55th International Conference on Environmental Systems
12-16 July 2026, Rio Grande, Puerto Rico
ICES-2026-468

Overview of Past and Future EVA Suit Testing and Training in Chamber B at NASA JSC

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The Crew and Thermal System Division's Chamber B has received an increase in demand for next generation suit testing. Chamber B is the National Aeronautics and Space Administration (NASA) Johnson Space Center's only human-rated thermal vacuum (TVAC) chamber. Historically it was used in Gemini, Apollo, Skylab, Shuttle, and the International Space Station (ISS) suit tests. Recently, the chamber has been returned to service with new capabilities for suit testing. In 2023, The Exploration Extravehicular Mobility Unit (xEMU) underwent a 5-day, extensive thermal vacuum test that included both a full-bodied Exploration Pressure Garment Suit (xPGS) as well as a high fidelity Short xEMU. SpaceX has also used the chamber for human-in-the-loop (HITL) qualification and acceptance testing on their flight Polaris Dawn suits for the first-ever commercial extravehicular activity (EVA). Current chamber Manlock B2 upgrades include the support of two test subjects at the same time with updated chamber interface and support systems for the next generation of suits. This paper will discuss the history of spacesuit testing in the chamber, the recent testing for commercial and NASA suits, and upgrades to accommodate new test requirements.

Nomenclature

ABO	=	Aviator's Breathing Oxygen
ALM	=	Apollo Lunar Module
AVAT	=	Artemis Vehicle Airlock Trainer
AxEMU	=	Axiom Extravehicular Mobility Unit
BTU	=	British thermal unit
CO_2	=	Carbon Dioxide
CTSD	=	Crew and Thermal Systems Division
CTS	=	Crew Transfer System
DCU	=	Display and Control Unit
DCS	=	Decompression Sickness
EMU	=	Extravehicular Mobility Unit
ESCU	=	Exploration Service and Cooling Umbilical
EVA	=	Extravehicular Activity
°F	=	Fahrenheit
ft	=	feet
HITL	=	Human-in-the-loop
HLS	=	Human Landing System

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43 HMS = Human Metabolic Simulator
44 *hr* = hour
45 *Hz* = hertz
46 *in* = inch
47 IR = Infrared
48 ISS = International Space Station
49 JSC = Johnson Space Center
50 JWST = James Webb Space Telescope
51 *K* = Kelvin
52 *kg* = kilogram
53 *km* = kilometer
54 *kPa* = kilo Pascal
55 *L* = Liter
56 *lb* = pound
57 LEO = Low Earth Orbit
58 LN_2 = Liquid Nitrogen
59 *m* = meter
60 MCC = Mission Control Center
61 *min* = minute
62 MLB1 = Manlock B1
63 MLB2 = Manlock B2
64 *mPa* = millipascal
65 *MPa* = megapascal
66 *mph* = miles per hour
67 NASA = National Aeronautics and Space Administration
68 O_2 = Oxygen
69 PLSS = Portable Life Support System
70 *psi* = Pound per square inch
71 *psid* = Pound per square inch differential
72 *psig* = Pound per square inch gage
73 RT = Rescue Technicians
74 RTF = Return to Flight
75 SSATA = Space Station Airlock Test Article
76 SESL = Space Environment Simulation Laboratory
77 SxEMU = Short Exploration Extravehicular Mobility Unit
78 TC = Thermocouple
79 TVAC = Thermal Vacuum
80 VDC = Volts DC
81 xEMU = Exploration Extravehicular Mobility Unit
82 xInfoBand = Exploration Informatics Lighting Band
83 xPGS = Exploration Pressure Garment Suit
84 xPLSS = Exploration Portable Life Support System

I. Introduction

In the early 1960s, the National Aeronautics and Space Administration (NASA) became aware of the necessity of testing spacesuits and training astronauts for the Gemini and Apollo programs in a thermal vacuum (TVAC) environment [1]. This spurred the development of Johnson Space Center's (JSC) Space Environment Simulation Laboratory (SESL), which encompassed Chamber A and B, two human-rated TVAC chambers with solar simulation capabilities. Once an acceptance test of Chamber B was completed, the Gemini program was the first to use the chamber in a series of tests for the spacesuits and for other Extravehicular Activity (EVA) hardware throughout 1965 and 1966 (Figure 1) [1]. In 1966, TVAC testing of Apollo spacesuits and the Apollo Lunar Module (ALM) commenced [2]. Apollo astronauts utilized Chamber B for lunar surface EVA training by deploying scientific experiments in a simulated lunar environment while wearing their Extravehicular Mobility Unit (EMU) spacesuits (Figure 2) [2]. The astronauts found these training opportunities in the chamber to be extremely valuable and heavily contributed to their successful lunar EVAs [1].

Figure 1. Gemini testing.

As NASA transitioned from Apollo to Skylab, the EMU was updated for new EVA parameters. A series of human-in-the-loop (HITL) TVAC tests were conducted to verify the redesigned spacesuit [2]. After the Apollo and Skylab programs finished testing in the SESL, the chambers were temporarily deactivated. Upgrades to Chamber A began in 2007 to meet the deep space environment requirements of the James Webb Space Telescope (JWST) with testing completed in 2017. As a result, all the human-rated capabilities within Chamber A were deactivated. This left Chamber B as the only facility capable of human-rated TVAC testing.

Figure 2. Apollo lunar EVA training.

Chamber B was reactivated in 1988 to support testing of Space Shuttle and International Space Station (ISS) hardware and EMU spacesuits [2]. During the Shuttle Return to Flight (RTF) after the loss of Columbia, the chamber supported multiple tests for astronauts to practice repairing the shuttle thermal protection systems (Figure 3). Throughout the 2010s, the chamber supported multiple ambient tests of future spacesuit designs such as the Z-1 and Z-2 suit.

In 2023, the TVAC capabilities of Chamber B were used again for a non-HITL Exploration Extravehicular Mobility Unit (xEMU) suit test. Shortly after, SpaceX conducted a qualification test of the Polaris Dawn spacesuit in a series of non-HITL and HITL thermal vacuum tests. SpaceX also used the chamber's vacuum capabilities to complete an acceptance test of all four suits that were part of the first commercial EVA for Polaris Dawn [3]. Currently, the chamber is undergoing upgrades to support Axiom Extravehicular Mobility Unit (AxEMU) testing. Each of these test series and upgrades are discussed in more detail below.

II. Overview of Chamber B

A. Capabilities of the Chamber

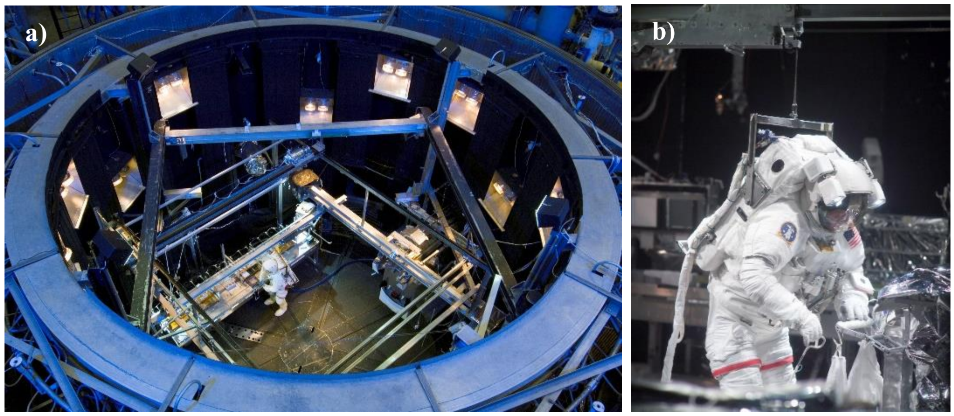

Figure 3. a) Subject in ISS EMU with lid removed.
b) Subject in Shuttle EMU completing RTF EVA practice.

Chamber B is made up of three compartments: the main chamber, Manlock B1 (MLB1), and Manlock B2 (MLB2) (Figure 4). The main chamber has TVAC capabilities and has a working dimension of 25 ft (7.6 m) in diameter and 26 ft (7.9 m) in height with a load bearing floor of 20 ft (6.1 m) in diameter that can bear up to a concentric load of 37.5 ton (34,019 kg) [4]. Outside of the chamber, there are 50-ton (45,359 kg) capacity rolling bridge cranes that can be used to take off the chamber head for larger test articles (Figure 3a) [4]. Manlock B1 and B2 are the only ways to ingress the chamber at the ground level and act as a dual airlock system with vacuum capability only. Both Manlocks can also be used as independent vacuum chambers. The vacuum system consists of staged roughing pumps including a train of four Root blowers and six Stokes pumps, four valved and trapped oil diffusion pumps, and two –424°F (20 K) cryopumps [4]. This allows the chamber to reach pressures as low as 1.5×10^{-4} Torr (19.9 mPa) at ambient temperatures. When the chamber is fully conditioned cold with cryogenics a pressure of 3.5×10^{-6} Torr (0.466 mPa) is achievable. It can take between 5 to 8 hours to fully reach test conditions from site pressure.

The cooling capabilities of the chamber come from liquid nitrogen (LN_2) panels that are coated in black paint with a measured emissivity of 0.90. Behind each of the LN_2 panels, there are fifteen gaseous helium cryopumping panels, which help lower the pressure by using their surface area to trap gases. The chamber has another set of LN_2 panels behind the helium panels, and the floor can be cooled with LN_2 to simulate the lunar surface. The full shroud of LN_2 panels and the lunar surface plane can be cooled to –270.7°F (105 K). The chamber has previously accommodated infrared (IR) lamps, self-regulating heater tape, and heater bars to provide heating to test articles inside of the chamber. Other heating methods can be accommodated in the chamber. A thermal enclosure of aluminum framing with steel heater bars (referred to as a heater cage) grouped in zones can be created to provide elevated temperatures. By varying the voltage to each of the heater bar zones and measuring them via thermocouples (TCs), the test articles can be subjected to planned thermal environments. In addition, the chamber has feedthroughs for sensors and instruments including TCs. The data is displayed in real-time and logged at 1-Hz.

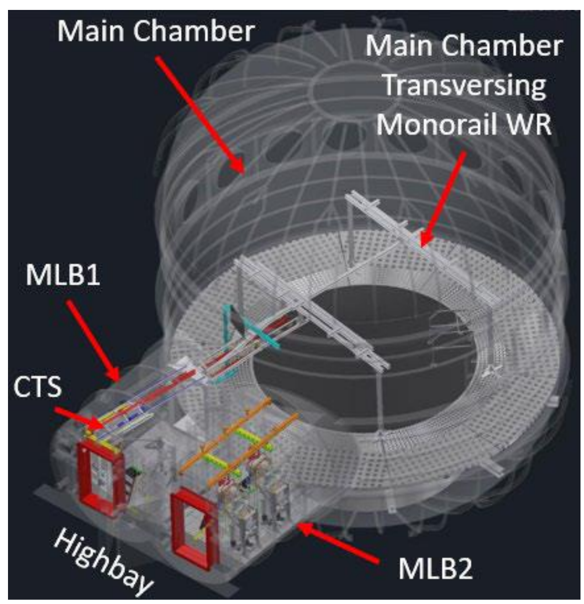

Figure 4. Chamber B model.

B. HITL Components for TVAC Testing in Chamber B

The chamber is equipped with the Crew Transfer System (CTS) which can transfer one suited test subject from MLB1 into the main chamber (Figure 4). The CTS allows the test subjects to ingress and egress the main chamber while the main chamber is preconditioned and kept at the target TVAC conditions. During the main chamber conditioning and while at steady state at full vacuum, both Manlocks may remain at site pressure. Once the suit and test subject are ready for testing, the CTS interfaces with the EMU by latching onto the Portable Life Support System

(PLSS) and a weight relief trolley above the CTS offloads a portion of the suit weight. The Manlock doors are then closed and the Manlock is pumped down and equalized with the main chamber. The CTS will remotely traverse into the main chamber once the door between MLB1 and the main chamber is remotely opened. The test subject will unlatch themselves from the CTS and the weight relief trolley will transition onto the traversing monorail (Figure 4). The monorail provides two degrees of freedom and 200 ft^2 (18.6 m^2) of available working space throughout the main chamber (Figure 3b) [4]. After completion of the simulated EVA, the test subject will latch themselves back onto the CTS which will then traverse back into MLB1. The door is then remotely closed and the Manlock is repressurized back to site pressure.

C. Safety Considerations for HITL TVAC Testing

Figure 5. RTs inside MLB2.

To allow the test and medical teams to monitor the test subject remotely, cameras with pan-tilt-zoom capability are used in the manlocks and main chamber. Throughout the chamber, viewports allow direct line of sight to the test subject. During an EMU EVA test in the main chamber, two rescue technicians (RTs) are stationed in MLB2 where they are constantly observing the test subject. The RTs are provided with oxygen (O_2) through masks, communications through a belt pack and cap, and cold weather clothing (thermal underlayers, flight suit, jacket, scarf, goggles, and boots). MLB2 is kept at 379.4 Torr (0.05 MPa) throughout the HITL test. In the case of an emergency that requires extraction of the crew member, the chamber can be repressurized to 379.4 Torr (0.05 MPa) with dry gas in under 90 seconds. The RTs will disconnect from facility supplied O_2 and utilize their bail-out O_2 bottle. When the chamber is repressed quickly, it will immediately begin fogging so it is imperative the RTs retrieve the test subject as soon as possible and extract them to MLB1. The door can be remotely closed to the main chamber and the Manlocks can be repressed in less than 30 seconds to bring them to site pressure. The Manlocks are also equipped with a fire suppression system that will provide a water deluge in case of smoke or fire. The facility also has power kill capability if there is a fire. Biomedical data such as heart rate can be provided to the medical team. A hyperbaric chamber at JSC is available throughout the test and for a pre-established time after the test for treatment of any decompression sickness (DCS) cases.

III. SpaceX Suit Testing

In September 2024, Polaris Dawn launched on SpaceX's Falcon 9 rocket to low-Earth orbit (LEO) for a nearly five-day mission. One of the goals of the mission was to complete the first-ever commercial EVA, and it utilized SpaceX's new EVA suit. The suit does not have a PLSS and is tethered to the life support system of the SpaceX Dragon vehicle. SpaceX used Chamber B for a series of tests throughout 2023 and 2024 to prepare their new suit for the EVA. The first series of tests were non-HITL TVAC tests for the suit only. The main chamber was preconditioned with the LN_2 shrouds and a custom heater cage. For multiple test points, the suit was attached to the CTS through shoulder straps and was brought into the main chamber to the heater cage, which was placed at the end of the CTS.

SpaceX proceeded onto a HITL TVAC test series with the same heater cage where the test subject walked into the main chamber from MLB1 without the need of the CTS. A custom-made handrail was created to allow the test subject to stabilize themselves while entering the chamber. After the TVAC test series was completed, SpaceX brought all four of the suits and the full crew of the Polaris Dawn for an acceptance test at vacuum only. The test was done with two crew and two suits at one time in the MLB1. The crew had a chance to experience the suits, flight-like leak check seats, and a flight-like vehicle hatch at vacuum [3]. During the test, the crew also generated a representative metabolic rate profile for the EVA duration. All these tests contributed to the success of the Polaris Dawn mission [3].

IV. xEMU Suit Testing

The xEMU is the government reference design for next generation LEO and lunar spacesuits [5]. The xEMU was developed using many lessons learned from the Apollo-era suits as well as more than two decades of experience operating the current EMU on the Shuttle and ISS. After more than a decade of working on the xEMU technologies, the project put its designs to the test using Chamber B. Utilizing both the LN_2 cooled lunar plane and shrouds to simulate a lunar environment, two versions of the xEMU underwent a week of non-HITL testing in 2023 (Figure 6).

The Short-xEMU (SxEMU) is an Exploration Portable Life Support System (xPLSS) connected to a hard upper torso and considered Suit 1 during Chamber B testing. The suit rode on Chamber B's CTS with a human metabolic simulator (HMS) to perform simulated EVAs by ingressing and egressing the main chamber. Suit 2 is a full Exploration Pressure Garment Suit (xPGS) that stood static inside the main chamber (Figure 7). xEMU thermal requirements ranged from –292°F (93 K) for permanently shaded locations at the lunar South Pole, up to 220°F (378 K) for locations with full solar radiation (i.e., lunar equator) [5]. Two separate heater cages were built, one for each suit. Suit 1 had a heater cage located at the end of the CTS inside the chamber. The heater cage for Suit 2 provided heating on all four sides and the top of the suit. The cameras in the chamber allowed for constant monitoring of the test articles. Additionally, IR cameras were placed on both heater cages to allow for a qualitative look at how the different parts of the suits were reacting to the thermal environment.

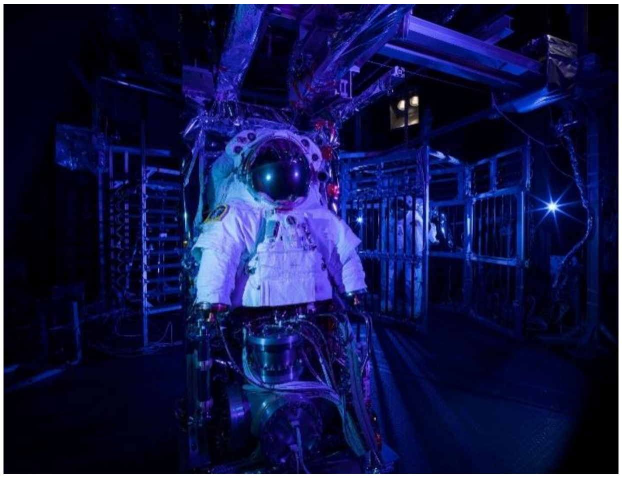

Figure 6. Suits 1 and 2 in the main chamber.

Figure 7. Suit 2 xPGS test article in heater cage.

The primary objective of SxEMU testing was to verify the functionality of the prototype at vacuum pressures and extreme space and lunar surface temperature conditions [6]. For the five planned EVAs, the SxEMU was brought in and out of the main chamber from MLB1 on the CTS while the main chamber was kept at condition. The high fidelity xPLSS on the SxEMU was the focus during the testing, with scrutiny on the oxygen systems, thermal loop, batteries, and carbon dioxide removal. While in MLB1 between EVAs, the oxygen systems were refilled with nitrogen since the xEMU had not yet been certified for oxygen usage. During these periods, the suit batteries were recharged, and the HMS water tank was filled. Suit 1 presented a unique problem of needing live suit data and temperature readings while still maintaining its maneuverability. An Exploration Service and Cooling Umbilical (ESCU) was created to allow the suit to run off facility supplied water and power while bundling the sensor and data wires in a single package.

The primary objective of Suit 2 testing was to gather system-level data on the thermal performance of the xPGS in a high-fidelity simulated space environment [5]. Secondary objectives included testing of the integrated communication system, Exploration Informatics Lighting Band (xInfoBand), and liquid-crystal display screen on the Display and Control Unit (DCU). Due to the nature of the test, once the chamber was sealed, the suit was inaccessible. Power, data, air, and TC lines were fed from chamber penetrations into the suit to allow for control and reporting of suit parameters. Eleven thermal test points were explored over the course of the test, each with its own heater bar setup and duration. The test points explored directional heating of individual sides of the suit, as well as full cold and full hot cases to obtain a wide range of thermal data. The boots of the suit remained in contact with the chamber's lunar plane during the entire test duration. The first seven test points were conducted with LN_2 flowing to the floor to study the contact conductance of the boot and floor interface and the thermal conductance of the boots themselves. For the final four test points the LN_2 was shut off to allow for the suit to reach its hottest test points.

V. xEVAS Modifications

As part of the Exploration Extravehicular Activity Services (xEVAS) contract, Chamber B was commissioned for upgrades to accommodate the next generation spacesuits for ingress into the main chamber through MLB1 using the CTS. A 3600 psi (24.8 MPa) bulk gas storage tank was commissioned along with a compressor recharge station to store a large quantity of 100% O_2, which meant the facility would no longer need to use bottled gas supply. Along with the storage, a new O_2 control cabinet, cooling water cabinet, feedwater tank, and power supplies were installed to supply MLB1. A new ISS umbilical panel was installed into the chamber to provide a flight-like mating interface for umbilicals during prebreathe and recharge operations.

Figure 8. MLB1 post modifications.

As part of the MLB1 upgrades, a new weight relief trolley was manufactured to accommodate the next generation spacesuits allowing for variable offload weights from 350 lbs to 750 lbs (158.7 kg to 340.2 kg). A new subfloor was incorporated into MLB1 for a rail mounted don/doff stand which allows the donning of rear entry suits (Figure 8). Modifications to the CTS were made to allow a transition from the donning stand to the CTS. It includes a manual jack system to adjust test subject height to connect the weight relief trolley.

As part of the xEVAS modifications project, a new treadmill as seen in Figure 9 was needed to accommodate the full anthropometric range of test subjects. The original treadmill rested on the surface of the chamber which did not allow full height range for the test subjects. The new treadmill mechanism was recessed into the lunar surface of the chamber floor itself. An all-metal construction and vacuum sealed motor box with cooling air allows for the treadmill to be used at ambient temperatures and TVAC environment for testing. The treadmill can reach speeds up to 5 mph (8km/hr) to provide metabolic load for suit testing. A handrail located around the treadmill provides stability for the test subject. The handrail has a push bar function where weights can be added for upper body exercise. When not in use, the handrails may be removed with a cover plate installed to hide the treadmill and restore the floor to its full use volume.

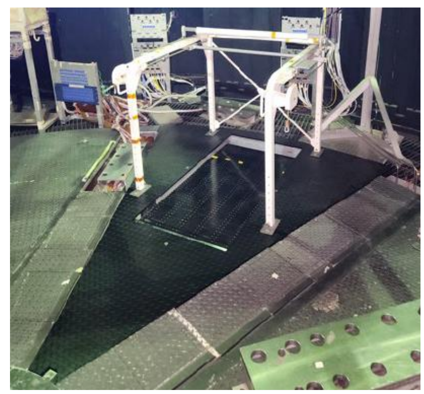

Figure 9. Chamber B treadmill.

VI. Artemis Vehicle Airlock Trainer Development

For future vacuum testing and training capabilities, Chamber B MLB2 is being adapted into the Artemis Vehicle Airlock Trainer (AVAT) (Figure 10). AVAT is a human-rated, highly adaptable airlock training facility developed to provide high-fidelity crew and flight operator training for Artemis missions. Building on the proven success of the Space Station Airlock Test Article (SSATA) Chamber, which served to train ISS crew members on EVA airlock operations and procedures, AVAT delivers similar capabilities tailored for Artemis operations while introducing advanced features that support future mission configurations.

AVAT supports dual-suited crew training in reduced-pressure environments ranging from 1×10^{-4} Torr (13.3 mPa) to 760 Torr (101.3 kPa), enabling astronauts to practice don/doff procedures, EVA airlock operations, and tool handling under flight-like conditions. The chamber also allows crews to gain experience with space suit mobility in vacuum, replicating EVA pressure differentials for authentic movement training. With capacity for two simultaneous test subjects, AVAT facilitates cooperative exercises such as mutual assistance during suit ingress and egress.

As a generic airlock trainer, AVAT can be easily reconfigured to replicate multiple Artemis airlock designs with high-fidelity panels and controls, creating a flight-like operational environment. This flexibility ensures that astronauts experience realistic airlock procedures, including valve actuation and switch operations, prior to mission deployment. AVAT is also integrated with the JSC’s Mission Control Center (MCC), enabling joint training for flight controllers and crew to strengthen coordination during pre-EVA operations. The chamber is engineered for future compatibility with enriched oxygen environments (up to 40% O_2) to support Human Landing System (HLS) vehicle conditions. All materials have been evaluated for vacuum and enriched oxygen compatibility, ensuring safety across a wide range of operational scenarios.

AVAT includes a suite of utilities and systems to support realistic training. These include:

- Weight Relief System to offload weight and enable crew mobility;
- Don/doff stands with standardized interfaces for multiple suit types including both rear entry and waist entry suits;
- Panel mounts for high-fidelity airlock components;
- O_2 supply at 3000 ± 50 psig (20.7 ± 0.34 MPa), cooling water rejection capabilities of 2000 BTU/hr (586 Watts), vehicle power at 28 VDC, feedwater supplied at 4–5 psid (27.5–34.5 kPa), and vacuum access pumping speeds exceeding 1,900 L/min at 0.5 Torr (66.6 Pa); and
- Adjustable lighting from 500–5,000 lumens to simulate varied conditions.

The facility is projected for heavy use starting in 2027. AVAT will support Artemis III and subsequent missions, playing a critical role in preparing astronauts for lunar EVAs using the next generation suit and ensuring mission readiness through realistic, integrated training scenarios. By extending SSATA's proven training model to Artemis, AVAT represents a significant advancement in EVA training infrastructure, combining high-fidelity simulation, adaptability, and integrated operations support for the next era of human space exploration.

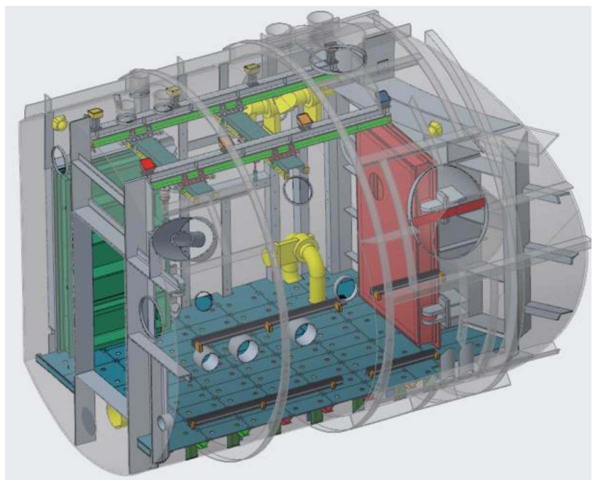

Figure 10. AVAT Chamber Layout (Don Stands not Shown).

VII. Conclusion

Chamber B has an extensive history of supporting spacesuit testing and training since its first acceptance test in 1964. From the Gemini program to ISS, Chamber B has provided critical TVAC testing capability for NASA's suit development. The Apollo program used the chamber to train astronauts for lunar EVAs, and the astronauts found it was crucial for the success of their missions. The next generation spacesuits are being developed for commercial EVAs and for future lunar EVAs during the Artemis missions. Chamber B is a unique and essential facility to meet the thermal vacuum qualification and acceptance requirements for these new suits. Within the chamber, a wide range of TVAC conditions can be simulated from LEO to lunar environments. For both SpaceX and xEMU testing, the custom-built heater cage and the shrouds can be adjusted to meet the thermal conditions. After the tests were completed, all instrumentation and facility data was provided as a package to the test requestors to meet their qualification and acceptance requirements. Unlike other lunar-environment test and training facilities such as ARGOS and Neutral Buoyancy Laboratory (NBL), Chamber B is the only environment where flight-like life support systems are required. This includes, but is not limited to, CO_2 scrubbing, primary and secondary O_2 supply, and active cooling. The chamber is the only opportunity for suit testing at the expected TVAC conditions where the suit must operate as expected to keep the crew member safe. MLB2 of Chamber B is being adapted into AVAT, an airlock training facility with dual suit capacity, which is critical for training Artemis crew and flight controllers. Astronauts will utilize the next generation suit in AVAT for lunar EVA preparation. In addition to preparations for future Artemis missions, Chamber B has the capability to support other commercial requests including future modifications to the SpaceX EVA suits. Chamber B has played a prominent role in suit testing and training in the past, and it will continue to play a pivotal role with the development of next generation spacesuits.

Acknowledgments

We would like to thank the engineers, technicians, test directors, and management of EC4 Systems Test Branch of CTSD. We are also grateful for all the support from EC5 Space Suit and Crew Survival Systems Branch, ES2 Structures Branch, EC Crew and Thermal Systems Division, and our commercial partners.

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