Conceptual Design of Countermeasures for High Altitude-Induced Chronic Intermittent Hypoxia

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I. Introduction & Problem Statement

The Atacama Desert of Chile is an ideal place for a telescope installation. With its incredibly dry environment and high altitude, images from telescopes are less prone to be distorted with water droplets and atmospheric scattering. The University of Tokyo Atacama Observatory (TAO) is an astronomical observatory that is set to be built in the next few years. It will be located on the summit of Cerro Chajnantor, at an altitude of 5,640 m (18,500 ft) in the Atacama Desert, making it the highest telescope in the world. However, the contractors, technicians, and scientists that will arrive at the site beginning in early 2016 will only live on site for a few days at a time. Instead, the main base camp will be located at San Pedro, located at 2,400 m (7,900 ft), and many of the people who will be staffing the observatory have homes at sea level. This continuous travel over 10,000 feet of elevation difference can lead to a medical condition known as intermittent hypoxia. These effects have already been seen in Chilean miners that undergo a similar but less extreme altitude difference every few days (Farias et al., 2013) The objective of this project is therefore to determine how scientists and workers can temporarily live and work at the TAO site without experiencing large adverse health effects at the high altitude and when they readjust to life at the base camp or at sea level. An extended version of this report will be submitted to the Ministry of Education of Chile in partnership with the University of Chile for funding to pursue the implementation of these results over a four year time span.

II. Literature Review

A. Hypoxia

Hypoxia is a condition resulting from inadequate oxygen delivery to the body's tissues (Martin, 1985). Hypoxemia is a related condition in which there are insufficient oxygen levels in arterial blood, which can cause hypoxia (Martin, 1985). While there are several different categories of hypoxia, the one most relevant for the purposes of this study is high altitude-induced hypobaric hypoxia, which does result from hypoxemia. At high altitudes, even though the concentration of oxygen is the same as at sea level (21%), the decrease in total barometric pressure means that there are less oxygen molecules available, so the partial pressure of oxygen (PO_2) in the inspired air decreases (Martin, 1985; Farias et al., 2013). For example, the barometric pressure at sea level is 760 mmHg. Assuming 21% oxygen and a loss of 47 mmHg attributable to the saturated vapor pressure of humidified air, PaO_2 in the body is 150 mmHg. This is the baseline for all high-altitude oxygen-level comparisons. In contrast, the total barometric pressure at TAO (5,640 m) is only 375 mmHg. After doing the same calculations, the new PaO_2 is only 69 mmHg, less than half of the amount of oxygen at sea level. This change in oxygen levels triggers physiologic responses to attempt to maintain tissue oxygenation (Martin, 1985; Farias et al., 2013).

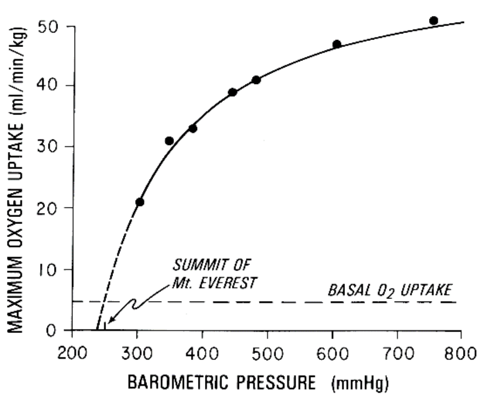


Figure 1: Maximal oxygen uptake plotted against barometric pressure. Data from the Silver Hut expedition to summit Mt. Everest (West, 2000).

Upon ascending to altitude, the body begins to experience changes in physical performance, mental performance, and the ability to sleep. One main physical effect of oxygen deprivation is hyperventilation, which is the body's way of ridding itself of carbon dioxide in order to make more room for oxygen. Ascending to altitude also decreases maximal oxygen consumption, which greatly increases fatigue (West, 2004). The change of maximal oxygen consumption is illustrated in Figure 1. Additionally, there are a number of cardiovascular adjustments made to maintain tissue oxygenation including increased heart rate, blood pressure, cardiac output, and myocardial contractility (West, 2004, Farias et al., 2013; Richalet, 1990). Visual sensitivity has also been shown to decrease by approximately 50% at an altitude of 5000 meters (McFarland, 1972).

Mental performance is also impaired at high altitude, as exhibited through increased arithmetic errors, reduced attention span, increased mental fatigue, impaired decision making, altered short-term memory, lower productivity, changes of mood, or even euphoria (West, 2004; Martin, 1985; Gerard et al., 2000). These cognitive changes are directly attributable to oxygen deprivation (West, 2004). Sleep is also impaired at high altitudes, and is characterized by frequent waking during slumber, not feeling well-rested in the morning, and the occurrence of unpleasant dreams (Barcroft et al., 1920). Most of these symptoms are thought to be a result of periodic breathing, in which groups of breaths are alternated with intervals of apnea or near-apnea (Weil, 2004).

Additionally, there are several high altitude diseases that can affect performance, the most common of which is acute mountain sickness (AMS). AMS occurs upon ascent from near sea level to altitudes over 3000 meters (West, 2004) and is characterized by headache, lightheadedness, breathlessness, fatigue, insomnia, and nausea (Bartsch, 2004; Hackett and Roach, 2001). These symptoms typically start two to three hours after ascent, but disappear after a few days (West, 2004).

While we have enumerated many of the unpleasant symptoms of high-altitude hypobaric hypoxia, it is important to discuss the adaptive ability of the human body to these extreme environments. The body improves its tolerance to altitude through a series of adaptive changes known as acclimatization (West, 2004). In addition to the hyperventilation and cardiovascular adjustments mentioned previously, another important adaptive feature is polycythemia, or elevated red blood cell count, which provides increased blood oxygen capacity over the course of several weeks (Pugh, 1964). Lastly, there are a number of acid-base adjustments that the body makes over the course of several days to regulate the increased pH levels of cerebrospinal fluid and arterial blood that result from a reduction in alveolar and arterial PCO_2 (West, 2004).

Given the situation of interest, we are not simply dealing with high altitude-induced hypoxia, but intermittent high altitude-induced hypoxia. Those working at the observatory site will be periodically traveling from homes or base camps at lower altitude up to the summit, exposing themselves to episodes of hypobaric hypoxia interspersed with periods of normal oxygen and pressure levels. While there have been a limited number of studies looking at this particular situation, results suggest that a cumulative effect begins with the first exposure to hypoxia (Neubauer, 2001). In general, the long term adjustments that result from this intermittent exposure are similar to those seen in chronic hypoxia, as described previously – changes in ventilation, cardiovascular function, red cell mass, and other physiologic adaptations (Farias et al., 2013). What appears to differ in the case of intermittent exposure is the time required for acclimatization. While the body will acclimatize to continuous hypobaric exposure in a few months, intermittent exposure requires years for acclimatization, with biological parameters stabilizing after 18 months of exposure (Richalet, 1990; Jimenez, 1995).

B. Previous investigations into high altitude intermittent hypoxia

While TAO has not yet been constructed, there have been other examples of high-altitude intermittent hypoxia in Chile. Many mine workers in the Andes mountain range have work shifts ranging from 4-20 days at the high altitude work site (over 4,000 m) followed by rest days at sea level (Farias et al., 2013). This high-altitude, sea level cycle repeats for years, and workers develop Chronic Intermittent Hypoxia (CIH) where they must undergo an acclimatization process to the requirements of hypobaric hypoxia, including lower atmospheric pressure and oxygen levels at high altitude, and then must undergo the reverse acclimatization process when they return to sea level (Farias et al., 2013).

As described previously, altitude acclimatization induces a series of adaptive physiological adjustments to compensate for the reduced available partial pressure of oxygen. On the first day of re-ascent to high altitude after 3-7 days of rest at sea level, most miners, regardless of the number of years of exposure to CIH, experience Acute Mountain Sickness. After a few days, the symptoms pass, and the body begins to re-adjust. The physiological responses and effects of high-altitude acclimatization include hematocrit increase, increase in pulmonary hypertension, decrease in maximum VO_2, decrease in cardiovascular disease, decrease in oxidative metabolism, and a decrease in sleep quality (Farias et al., 2013). The main issue with CIH is that these responses will reverse as the body re-adjusts to life at sea level, and this constant battle of physiological changes in response to environmental responses causes extremely large amounts of stress on the body.

C. Current countermeasures

There are currently two main methods to address hypobaric hypoxia - treatments by increasing oxygen or treatments by increasing pressure. The most straight-forward method to counteract the decrease oxygen level in the blood is to breathe air that is more highly saturated with oxygen for a short period of time (Kasic et al., 1991). Because the hypoxic health effects stem from a lack of oxygen in the bloodstream, breathing in pure oxygen for some amount of time can counteract those effects (Kasic et al., 1991). More serious cases of hypoxia could necessitate oxygen therapy that involves breathing in pure oxygen from a gas mask for several hours. However, periodically taking a few breaths of pure oxygen from a portable, supplemental oxygen canister is oftentimes enough to relieve the symptoms of hypobaric hypoxia and acute mountain sickness.

The other main type of countermeasure is to treat hypoxia through increasing the pressure of the local environment. Kasic describes an experiment where the effectiveness of oxygen therapy and hyperbaric chambers were compared. He found that although the mean arterial oxygen saturation increased more during oxygen treatment, both treatments were equally effective at providing relief to hypoxia (Kasic et al., 1991). In fact, for very severe cases of hypoxia, the only treatment may be physically descending to a lower altitude to increase oxygen intake and PaO_2. However, the person suffering from hypoxia may not be able to descend without aid, so Gamow bags may be used to immediately help treat the person from severe altitude sickness. A Gamow bag is a portable hyperbaric bag large enough to accommodate a person. The bag can be quickly pumped up to a designed pressure meant to simulate atmospheric pressure at a much lower altitude, and the hypoxic person may rest inside the Gamow bag for immediate treatment. For example, the effective altitude inside a bag can be 1000-3000 meters lower than the actual altitude, and a person can quickly get higher oxygen levels in their blood while his/her companions carry the Gamow bag to a lower altitude (Peacock). Gamow bags are often carried and used by high-altitude mountain climbers in case of severe altitude sickness.

Another countermeasure that improves the effects of hypoxia through increasing the local pressure is an entire habitat. Like a scaled-up version of a Gamow bag, a pressurized habitat creates a space that is at a higher pressure and therefore simulates the environment at a lower altitude. However, instead of just being large enough for one person, a habitat can be designed and built to be like a house. Unlike unpressurized houses though, a correctly pressurized habitat can ensure that the people living inside will have enough oxygen in their blood to not get hypoxia. Habitats can take many forms - they can be inflatable, hard shelled or ribbed, and they can be modular and capable of being disassembled or more rigid and permanent. Two currently existing habitats that were meant to simulate extreme environments are the habitats used in HI-SEAS and Mars 500.

Hawaii Space Exploration Analog and Simulation, also known as HI-SEAS, is a human spaceflight analog for Mars at an isolated location on the slopes of the Mauna Loa volcano in Hawaii at an altitude of 8,200 feet above sea level. Six to eight people participate in each HI-SEAS mission, and they attempt to simulate living in a Martian environment as closely as possible by living in an isolated, inflatable habitat from four to twelve months and donning an extravehicular (EVA) suit and leaving the airlock when exiting the habitat. The habitat itself is based on a dome design and is 36 feet in diameter, enclosing a volume of 13,570 cubic feet. It includes a kitchen, dining room, bathroom with shower, laboratory, exercise room, living room, and several bedrooms. A converted steel shipping container is attached to the habitat and used as a workshop.

The Mars 500 project was a series of experiments conducted between 2007 and 2011 to study the psychosocial effects of long-term isolation in crew members to simulate the confined and isolated environment of a Mars mission and landing. The crew members lived in a multi-module facility located in a Moscow research institute. The habitat, utility, and medical modules simulated the main spacecraft, the fourth module simulated the Mars lander spacecraft, and the fifth module simulated the Martian environment. All modules were self-sustainable and contained communications, ventilation, electrical, and air and water monitoring systems within the facility. The habitat module was a steel 12 feet by 66 feet long cylinder. It was designed with a kitchen, dining/living room, bathroom, and individual bedrooms each about 32 square feet. However, the Mars 500 missions did not simulate the Martian atmosphere, so all modules were maintained at the natural atmospheric pressure.

III. Specific Aims

The objective of the following work is to provide a conceptual design for a countermeasure, or system of countermeasures, to address the issue of intermittent high altitude-induced hypoxia. We will address this objective through three specific aims: 1) designing a habitat that meets all of the necessary environmental, living, and work requirements established for this extreme environment, 2) designing an “exploration” capability that allows workers to safely perform outdoor work while maintaining a similar environment to the habitat, and 3) suggesting a suite of sensors to be used for monitoring workers’ vitals to verify whether the countermeasures are having the desired effect.

IV. Methods

A. Analysis/Developing System Requirements

1. The basic requirements

Before specific countermeasures could be designed and suggested, a set of system requirements was necessary to understand the extent of the challenge and determine a baseline for our solution. The basic requirements were defined as follows. Per the request of the current scientists and professionals at the ALMA observatory, it was required that the solution maintain the pressure at the base camp of San Pedro, 850 mbar. And second, in order for the necessary work to be completed, the solution must allow for a crew of at least five people, with the option to be expandable to 15. Once those two very basic requirements were put in place, the remaining constraints were largely based on human needs as outlined by previous research and NASA documentation.

After obtaining an understanding of our basic system requirements, we began to explore potential solutions. We looked into options similar to the Gamow Bag and other temporary countermeasures, but these solutions only addressed the issue of intermittent hypoxia - they did not solve the problem. Therefore, we began to explore countermeasures that might prove to completely eliminate the problem. It was at this point when we decided to design a habitat to be placed at the summit while also supplying a means of movement and work outside the habitat while maintaining the required 850 mbar of pressure both in and out of the habitat. The result was a conceptual design of a habitat in addition to research of potential suits and helmets that are further explained below.

2. Habitat methodology

In defining the system requirements for the habitat, we assessed the needs of future workers at the Tokyo Atacama Observatory. A list of requirements as well as desired elements were generated with input from current scientists and professionals at the ALMA observatory (also located on Cerro Chajnantor in Chile). System requirements were divided into operational, environmental, structural, and power categories.

Operationally, the site is to be designed for five residents—four scientists and one housekeeper for more than 3 days but less than 2 weeks. Thus all living and working spaces in the habitat should accommodate five people. Another capability that should be integrated in the habitat is the ability to enter and exit the habitat numerous times per day, as scientists will be performing various types of work (indoor and outdoor) and will certainly take breaks for eating or using the restroom. Any radio communication must be limited to the 60 MHz range to avoid frequency interference. One final operational constraint is that all aspects of the site must be removable once the observatory is no longer under operation, i.e. installation and removal of all habitat components should be designed as logistically simple as possible.

Environmental requirements are to be provided by the environmental control and life support system (ECLSS). This includes controlling the atmospheric composition (monitoring partial pressures of nitrogen, oxygen, carbon dioxide, etc.), maintaining total habitat pressure, removing carbon dioxide from the air, maintaining temperature and humidity levels, and providing potable water. In order to determine the supplies needed to maintain safe and healthy environmental levels within the habitat, requirements were developed for the amount of consumables needed. As baseline life support values (e.g. daily oxygen consumption, carbon dioxide production, water consumption, water production, heat production, food consumption, etc.) are available in several references (NASA 2015, NASA 2010), consumable requirements can be developed using the number of inhabitants, total volume of the habitat, and the desired environmental composition. Given the final design decisions of our habitat, these requirements were determined through the calculations shown in Appendix C. With regards to thermal control, the habitat's interior must be kept at a comfortable temperature while its exterior is exposed to the relatively cold temperature range of this region of the Atacama Desert, which ranges from winter low temperatures of around -10 degrees C to summer high temperatures around 4 degrees C (ALMA, 2013).

Structural requirements were a result of a combination of environmental and operational requirements. Maintaining the pressurization and atmospheric composition of the habitat requires an airlock between the habitat and the exterior environment, and maintaining thermal control requires insulation. The operational necessity of simple installment and removal also drove the structural decision to design an inflatable habitat, discussed further in the following section. Finally, power requirements were estimated based on the appliances and electrical devices being used in the habitat, along with the power needs of the ECLSS system.

3. EVA methodology

The requirements of the system concerning work being done outside of the habitat were dependent on the habitat design as well as the needs of the workers and the constraints of the environment. As stated above, one key requirement was to maintain the pressure at 850 mbar and to eliminate all the effects of chronic, intermittent, hypobaric hypoxia rather than focus on addressing one aspect. Therefore, we decided to treat the work being done outside like an extra vehicular activity (EVA) on the ISS. Beginning with the list of requirements and desires from a lead scientist at ALMA, we determined the main concerns for EVA were composition of air, pressurization, and operations which includes mobility, ease of use, and comfort. Minor concerns included other consumables such as water and sensor integration. We developed further requirements by considering SCUBA operations and space EVAs.

Because the habitat was being designed to maintain 850 mbar, with no added protection the workers would undergo several transitions each day working in the 500 mbar atmosphere outside and returning to the habitat for breaks. While the 350 mbar pressure difference is relatively minimal, the repetitive nature of these transitions, length of time spent outdoors (up to 4 hours), and fast rate of transition all present a risk of decompression sickness (DCS) that needed to be addressed. DCS also is highly dependent on individual factors including age, dehydration, and body type (Vann, 1989). For these reasons, we determined having just the habitat was not enough to eliminate the intermittent hypoxia effects and thus we considered options to eliminate the 350 mbar pressure difference and maintain the same partial pressure of oxygen. The two main options were: direct pressure on the skin or adjustment of the concentration of oxygen. Physiologically, concentration of oxygen and partial pressures are directly related as shown by the alveolar gas equation. When adjusting the concentration of oxygen, however, there is a risk of oxygen toxicity that arises in addition to the risk of DCS due to pressure changes. Our design requirements then focused on finding a balance to mitigate both DCS and oxygen toxicity risk. As a result, we did research into current suits as well as breathing apparatuses.

From this research, we produced specific requirements for both the suit and potential breathing apparatuses. The main suit requirements were comfort, mobility, and thermal protection from the cold. There was initial interest in using a concept similar to the BioSuit to maintain pressure on the skin at 850 mbar, however the pressure that this suit could provide (1/3 atm) was unnecessary for our application after calculations were done with the alveolar gas equation (Table 1). Additionally, we determined a skin tight suit would not be comfortable or easy to take on and off as frequently as needed. The desired requirements for breathing apparatuses from the workers were to not have nose cannulas and to humidify the air to prevent dryness. From there, we looked into both masks and helmets. Other requirements we focused on were comfort to ensure the apparatus would be used and the ability to consistently maintain pressure. Therefore we eliminated masks in our considerations to focus more on a new helmet design.

The requirements for composition of air were decided upon through research into both SCUBA diving and space walks to determine common compositions. Space walks use 100% oxygen however this requires a long prebreathe to purge nitrogen from the system and presents a fire risk. Also, breathing pure oxygen for extended periods of time increases the risk for oxygen toxicity and there is no research into the effects of repetitive consumption of pure oxygen. On the other hand, typical SCUBA compositions are compressed air, Nitrox 32 (32% oxygen), and Nitrox 36 (36% oxygen). SCUBA also has dive tables that can be used to plan out repetitive dives while keeping track of the nitrogen in your system without extensive prebreathes. Thus, we focused more on SCUBA.

Operationally, the scientists and other workers would have a 10-11 hour work schedule with a lunch break and other smaller breaks interspersed. They would need to be able to come and go from the habitat in an efficient manner. Also, their daily tasks could range widely and often would involve tasks needing high dexterity and specialized tools. These operational requirements further defined and narrowed our scope.

4. Sensor suite evaluation

To accurately determine the effectiveness of the habitat and "suit" countermeasures against the hypoxia, the most important parameters that need to be quantified based on basic physiological, environmental specific, and hypoxia-specific parameters of interest were determined. As part of the basic physiological monitoring of scientists and workers living near TAO, body core temperature, heart rate, heart rate variability, and blood pressure were determined to be essential in measuring their overall health. In terms of hypoxia monitoring, the most important measurement is oxygen saturation in the blood. A similar measurement that is equally as important is the carbon dioxide saturation. Knowing both oxygen and carbon dioxide levels gives information about the gas composition of the environment and how the scientists and workers are responding to that environment. A less essential but interesting parameter is activity intensity. It would be worthwhile to determine if there are any correlations among activity levels at high-altitudes, blood oxygen levels, and susceptibility to hypoxia.

B. Results/System Design

1. ECLSS design

The ECLSS requirements were derived from a combination of four analyses: Top-Level Design Variables, Concept of Operations, Human Consumption and Production Assumptions, and Safety Limits (Appendices C-F). From these requirements sizes for power and consumable storage were created.

The Top Level Design Variables allowed for the scaling of consumables and definition of the size of tanks, their pressure, and how fast the habitat could be inflated. The Concept of Operations defined what tasks and for how long a crew member would perform them, allowing for specific derivations of consumption and production values, temperature, and energy needs for different activities.

The Human Consumption and Production Assumptions defined the inflow and outflow of oxygen, carbon dioxide, water (respiration/perspiration, urine, hydration), heat, and food, grouped into three operations. Food energy was broken down in 30% fats, 50% carbs, and 20% protein (NASA 2015). Estimates for how much to allocate for each subsystems, as well as which technologies to use, are dependent on mission duration (Table 2.3 in NASA 2015). For this habitat, most technologies and values were taken from lengths of "Very Long" (~10 years) and longer. However, to simplify and reduce costs, some values were taken from shorter mission lengths due to the fact that our crew member mission lengths will only be a week, but the total habitat mission length should be on the order of decades. For example, although a planetary mission of 10 years requires the crew to grow their food, our ability to switch crews every week, and the two hours commute to base camp, led us to the design decision to store food and resupply weekly, rather than include the necessary architecture to grow crops inside the habitat.

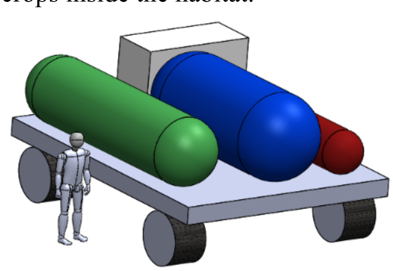


Figure 2: ECLSS Trailer

Sizes of tanks for air, water, and waste, as well as the size of a generator for power, were created based on requirements. These four components will be mounted on a trailer that can be towed away from the habitat for refill and maintenance (Figure 2). The tanks were given a cylindrical shape with half-spheres on each end. The tank diameters are 1.156, 1.488, and 0.0744 meters for oxygen, water, and waste tanks, respectively. The tank heights are 3.46, 2.23, and 2.23 meters for oxygen, water, and waste tanks, respectively.

Total power required for the habitat was estimated from pumps used for tanks and the sum of all the appliances expected to be used inside the habitat. The estimated total wattage was 39 kilowatts while the total kilowatt-hours per day was estimate at 229 kWh. A 48 kW generator was chosen for this and included in the ECLSS trailer. Alternatives to use a combination of a generator, solar panels, and wind power have been suggested, but the analysis has yet to be completed.

2. Habitat design

The habitat design was created with the influence of three components: meeting the derived ECLSS requirements stated above, meeting user and environmentally defined requirements for working in the Atacama desert, and a study of existing habitats with input and guidance from architect/designer Gui Trotti. The habitat will not only be used during the construction of observatories, but also during the continual daily maintenance of them.

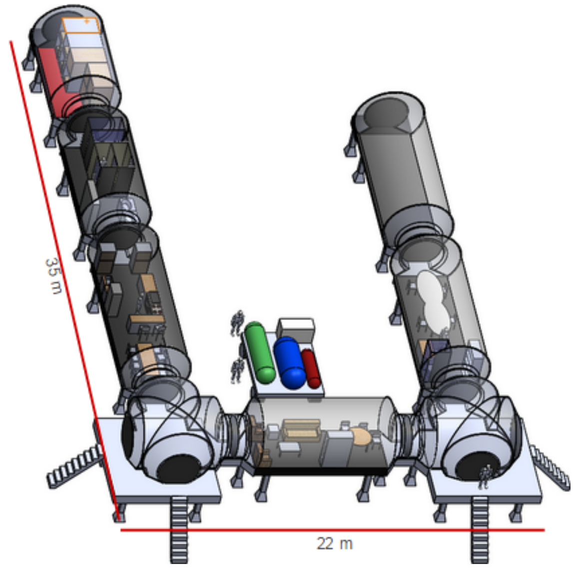


Figure 3: Habitat Design

The proposed habitat is composed of modules that attach together to form a user defined configuration. The current configuration uses 6 modules and two air locks, as well as the ECLSS trailer placed in the center for convenient access to all modules. The list of the currently designed modules includes a bedroom, bathroom, kitchen with dining area, a living room, a work/office room, an airlock, and an empty module that can be used as a gym or machine shop module. The ECLSS system is currently designed and scaled for the habitat configuration seen in Figure 3. The habitat and ECLSS together provide storage and consumables, as well as the necessary environmental controls, for a crew of 5 for 6 days. The habitat provides the atmospheric equivalent of the altitude at basecamp, minimizing the exposure of intermittent hypoxia by maintaining the same partial pressure of oxygen.

The habitat presented in the figure has a total of 922 cubic meters of habitable volume. Each module is a cylindrical inflatable cover attached to a solid platform. All platforms are 3.048 meters wide, but vary in length. The largest length the platforms can be is 13.5 meters. This limit in platform size is two-fold; it allows for easy manufacturability of the modules as well as allows the modules to fit on top of a standard flatbed truck for transportation from San Pedro de Atacama to the summit. The platform is 2 feet high and made of trusses. This allows emergency ECLSS tanks to be stored in the platform itself. Each platform is raised on struts. The struts are located at the edges of the platforms, at a distance wider than a flatbed truck. This allows a truck to easily transport the module to the desired location, lower the leg struts to raise the platform, drive the flatbed away, and lower the platform to the desired height. The leg struts adjust independently, allowing the modules to be located on uneven terrain. By raising the platform, the entire habitat is removable with minimal damage and contact to the terrain.

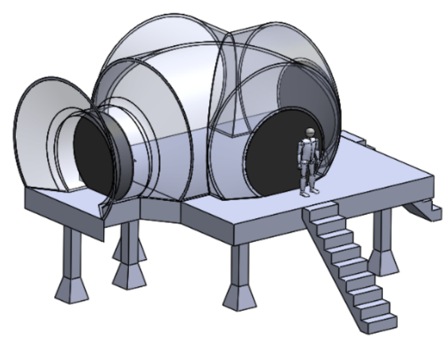
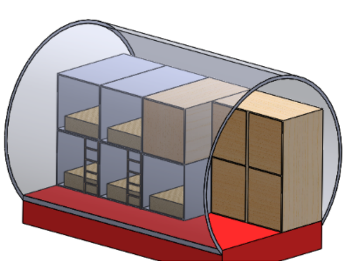


Figure 4: Airlock Design

The modules are all independently operated by the centralized ECLSS and connected via "connection" platforms. The connection modules also isolate each individual module, allowing for isolation of modules during emergencies. While a module is isolated, the emergency ECLSS inside the platform can allows for quick egress of the crew. To expand the habitat, a new module can be attached to the existing configuration using a connection module. A new module can easily be added to the habitat without the need to depressurize the entire habitat.

To connect two modules perpendicular to each other, an airlock must be used. An airlock is a square base platform with four doors. Two adjacent doors make use of a connection module to attach modules while the other two doors are used for ingress and egress of the habitat. The ingress and egress sides of the airlock have stairs leading from the raised platform to the terrain. Although also an inflatable, the airlock is the only module with hard ribbing to maintain its structure during depressurization when entering and exiting. When not in use for entering and exiting, the airlock is used as a passage between two modules connected to it. The airlock module houses components and tools used for outside activity.



The bedroom module makes use of Japanese Sleep Pods with extra long twin size beds in each one. The pod provides a small shelf for holding items, lighting, as well as individual temperature control. Although not pictured, each pod has a door that can be used for privacy. Additionally, in an emergency where a crew member is displaying symptoms of hypoxia due to the high altitude, a crew member can be placed inside a pod and increase the percentage of oxygen in the air for an individual pod.

3. EVA design

After substantial deliberation, it was determined that the best solution for the work outside of the habitat would include a breathing apparatus in addition to a compression garment to account for the lack of pressure of ambient air outside the habitat. Due to the fact that the summit is at an altitude that provides near half an atmosphere of pressure, the substantial decrease in oxygen concentration causes more problems physiologically than does the lack of pressure on the skin. Based on the limited previous studies and work done by researchers in the field, we determined that in order to completely eliminate the effects of hypoxia, we must maintain a constant partial pressure of oxygen throughout the entire 5-14 day mission. And specifically, from the requirements mentioned above, we determined that our partial pressure of oxygen needed to stay constant at 101.5 mbar between the habitat and work outside in order to maintain the 850 mbar total pressure required. This allowed us to manipulate the fraction of inspired oxygen and atmospheric pressure in the alveolar gas equation to calculate our final recommended composition and pressures of EVA breathing air. The saturated vapor pressure of water and partial arterial pressure of CO_2 were held constant at the values appropriate for our altitude. The respiratory exchange ratio is approximately the same for all altitudes and people. For an EVA without any extra pressure from a suit, the concentration of oxygen would need to be 37.3%. The realm of concentrations of oxygen between 21% and 100% is not very well studied in regards to oxygen toxicity risk. Therefore, we considered a second option of 32% oxygen concentration, which is a more common level used in diving. For this fraction, you would need an additional 74.8 mbars of pressure applied to the skin to maintain the required partial pressure of oxygen. These results are summarized in Table 1.

Table 1: Calculations of Fraction of Inspired O2 to match Habitat and EVA (pressures in mbar)

	Fixed	**Variables**			**Constants**		
	P_AO_2	**F_IO_2**	**P_{atm}**	**Extra Pressure on Skin**	**PH_2O**	**P_aCO_2**	**RER**
Habitat	101.5	21%	850	0	62.66	53.33	0.8
EVA (No Suit)	101.5	37.3%	500	0	62.66	53.33	0.8
EVA (Suit)	101.5	32%	500	74.8	62.66	53.33	0.8

Design of an operational schedule was based on analysis of PADI dive tables for two different air compositions: Nitrox 32 and Nitrox 36. Dive tables are used by SCUBA divers to plan out how long they can stay at a certain depth under the water as well as what amount of rest they need between repeated dives to manage the nitrogen in their bodies to avoid decompression sickness. To draw the parallel between our EVA and a dive, we determined that our transition in pressure from habitat to outside was approximately similar to taking an 8.28 ft dive under water. Dive tables typically start at 40-50 ft dives so when we created an operational schedule, we used this smallest value which was still 30-40 ft deeper than our "dive" thus representing a much higher pressure difference than our scenario. This meant we could design schedule that was almost guaranteed to be safe since the constraints were much stricter than ours. We produced two example schedules for both Nitrox 32 and Nitrox 36 for 8 hours of work. This schedule required two 1-1.5 hour breaks and three 2-3 hour blocks of work. This schedule could be adjusted by changing the periods of work and rest to better fit the actual scenario. However, we proved it was possible to create an operational schedule that could lessen DCS risk for the workers at this site (see Figure 6 for 32% O_2 and Appendix G for 36% O_2).

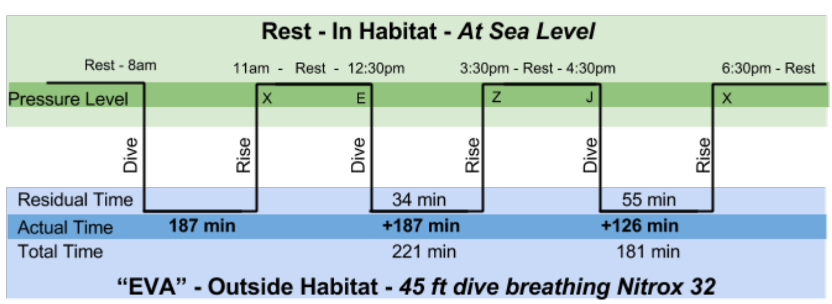


Figure 6: Operational Schedule based on PADI Dive Table for 32% O_2

Once an adequate understanding of operational schedules and oxygen requirements was reached, we began to search for commercially available helmets that might suit our needs. We found a conceptual design for a SCUBA helmet that we adopted and expanded for use in this situation. The Immersed Senses helmet, shown in Figure 7 is a completely interactive scuba diving helmet. Designed by ID student Adam Wendel in 2010, this concept was created as the "next generation of deep sea diving," integrating several pieces of cutting edge technology to completely eliminate the need for oxygen tanks and physical dive tables. The battery-operated system uses a centrifuge mechanism to extract oxygen from seawater to begin an electrolysis reaction. The saltwater is then charged by an anode/cathode to generate breathable oxygen. Internal devices circulate oxygen within the helmet while also scrubbing carbon dioxide from the system.

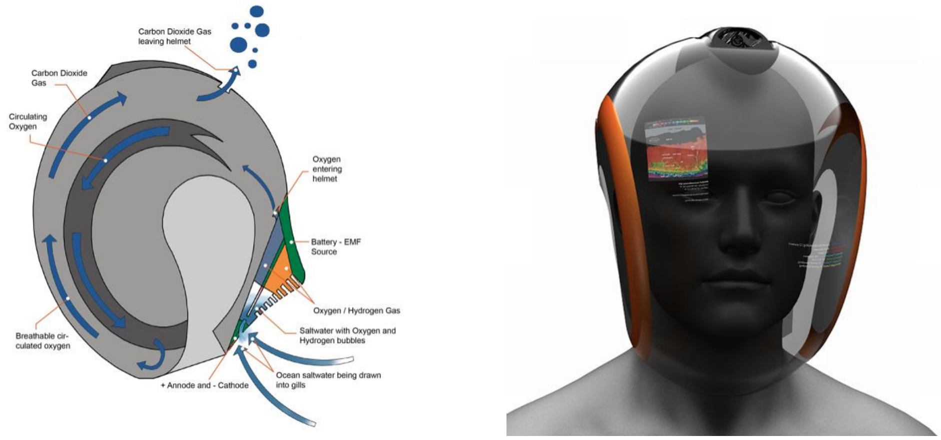


Figure 7: The Immersed Senses Scuba helmet created by Adam Wendel, 2010.

Beyond the breathing mechanism inside the helmet, it also includes a large OLED glass display providing a panoramic view of the surroundings and offers access GPS maps as well as software to identify surroundings. A task list or operational schedule is flashed on the screen in addition to current oxygen levels, specific locations, and other needed information.

This concept, though not entirely applicable in our situation, sparked the idea of completely eliminating the need for an oxygen tank, or using today's technology to minimize the size of the tank and other units that must be carried, especially when these workers will be doing significant work during their "EVA"s. An ideal helmet in this situation would take in ambient air and mix that air with concentrated oxygen to reach the desired enriched oxygen mixture within the helmet. This need gave way to further research into systems that could potentially provide us with those solutions. The result of these findings included two devices: the oxygen concentrator and the Nitrox Sitk, pictured in Figure 8.

The oxygen concentrator takes ambient air (approx. 80 percent nitrogen, 20 percent oxygen) and runs it through a system of molecular sieve beds to remove the nitrogen from the air, releasing a mixture of 95 percent oxygen, with the rest of the air composition being trace elements. This technology would remove the need for pure oxygen tanks, and this air could then be fed into the Nitrox Stik system to create the enriched oxygen mixture. The Nitrox Stik combines pure oxygen with ambient air to make Nitrox. An oxygen analyzer and several regulators are used to ensure the desired levels of oxygen are being met and that the system is working as it should.

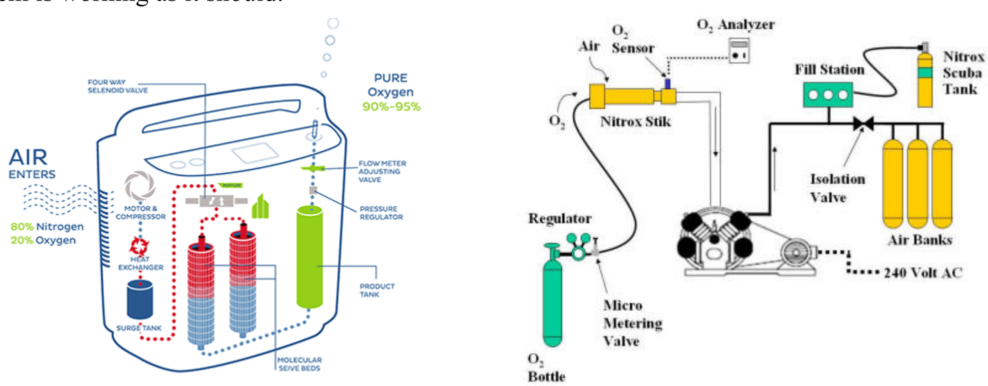


Figure 8: The oxygen concentrator (left) and Nitrox Stik (right) that could be used to turn ambient air into a desired enriched oxygen mixture.

Both of these systems could be integrated to feed either Nitrox 32 or Nitrox 36 into the helmet. An LED display could provide the researcher with his/her task list for the day, offer communication between researchers and others on site, and could even give updates on life support system readings. This technology could be the way to eliminate the need for bulky tanks and oxygen lines, and would make moving around in these environments much easier.

As mentioned previously, the oxygen concentration of the Nitrox could be in a range, depending on whether or not a "suit" would be desired. To reiterate, the 32 percent oxygen composition is a more commonly breathed mixture, which is more understood and the effects have been documented, but in order to maintain the same partial pressure of oxygen in our situation, we would need to supplement this breathing air with 74.8 mbar of pressure on the skin. To do so, a custom compression garment that provides the necessary pressure could be manufactured. In our research, we found several garments used for other applications that could help in this supplementation. Most notably include Jobst Compression sleeves or socks, which provide up to 55 mbar of pressure, or Innovation in Textile's full-body athletic compression garment, which can provide up to 42 mbar of pressure on all areas of the skin. Commercially available units such as these could help supplement a lower concentration of oxygen and reduce the need for prebreathe in many cases.

4. Sensor suite

The proposed sensor suite contains two sensors that were chosen because they met the desired parameters of interest, would not affect the mobility of the scientists and workers, and satisfied the strict radio frequency requirements. The first sensor in the suite is the Samsung Simband, a health sensor that is worn on the wrist. The Simband has an number of sensors in a small, lightweight band to measure heart rate, blood pressure, blood oxygen and carbon dioxide levels, heart rate and heart rate regularity via electrocardiography (ECG), blood flow and body fat using bioimpedance, the electrical conductivity of skin, which gives insight into the amount of sweat produced, via galvanic skin response, and skin and core body temperature (Samsung). Unlike other pulse oximeters which require a finger cuff, the Simband, is worn like a watch, so it will remain unobtrusive and will not affect the work of the scientists and workers. Simband has a real-time display that allows wearers to constantly monitor their vitals with the ability to store locally.

The last sensor in the suite is the ActiCalZ, a physical activity monitoring system that measures step counts, activity level, and energy expenditure using an omni-direction accelerometer. The waterproof ActiCal gives the wearers additional flexibility and can be worn on the wrist or ankle or clipped onto a belt depending on their preferences. It has a 32 Hz sampling rate, and all the data is initially stored on its on-board memory. The raw and processed data can be transferred to a computer using a 9-pin RS-232 serial port or a 9-pin serial to USB adapter (ActiCal).

V. Discussion - reiterate results, provide justifications, more detail, and limitations

A. Habitat design

1. Discussion of results

The habitat design proposed satisfies the requirements placed by the University of Chile as well as all the derived human requirements. Easy transport is made feasible by limiting the size of modules to the size of a flatbed truck. Modularity is achieved by connecting each module with a connection module or an airlock. Maintenance is fairly straightforward with a centralized and mobile ECLSS trailer. Emergency mitigation is achieved through the ability to isolate modules through connection modules.

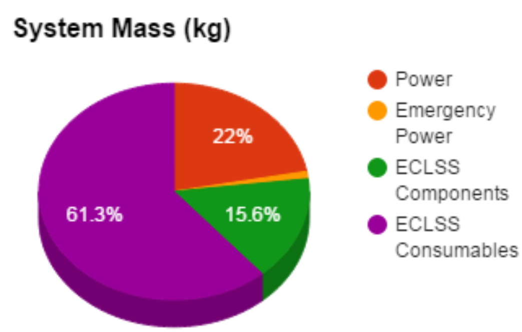


Figure 9 – System Mass

It is clear that the habitat structure itself has the largest mass of the habitat. However, if we only compare ECLSS components, we find that consumables account for the largest total mass (1914 kg). Consumables include oxygen consumed, oxygen to fill the habitat, water for hydration, medicine, hygiene, and food preparation, as well as food mass. Power, which currently only consists of a generator at 687 kg, can be lowered with the use of solar and wind energy. ECLSS components, which refers to component mass (empty tanks, cartridges), account for 486 kg of the total ECLSS mass.

2. Limitations & future work

There are a number of improvements that could be made to the habitat design. For example, the power considerations calculated here suggested the need for a 48 kW generator, but at high altitude the efficiency of such a system decreases by approximately 50%. Further calculations should be done to look into alternatives such as wind power, possibly combined with the solar panel option that we investigated here. Additionally, the current habitat design does not include windows, which will affect the structural and architectural design of the habitat.

The main limitation of our habitat design is that it is primarily conceptual. While we have done a thorough evaluation of the structural, operational, and environmental requirements and come up with estimates of power, life support consumables, and other values, much work would remain to be done if this concept were to become a reality. Most importantly, a full engineering analysis of the habitat would need to be performed in order to ensure structural stability, use of appropriate insulation, feasibility of the inflatable architecture, and a number of additional considerations. Furthermore, a meeting would need to be held with all of the stakeholders in this project in order to be sure that all requirements and needs have been discussed. While we held bi-weekly meetings with a couple of current scientists at the ALMA observatory, we would need to meet with those who will actually be using the facility – presumably the Japanese scientists in charge of the Tokyo Atacama Observatory. Such a meeting would likely bring up a number of design considerations that may not have been thought of previously.

B. EVA design

Similar to the habitat design, the helmet design is almost entirely conceptual. Our suggestions provide a way of understanding the issue and attempt a solution, however actual implementation will require substantial work beyond what we have laid out here. Perhaps the biggest obstacle we are fighting against is that individual people have such varying responses to hypoxic environments. We are operating at an altitude in which many people can walk outside, breathe and work relatively normally, and come back inside without any issues. However these levels of oxygen could be fatal to others. This uncertainty has caused a lot of misunderstanding in the field, and we have experienced quite a bit of that ourselves. It is puzzling to try to suggest a solution when different people react this environment in such different ways, and they also have different preferences as to breathing apparatuses and garments.

The best solution to offer is a suggestion of where to start in tackling this problem, and a lot of the implementation will be trial and error until the exact needs and predispositions are better understood. Our solution combines some of the existing countermeasures used to combat high altitude issues and new technologies in a more unifying way than has been done in the past. Treating the work outside the habitat like an EVA also presents a new way to consider the issue that can lead to more comprehensive solutions that prevent and eliminate the entire problem rather than the current method of reacting when issues arise.

For future work, a new helmet design must be created either integrating the technology described above, or using these concepts to create a self-sufficient device that is easy to don and is comfortable for the users. From there, it would be necessary to study the effects of prolonged use of enriched oxygen mixtures at various levels for extended periods of time. Before this technology can be widely used, it is critical to understand the effects that these countermeasures could have.

VI. Conclusion

As TAO is set to be built in early 2016, contractors, workers, technicians, and scientists will soon begin to arrive at Cerro Chajnantor, and they will be exposed to the harsh, high-altitude environment. Due to the decreased oxygen levels, they may become highly susceptible to hypobaric hypoxia and chronic intermittent hypoxia, especially if they have homes at sea level and need to make the large vertical ascent and descent every few days. Therefore, a conceptual design of a countermeasure including a pressurized habitat and exploration capability and a sensor suite for further understanding the physiological issues of hypoxia was created. The modular, portable, and inflatable habitat provides a pressurized environment where TAO staff can live without suffering from low oxygen levels. They can also work on the telescope installation outside the habitat using a combination of helmets and compression garments without worrying about decompression sickness or re-adjusting to the slightly higher pressure habitat. As they are working in the high-altitude environment, they will also be wearing two sensors that will monitor that important physiological parameters such as heart rate, blood pressure, core body temperature, blood oxygen and carbon dioxide levels, and energy expenditure so the causes and effects of hypoxia can be better understood. Further design and implementation of these countermeasures may be possible in the future through a potential collaboration with the University of Chile and TAO.

VII. Outreach

For outreach, we worked with the Society of Women Engineers (SWE) program called Keys to Empowering Youth (KEYs) which involves 30-40 middle school girls visiting MIT for a day of hands-on learning. We presented about humans in extreme environments focusing on space, SCUBA diving, and high altitude. Our goal was to introduce the girls to this intersection of life sciences and engineering as well as inspire them to be curious about STEM. We provided the students background on the various extreme environments and the current difficulties and countermeasures for living and working in them. Then, we described the basic requirements for designing a habitat and suit, giving a variety of examples. We ended with a challenge for them to work in teams and design their own habitats or suits for Mars, emphasizing creativity. The team interacted with the groups to see what they were creating and to provide insight on their designs. The girls enjoyed this task and produced several creative and also practical designs.

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APPENDICES

Appendix C: Top Level Design Variables

Hab/airlock combined value	922.22	*m^3*
Number People	5	people
"Number Days"	6	days
Habitat Temperature	295.15	K

Appendix D: Concept of Operations

*Note: This is worst case scenario (full 8 hours of EVA consumables). In addition, the housekeeper will spend 0 hours in EVA and all their time inside the habitat. Values show total hours of a specific operation and are not indicative of time of day in which that operation is executed.

Operations (Day)	Time Start (hr)	Time End (hr)	Time Spent (hr)
Sleeping Habitat	0	8	8
EVA	8	8	0
Active habitat	8	24	16

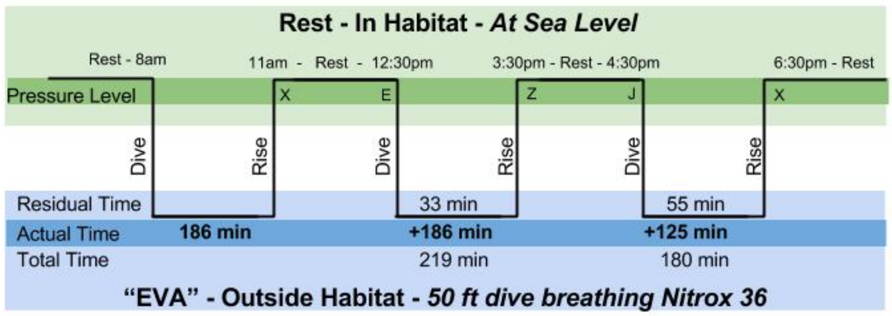
Appendix E: Human Consumption and Production Assumptions
*Values compiled from Human Integration Design Handbook and the NASA Baseline Values and Assumptions Document. Values separated into three operations. Values are presented in Crew Member Days (CM-d) or Crew Member Hours (CM-h)

Awake, EVA	**Use/CM-d AVG (kg or MJ)**	**Consumption/CM-h EVA (kg or MJ)**	**Molar Mass (kg)**	**Consumption/ CM-h (mol)**
Oxygen	-	0.075	0.032	2.344
Carbon Dioxide	-	-0.093	0.044	-2.114
Water (respiration/perspiration)	-	-0.294	0.018	-16.343
Water (urine)	-1.7	-0.071	0.018	-3.935
Water (hydration)	2	0.365	0.018	20.278
Heat Load (sensible) (MJ)	6.31	-0.566	-	-
Heat Load (latent) (MJ)	5.51	-0.494	-	-
Food Energy (MJ)	-	1.062	0.04611897131	-
Awake, Habitat	-	-	-	-
Oxygen	-	0.03408	0.032	1.065
Carbon Dioxide	-	-0.0432	0.044	-0.982
Water (respiration/perspiration)	-	-0.07062	0.018	-3.923
Water (urine)	-1.7	-0.071	0.018	-3.935
Water (hydration)	2	0.125	0.018	6.944
Heat Load (sensible) (MJ)	-	-0.329	-	-
Heat Load (latent) (MJ)	-	-0.171	-	-
Food Energy (MJ)	14.393	0.8995625	0.03906487489	-
Sleep, Habitat	-	-	-	-
Oxygen	-	0.0216	0.032	0.675
Carbon Dioxide	-	-0.0273	0.044	-0.620
Water (respiration/perspiration)	-	-0.0378	0.018	-2.100
Water (urine)	-1.7	-0.071	0.018	-3.935
Water (hydration)	-	0	0.018	0.000
Heat Load (sensible) (MJ)	-	-0.224	-	-
Heat Load (latent) (MJ)	-	-0.092	-	-
Food Energy (MJ)	-	0	0	-

Appendix F: Safety Values

Safety Values	
Max EVA CO2 partial pressure (kPa)	3
Min EVA O2 partial pressure (kPa)	21
Max habitat CO2 partial pressure (kPa)	1.03
Min habitat O2 partial pressure (kPa)	29.7
Max ppH2O (kPa)	1.86

Appendix G: EVA Operational Design for Nitrox 36



Operational Schedule based on PADI Dive Table for 36% O_2