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Pressure Suit Vacuum Chamber Testing

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Contents

Overview

The University of Arizona's Center for Human Space Exploration is interested in testing pressure suits it has developed as well as suits its partners have developed at the Midland TX Spaceport high altitude chamber. We would like to do both uncrewed and crewed "flights" in the chamber to 60,000 ft MSL and above.

Anticipated testing details and outline described in this document as provided by the Midland Chamber Facility and UA personnel.

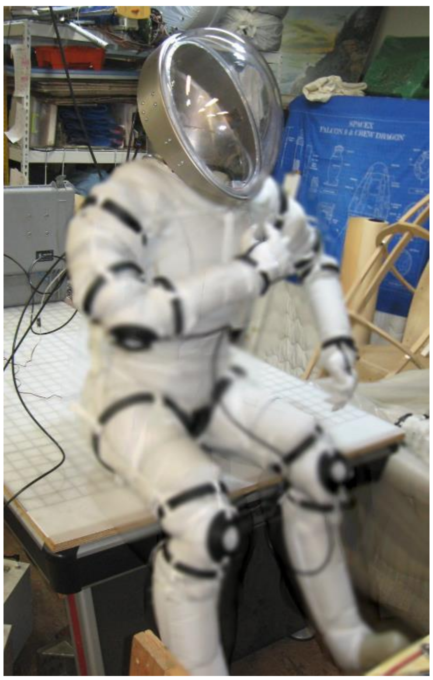


Figure 1 Pressure suit designed, developed and tested by Flagsuit and UA

Figure 2 Pressure suit testing flight. Suit designed by Cameron M. Smith

Midland Testing Process

Upon arrival in Midland the testing team will overview all site safety procedures and assigned roles for testing. Next, integration of gaseous oxygen supplied by Airgas in Odessa Texas, sensors, radios, chamber plate and suit will be installed inside/around the chamber as appropriate. An operating safety "no walk" zone will be established.

An initial uncrewed dry run without reduced pressure in the chamber will be shown successful (full suit pressure (~4psi). A second test briefing will then take place to establish the flight profile of uncrewed testing.

Following the initial test, we will operate an uncrewed full flight profile to near space altitudes, checking nominal operation of suit with our sensor array. Once three full profiles have been successfully flown and suit efficacy at altitude has been proven (full pressure and nominal gas flow) we will move to human in the loop testing.

Human in the loop testing consists of an appropriately trained volunteer test subject. This test subject will have successfully passed a hypobaric program to understand their signs of hypoxia. The volunteer will be medically checked out for the flight by the assigned medical personnel.

Before human in the loop testing, a safety briefing will be had to reestablish clarity in roles and emergency response procedures.

Emergency Communication Systems

An intercom system is provided within the MACC. One channel provides communication between the control room and the chamber room. This allows for both operational communication and notification of emergencies. It also allows the test conductor to convey information to personnel in the room during non-operational events.

Systems used to notify building occupants of an emergency are covered by various NFPA codes and standards. Requirements exist for speakers used for emergency communications and alarm signals, as well as for mounting and locating audible and visual indicating appliances such as bells, horns, chimes, or strobe lights (NFPA 72, 101).

A second and third channel provide communication between the control room and the Cabin and Suit chambers. This system can be used to provide instructions to individuals within the chambers to assure they understand the activities that will take place and to provide warning and instructions in cases of emergency.

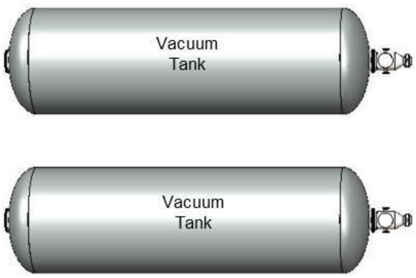
Emergency Stop Button

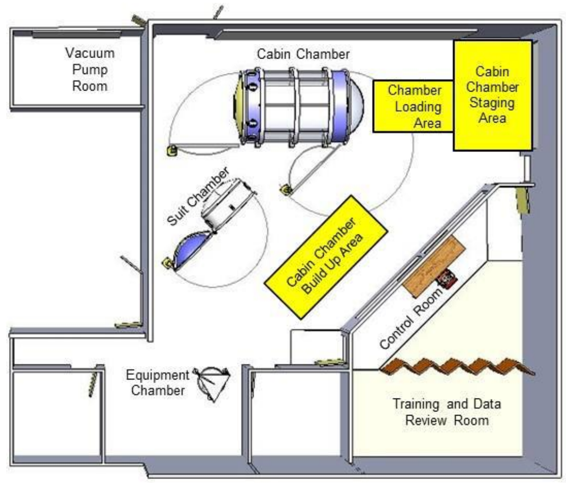
A button is installed in the Suit Chamber and in the Cabin Chamber as well as in the control room that will allow occupants of the chamber or participants in the control room to interrupt control signals to several valves. This will cause the valves to rotate to their Safe position, closing off the vacuum source and opening the outside air source; bringing about a rapid return to ground level air pressure inside the Chamber.

Note: the emergency stop button returns to chambers to ground level very quickly. Doing so when personnel in the chambers are at high altitudes may cause severe injury, so this action should only be taken in life threatening situations.

A key is attached to the Emergency Stop Button, which will need to be inserted before the button can be returned to the normal run position after it was pushed. This will avoid a rushed and potentially damaging reset of the system after a trip of the Emergency Stop actions.

Facility Layout





Safety Contacts

In case of emergencies, personnel should call 911 for police, ambulance, or fire. In the event of a depressurization accident, the nearest hospital should be called. Hyperbaric chambers and other emergency care can be found at the following nearby facilities.

Facility	Phone	Location
Memorial Hospital and Medical Center	915-685-1532	2200 W Illinois Ave.; Midland, TX
Westwood Medical Center	915-522-3563	4214 Andrews Highway; Midland, TX
Medical Center Hospital	432-640-4000	500 W 4th St.; Odessa, TX
Shannon Medical Center	325-653-6741	120 E Harris Ave.; San Angelo, TX
Covenant Medical Center	806-796-6117	3615 19th St.; Lubbock, TX
Cardinal Health	806-795-8251	4324 23rd St.; Lubbock, TX
Southwest Regional Wound Care Center	806-793-8869	2002 Oxford Ave.; Lubbock, TX
Abilene Regional Medical Center	325-690-4662	6250 US-83; Abilene, TX

Hendrick Medical Center	915-670-4185	1900 Pine St.; Abilene, TX
West Texas Hospital	325-692-1116	5602 Health Center Drive; Abilene, TX

Assigned Roles

Test Conductor/Responsible Engineer: TBD
Oversee all aspects of test operations, responsible for successful completion of test objectives and safety of participants. Monitor and operate gas flow equipment. Authority for abort execution.

Chamber Operator: TBD
Control the chamber pressure and execute an abort in case of an emergency.

Lead Test Technician: TBD
Assist test set up equipment, suit donning, and test documentation. Set up video cameras and data acquisition. Perform rapid egress of subject in an abort.

Test Technician 2: TBD
Assist with test set up equipment, suit donning, and test documentation. Set up video cameras and data acquisition. Perform rapid egress of subject in an abort.

Biomedical Safety Representative: TBD
Provide biomedical training to subject. Monitor pre-breathe execution, physiologic data, subject behavior and performance. Monitor for biomedical test termination criteria, determine necessity for abort, and inform test conductor of abort mode.

Flight Surgeon: TBD
Determine fitness for duty. Provide consultation on any subject signs or symptoms. Evaluate any injuries and determine need for transport to definitive care or hyperbaric chamber.

Emergency Medical Provider: TBD
Provide immediate medical care prior to patient transport if needed.

Example Testing Checklist and Operations

☐ Pre-test verify proper suit configuration

a. Suit pressure garment pre-test inspection completed by (initials):

☐ Verify test setup per Suit Qualification Milestone Vacuum Chamber Test Procedure (or similar)

☐ A dry run of all emergency test protocol will be conducted prior to the manned chamber test.

a. completed date and inspector initials:

☐ A full duration unmanned dry run at pressure will be conducted prior to the manned test.

a. completed date and inspector initials:

☐ No other operations will be conducted in the chamber facility while testing is in progress.

☐ All test participants will be familiar with the proper exit route

☐ All test personnel have been trained/briefed on contingency and emergency procedures

- Power outage
- Suit failure / rapid depressurization
- Fire in the chamber
- Fire in the suit
- Test subject medical issue (Hypercapnia, Hypoxia, DCS, Cardiac event, Overheating)
- Suit over-pressurization

☐ Test personnel have been briefed on test abort criteria and response

☐ Test personnel and test subject have been trained / briefed on hand signals for use in case of loss of communications

☐ Test subject has been screened for medical risks including:

FAA 3rd Class Medical, USAF 3rd Class Medical, or equivalent	Date completed:
Chest X-Ray	Date completed:
Spirometry	Date completed:
Complete Blood Count	Date completed:
Pregnancy Test	Date completed:
Physiological Training / Hypobaric Chamber exposure	Date completed:

☐ Go/No Go: Flight Surgeon clearance granted: Y / N

☐ Subject completes training on middle ear equalization, avoidance of breath holding, and low flatulence diet

☐ Physician performs a physical exam to evaluate the subject's fitness for duty within two days of

☐ Medical support placed on standby morning of test: EMS, helicopter transport, airport tower, Level 1 Trauma Center, and hyperbaric facility

a. details to be provided

☐ Test subject has donned suit unit

a. sensor testing

b. life support testing

c. ________ minute prebreathe as per NASA operations

☐ Test Subject has taken pre-test preps and medications:

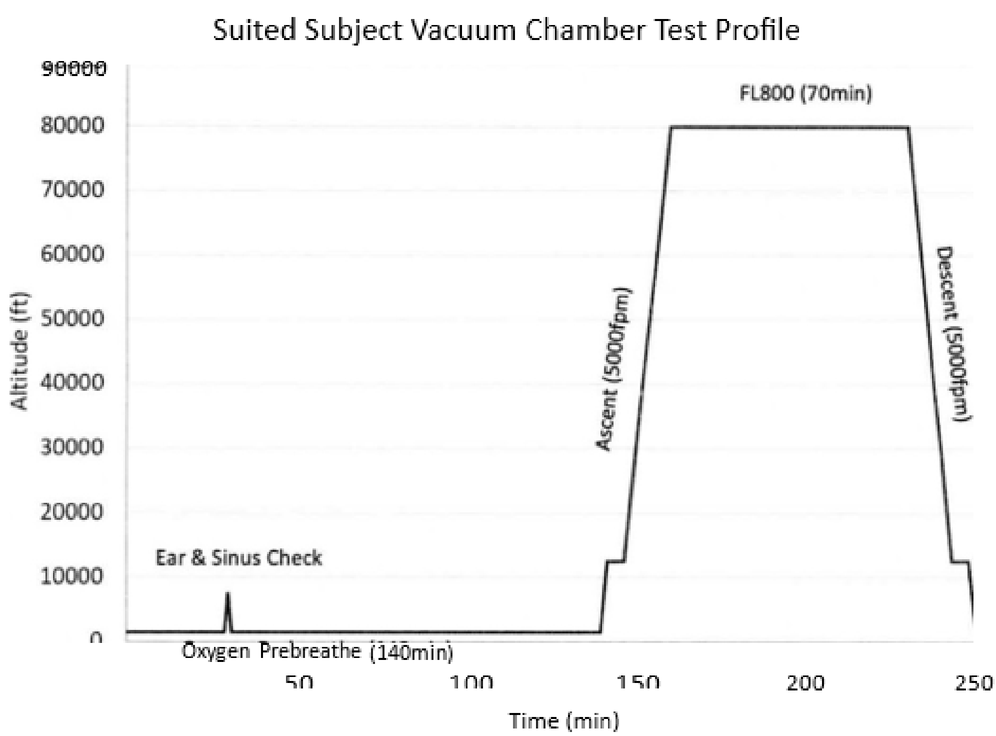
a. remove contact lenses: Y / N

b. Aspirin 2x 180mg optional: Y / N

c. Oxymetazoline (Afrin) nasal spray optional: Y / N

d. Eyedrops optional: Y / N

☐ Test pressure profile: (example)



☐ Verify all electrical systems inside the chamber powered off for duration of testing with oxygen

☐ Test subject enters chamber and connects to umbilical

a. Perform comms check: verify suit avionics operating properly

b. Life support system check

☐ Don oxygen mask and perform pre-breathe on 100% oxygen in order to reduce the risk of decompression sickness (DCS). 2 hours 20 minutes total pre-breathe time.

a. Record Time at start of pre-breathe:

b. Calculate Time for ear & sinus check (Start + 1 hrs 50 min):

c. Calculate Time at end of pre-breathe (Start + 2 hrs 20 min):

d. Remain visors up to continue pre-breathe on mask, Remain on oxygen mask throughout, Zippers may remain open for comfort

e. About 2 hours prior to climb to test altitude] Subject uses Afrin nasal spray (1-2 sprays in each nostril)
- Record Time of nasal spray:

☐ Test technician enters chamber

☐ Climb to 7,500 ft at 5,000 feet per minute. Maintain 7,500 ft for 5 minutes. Descend to ground level at 5,000 feet per minute.

a. Subject and Test Technician perform middle ear equalization throughout ascent and descent to identify any issues that may lead to injury during full altitude profile

☐ Go/No Go: Flight Surgeon clearance granted for climb to altitude: Y / N

☐ Camera on

☐ Data logging on: Y / N

☐ Test director polls team, ready to close chamber: Y / N

☐ Test Technician verify grounding straps on, pockets empty

☐ Test Technician is ready in chamber with test subject

☐ Verify fire extinguisher present, medical oxygen in chamber

☐ Close suit zippers and visually confirm

☐ Connect seat restraint harness if required

☐ Close chamber outer door

☐ Test Technician don oxygen mask and start flow
☐ Ascend and maintain 12,500 ft at 5,000 fpm
a. Record Time at start of ascent:

- Subject remains on oxygen mask until reach 12,500 ft.
- Test Technician to stay on oxygen mask during ascent and when at altitude, except when it is necessary to remove mask to assist Test Subject.
- Monitor health of Subject and Test Technician and adjust ascent rate as needed

☐ Test Technician purge suit with medical oxygen through umbilical connector fan air port
  a. Purge for 10 minutes at approximately 8 LPM

☐ Go/ No go: Pre breathe verification time complete: Y / N

☐ Subject removes oxygen mask and closes visor, with assistance from Test Technician

☐ Initiate oxygen flow to suit at 22.95 slpm ± 2 lpm

☐ Confirm visor seal inflation: Y / N

☐ Monitor suit pressurization

☐ Ensure that suit reaches expected delta pressure of 21.8 psi
  a. Before proceeding, record suit pressure:

☐ Test Technician confirm flow to both oxygen masks is OFF

☐ Perform Comms check: verify suit avionics operating properly

☐ Depressurize chamber, Test Technician exits chamber

☐ Confirm medical oxygen and fire extinguisher removed from main chamber

☐ Ascend main chamber to 77,000 ft. at 5,000 fpm
  a. Start timer when 63,000 ft is reached:
  b. calculate time to stop:
  c. record final altitude:
  d. record suit pressure:

Monitor suit pressure and suit delta pressure (calculated based on suit and chamber pressure transducers) to ensure suit is maintaining pressure as expected.

Record chamber pressure, suit pressure, flow rate at 5 minute increments

Subject should remain still (except to relieve any hot spots), report any pain or discomfort to test personnel, and otherwise remain in communication periodically.

☐ After 70 minutes at altitude, descend and maintain 12,500 ft at 5,000 fpm

☐ Terminate gas flow to depressurize the suit

☐ Descend to ground level at 5,000 fpm

☐ Open chamber and assist test subject in egressing

☐ Doff suit with assistance from Test Technician (grounded)

- Non-grounded personnel to stay back due to residual oxygen in suit
- Suit to remain in place 30 minutes to allow residual oxygen to dissipate

☐ Flight surgeon performs post-test medical evaluation of test subject.

☐ Record oxygen bottle pressure

Test Abort Criteria

The test will be aborted if the test subject or any personnel are in danger, and/or if any equipment required for safety or to fulfill test objectives is not functioning properly.

Subject requests test termination with hand signal or verbal, pain indicative of Type I decompression sickness if any of the 1 or 2, depending on severity following are met:

a. Pain is moderate to severe with impairment of function
b. Pain is mild to moderate and constant, beginning early in test, and progressive

If Loss of Comm - Continue Test

- Look for OK hand signal from subject every minute
- Monitor subject for Abort hand signals

Hand signals

OK	One arm
Loss of comm	Touch visor
Level off	One arm e
Abort Category 2 (not feeling great, no comm)	Both hands ↔↔↔
Abort Category 4 (fire in suit or rapid depress, no comm)	Both hands

TEST ABORT Category 1:
For a non-time-critical abort, the standard descent profile at 5,000 feet per minute will be followed. Maintain oxygen flow to the ground. Total time: 17 minutes.

TEST ABORT Category 2
For a semi-time-sensitive abort, a descent at 10,000 feet per minute will be performed, the fastest descent rate without risk of barotrauma. Maintain oxygen flow to the ground. Total time: 8.5 minutes.

TEST ABORT Category 3
For a rapid abort, a rapid descent to 25,000 ft followed by a controlled descent to ground level at 10,000 feet per minute will be performed, which should prevent ear damage. Maintain oxygen flow to the ground. Total time: 3 minutes

TEST ABORT Category 4
For an immediate abort, an immediate descent to ground level will be performed. This is likely to cause barotrauma and should only be used in serious emergencies. Maintain oxygen flow to the ground. Total time: <45 seconds.

Fire in chamber or suit, follow abort category 4

1) Fight Fire
2) Shut off power to comms
3) Terminate oxygen flow and safe flow panel

Wall, floor, and ceiling penetrations for cables, etc. have been sealed to prevent the spread of fire and smoke. Any new penetrations must be similarly installed.

Fire extinguishers are installed in the facility and are mounted on the walls with no more than 150 feet of separation between them. Additionally, two fire extinguishers are available for use inside the Cabin Chamber (near the front and back doors) and one for use inside the Suit Chamber.

Post Abort

1) Call in emergency services (conditional)
2) Terminate oxygen flow and safe flow panel
3) Disconnect umbilical
4) Open visor

Chamber controls for Abort (example)

Category	Descent Rate	Procedure
1	5,000' per minute	Controlled
2	10,000' per minute	Controlled
3	Rapid to 25,000'	Full open
	10,000' per minute to ground level	Controlled
4	Rapid to ground level	Full open

Testing Notes

Record of chamber pressure, suit pressure and flow rate:

Time	Chamber Pressure	Suit Pressure	Flow Rate

APEX Risk Analysis of CHaSE Pressure Suit Testing

Introduction

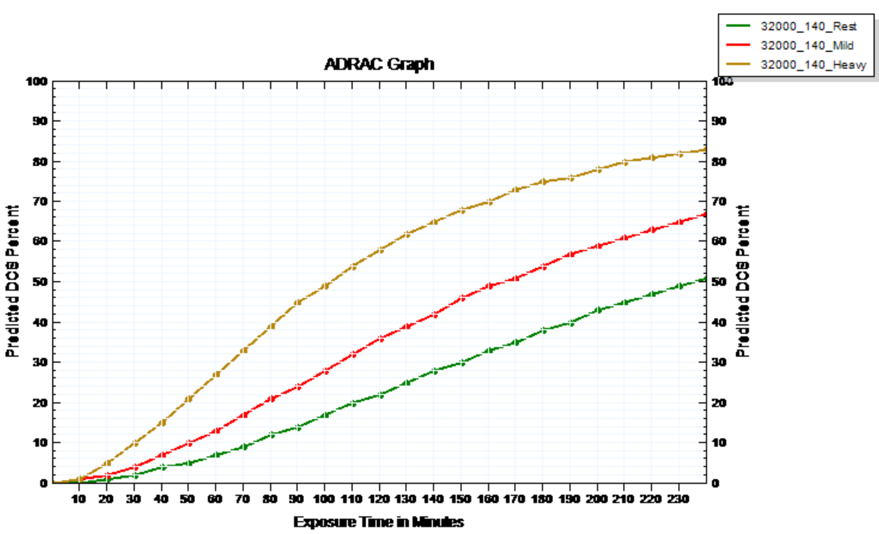
Space suit testing in hypobaric chambers is a crucial step in evaluating the safety and performance of suits designed for high-altitude and space environments. This testing involves subjecting the suits and wearers to simulated high-altitude conditions, where reduced atmospheric pressure can lead to a range of physiological challenges. The primary risks associated with such testing include decompression sickness (DCS), arterial gas embolism (AGE), hypoxia, hypercarbia, and barotrauma, among others. Therefore, meticulous planning and risk mitigation strategies are essential to ensure the safety of subjects during space suit and hypobaric chamber testing.

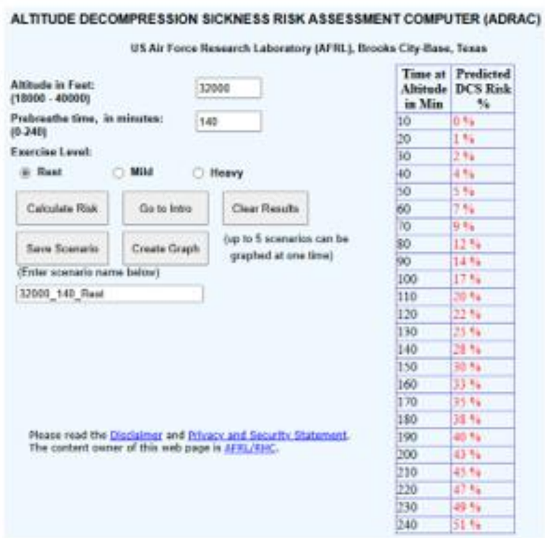
Flight Profile

The chamber profile for testing to 80,000 feet involves a gradual ascent through various altitude thresholds, allowing for real-time monitoring of physiological responses and suit performance. At an altitude of 80,000 feet, the ambient pressure is 0.221 PSI (11.43 mmHg). The CHaSE suit is designed to maintain at least an internal pressure of 4 PSI above the ambient pressure, providing a protective environment for the wearer as they are exposed to extreme hypobaric altitude pressures. The suit's internal pressure of 4 PSI (206 mmHg) is equivalent to a pressure altitude of 31,900 feet based on the standard atmosphere.

Risks and Risk Assessment

1. Decompression Sickness (DCS)
    a. Likelihood: Low-to-moderate. As ambient pressure decreases with altitude, the body becomes more prone to nitrogen bubble formation in tissues and blood. Despite the use of pre-breathing protocols to reduce nitrogen saturation, the extreme altitudes involved in this testing significantly increase the risk. DCS is more likely if there are rapid ascents or if the pre-breathing regimen is insufficient. The Air Force Research Lab (AFRL) hosts the Altitude Decompression Sickness Risk Assessment Computer (ADRAC), which is one of the most accurate prediction calculators for DCS risk (Login to CBDN (istdayton.com)). It "predicts DCS for a population of people that reflect the USAF flying personnel with respect to gender, and a suit pressure of 4 PSI (~32,000 ft) pressure altitude, the following risks are calculated: age, physical fitness, height, weight, and general health," limiting this modeling to healthy volunteers for suit testing. Assuming no issues with the chamber function NASA keeps the risks of Type 1 DCS < 15% for their Extravehicular Activities (EVAs). The CHaSE profile does not include activity testing, so the Rest profile for the planned 140-minute prebreathe at 100% oxygen limits the DCS risk to 9% for a 70-minute excursion.
    b. Severity: DCS severity can range from mild to life-threatening. Mild cases may present as joint pain and skin manifestations (type 1), while severe cases (type 2) can lead to neurological symptoms such as dizziness, cognitive impairment, paralysis, and respiratory distress. In extreme cases, untreated DCS can result in permanent neurological damage or death. The severity of symptoms often depends on the altitude reached, the rate of ascent, the duration of exposure, and individual physiological factors.





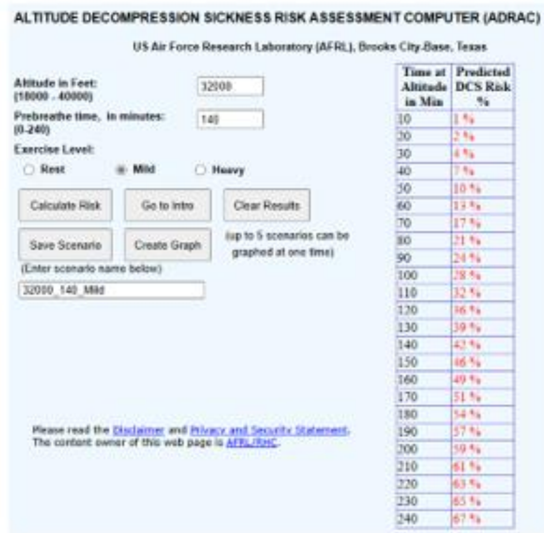
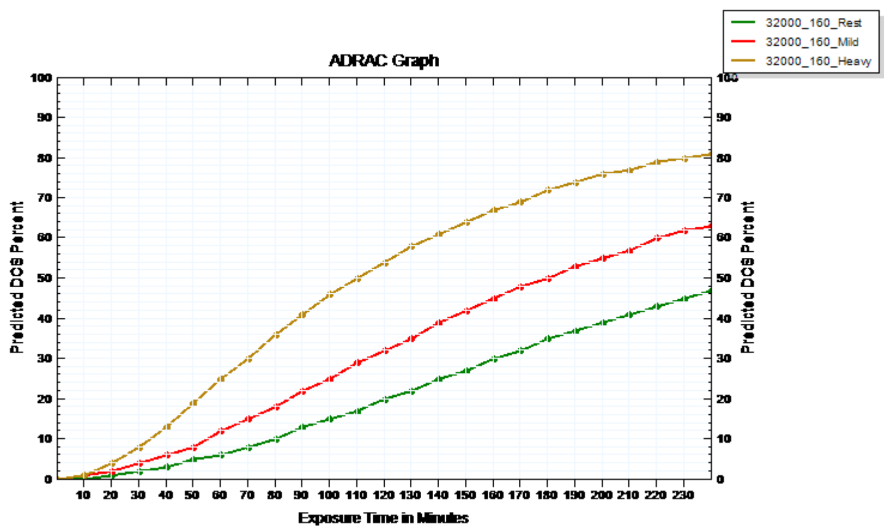


Figure 2: ADRAC DCS Risks for 32,000 ft with a 140-minute 100% Oxygen prebreathe protocol. Risks are broken down based on activity levels at altitude including Rest, Mild Activity, and High Activity.



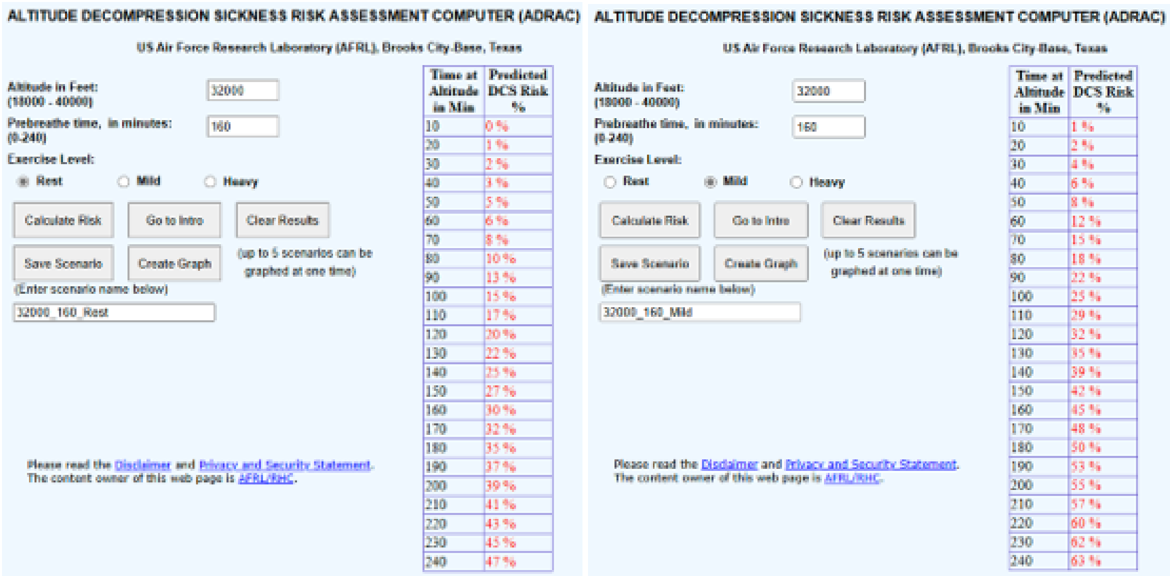


Figure 3: ADRAC DCS Risks for 32,000 ft with a 160-minute 100% Oxygen prebreathe protocol. Risks are broken down based on activity levels at altitude including Rest, Mild Activity, and High Activity.

c. Mitigation:

i. Volunteer selection and screening is important to mitigate DCS risks. Individuals who have undergone recent dives, within 12 hours for single stage dives and within 18 hours of multistage dives, should be prevented from participating in altitude chamber testing. Individuals with previous type 2 DCS from altitude exposure should be excluded from chamber testing as well.

ii. Pre-breathing Protocols are the fundamental mitigation strategy. They involve a pre-breathing regimen with 100% oxygen before ascent to reduce the body's nitrogen load. The recommended pre-breathing duration should be based on the planned altitude exposure and duration of exposure, with longer times for higher altitudes and durations. The anticipated 32,000 ft pressure altitude that will be experienced in the CHaSE suit testing would require at least a 140-to-160-minute pre-breath to reduce the risk to below 15% for mild exercise, leaving a safety buffer for the procedure which will be performed at Rest.

iii. A controlled ascent profile that is gradual can help allow for early and safe identification of DCS symptoms. The chamber ascent rate should be slow enough to allow the body to adapt to pressure changes more safely. The CHaSE ascent profile is set at 5,000 ft/min, which requires careful real-time communication to help catch DCS symptoms early.

iv. Continuous physiological monitoring of the subject for early signs of DCS, such as joint pain, skin rashes, or neurological symptoms. Doppler ultrasound may be used to detect venous gas emboli (VGE) and evaluate bubble formation in real-time, but this protocol does not have it as a monitoring device.

v. An emergency descent protocol for rapid recompression to a safer pressure altitude if DCS symptoms occur is required. The subject should be stabilized and provided with 100% oxygen during descent.
vi. Access to ground level oxygen (GLO) and immediate access to hyperbaric treatment are paramount to mitigate DCS if it occurs. 80-90% of altitude DCS cases resolve upon re-pressurization to ground level, but standard Air Force and NASA protocols would dictate 2 hours of 100% GLO even if the symptoms resolve. If symptoms do not resolve within 30 minutes, are type 2 in nature, or recur after 2 hours of GLO, hyperbaric treatment is mandatory. A hyperbaric chamber should be identified prior to testing and be on alert and available during testing, with emergency medical teams trained in ACLS also alerted to the testing and potential need for transport to hyperbaric treatment (HBOT) facilities. Early intervention with hyperbaric oxygen treatment is crucial to reduce the severity of DCS and prevent long-term complications.
vii. Subjects should undergo a post-test observation period of 24 hours to monitor for delayed onset of DCS symptoms. This includes neurological assessments and the availability of medical personnel trained in DCS management.

2. Arterial Gas Embolism (AGE)
   a) Likelihood: The likelihood of AGE during hypobaric chamber testing and space suit evaluations is low but dependent on the suit protecting the individual from rapid decompression. AGE can happen if a sudden pressure changes leads to lung over-expansion and alveolar rupture. This can lead to pneumothorax if rupturing into the pleural space, pneumomediastinum if rupturing into the mediastinal space, and AGE if the rupture is into the pulmonary veins and, subsequently, into the arterial circulation. Rapid ascent rates, suit pressurization failures, or breathing equipment malfunctions can elevate the risk of AGE. Additionally, individuals with obstructive lung diseases and pulmonary blebs may be at increased risk.
   b) Severity: AGE is a severe and potentially life-threatening condition. It can lead to immediate and catastrophic outcomes such as stroke-like symptoms, including sudden loss of consciousness, confusion, seizures, or focal neurological deficits if the bubbles reach the cerebral circulation. Cardiovascular collapse can occur if bubbles enter the coronary arteries, leading to arrhythmias or myocardial infarction. The onset of symptoms can be rapid, often within minutes, and can result in permanent neurological damage or death if not treated promptly.
   c) Mitigation: Precluding individuals at higher risk for pulmonary rupture is important, and volunteers with a history of severe obstructive pulmonary disease or spontaneous pneumothorax or blebs without adequate documentation of surgical correction should be excluded from participation. A class III FAA license with previous hypobaric altitude chamber clearance should be required for participants. Additional steps in AGE mitigation are like DCS risk mitigation procedures. Gradual ascent profiles, ensuring controlled pressurization of the suit to prevent rapid pressure changes. Real-time physiological monitoring, including cardiovascular and neurological assessments, will facilitate early detection and response to symptoms of AGE. Ready access to EMS providers trained in neurological and cardiovascular resuscitation, chest tube placement, and transport are required.

3. Hypoxia
   a) Likelihood: Dependent on equipment reliability. The risk of hypoxia during hypobaric chamber testing and space suit evaluations is high. At extreme altitudes like 80,000 feet, the ambient oxygen partial pressure is incompatible with human life. FAA and FAR regulation for commercial aircraft pilots state that supplemental O_2 is required for flights > 10,000 ft, 100% O_2 is required for flights > 33,000 ft, and positive pressure breathing is required for flights > 40,000 ft. Pressure suits are required for flights > 50,000 ft, as even 100% oxygen at the ambient pressure would be insufficient. The CHaSE suit's internal pressurization to 4 PSI (206 mmHg) provides some atmospheric protection. This is a pressure altitude of ~32,000 ft, which requires 100% oxygen at a rate above the operators ventilatory requirements to be delivered reliably. Equipment failure, inadequate suit ventilation, or delays in oxygen delivery can significantly increase this risk. Notably, this 100% oxygen environment increases the risk for fire.
   b) Severity: Mild-to-Severe. Hypoxia is a severe and potentially life-threatening condition. Mild-to-moderate hypoxia can lead to impaired cognitive and motor function, decreased situational awareness, and loss of consciousness. Hypoxia can progress to Acute Mountain Sickness (AMS), characterized by symptoms such as headache, nausea, dizziness, and fatigue. If left unaddressed, hypoxia can lead to more severe conditions like High-Altitude Cerebral Edema (HACE), where fluid accumulation in the brain causes confusion, ataxia, and possible coma. High-Altitude Pulmonary Edema (HAPE) can also occur, leading to respiratory distress and hypoxemia. In extreme cases, hypoxia can result in irreversible neurological damage or death.
   c) Mitigation:
      i. Suit Oxygen Delivery System: The CHaSE suit must be equipped with a reliable oxygen delivery system capable of maintaining a high fraction of inspired oxygen (FiO_2) to ensure that the partial pressure of oxygen inside the suit remains sufficient. The goal is to maintain an oxygen partial pressure in the alveoli similar to that at sea level, around 100 mmHg, to prevent hypoxia. Redundant oxygen supply systems and automatic regulation of oxygen flow are crucial to ensure continuous oxygenation. Adequate oxygen flow rates and suit ventilation are required, as expired CO_2, if not readily cleared, can build up and dilute the inhaled fraction of oxygen. Most individuals ventilate between 6-8 liters/minute at rest, and suit ventilation and oxygen flow should exceed this with a safety factor.
      ii. Continuous Monitoring: Continuous real-time monitoring of the subject's oxygenation status is essential. This includes the use of pulse oximetry to track blood oxygen saturation (SpO_2) levels. Alarms should be set to trigger if SpO_2 falls below safe thresholds (< 90%), prompting immediate corrective actions.
      iii. Controlled Ascent and Descent: Maintain a controlled ascent profile with gradual altitude increases to allow the body to adjust to decreasing ambient oxygen levels. In the event of hypoxia symptoms, a rapid descent protocol should be in place to quickly return the subject to a lower altitude where oxygen partial pressure is higher.
      iv. Training and Preparedness: Test subjects and support personnel must be trained to recognize early symptoms of hypoxia, such as confusion, visual disturbances, or euphoria, which can impair the subject's ability to self-

assess. Drills for emergency procedures, including activating emergency oxygen supplies and initiating descent, are crucial.

4. Hypercarbia
   a) Likelihood: The risk of hypercarbia (elevated levels of carbon dioxide in the blood) during hypobaric chamber testing and space suit evaluations is low and dependent on the suit's ventilation efficiency. At high altitudes, the suit must not only provide adequate oxygen but also ensure effective removal of CO_2 produced by the wearer to prevent CO_2 buildup and displacement of inhaled O_2. If the ventilation system is inadequate, malfunctioning, or overwhelmed by increased metabolic activity (e.g., during exertion), CO_2 can accumulate within the suit, leading to hypercarbia and hypoxia.
   b) Severity: Hypercarbia can range from mild to life-threatening. Mild hypercarbia may cause symptoms such as headache, dizziness, and a feeling of shortness of breath. Moderate to severe hypercarbia can lead to confusion, reduced cognitive function, muscle twitching, and anxiety. If CO_2 levels continue to rise unchecked, it can result in severe respiratory acidosis, loss of consciousness, and even death. Elevated CO_2 levels can also exacerbate hypoxia, further compromising the subject's physiological stability and increasing the risk of other altitude-related conditions.
   c) Mitigation:
      i. Training and Preparedness: Both test subjects and support personnel must be trained to recognize early symptoms of hypercarbia, such as headache, confusion, and dyspnea.
      ii. Suit Ventilation and Airflow: Proper ventilation within the suit is critical to ensure that exhaled CO_2 is continuously flushed. The suit should be designed to provide a continuous flow of fresh oxygen while directing airflow to optimize CO_2 removal. This includes maintaining a steady airflow rate that matches or exceeds the subject's ventilation rate, particularly during exertion. An airflow rate of at least 6 to 8 liters per minute per occupant is often targeted for adequate CO_2 clearance in resting individuals, and greater clearance rates are required if activity is planned.
      iii. Continuous CO_2 Monitoring: Real-time monitoring of CO_2 levels within the suit is essential for early detection of hypercarbia. In-suit CO_2 monitors should trigger alarms if CO_2 levels exceed safe thresholds, typically around 5,000 ppm (0.5% CO_2 by volume), to prompt immediate corrective actions.
      iv. Emergency Oxygen Purge: The suit should be equipped with an emergency oxygen purge system capable of rapidly increasing the oxygen flow rate to flush out accumulated CO_2.

5. Barotrauma
   a) Likelihood: The likelihood of barotrauma during hypobaric chamber testing and space suit evaluations is low, but it is dependent on the suit protecting the participant from rapid depressurization and the flight protocol allowing adequate time for identification of barotrauma. Barotrauma occurs when there is a significant pressure differential between the external environment and the body's internal air spaces (e.g., lungs, sinuses, middle ear). In the context of space suit testing, barotrauma risk arises if the suit pressurization system fails to regulate pressure changes smoothly or if the suit experiences a sudden loss of pressure. Rapid pressure changes can lead to the over-expansion or collapse of air-filled spaces, causing tissue damage.

b) Severity: Barotrauma can range from mild to severe. Mild forms may include ear barotrauma, with symptoms such as ear pain, discomfort, and temporary hearing loss due to eustachian tube dysfunction or middle ear squeeze. Moderate to severe barotrauma can lead to more serious conditions like sinus barotrauma, pneumothorax (lung collapse), or pulmonary barotrauma, where over-pressurization of the lungs leads to alveolar rupture. Severe cases can result in arterial gas embolism (AGE) if air enters the arterial circulation, leading to potentially life-threatening outcomes such as stroke or cardiac complications.

c) Mitigation:

   i. Pre-Testing Screening and Training: Subjects should undergo pre-testing medical screening to identify any pre-existing conditions that could increase the risk of barotrauma, such as eustachian tube dysfunction, sinusitis, or lung abnormalities like bullae. Participants should not have an active upper respiratory infection that could increase the risks of sinus or middle ear barotrauma. Additionally, subjects should be able to perform middle ear equalization maneuvers independently, such as the Valsalva maneuver or Toynbee maneuver.

   ii. Suit Pressure Regulation: The CHaSE suit must have a reliable and responsive pressure regulation system to maintain a stable internal pressure environment. The suit should automatically adjust its internal pressure in response to changes in external pressure, preventing sudden pressure differentials. Redundant pressure control systems are essential to ensure continued suit integrity and pressure management if the primary system fails.

   iii. Controlled Ascent and Descent Rates: The primary mitigation strategy for barotrauma is maintaining controlled ascent and descent rates during hypobaric chamber testing. Rapid pressure changes can overwhelm the body's ability to equalize internal pressures, leading to barotrauma. Ascent rates should be kept slow to allow time for pressure equalization in air-filled spaces like the lungs, ears, and sinuses. In the event of an emergency descent, a gradual rate should still be used to avoid causing barotrauma.

   iv. Real-Time Monitoring: Continuous monitoring of the participant with active feedback on ear or sinus discomfort can prompt early intervention.

   v. Emergency Procedures: In the event of suit depressurization or a malfunction in the pressure regulation system, immediate emergency procedures must be in place. This includes protocols for gradual descent and stabilization of the subject. If signs of barotrauma, such as chest pain, difficulty breathing, or ear pain, are observed, emergency medical evaluation and intervention should be initiated.

   vi. Post-Test Medical Evaluation: After high-altitude exposure, subjects should undergo a thorough post-test medical evaluation to identify any delayed-onset barotrauma symptoms. EMS providers should be readily available if any significant barotrauma were to occur.

6. Ebullism

   a) Likelihood: Low if suit pressure is maintained adequately. The risk of ebullism becomes significant above 63,000 feet (the Armstrong limit), where the ambient pressure is so low that the boiling point of bodily fluids drops below human body temperature. During CHaSE space suit testing up to 80,000 feet, ebullism is a considerable risk if the suit fails to maintain adequate internal pressure. The suit's internal pressurization to 4 PSI is crucial for preventing ebullism; however, any malfunction or breach in the suit's pressurization system at these altitudes could lead to the rapid onset of this condition.

b) Severity: Ebullism is a life-threatening condition characterized by the formation of gas bubbles within the body's fluids and tissues. It results in immediate and severe physiological consequences, including the rapid expansion of gas in body cavities, skin, and eyes, as well as the potential boiling of saliva and other body fluids. This can cause severe tissue damage, circulatory collapse, respiratory distress, and loss of consciousness. If not promptly addressed, ebullism can lead to irreversible injury or death due to cardiovascular and pulmonary failure. The severity and speed at which ebullism progresses make it one of the most critical risks during high-altitude exposure.

c) Mitigation:

    i. Pre-Testing Suit Checks: Comprehensive pre-testing checks of the suit's pressurization system are vital. This includes pressure integrity tests, leak detection, and validation of all pressurization components. Any potential points of failure should be identified and addressed before high-altitude exposure.

    ii. Suit Pressurization Integrity: The primary defense against ebullism is maintaining suit integrity and pressure. Redundant pressurization systems, including backup pressure regulators and emergency pressure retention mechanisms, should be integrated into the suit design to ensure that internal pressure is maintained even in the event of a system failure.

    iii. Pressure Monitoring and Alarms: Continuous real-time monitoring of the suit's internal pressure is essential. The suit should be equipped with pressure sensors and alarms that trigger immediately if internal pressure falls below safe thresholds. These alarms should prompt immediate corrective actions, such as activating backup pressurization systems or initiating emergency descent protocols.

    iv. Emergency Descent Protocol: In the event of suit pressurization failure, an emergency descent protocol must be in place to rapidly reduce altitude and increase ambient pressure. The descent must be executed as quickly as possible while avoiding further risks.

    v. Medical Emergency Preparedness: Due to the rapid onset and severity of ebullism, medical personnel must be prepared to provide immediate intervention. This includes advanced life support measures and treatment for potential complications such as respiratory and circulatory collapse. Rapid access to pressurized environments, such as hyperbaric chambers, can aid in stabilizing the subject by restoring tissue perfusion and minimizing damage.

7. Thermal Stress and Fluid Shifts

    a) Likelihood: The likelihood of thermal stress and fluid shifts during hypobaric chamber testing and space suit evaluations is moderate to high, depending on the suit's thermal regulation capabilities and the conditions of the test environment. At high altitudes, the external environment can be extremely cold due to adiabatic cooling, leading to a significant risk of hypothermia if the suit fails to provide adequate insulation and temperature control. Conversely, the metabolic heat generated by the wearer, especially during physical exertion, can lead to hyperthermia if not adequately managed. Fluid shifts are also a common physiological response to changes in pressure and can be exacerbated in the hypobaric environment, leading to dehydration and impaired circulatory function.

b) Severity: Thermal stress can range from mild to severe, though the anticipated exposure during the CHaSE testing should limit this to mild severity.

c) Mitigation:

   i. Suit Thermal Regulation Systems: The CHaSE suit must be equipped with an advanced thermal regulation system capable of maintaining a stable internal temperature regardless of external conditions.

   ii. Continuous Physiological Monitoring: Real-time monitoring of the subject's core body temperature, skin temperature, and vital signs is crucial for early detection of thermal stress.

8. Fire Risk

a) Likelihood: The risk of fire is heightened during CHaSE spacesuit testing due to the use of 100% oxygen within the suit. In an oxygen-rich environment, materials that are usually non-flammable can ignite easily, and any potential ignition sources, such as electrical equipment, static discharge, or even friction, can act as triggers. Despite the decreased pressure, the enriched oxygen environment dramatically increases the Flammability Index. The likelihood of a fire depends on strict adherence to protocols that limit ignition sources and ensure that suit and chamber materials are non-flammable or flame-retardant.

b) Severity: In the event of a fire, the severity is extreme. A fire in an oxygen-rich environment can spread rapidly, causing severe burns, damage to the suit's integrity, and potentially compromising the chamber's pressurization. The rapid consumption of oxygen can lead to hypoxia or asphyxiation for the subject if the fire depletes the available breathable air. Given the confined nature of a hypobaric chamber, fire can result in catastrophic injury or fatality.

c) Mitigation:

   I. Material Selection: All materials used in the suit, chamber, and equipment must be non-flammable or have flame-retardant properties, tested for compatibility with 100% oxygen environments.

   II. Control of Ignition Sources: Strict protocols must be in place to minimize potential ignition sources. This includes proper grounding of electrical equipment, use of antistatic materials, and avoiding the use of devices that could generate sparks or excessive heat.

   III. Emergency Protocols: An emergency fire suppression system, compatible with the hypobaric environment, should be installed within the chamber. Emergency egress procedures and fire response training for all personnel involved in the testing are essential.

   IV. Pre-Testing Safety Checks: Routine safety checks before testing should include a thorough inspection for potential ignition sources, verification of suit and chamber material compliance, and functionality testing of fire suppression systems.

Conclusion

The CHaSE pressure suit testing at altitudes up to 80,000 feet presents a complex array of physiological risks that must be managed to ensure the safety of test subjects. The primary risks—decompression sickness (DCS), arterial gas embolism (AGE), hypoxia, hypercarbia, barotrauma, ebullism, thermal stress, and fluid shifts—each pose unique challenges requiring risk assessment and mitigation strategies. By implementing participant selection criteria, pre-breathing protocols, controlled ascent profiles, advanced suit pressure regulation, real-time physiological monitoring, and emergency response procedures, these risks can be significantly reduced. Additionally, the suit's design must incorporate redundant systems for pressure control, thermal regulation, and CO_2 removal to safeguard against unexpected environmental or equipment failures. By adhering to these rigorous safety measures, CHaSE can confidently conduct space suit testing in hypobaric chambers, advancing the development of life-support systems for high-altitude and space exploration while minimizing risks to human participants.

Participant Medical Checklist for CHaSE Suit Testing

Pre-Testing Screening

1. **Medical History:**
    - No history of recent SCUBA diving within:
        - 12 hours for single-stage dives
        - 18 hours for multi-stage dives
    - No history of severe obstructive pulmonary disease (e.g., COPD, emphysema).
    - No history of spontaneous pneumothorax or pulmonary blebs without surgical correction.
    - No history of type 2 DCS from previous altitude exposures.
    - No history of untreated or poorly controlled sinusitis or upper respiratory infections.
    - No history of severe cardiovascular disease (e.g., myocardial infarction, arrhythmias).
    - No history of epilepsy or unexplained seizures.
    - No history of significant ear problems (e.g., severe eustachian tube dysfunction).
    - No history of claustrophobia or severe anxiety that could be exacerbated by hypobaric conditions.
2. **Physical Examination:**
    - **ENT Evaluation:**
        - Clear sinuses and nasal passages.
        - Ability to equalize middle ear pressure (e.g., successful Valsalva or Toynbee maneuver).
    - **Pulmonary Function Testing (PFT):**
        - Normal spirometry results (FEV1, FVC within normal limits).
    - **Chest X-Ray:**
        - Absence of lung bullae, blebs, or other structural abnormalities.
    - **Cardiovascular Evaluation:**
        - Blood pressure within normal limits.

        - Normal ECG results.
    - **Neurological Examination:**
        - No focal neurological deficits.
    - **Class III FAA License:**
        - Current Class III FAA license AND previous certification in hypobaric altitude chamber testing.
3. **Laboratory Testing:**
    - **Complete Blood Count (CBC):**
        - Hemoglobin and hematocrit within normal ranges.
    - **Electrolyte Panel:**
        - Sodium, potassium, chloride, and bicarbonate levels within normal ranges.

Pre-Testing Protocol

1. **Pre-Breathing Protocol:**
    - Minimum of **140 to 160 minutes of 100% oxygen pre-breathing** before chamber ascent.
    - Ensure no leaks or malfunctions in the oxygen delivery system.
2. **Hydration:**
    - Ensure adequate hydration with oral fluids (e.g., water, electrolyte solutions) before the start of the test.
    - Avoid diuretics (e.g., caffeine, alcohol) 24 hours before testing.
3. **Medications:**
    - Avoid medications that may impair cognitive function, thermoregulation, or pressure equalization (e.g., sedatives, antihistamines).
    - Continue essential home medications (e.g., antihypertensives).
    - Consider pre-testing Afrin.

In-Testing Monitoring

1. **Vital Signs:**
    - Continuous monitoring of heart rate, blood pressure, and respiratory rate.
    - Pulse oximetry to monitor blood oxygen saturation (SpO_2).
2. **Real-Time Feedback:**
    - Participant must provide real-time feedback on any symptoms, including:
        - Joint pain, dizziness, or tingling (potential DCS symptoms).
        - Shortness of breath or chest pain (potential AGE or barotrauma symptoms).
        - Confusion, headache, or nausea (potential hypoxia or hypercarbia symptoms).
3. **CO_2 Monitoring:**
    - In-suit CO_2 sensors to ensure levels remain below 5,000 ppm (0.5% CO_2 by volume).
4. **Temperature Monitoring:**
    - Continuous monitoring of core body temperature to detect thermal stress.

Post-Testing Protocol

1. **Immediate Post-Test Evaluation:**

    - Full neurological assessment.
    - ENT evaluation for ear and sinus barotrauma.
    - Cardiopulmonary assessment, including auscultation and oxygen saturation check.
2. **Observation Period:**
    - **24-hour post-test observation** for delayed onset of symptoms.
    - Access to emergency medical support and hyperbaric treatment if symptoms of DCS, AGE, or barotrauma develop.
3. **Post-Test Hydration and Rest:**
    - Encourage adequate fluid intake post-test.
    - Monitor for symptoms such as fatigue, headache, or dizziness.
4. **Follow-Up:**
    - Scheduled follow-up evaluation within 48 hours post-test to reassess for any late-onset symptoms.

Emergency Preparedness

- **Access to EMS:** On-site EMS team trained in advanced cardiac life support (ACLS) and altitude-related emergencies with access to at least 2 hours of 100% oxygen.
- **Hyperbaric Chamber Access:** Identified hyperbaric facility on alert during testing.
- **Emergency Descent Protocol:** Prepared for rapid recompression if needed.
- **Fire Suppression:** On-site fire extinguishers and protocols are required during 100% oxygen testing.

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