the profile testing also shows that the response time for the slow and rapid profiles is the same during start-up, stop and steady state operation for the slow and rapid profile. There is an altitude offset of approximately 400 feet for the slow profile, which prevents the slow profile from reaching 30,000 feet, and a maximum altitude offset of approximately 400 feet during the rapid profile. This is because of the composition of gas present in the system; as the altitude set point of the system changes, the system produces gas to replace what is already present. Moreover, the oxygen sensor present in the system takes a finite amount of time to detect the oxygen content in the flow.

Human Testing of ODHT Device

To complement the engineering testing, the development team conducted an initial research effort to test the ODHT with human subjects. The goal of this study was to test the ODHT under conditions similar to those intended for the target transition training. During testing, the ODHT delivered a low oxygen air mixture through a hose and pilot's mask assembly while the student interacted with a flight simulator. During this interaction, data was collected on the participant physiological response, subjective account of symptoms, and system performance.

Participants

Participants were recruited from a list of current and former Embry-Riddle Aeronautical University students, and were required to be pilots and have had previous experience with the High Altitude Lab (HAL)—a normobaric chamber where individuals experience symptoms of hypoxia in an oxygen-depleted environment (see Harmon, 2010). These prerequisites for participation limited required training for the flight simulation, ensured that participants had a basic understanding of their individual hypoxia symptoms¹, and were a similar population to that of the target transition.

Participant's ($n = 10$) were pilots, ranging from private/instrument to flight instructor and multiengine ratings and certificates. No participants had acted as pilot in command of a pressurized aircraft or in flight conditions requiring the use of supplemental oxygen. Two women and eight men participated². All were in good physical shape and held at least a 3rd class Federal Aviation Administration (FAA) medical certificate.

Method

Researchers briefed each participant about the test event, which included an overview of the research protocol and identification of the types of hypoxia symptoms that may be experienced³. Each participant signed an informed consent form. Each participant was fitted for a mask and helmet; three different sizes of U.S. Navy issued masks and helmets were available to allow for a broader anthropomorphic selection of participants similar to the population from which Naval Aviation draws its aviators, flight officers and enlisted aircrew. Following this, each participant was given the opportunity to practice removing the oxygen mask from the helmet, as none were familiar with the bayonet fittings that held it on. As a part of the brief, participants were provided two options for recovery following the experience of hypoxia symptoms: 1) breathe normally in the mask as the ODHT delivered room air, or 2) remove the mask and, if necessary, don the provided airline mask to receive 100% oxygen.

Participants were seated at a Frasca Mentor™ Advanced Aviation Training Device (AATD), a C-172 simulator with a G-1000 instrument panel and artificial visual environment (Cessna 172, n.d.). Participants flew the simulator from takeoff through an instrument scenario to the final approach fix for the Daytona Beach International Airport while the ODHT went through a standard training profile. The training profile used during this research was the Slow Profile⁴ (see Figure 6, left diagram). Participants were instrumented with an integral pulse oximeter and remote device worn for typical HAL training as a backup device⁵. During the test event, one instructor monitored the ODHT readouts on altitude and blood oxygen saturation levels (SpO₂) and queried subjects about their experience of hypoxia symptoms; another instructor acted as Air Traffic Control and stood by to assist with subject recovery as needed. The instructor initiated the ODHT Slow Onset profile as the participant began the takeoff roll. All participants completed the full ODHT Slow Onset profile without feeling the need to stop due to severe symptoms.

¹While participants had experienced hypoxia symptoms, none had previously undergone training in a mask on hypoxia inducing device. All participants had experience with airline-style oxygen masks, and were therefore familiar with the feeling of breathing through a diluter-demand system.

²One profile was incomplete due to an internal ODHT problem, which was fixed prior to the next session. However, the participant did reach a high enough altitude in the profile to experience symptoms.

³The hypoxia symptom review mirrored material presented to U.S. Navy students who participate in this type of training at the ASTCs.

⁴The standard Slow Profile used during U.S. Navy training at the ASTCs starts by climbing from 0 feet to 10,000 feet (an effective oxygen altitude of 14.3%) during the first minute. After holding 1 minute, the system climbs from 10,000 feet to 30,000 feet at a rate of 3,000 feet per minute.

⁵The integral pulse oximeter reading and that of the secondary remote device were in close agreement on blood oxygen saturation levels (SpO₂) throughout the profile.

Results

All 10 participants experienced the same or similar symptoms using the ODHT that they had previously felt in the HAL. Most pointed out that the onset was slower in the ODHT than what they experienced with the HAL; only one participant reported feeling the onset of symptoms quicker when using the ODHT. The most common symptoms were light-headedness, dizziness, and difficulty concentrating. Four participants experienced hot flashes, which they noted were unique symptoms compared to their previous HAL experience. At the conclusion of the Slow Onset profile, the majority of participants recovered by breathing ambient air; one participant felt the need to recover with 100% oxygen after removing the mask, and the backup oxygen was provided for this reason. For each participant, altitude, heart rate, and SpO2 were logged for further analysis (see Figure 7 for sample data). This data demonstrates participant's physiological reaction to the hypoxia conditions, as evidenced by the reduction of SpO2 and the increase in heart rate as the altitude continues to increase over time.

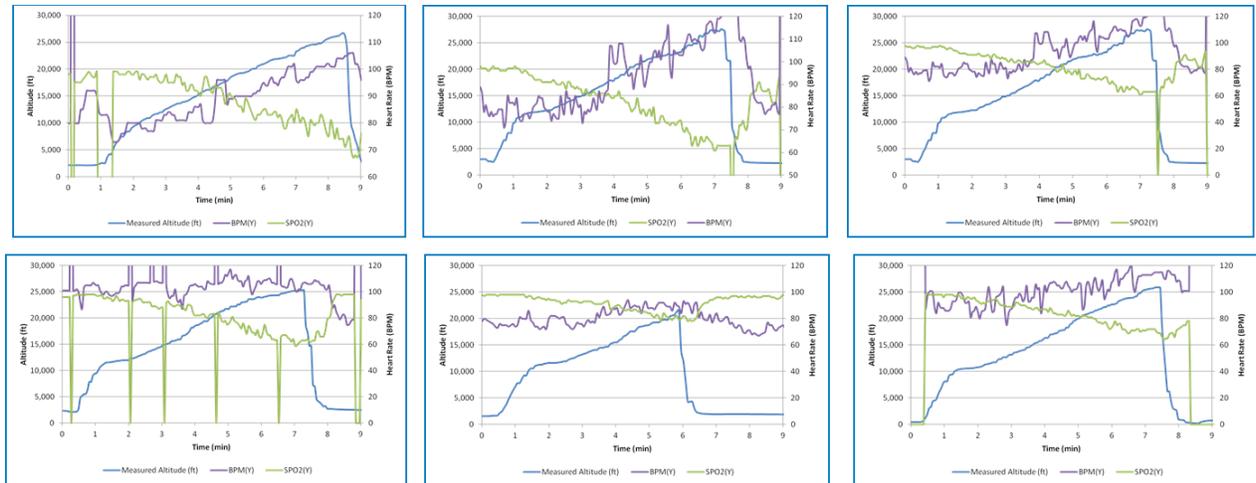


Figure 7. Sample of Data Logs of Participants' SpO2 and Heart Rate during Slow Onset Profile Tests

Discussion

During this testing, the majority of the human subjects were breathing an average flow rate of between 10 and 15 Standard Liters Per Minute (SLpm) under hypoxia conditions (see Figure 8). Even the heaviest breathers within the sample space of human subjects tested only breathed approximately 25 SLpm when the altitude was close to 30,000 ft, which is still approximately 10 SLpm lower than the device's capability. This is a very significant result since it has a direct impact on the device cost. If the device's average flow rate can be reduced, fewer cells will be needed within the electrochemical stack. Considering that the stack makes up almost 45-50% of the overall device's production cost, it can have a huge positive impact in reducing device procurement cost down the road. It should be noted that a better flow averaging method and larger statistical population data are needed to finalize the average flow rate needed for the device down the road.

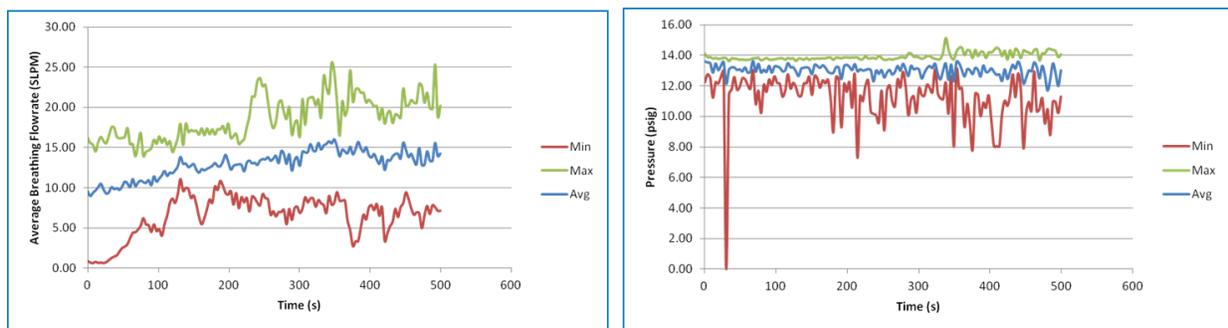


Figure 8. Minimum, Maximum and Mean of the Average for Breathing Flow Rate (top) and Pressure of the Breathing Air Delivered (bottom) During Human Subjects Testing

Moreover, a review of flow rates suggests that the ODHT responded well to participants' increased breathing. Three participants experienced what they described as air hunger, or shortness of breath. Participant 1 complained of air hunger at 8:40 into the profile. However, both average breath rate and flow rate did not increase until after 10 minutes. Participant 9 complained of air hunger at 6:40, and immediately after both the average breath rate and flow rate increased momentarily. Participant 10's breathing rate increased significantly at 3:50, but didn't verbalize his feeling of shortness of breath until 4:45. At that time both average breath rate and flow rate increased. He attributed it partially to the weight and pressure of the helmet and mask, which he said made him feel top heavy and had to work harder to breathe. From a review of flow rates, it appeared the ODHT responded well to subjects' increased breathing. Researchers specifically queried participants who noted this experience of air hunger, asking about the volume of reduced oxygen air supplied through the mask; all stated the flow was not the problem, but rather it was the feeling of not having enough air.

In general, results observed during this study were in line with expectations. First, as noted previously, most participants felt the onset of symptoms was slower with the ODHT than their previous experiences with the HAL; when students experience hypoxia within the HAL, they are introduced to an instant exposure to 6% oxygen vice the incremental altitude adjustments of the ODHT profile. Second, individual reports of symptoms are similar to those reported in early testing of previous devices. Table 2 provides an overview of estimated reporting rates (based on figures from existing literature) for current mask on hypoxia training, and percentage rates of symptoms reported in the current study using the ODHT. Participants were also asked to make a comparison of symptoms experienced during the ODHT study and those previously experienced in the HAL based on recollection; this subjective reporting indicates similarities between these environments as well, with a few noted differences highlighted by the descriptions quoted below:

I experienced most of the same symptoms as the HAL. One difference I noticed was even though my fingers and lips didn't necessarily seem blue in color, I did feel a tingling sensation similar to how you feel after your leg falls asleep. Secondly I had a slight headache after the HAL that I did not experience after the ROBD [ODHT].

My symptoms were nearly similar to the HAL. I lost vision first and slowly was losing my ability to be sharp. One difference was the weight of my left arm and feeling like I couldn't get enough breath. Significantly different was the extent to which my symptoms onset and felt. The onset was much slower than the HAL and the depth to which my symptoms went was much less shallow. There is no doubt I was hypoxic, but it was not nearly as intense.

Table 2. Symptom Distribution Comparison from Historical Research and Current Study

Hypoxia Symptom	Estimated Percentage (%) of Reported Symptoms from Archival Research			Current Study
	Artino et al., 2006	Artino et al., 2009	Deussing et al., 2011	
Tingling	37	36	36	
Dizziness	42	47	47	
Difficulty Concentrating	51	56	56	
Hot Flash	20	17	17	
Air Hunger	59	44	44	
Blurred Vision	27	35	35	
Lack of Coordination	25	23	23	
Euphoria	14	19	19	
Fatigue	13	11	10	
Headache	9	12	11	
Tunnel Vision	14	17	18	
Nausea	7	9	9	
Apprehension	6	5	5	
Stress	4	7	8	
Lights Dimming	16	20	20	
Cold Flash	2	2	2	
Sample Size (n)	121	156	566	10
Device	ROBD2 30 LPM	ROBD2 50 LPM	ROBD2 50 LPM	ODHT

Some limitations exist with this current study. Two participants complained about the fit of the mask and the heaviness of the extension hose. Further, this was not a large sample and relied on a population of opportunity vice the target transition. Additional research with a larger sample, including U.S. Navy aviators, is necessary to provide more conclusive evidence of the reliability and benefits of the device.

CONCLUSIONS AND FUTURE DIRECTIONS

Preliminary findings associated with the human testing of the ODHT suggest that individual's subjective experiences of hypoxia are similar to those with chamber and other NHT training devices. Future studies with larger samples and controlled comparisons to current U.S. Navy training devices is necessary to provide direct evidence of training similarities. Additionally, while more research is needed to determine definitively, this initial study indicates that the ODHT shows promise in reducing the symptom of air hunger as a function of the device delivery system. Specifically, the introduction of a technology that provides true pressure-on-demand reduces or eliminates existing training gaps. This provides instructors with more confidence that if trainees encounter air hunger it is likely a symptom of hypoxia rather than a device delivery limitation. Additional Testing and Evaluation of the ODHT from fleet aviators is being pursued to further validate the findings. Specifically, the authors are seeking future studies in collaboration with Aviation Survival Training, providing access to students undergoing initial or refresher training, as well as demonstrations during high visibility aviator conferences (e.g., Tailhook Reunion) or platform Safety System Working Group.

This new technology also provides additional training opportunities. First, the smaller footprint of the ODHT due to the elimination of compressed gas tanks will allow for smoother integration into current and future platform simulators with no requirement for oxygen prescriptions. While limitations to training cycles and other considerations (e.g., safety personnel, curriculum updates) may impact feasibility, the ease of setup through these advances provides an opportunity to consider hypoxia training as an integrated part of malfunction and other emergency procedure training within high fidelity trainers. Further, through introduction of training within existing simulator devices, there are opportunities to train multiple aircrew at the same time. This will allow for crew resource management (CRM) training during an emergency in addition to recognition and performance of emergency procedures.

As the military continues to identify predictive and proactive means to address the hypoxia challenge facing military aviators, continued analysis of reporting requirements and potential engineering solutions (e.g., physiological sensors for alerting, contamination sensors/analysis) is essential. As noted by the Air Boss in a message addressing Aviation Physiological Episodes (PHYSEPS) in 2015, there is an "urgency for accelerated mitigations and solutions" that address safety of U.S. Navy and Marine Corps aircrew. However, while this message also notes that while material solutions and system reliability are critical for "aggressively moving to eliminate this risk," the call also addressed awareness training and improved reporting. As highlighted by this paper, there are continued opportunities to increase the fidelity and safety of associated training as well. Others may include enhancing the fidelity of DHT training through reconfigurable cockpits that allow aircrew to fly in their respective aircraft and manipulating representative controls in a controlled training environment. Finally, as a part of addressing the call for improved reporting, consideration for a persistent database to document symptomology and physiological baselines for aviators may be beneficial. Using data science and emerging analysis technologies, the collection and storage of data from training environments through operation may provide data crucial to fully understanding the breadth and depth of the challenge.

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