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Exploration Extravehicular Mobility Unit (xEMU) Chamber B Thermal Vacuum "Suit 2" Pressure Garment System Hardware and Test Design

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NASA's Exploration Extravehicular Mobility Unit (xEMU) is the government reference next-generation space suit design and is engineered to protect astronauts from extreme lunar environmental temperatures. To evaluate the xEMU hardware thermal requirements, the xEMU Testing Team invented, designed, and executed a dual-suit, uncrewed thermal vacuum (TVAC) test at Johnson Space Center's (JSC) Chamber B. This paper details the test hardware design and test methodology for the "Suit 2" Pressure Garment System (PGS) test article. The uncrewed "Suit 2" PGS test article consisted of a full PGS assembly with simulated Portable Life Support System (PLSS) functionality provided by test equipment, including a ventilation loop and two distinct thermal control loops. This paper will discuss in depth the test hardware design, including internal suit thermal boundary simulation, sensor quantity and placement, test support equipment rigs for gas flow, water flow, and power. Custom hardware designed to add additional penetrations to the suit or provide additional interfaces for sensors will also be discussed. This paper will also address the assembly and integration sequence for the test article. In addition to test hardware design, this paper will provide insights into the test methodology for this test article, including a discussion of thermal steady-state testing, simultaneous dual suit thermal vacuum testing, and hazard mitigation and controls.

Nomenclature

xEMU = Exploration Extravehicular Mobility Unit
TVAC = Thermal Vacuum
JSC = Johnson Space Center
PGS = Pressure Garment System
PLSS = Portable Life Support System
q = Heat Transfer
U = Coefficient of Heat Transfer
A = Heat Transfer Area
dT = Temperature Delta
T = Temperature
cDAQ = Compact Data Acquisition System
SxEMU = Short Exploration Extravehicular Mobility Unit
DCU = Display and Control Unit
σ = Stefan-Boltzmann Constant

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I. Introduction

THE Exploration Extravehicular Mobility Unit (xEMU) is the government reference design next-generation lunar spacesuit. After over a decade of development of xEMU technologies, the xEMU project performed a Design Verification Testing (DVT) phase in 2021, 2022, and 2023**,** culminating in thermal-vacuum (TVAC) testing of the xEMU spacesuit at Johnson Space Center's (JSC) Chamber B. The xEMU thermal-vacuum test include two test articles: a short-xEMU (SxEMU) including the Exploration Portable Life Support System (xPLSS), and "Suit 2" a full Exploration Pressure Garment System (xPGS). While both test articles were simultaneously exposed to thermal-vacuum conditions, the test was designed such that the two test articles and their respective thermal environments were able to be independently controlled. Reference 1 provides a top level overview of the test.

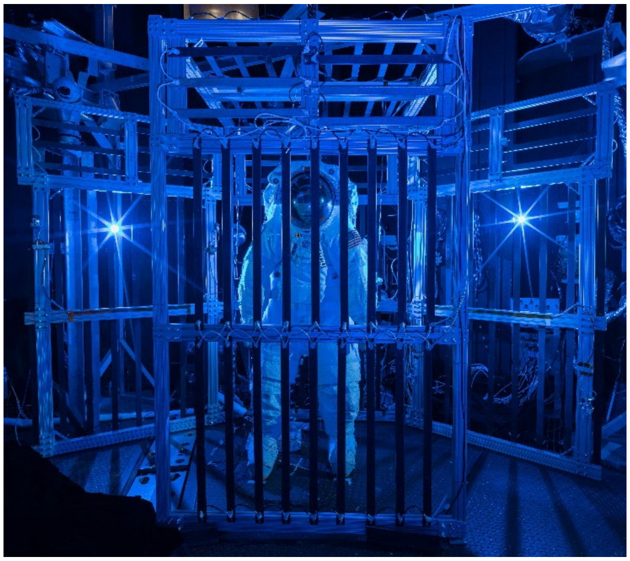
Figure 1. Suit 2 xPGS Test Article.

This paper will focus on the xPGS test article, aptly named "Suit 2" as it was the second test article added to the test. Figure 1 and Figure 2 picture the Suit 2 test article installed inside of a custom heater cage at JSC's Chamber B[2]. The Suit 2 test article included a composite Hard Upper Torso, Helmet/Extravehicular Visor Assembly (EVVA), Liquid Cooling Ventilation Garment (LCVG), Arms, Phase VI Gloves, Waist-Brief Hip, Legs, and Boots. Additional instrumentation was installed inside the suit to collect thermal and audio data. Test support equipment was also developed to simulate the life-support functional nominally provided by the PLSS. In particular, this paper will examine the test design and hardware developed to perform uncrewed thermal-vacuum testing of the xPGS test article. Considerations included the simulation of the thermal load nominally provide by the astronaut in crewed testing, hazard mitigation to minimize catastrophic risks, and design of test support equipment with readily available parts. Reference 3 provides test results from the Suit 2 test article.

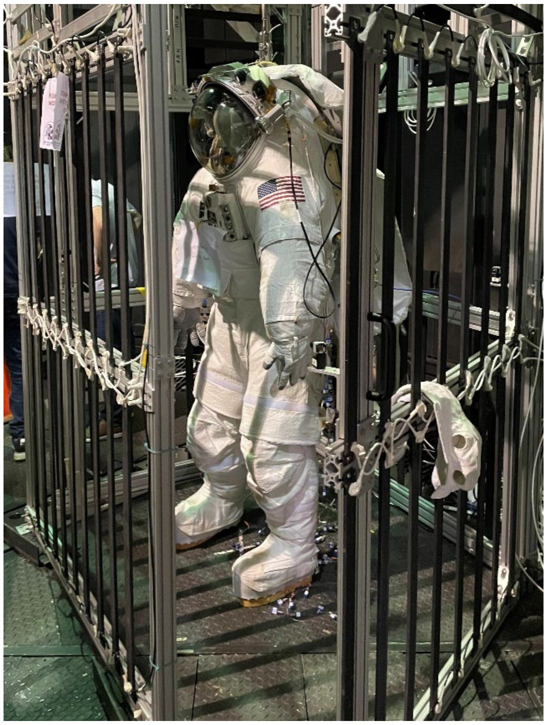
Figure 2. Suit 2 xPGS Test Article.

II. Test Objectives

The primary objective of the Suit 2 test article was to gather system-level data on the thermal performance of the xPGS in a high-fidelity simulated space environment. Secondary objectives included: performing dual-suit audio testing of the integrated communication system (ICS) at sub-ambient pressures[4], testing performance of the Exploration Informatics Lighting Band (xInfoBand)[5], characterizing performance of the Liquid-Crystal Display (LCD) screen on the Display and Control Unit (DCU)[6], and evaluating component-level thermal performance of the lunar boots, composite Hard Upper Torso (cHUT), and Helmet/EVVA. In addition to the primary and secondary technical objectives, a priority for the Suit 2 test article was to be designed in a way such that all catastrophic hazards were mitigated. Any failure of the Suit 2 test system could not lead to a re-pressurization of the vacuum chamber and early termination of the simultaneous SxEMU thermal vacuum test.

The xEMU spacesuit was designed for both low-earth orbit (LEO) and lunar extravehicular activities (EVAs). With the lunar temperatures encompassing the LEO thermal environments, the xEMU thermal requirements ranged from 93K (-292°F) for a cold location at the lunar South Pole and up to 378K (+220°F) for a hot crater location at the lunar Equator. Perhaps the most demanding thermal requirement for the xEMU is a two-hour exposure time duration in a lunar Permanently Shadowed Region (PSR) where temperatures are estimated to be 40K (-387°F) in a shadowed polar crater. Heat leak data from historic Extravehicular Mobility Unit (EMU) EVAs indicate radiative heat flux with the LEO environment is logarithmic and does not significantly change lower than ~144K (-200°F). Figure 3 shows these trends. However, a unique aspect of lunar EVAs is the thermal conduction pathway present between the bottom of the xPGS boots and the lunar surface. With a linear relationship between conductive heat flux and temperature, entering a PSR is expected to substantially impact the heat leak though the lunar boots.

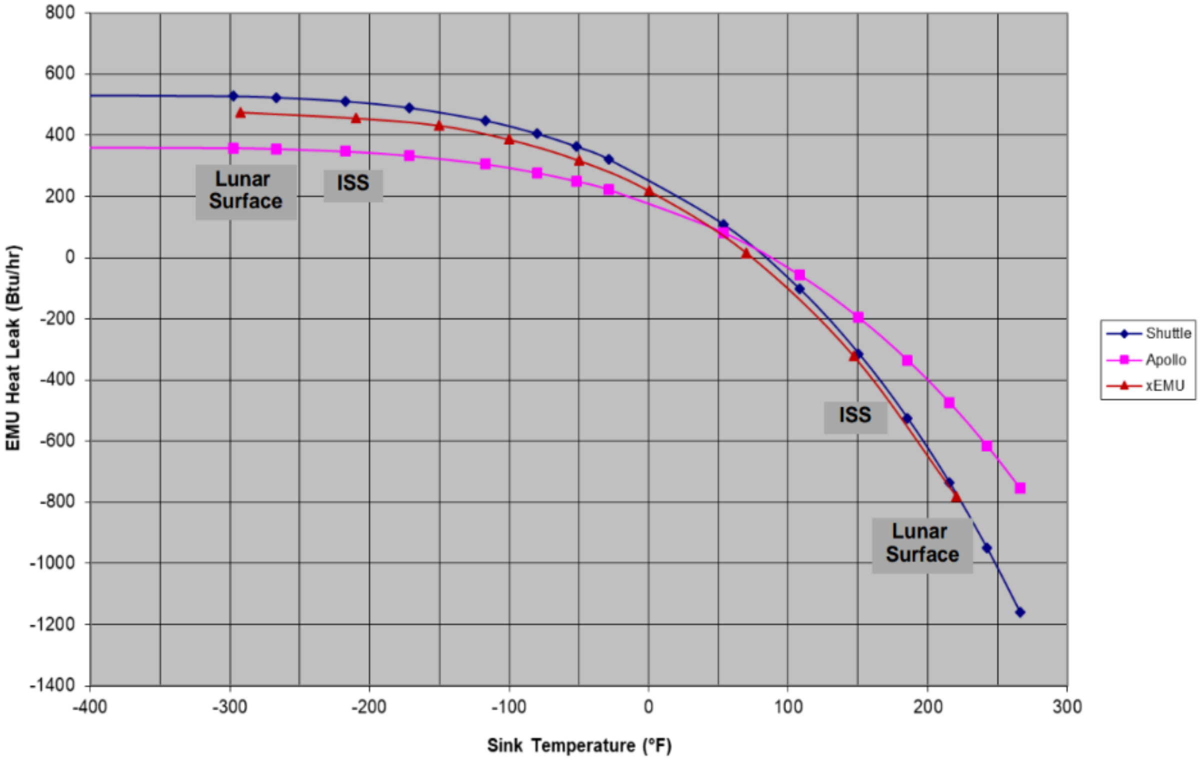

Figure 3. Comparison Between Apollo, EMU, and xEMU (Modeled) Heat Leak Rates

Johnson Space Center's Chamber B utilizes liquid-nitrogen chilled cold panels on the walls and floor of the chamber to provide cold environments. It was anticipated prior to the test that the minimum cold environment provided by Chamber B would not reach the 93K (-292°F) environment. For the hot environments, a custom heater cage was designed to surround Suit 2, with independently controllable heater zones. By testing various thermal profiles and allowing the test article internal and external temperatures to steady state with the environment temperature, the thermal performance of the xPGS can be characterized and relevant test data can be used to validate xEMU thermal models.

III. Test Article Configuration

The Suit 2 test article was comprised of spacesuit hardware built during the Design Verification Testing phase of the xEMU project. This hardware was intended to be the final set of hardware built prior to assembling flight-fidelity hardware. The Suit 2 test article was a full xPGS with simulated life-support functions provided by test support equipment because it did not include a Portable Life Support System (PLSS). It was located inside of a custom heater cage to provide control of the thermal environments during the test and, unable to be accessed once the main vacuum chamber was depressurized.

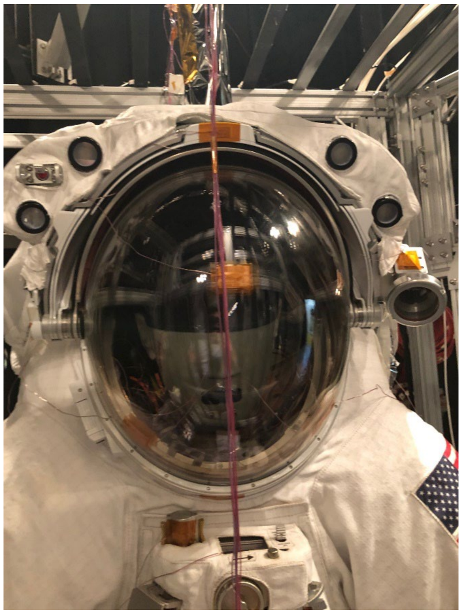

Figure 4. Helmet/EVVA Configuration

A. Helmet/EVVA Configuration

As there was no access to the Suit 2 test article once the chamber was depressurized, a single visor/shade configuration had to be chosen. Figure 4 shows the helmet and EVVA. For this test, the visors/shades were stowed for the duration of the test. At the time of this test, the current plan for Artemis III is to land near the lunar south pole, where cold environments (particularly in permanently shadowed regions) will be more extreme than hot environments. Keeping the visor and shades stowed was more thermally stressful for the helmet and more operationally representative of an expected visor/shade configuration in a cold/dark environment than a visor/shades deployed configuration. For these reasons, the visor/shades were stowed during this test to improve the fidelity of the data collected in the cold case. While in a hot case it is operationally expected to deploy the visor/shades, again it is more thermally stressful to stow the visor/shades and stowing the visor/shades provides the opportunity to better test the thermal performance of the helmet bubble.

B. Hard Upper Torso Material

The xEMU project developed Hard Upper Torsos (HUT) with two different options for the HUT shell material: aluminum or an S-glass composite material. While identical in design, the two different material types of HUTs have unique thermal characteristics. The aluminum 6061-T6 HUT will distribute better than the thermally insulative S-glass material. The difference in thermal conductivities between two different HUT shell materials specifically affects the behavior of the HUT shell when interfacing with exposed metallic components. Components such as the HUT-mounted purge valve and Negative Pressure Relief Valve (NPRV) are intentionally not covered with Environmental Protection Garment (EPG) and consequently are high heat-leak locations. Thermal modeling completed prior to the test estimates that the aluminum HUT shell will pull heat away from these exposed metallic components in a hot environment and lead to higher, but more evenly distributed temperature across the interior HUT shell. Conversely, the composite HUT shell thermally insulates the exposed metallic components and in a hot case leads to lower HUT shell temperatures with much higher temperatures on exposed metallic components. The xEMU project intended for the composite HUT to be the flight material and for that reason the composite HUT was chosen to be tested on the Suit 2 test article that saw much higher thermal extremes than the PGS-side of the SxEMU test article. Figure 5 shows the populated composite HUT used for Suit 2.

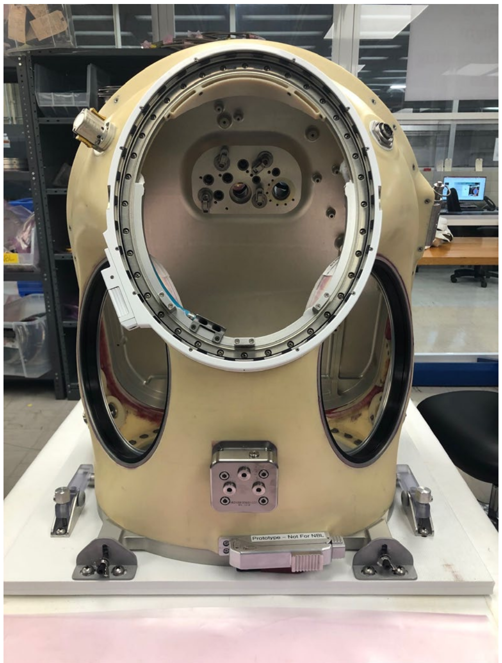

Figure 5. Composite HUT.

Figure 6. Camera Thermal Simulator

C. xINFO Camera Thermal Simulator

The Suit 2 test article included an xINFO Lighting Band, however, did not include a camera. The camera nominally has a USB harness running from the camera to the xPLSS. However, the Suit 2 test article did not include an xPLSS. Prior testing of the camera found a harness-length limitation of ~10 feet. With the Suit 2 test article located more than 10 feet away from the vacuum chamber penetration plate, it was decided not to include a real xINFO camera, as telemetry could not be received from the camera and the xINFO camera had prohibitive thermal limits. A camera thermal simulator was developed with a simple resistor setup to generate a similar amount of heat as the real xINFO camera to provide high fidelity thermal loading of the Helmet/EVVA from the camera. Figure 6 shows the camera simulator.

D. Boot Thermal Insert

Figure 7. Extra Boot Thermal Inserts.

One of the unique aspects of the Suit 2 test article was the ability to have the spacesuit boots in contact with the liquid-nitrogen chilled chamber floor, simulating having the boots in contact with the lunar surface. The xEMU boots are designed for contacting a 40K (-387°F) lunar regolith-ice mixture in a PSR at the lunar south pole. However, due to uncertainties in thermal modeling and a lack of thermal test data on the xEMU boots, a second thermal insert was installed between the bottom of the boot outsoles and the liquid-nitrogen chilled chamber floor to slow the conductive heat transfer. It was anticipated that the boot temperatures and thermal time constants observed during thermal vacuum testing will be significantly affected by the additional thermal insert. It is important to note that once the effective thermal conductivity of the boots is calculated with test data, the boot thermal model can be updated with that data and make predictions of boot temperatures without the additional thermal insert. Figure 7 shows the boot set up with inserts as installed in the chamber.

E. Electrical Passthrough Adapter

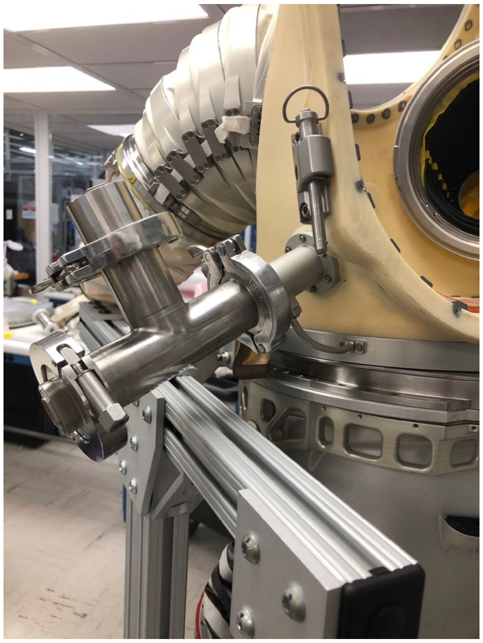

Figure 8. Electrical Passthrough Adapter

To power and receive data from the internal instrumentation located inside of the test article, a custom electrical passthrough was designed. The part utilizes a KF-40 Tee with a potted ethernet and potted DB-9 connector. To interface with the Hard Upper Torso (HUT), a custom part was designed to interface between the bolt hole pattern for the NPRV, located on the crew-left side of the HUT, and a KF-40 flange. Additionally, a strut was manufactured to help support the weight of the KF-40 Tee that interfaced with the body seal closure at the nominal oxygen line clamp location. Figure 8 shows this assembly as installed on Suit 2. Simplified structural analysis was performed by hand to assess a loading case where a kick load is applied at the end of the electrical passthrough adaptor while the suit/adaptor is pressurized. A custom EPG piece was manufactured to cover the electrical passthrough adapter to avoid leaking heat from the part into the HUT.

F. LCVG Modifications

As this was an uncrewed test, the thermal load of a crewmember was not present, and a modified Liquid Cooling and Ventilation Garment (LCVG) was designed and installed into the xPGS for this test. This modified LCVG included fluid passages in the hands and feet of the suit to control the thermal conditions in the extremities, as shown in Figure 9. The water which was pumped through this LCVG was held to approximately 75°F to simulate a suited crewmember inside the test article. The Auxiliary Thermal Loop (ATL) was not used.

This temperature setpoint is derived from a simplified assumed average of a nominal LCVG water temperature of 50°F supplied by the PLSS and a core body temperature of ~100°F. Plastic pellet was used to fill the volume of the comfort gloves and socks to ensure contact between the tubing and the glove/boot bladders. The LCVG extensions were optimized around minimizing pressure drop, assembly complexity, and flow rate. The flow rate was intentionally kept low to increase the temperature delta of the water across the LCVG to reduce uncertainty in resistance temperature device (RTD) measurements while concurrently providing sufficient heat flux to maintain internal suit temperatures within safe limits. RTDs were located at the entry/exit of the Primary Thermal Loop (PTL) fluid lines in the hatch to capture the temperature delta across the PTL. A third RTD was located at the outlet of the LCVG, upstream of the

LCVG extension lines running to the gloves and boots, to capture component-level data on the heat flux of the LCVG isolated from the LCVG extensions.

Three RTDs were used to measure and control the temperatures in the PTL. S2-RTD-130 was nominally at the inlet of the gloves and boots. S2-RTD-120 was located before the water flowed into the LCVG and was controlled to 75°F (24°C) for all of the cold test points. Finally, S2-RTD-110 was in the return line prior to the water leaving the suit and returning to the chiller. All cold test points were performed in this configuration. It meant that the simulated hands and feet were slightly warmer than the LCVG. This is consistent with simulating a person wearing a LCVG because the hands and feet are not covered with tubing normally and would be closer to a human's body temperature. However, the flow direction of the water in the PTL was reversed halfway through the test to perform the hot cases. In these test points flow went to the LCVG first, via S2-RTD-110. Water temperatures at S2-RTD-110 were controlled to 75°F (24°C), which was the inlet to the suit and the LCVG in this configuration. Because these were hot environment tests, the water flowing through the LCVG would pick up heat from the environment and would end up slightly warmer than the LCVG in the gloves and boots, again providing a good simulation of the temperature distribution a human would impart into a spacesuit.

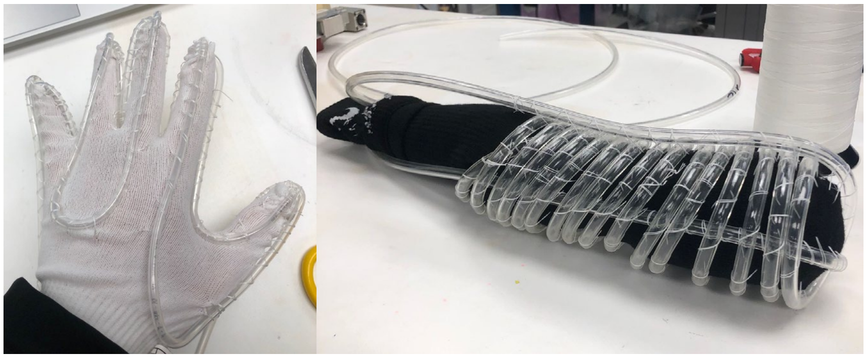
Figure 9. LCVG Extensions.

G. Backplate Assembly

The Suit 2 test article did not include a Portable Life Support System (PLSS), rather the internal atmosphere and temperature were controlled by test system equipment external to the chamber (see Section IV). A weight relief plate was installed onto the hatch to assist in off-loading the test article in the vacuum chamber. Offloading the test article using the weight-relief plate eliminated the need for a custom test stand to be built. An added benefit of using the weight-relief plate to fixture the test article in the vacuum chamber is that the plate does not block radiation heat transfer between heater cage/liquid-nitrogen shrouds and the test article as a traditional donning stand would.

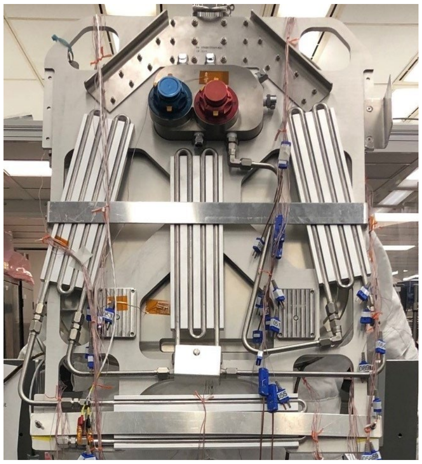
Figure 10. Backplate Assembly.

Heat-exchangers were then mounted to the weight relief plate to provide a similar thermal boundary as the xPLSS backplate nominally provides to the back of the PGS. A PLSS Interface Pad was installed on the hatch to provide fluid and gas line interfaces between test support equipment and the suit. The weight relief plate was covered with a custom EPG piece with seven layers of mylar to provide thermal protection. Figures 10 and 11 show the weight relief plate and how it was integrated into the Suit 2 test article.


Figure 11. Custom EPG Covering Backplate

H. Audio

During testing both Suit 2 and SxEMU had internal microphones and speakers which allowed for testing at ambient and sub-ambient conditions for the Integrated Communication System (ICS). Similar to the SxEMU, a manikin head that housed audio equipment (microphones and a speaker) was installed in the Helmet's cavity to support the audio test objectives. This is shown in Figure 12. The internal audio instrumentation also included a measurement microphone that was connected to the audio test equipment for Suit 2 that was located outside the chamber. The audio equipment installed supported suit-to-suit communication which allowed for speech intelligibility assessments to simulate suited crewmembers speaking to each other. More detail on the audio equipment integral to the test articles used as part of this test series are contained in Reference 4.

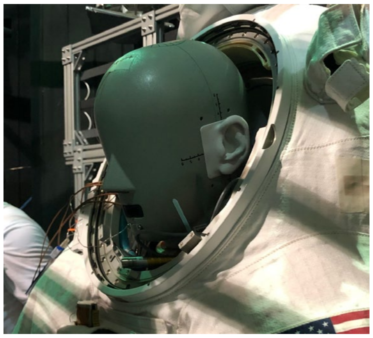

Figure 12. Audio Manikin Head.

I. Display and Control Unit

The Suit 2 test article used a DCU, shown in Figure 13, constructed with an Ultem body as opposed to an aluminum body. The Ultem housing was prototyped as a mass consideration assessment, however, was not chosen as the flight design. By having both an aluminum DCU (SxEMU test article) and an Ultem DCU (Suit 2) both tested during the same thermal vacuum test, a direct comparison of thermal performance could be carried out post-test. This Ultem DCU had a Liquid Crystal Display (LCD) which interfaced with the test system, as well has having fluid interfaces with the PLSS-simulating fluid loop to control temperature in the DCU. It should be noted that the internal electronics which would normally be present in the DCU were not all powered for this component. A modified SCC was machined that mimicked the geometry of the flight Service and Cooling Connection (SCC) design, however replaced the custom quick disconnect mechanics with straight threads where off-the-shelf fluid fittings can be interfaced. A jumper was constructed to join the vehicle supply and return lines.

Figure 13. Suit 2 DCU.

J. Internal Instrumentation

To collect data during the test, a variety of sensors were installed on the inside of the test article. 48 internal Type-T thermocouples were placed at critical locations, affording the ability to assess the internal touch temperatures of the suit. Also heat transfer at specific locations was evaluated by stacking thermocouples at key locations from the inside of the suit, exterior of the suit, and exterior of the EPG. Figure 14 shows some of the thermocouple locations. Thermocouples were secured to the suit hardware with either Kapton tape or 3M 4411N Sealing tape. In addition to thermocouples, 7 RTDs were used to measure the temperature delta between the supply and return of the primary thermal loop, vehicle loop, and gas loop. Custom hardware was developed to interface the RTDs with the water and

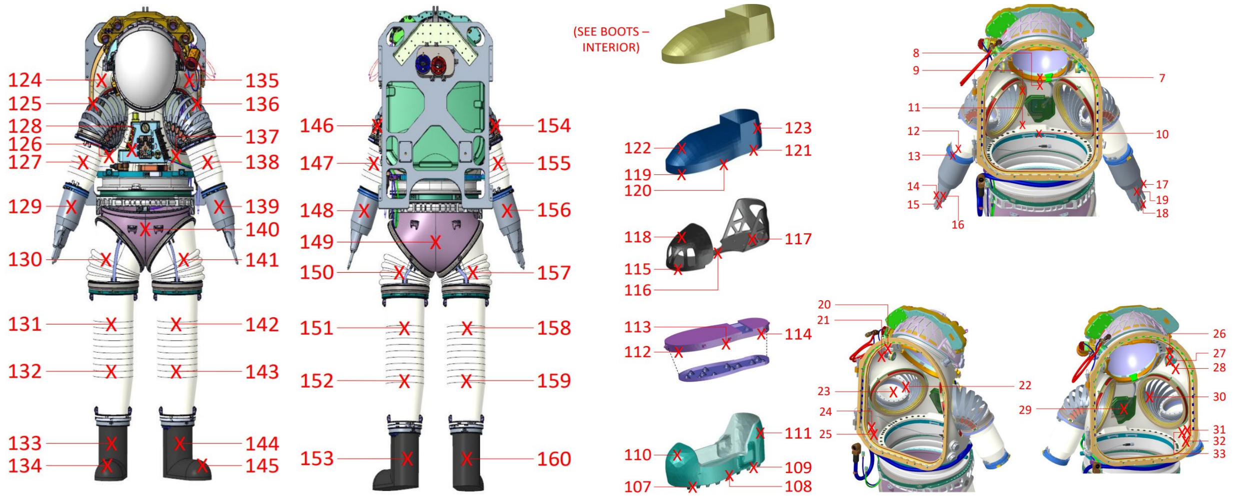

Figure 14. EPG, External Boot, and Internal Upper Torso Thermocouple Locations

gas loops. A manikin was also used to provide volume to the LCVG and to position the LCVG inside the suit in a more realistic fashion. A compact data acquisition system (cDAQ) was installed inside the hollow torso of the manikin to provide an interface for the thermocouples and RTDs. The cDAQ consolidated the number of electrical penetrations needed though the suit pressure barrier. Figure 15 shows more of the internal instrumentation as it was built up in the manikin.

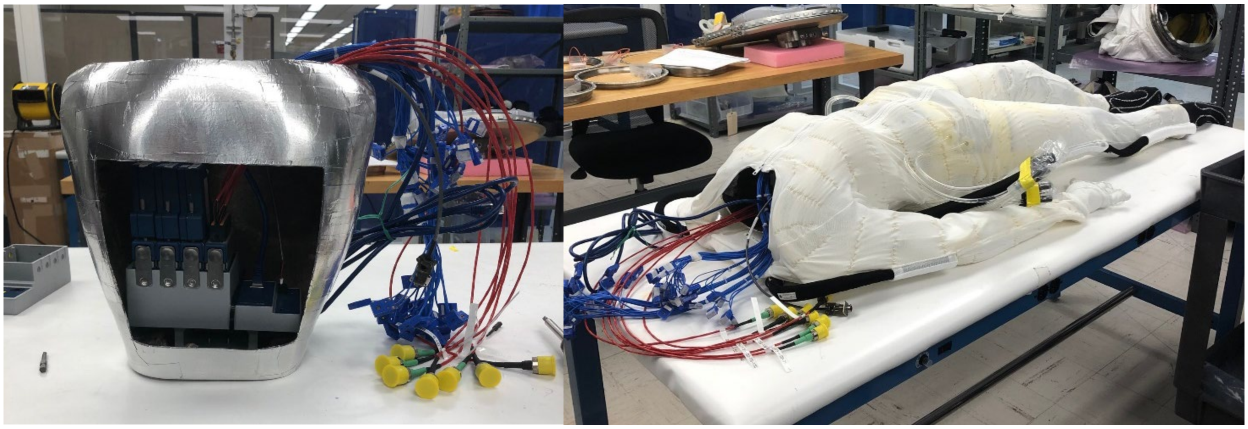

Figure 15. Internal Instrumentation.

IV. Test Support Equipment

A. Vent Loop Cart

To simulate the gas-flow though the spacesuit nominally provided by the xPLSS, a vent loop cart was developed. It drew air from the ambient environment in the building through the suit in the chamber at vacuum and then back outside of the chamber using two small scroll vacuum pumps. The flow rate was set by a flow controller and the internal pressure of the spacesuit was controlled manually though a needle valve during chamber depressurization and repressurization.

Pressure transducers were included on both the inlet and outlet gas lines to monitor suit pressure. The pressure drop of the gas lines between the pressure transducers outside the vacuum chamber and the spacesuit was tested and found to be negligible. A flow meter was also located on the return gas line for redundancy. The internal pressure of the spacesuit was set at 4.3PSIA during vacuum operations and the flowrate was maintained at 6ACFM. Figure 16 shows the Vent Loop Cart.

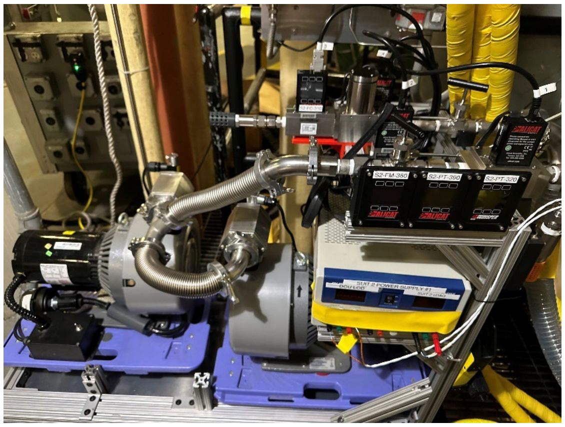

Figure 16. Vent Loop Cart.

B. Chiller Carts

The Suit 2 test article used two separate chiller carts, shown in Figure 17, to independently flow water though two separate thermal loops. The first chiller cart flowed water though the primary thermal loop, including the LCVG and LCVG extensions in the gloves and boots. The second chiller cart flowed water though the vehicle thermal loop, including the heat exchangers on the weight relief plate and the DCU. Both chiller carts were developed prior to this thermal vacuum test and the assemblies remained unmodified. Flow meters were added to the supply lines, downstream of each respective chiller cart, to collect flow rate data. Each chiller cart could control the flow rate and temperature of the water.

Figure 17. Chiller Carts.

C. Data Acquisition System

The xEMU Thermal Vacuum Test LabVIEW-based test system software was responsible for collecting data from many independent sources, presenting that data to the test team, and logging that data to a file. Data sources include National Instruments data acquisition devices with many sensor input types both inside and outside of the vacuum chamber, serial instrumentation inside and outside of the chamber, and Open Platform Communication (OPC) tag data from the facility data acquisition system. The LabVIEW software also streams test data over the network so that engineers spread across the facility (and across the country) could view live test data.

The facility data acquisition system was responsible for monitoring chamber pressure, external thermocouples on Suit 2, and coupon temperatures. This data was streamed on the network via OPC tags, and the xEMU Thermal Vacuum Test LabVIEW-based test system software was configured to read these OPC tags and add this data to the overall data stream. Thus, the LabVIEW software was able to display any test parameter in the system, and the data files produced by the software contained all pertinent data in one file.

V. Test Methodology

A. Hazard Mitigation

While the SxEMU test article performed simulated EVAs, traversing in and out of main chamber on the Crew Transport System (CTS), the Suit 2 test article remained inside the chamber for the duration of the test. Consequently, the Suit 2 test article performed a single, 116-hour long EVA, continuously exposed to thermal vacuum conditions. As re-pressurizing the main chamber was time intensive and expensive, the test matrix and test support equipment for the Suit 2 test article needed to be designed in such a way that any failure of the suit or test support equipment would not require re-pressurizing the main chamber in order to safe the hardware. Primary failure modes considered are: 1) failure of the rigging offloading the test article, 2) major water leak from either water loop, 3) loss of gas pressure control in the test article, 4) loss of internal or external instrumentation, 5) loss of heater cage control.

1) *Rigging Failure* – The Suit 2 test article was offloaded from a weight-relief plated installed onto the exterior of the hatch. A structural failure of the rigging would cause the Suit 2 test article to no longer be suspended and collapse onto the chamber floor. Not only would the impact potentially cause damage to the spacesuit hardware, but the test article could also contact the heater cage and the liquid-nitrogen chilled floor underneath the test article. A conduction pathway either to the heater bars or liquid-nitrogen panel could cause extensive damage to the test article. If this failure were to take place, the chamber would need to be re-pressurized to secure the safety of the spacesuit hardware. While the likelihood of a structural failure of the rigging was low, the consequence of a failure was high. Therefore, an independent, secondary rigging system was installed. All rigging was load tested and certified prior to installation of the test article.
2) *Major Water Leak* – The Suit 2 test article flowed water though two separate thermal loops inside of the spacesuit from two chiller carts located outside of the vacuum chamber. The failure mode of loss of control of these water loops and/or a major water leak into the suit was considered. Should either a loss of control or a major water leak be realized, the effect would be partial or total loss of heat injection/removal from the suit. In that event, the heater cage could be adjusted to maintain a safe internal suit temperature. If a major water leak was discovered, there is the potential to damage the internal instrumentation electronics inside the spacesuit, however this was deemed as a non-catastrophic hazard. The effects of free water inside the suit due to a water leak were discussed extensively. Specifically in a cold environment, should the internal suit temperatures reach below the freezing point of water, it is probable that the free water could freeze on the inside of the suit. Ultimately, no failure mode due to freezing water inside the suit was theorized.
3) *Loss of Gas Pressure Control* – The Suit 2 test article flowed atmospheric air though the spacesuit gas loop. A loss of pressure control could either over-pressurize or depressurize the test article. In the over-pressurization case, a positive pressure relief valve set at 8.8 pounds per square inch differential (PSID) was installed onto the test article. In the depressurization case, a negative pressure relief valve was installed onto the return gas line from the suit, outside the chamber, and set to crack at 2.0 PSID. The gas loop test support equipment utilized two small vacuum pumps to suck gas out of the suit and locating the negative pressure relief valve outside of the chamber, upstream of the vacuum pumps had the effect of pulling gas though the RV from the atmosphere and through the vacuum pumps, rather than pulling gas out of the suit. Finally, a separate negative pressure relief valve was installed onto the test article to protect the test article from deleterious pressure gradients during chamber depressurization and re-pressurization. Flow rate calculations were performed for all relief valves to verify in a full-open configuration, the relief valves would protect the test article.

4) *Loss of Internal or External Instrumentation* – The external thermocouple data was collected though the facility data system, whereas the internal instrumentation data was collected though a separate data system developed for this test. It was determined so long as one set of data was received, either the external or internal thermocouples, the safety of the hardware could be ensured. In the event both data systems failed, the heater cage would be adjusted to maintain safe temperatures on the interior and exterior of the spacesuit.
5) *Loss of heater cage control* – As aforementioned, the xEMU was designed for a lunar cold temperature down to 93K (-292°F) for indefinite exposure. The minimum environmental temperature provided by the chamber was ~152K (-185°F). With significant margin between the cold thermal limit of the spacesuit and the minimum environmental temperature the chamber can provide, should the heater cage fail, the spacesuit can survive an indefinite cold soak.

In summary, the only failure scenario that would cause a re-pressurization of the chamber and early termination of the simultaneous SxEMU thermal vacuum test was a structural failure of two independent rigging systems. The realization of that scenario was exceedingly unlikely. All other failure modes, while might cause a premature end to useful data collection for the Suit 2 test article, would not require the chamber to be re-pressurized. In all other cases, the Suit 2 test article can be returned to a safe configuration while remaining at vacuum conditions, and the SxEMU thermal vacuum test could continue.

B. Test Matrix

The custom heater cage for the Suit 2 test article was designed with 14 independently controllable heater zones. Combined with the liquid-nitrogen shrouds in the chamber, it allowed for testing a variety of thermal profiles, including both maximum thermally stressful environments and expected thermal environments from different potential lunar EVA scenarios. During the Suit 2 thermal vacuum test, 11 unique thermal profiles were test, detailed in Table 1. A driving consideration in generating this test matrix was the lack of historical data for the time constant for an uncrewed spacesuit to reach thermal steady state with the environment temperature. Due to this uncertainty, 14 thermal test profiles were planned, however only 11 were tested. As seen in Table 1, the duration of many of the thermal test profiles exceeded the traditional 8-hour EVA time duration. The Suit 2 test article maintained each thermal profile until thermal engineers determined in real time that the test article had reached thermal steady state with the environment. The general test approach was to begin the test with cold environments and move towards hot environments in such a way that intermediate EVA operationally expected thermal profiles (or mixed environments) could be tested during the transition from maximum cold to maximum hot environments. Additional variables able to be changed included turning the xINFO lights and camera thermal simulator on/off and turning off liquid-nitrogen flow to the floor beneath the Suit 2 test article. Detailed below is the rationale behind each test point.

1) *Test Point 1: Chamber Cooling* – The Suit 2 thermal vacuum test began concurrently with chamber depressurization. Chamber B employs liquid-nitrogen cooled panels on the walls of the chamber for cryo-pumping to increase the vacuum quality of the chamber. This also has the effect of beginning to cool the environment and test article inside the chamber. It was anticipated that interesting thermal data would be collected during this period as the test article experience a combination of both radiation and convective cooling. Notably, the EPG on the spacesuit only provides protection from radiative heat

Table 1. Suit 2 Test Points.

Number	Profile Name	xINFO	Floor LN2	Duration
1	Chamber Cooling	On	On	4 Hr 40 Min
2	Cold	On	On	14 Hr 25 Min
3	Cold (Warming Front of Suit)	On	On	5 Hr 38 Min
4	Cold (Warming Front of Suit)	Off	On	5 Hr 52 Min
5	Max Cold	On	On	11 Hr 46 Min
6	Max Cold	Off	On	8 Hr 20 Min
7	Heating Front Top Half	On	On	14 Hr 25 Min
8	Heating Front	Off	Off	11 Hr 56 Min
9	Max Hot (Bubble 220F)	On	Off	9 Hr 45 Min
10	Max Hot (Even 200F)	On	Off	9 Hr 36 Min
11	Chamber Warming/Repress	Off	Off	12 Hr 16 Min

transfer. This test point will allow not only the study of the effects of convective cooling on the spacesuit, but also provide a data point to infer the safety of depressurizing a thermal vacuum chamber with a suited test subject.

2) *Test Point 2: Cold* - This test point was the first cold test point. The start time of this test point was chosen by thermal engineers during the test as the rate of change of the environment temperature began to slow. A majority of the test article was allowed to steady state during this thermal profile. The xINFO components were powered on to characterize their performance in a cold environment and also to slightly warm the Helmet/EVVA.
3) *Test Point 3: Cold (Warming Front of the Suit)* – After cold soaking for nearly 20 hours, concern was developed for certain components on the spacesuit, including the Helmet/EVVA and boots. To stabilize the test article and provide time to verify the material temperature limits of these components, the front of suit was slightly warmed by turning on individual heater zones.
4) *Test Point 4: Cold (Warming Front of the Suit)* – For this test point, the xINFO lights and camera thermal simulator were powered off. Keeping all other variables constant, this test point allowed for characterization of the thermal effects of the lights and camera on the Helmet/EVVA.
5) *Test Point 5: Max Cold* – With previous spacesuit material temperature limit concerns resolved and the chamber providing the maximum cold environment possible, the Suit 2 test article was allowed to thermally steady state in a maximum cold environment. The xINFO components were powered on for this test point to slightly warm the Helmet/EVVA and provide heating to the electronics of the xINFO components.

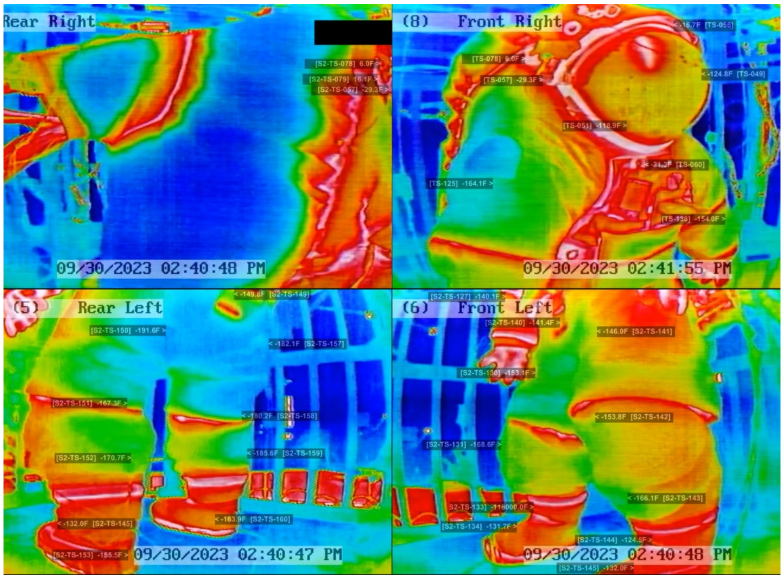

Figure 18. Suit 2 Thermal Image, Test Point 6 – Max Cold

6) *Test Point 6: Max Cold* – For this test point, the xINFO components were powered off. The test article remained in a maximum cold environment. The was the most thermally stressful cold environment tested for the test article. Figure 18 shows infrared images of Suit 2 during this test point.
7) *Test Point 7: Heating Front Top Half* – This test point imagines the scenario where the astronaut has been in a cold environment for a period of time, for example in a crater at the lunar south pole, and then positions the spacesuit such that the front top-half of the spacesuit (from the waist up) is heated. The lower torso and back of the spacesuit remain exposed to a cold environment. Perhaps the astronaut is standing behind a large bolder or is performing geology tasks at the crest of a crater. An environment temperature of 338K (150°F) was chosen as the target temperature for the front top-half of the spacesuit.

8) *Test Point 8: Heating Front* – This test point imagines the scenario where the astronaut emerges after a period of time in a cold environment to an orientation where the front of the suit is facing the sun. Perhaps the astronaut is returning from working in a crater at the lunar south pole and is facing the sun during the trip back to the vehicle. An environment temperature of 338K (150°F) was chosen as the target temperature for the front of the spacesuit. The thermal engineers made real-time adjustments to the power settings for the heater zones to get an even temperature across the front of the test article. Additionally, the liquid-nitrogen flow though the floor beneath the test article was turned off.

9) *Test Point 9: Max Hot (Bubble 220°F)* – The thermal requirements for the xEMU give a 377K (220°F) bounding hot environment temperature, which was the target temperature on the center of the Helmet bubble for this thermal test profile. It was found to be difficult to reach an average 377K (220°F) temperature across the test article without exceeding material temperature limits due to overlapping view-factors of the independent heater cage zones. Figure 19 shows test point 9.

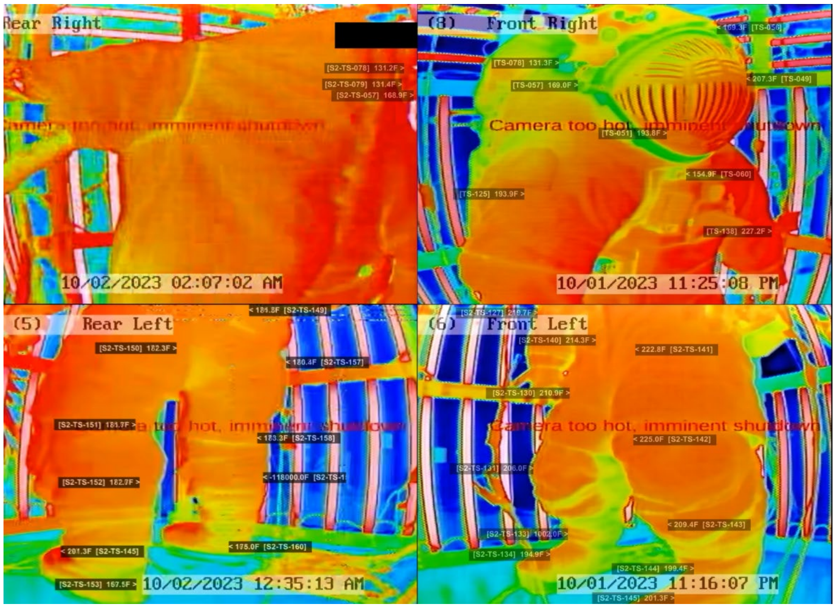

Figure 19. Suit 2 Thermal Image, Test Point 9 – Max Hot (Bubble 220°F)

10) *Test Point 10: Max Hot (Even 200*°F) – For this thermal profile, the heater cage power settings were adjusted to evenly heat the spacesuit to 366K (200°F) on all side of the test article.

11) *Test Point 11: Chamber Warming/Repress* – After the conclusion of test point 10, the high-voltage heater cage was powered off to avoid a discharge as the chamber pressure passed though the Corona arcing range. With the chamber walls still cold from liquid-nitrogen flowing through them, shutting off the heater cage surrounding the test article and beginning to slowly repressurize the chamber had the effect of rapidly decreasing the temperature of the spacesuit. As aforementioned, the EPG on the spacesuit only provides protection against radiation heat transfer, and repressurizing the chamber induces convective cooling (due to the chamber shrouds still being cold) that bypasses the thermal protection of the spacesuit. Interesting thermal data was collected.

Figure 20. Suit 2 Heater Cage

VI. Conclusion

The uncrewed "Suit 2" xPGS test article was designed to collect unique steady-state thermal data in a variety of maximumly stressful and operationally expected thermal test profiles. The test article also collected data on the integrated communication system (ICS), xINFO lighting band, display and control unit (DCU), lunar boots, hard upper torso (HUT), and Helmet/EVVA. The Suit 2 TVAC test met these objectives while also designing the test such that no failure of the test article or test system would impact the simultaneous SxEMU thermal vacuum test. While there are many lessons learned from pursuing an uncrewed approach to xPGS spacesuit thermal vacuum testing, this test provided unique datasets that cannot be obtained through a crewed testing methodology. These datasets will provide insights into future spacesuit development. Reference 3 provides several analyses of the data produced from the Suit 2 test article.

References

[1] Westheimer, D., Rodriggs, L., Falconi, E., Swartout, B., and Lewandowski, M., "xEMU Thermal Vacuum Testing Overview," International Conference on Environmental Systems, ICES, Louisville, KY, 2024.

[2] Sladek, C., Lewandowski, M., Andersen, N., and Westheimer, D., "Planning and Implementation of Extreme Thermal Environments in NASA JSC's Chamber B," International Conference on Environmental Systems, ICES, Louisville, KY, 2024

[3] Swartout, B., "Exploration Extravehicular Mobility Unit (xEMU) Chamber B Thermal Vacuum "Suit 2" Pressure Garment System Test Article Results," International Conference on Environmental Systems, ICES, Louisville, KY, 2024.

[4] Smith, S., and Turner, A., "xEMU Suit Integrated Audio Communications System: Ambient and EVA Pressure Testing System Performance," International Conference on Environmental Systems, ICES, Louisville, KY, 2024.

[5] Luty, R, "Exploration EMU (xEMU) Informatics Thermal Vacuum Performance," International Conference on Environmental Systems, ICES, Louisville, KY, 2024.

[6] Hargove, S., Sladek, C., and Thornton, C., "Display and Control Unit (DCU) Thermal Vacuum Testing Performance," International Conference on Environmental Systems, ICES, Louisville, KY, 2024.