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Exploration Extravehicular Mobility Unit (xEMU) Hard Upper Torso (HUT) Chamber B Thermal Vacuum Testing Results

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NASA's Exploration Extravehicular Mobility Unit (xEMU) is the government reference next-generation spacesuit 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 methodology, hardware setup, and results from the xEMU hard upper torso (HUT). Two HUTs, one composite HUT and one aluminum HUT, were tested simultaneously in Chamber B, with different thermal environments. For the aluminum HUT on the Short xEMU (SxEMU) test article, five thermal profiles were tested during five simulated EVAs. For the composite HUT on the second xEMU, eleven unique thermal profiles were tested including both cold and hot environmental cases over the course of five continuous days of testing. The radiative thermal environment was controlled through exposure to liquid-nitrogen shrouds on the chamber walls and through two separate heater cages surrounding each respective test article. Seventy-two temperature sensors were used to collect data in critical locations in the xEMU HUT assembly. This paper will document the testing results and compare the test data against the xEMU HUT and system-level thermal models for model validation.

Nomenclature

DVT	=	*Design Verification Testing*
EVA	=	*Extravehicular Activity*
HUT	=	*Hard Upper Torso*
LCVG	=	*Liquid Cooling Ventilation Garment*
NASA	=	*National Aeronautics and Space Administration*
NPRV	=	*Negative Pressure Relief Valve*
TC	=	*Thermocouple*
TVAC	=	*Thermal-Vacuum*
xPGS	=	*Exploration Pressure Garment System*
xPLSS	=	*Exploration Portable Life Support System*
xEMU	=	*Exploration Extravehicular Mobility Unit*
SxEMU	=	*Short Exploration Extravehicular Mobility Unit*
EPG	=	*Environmental Protection Garment*
DCU	=	*Display and Control Unit*
BTU	=	*British Thermal Unit*
PPRV	=	*Positive Pressure Relief Valve*
NPRV	=	*Negative Pressure Relief Valve*
MLI	=	*Multi-Layer Insulation*
ICS	=	*Integrated Communications System*
ISS	=	*International Space Station*

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I. Introduction

THE Exploration Extravehicular Mobility Unit (xEMU) project performed a thermal-vacuum test with two spacesuits consisting of Design-Verification-Test (DVT) fidelity hardware. These spacesuits were intended to be the final hardware build prior to qualification of the design. After NASA changed course to continue spacesuit development through a commercial services contracting mechanism, the xEMU became the government reference design and this test served as an assessment of that reference design which could be shared with the applicable industry partners to help them be successful in developing a new spacesuit for use on the International Space Station (ISS) and on the surface of the Moon.

Two spacesuits, the Short xEMU (SxEMU) and the Suit 2 test article were evaluated in the test. Figure 1 shows the general test configuration in the chamber with the SxEMU in a heater cage on the left and Suit 2 in a heater cage on the right. References 1 and 2 provide an overview of the test set up and heater cage designs. References 3, 4, and 5 provide additional information on the design and results of the Exploration Pressure Garment Subsystem (xPGS) portions of both test articles. The SxEMU utilized an aluminum HUT and the Suit 2 test article had a composite HUT.[6] This paper compares the thermal results from these two test articles to provide insight into the strengths and weakness of these two different material choices.

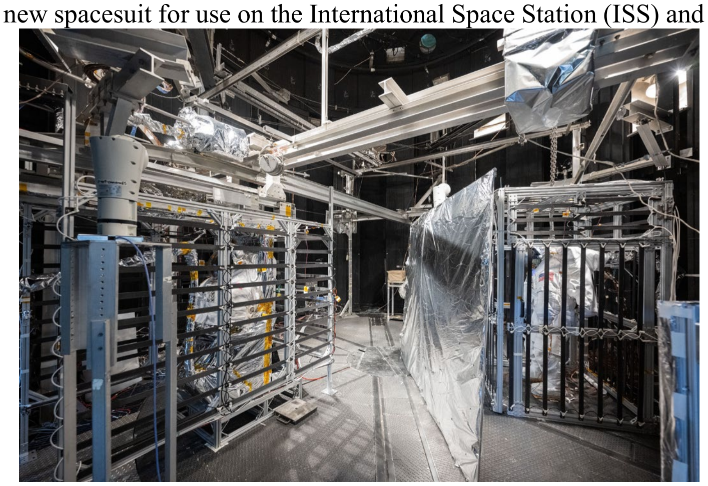

Figure 1. xEMUs in Chamber B.

II. Test Objectives

The primary objective of this test series was to test xEMU hardware in a high-fidelity simulated space environment. Objectives can generally be grouped into three categories: 1) demonstration in relevant thermal environments, 2) demonstration in a relevant pressure environment, and 3) demonstration at a high level of spacesuit integration.

A. Objective 1

The SxEMU aluminum HUT and Suit 2 composite HUT demonstrated a subset of xPGS and xPLSS components in relevant thermal environments. A crewmember wearing an LCVG was absent from the SxEMU, which represents a relatively massive, self-regulating thermal input to the spacesuit system. Instead of a crewmember, the SxEMU housed an instrumentation package to help assess the performance of the xPLSS and audio system. These did not behave similarly to a crewmember wearing an LCVG and provided additional limitation to the potential testing operations of the xPGS portion of the SxEMU. Understanding these caveats, the SxEMU HUT components were still exposed to a wide range of environment temperatures and different aspects of the performance were assessed. The Suit 2 test article did include a full LCVG that simulated the thermal load provided by a crewmember, however the thermal effects of a crewmember's head was not simulated. Numerous thermocouples were included on the hardware at varying levels within the layup of the xPGS components. This provides temperature profiles going through a cross section from inside of the suit, to outside of the suit, and then to the exposed portion of the Environmental Protection Garment (EPG), which consists of multiple layers of Mylar separated with layers of scrim material. Hot or cold spots could be observed across the HUT assemblies where higher areas of heat leak could be identified and compared against the xEMU HUT thermal models. Finally, surviving the temperature extremes that the hardware was exposed to is a successful test. Thermal requirements for the xEMU ranged from: Lunar Crater Hot at +220°F (378 K), International Space Station (ISS) Hot at +147°F (337 K), ISS Cold at -210°F (139 K), and Lunar Crater Cold at - 292°F (93 K).

B. Objective 2

This test was the first significant exposure to sub-ambient pressures for the xPGS components. Typically, xPGS development tests have been performed in lab-ambient environments with the suit pressurized to 4.3 psig (19 psia/131 kPa). During vacuum testing, the external portion of the suit was exposed to hard vacuum (< $1\text{x}10^{-5}$ Torr) and the internals were 4.3 psia (30 kPa). Simply surviving these space-like pressure conditions was significant demonstration for this xPGS hardware. Success criteria was no post-test observation of permanent damage and no significant post-test increase in suit leakage.

C. Objective 3

Finally, testing at a high level of spacesuit integration is always an important objective. The act of simply putting all of the pieces together is a key demonstration of the design of a complex and highly integrated spacesuit. The xPGS houses portions of the life support system (such as relieve valves and water bladders) and also supported use of the Display and Control Unit (DCU), which is mounted to the front.

III. Test Configuration

Two different HUT configurations were tested. The SxEMU test article is assembled with an aluminum HUT and the Suit 2 test article is assembled with a composite HUT. The aluminum HUT material is AL 6061-T6 and has a thermal conductivity of 96.6 BTU/hr/ft/F. The composite HUT material is S-glass fiberglass and has a thermal conductivity of 0.1693 BTU/hr/ft/F. Both are small-sized HUTs and are identical, other than the material difference. However, there are significant differences in thermal simulation quality and environmental temperature differences between the two test articles that will be discussed in this section. Additionally, thermocouples were installed in critical locations on the test articles to evaluate temperatures on the HUT/Hatch shell and thermally interesting locations, such as exposed metallic components. Table 1 and Table 2 outline the test matrices for both test articles.

A. SxEMU Configuration

The SxEMU test article was assembled with an aluminum HUT, pictured in Figure 3. Inside of the HUT, an internal instrumentation package was installed to assess the performance of the Exploration Portable Life Support System (xPLSS) functions. With the internal instrumentation package installed inside of the HUT, there was no internal volume remaining to fit a Liquid Cooling Ventilation Garment (LCVG) inside of the HUT. Also, as this was an uncrewed test, there was no astronaut inside of the HUT. The combination of the astronaut and LCVG inside of the HUT nominally provides significant heat flux for the HUT, and the heat flux capacity of the internal instrumentation was unknown prior to the start of the test. The temperature of the thermal loops in the PLSS connected to the internal instrumentation was controlled to 50°F, however the large delta in surface area between the internal instrumentation tubing and an LCVG make comparisons in heat flux and internal crew touch temperatures difficult between the two scenarios. While this test configuration for PGS does not afford significant thermal model validation, the thermal effects of the crewmember on the PGS components can be explored. This test article also provides a reference for the Suit 2 test article, which produced higher fidelity PGS thermal data. Figure 2 illustrates the SxEMU test article positioned inside Chamber B.

Figure 2. SxEMU Test Article.

The SxEMU performed five simulated EVAs, traversing in and out of the main thermally conditioned vacuum chamber into a thermally neutral crewlock for consumables recharge. The SxEMU's aluminum HUT experienced test conditions more closely matching operational cases in which the test article was exposed to thermal vacuum conditions for eight to ten hours, matching the time duration of a typical LEO or lunar EVA. The test article, in general, did not reach thermal steady state conditions with the environment. During each IVA phase, the HUT returned to ambient temperatures before beginning a new thermal profile. With the heat flux capacity of the internal instrumentation not characterized, a conservative environmental thermal test profile was developed to start with conservative temperatures and iteratively move towards more thermally stressful temperatures during each consecutive EVA. For the "cold" environment testing, a minimum temperature of 32°F was decided on to remove the possibility of freezing water inside the thermal loops located inside the HUT volume. Consequently, no useful cold environment test data was collected for the SxEMU PGS components. For the hot environment testing, a maximum environmental temperature of +170°F was reached.

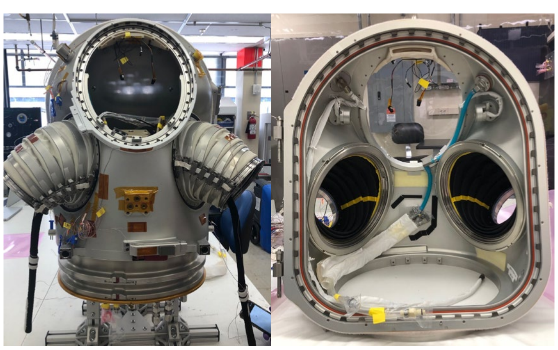

Figure 3. xEMU Aluminum HUT.

Table 1. SxEMU Test Matrix.

Test Point	1	2	3	4	5
Time at Vacuum	8.8 Hours	10.6 Hours	9.1 Hours	11.4 Hours	6.3 Hours
Environment	Cold	Cold	Hot	Hot	Hot
Suit Pressure	4.3 psia	4.3 psia	4.3 psia	4.3 psia	4.3, 5.0, 6.2, 8.2 psia

B. Suit 2 Configuration

The Suit 2 test article was assembled with a composite HUT (cHUT), pictured in Figure 5. The composite HUT was the intended flight design for the xEMU government reference design spacesuit. For this reason, it was decided to test a composite HUT on Suit 2 where it was exposed to the highest temperature extremes. The Suit 2 test article did not have a PLSS installed on the hatch, however the life support functions of the PLSS were simulated with test hardware. Specifically, thermally conditioned gas flowed through the suit and 50°F water flowed through the Hatch. The Suit 2 test article included two separate water loops: the first representing the heat load from a crewmember and the second simulating cooling from the PLSS. The Hatch boundary temperature, nominally set by the PLSS backplate, was controlled to 50°F using externally mounted cold plates through the second water loop. The Suit 2 test article included a full LCVG to provide representative heat flux to the HUT. Similar to the aluminum HUT on SxEMU, the composite HUT on Suit 2 included a full complement of PGS-located PLSS components including a Positive Pressure Relief Valve (PPRV), Negative Pressure Relief Valve (NPRV), HUT Purge Valve, and C-660 Communications Harness. Notably for the composite HUT, only a single PPRV was included and the NPRV was located on the crew-right side of the composite HUT where the second PPRV is nominally located under the EPG. This allowed for a custom electrical passthrough to be installed in the nominal NPRV location on the crew-left side of the composite HUT. This electrical passthrough was covered with EPG to avoid leaking significant heat into the HUT. Figure 4 illustrates the Suit 2 test article installed inside Chamber B.

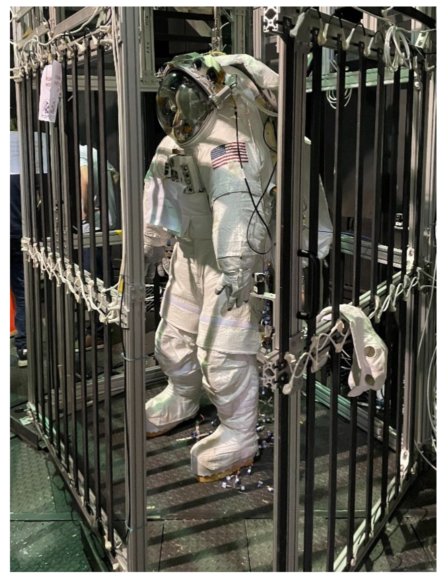

Figure 4. Suit 2 Test Article.

The Suit 2 test article remained inside the main thermally conditioned vacuum chamber for the duration of the test and was exposed to temperature extremes for 116 hours continuously. Additionally, unlike the SxEMU test article that performed simulated EVAs, the Suit 2 test article was allowed to reach thermal steady state with the environment temperature allowed a unique dataset to be collected with respect to HUT temperatures and thermal time constants. The maximum cold environment temperature reached was approximately -185°F while the maximum hot environment reached was slightly above +200°F. One important simulation quality variable to consider for the Suit 2 test article was the lack of the thermal effects provided by an astronaut's head on the upper half of the HUT. Prior modeling before this thermal vacuum test without a head indicated that in lunar environments, internal HUT temperatures near the head area will decrease an estimated 30°F in a cold environment and increase an estimated 15°F in a hot environment. When considering internal touch temperatures near the head area for the HUT, these temperature deltas must be considered.

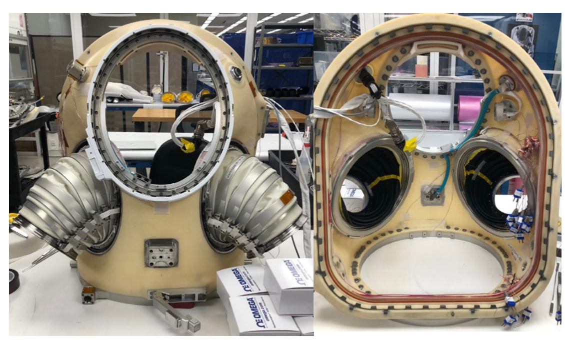

Figure 5. xEMU Composite HUT.

Table 2. 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

C. Thermocouple Configuration

To assess the thermal performance of the HUT assemblies, 32 thermocouples were installed on the SxEMU aluminum HUT and 37 thermocouples were installed on the Suit 2 composite HUT. Thermocouples were generally stacked, where possible, though the layers of the HUT assembly from the interior of the HUT, to the exterior of the HUT, and then to the exterior of the EPG to identify the temperature gradient across the different materials. Thermocouples were also placed on thermally interesting locations, usually where exposed metallic components without thermal insulation were located, such as the Purge Valve or NPRV. Due to the large size of the HUT, localized

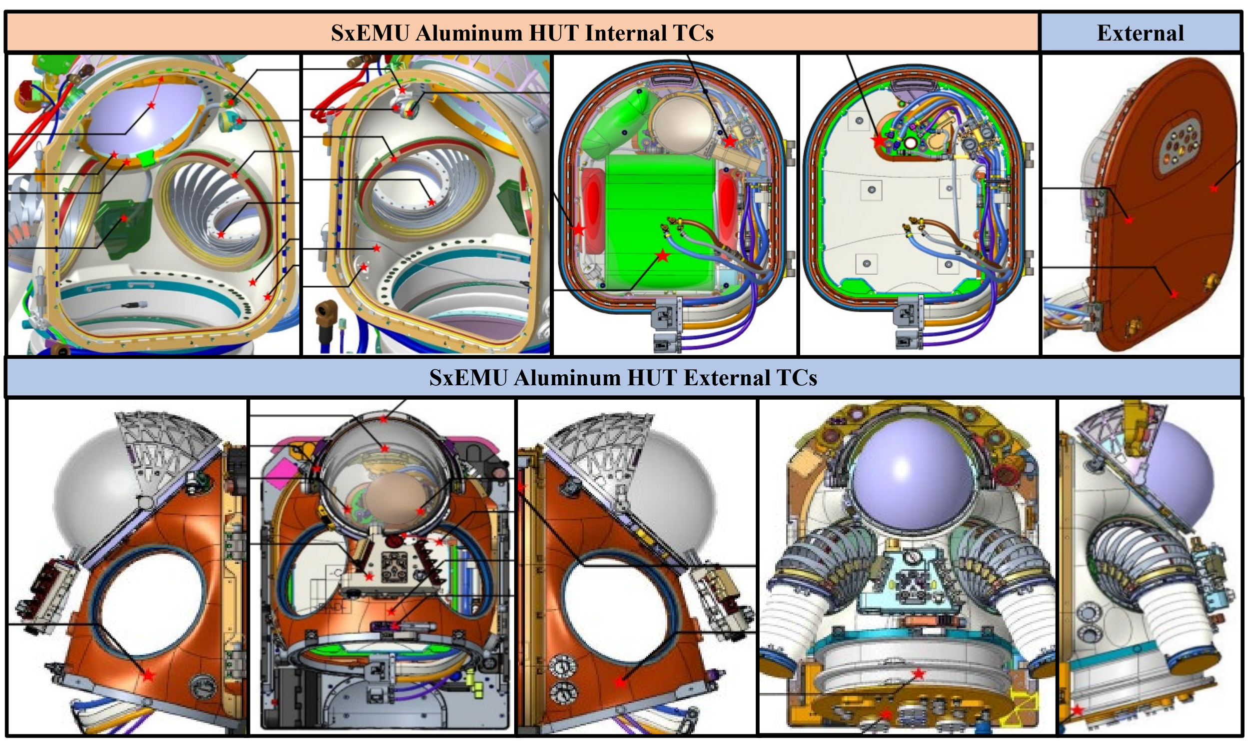

Figure 6. SxEMU TC Locations. (EPG not shown)

interfaces with the thermal loops, and differing radiation thermal environments on each side of the HUT, it is impossible to arrive at a single temperature of the HUT shell. Test data will be discussed further in the Results Summary section. SxEMU thermocouple locations are documented in Figure 6. Suit 2 TC locations are documented in Figure 7.

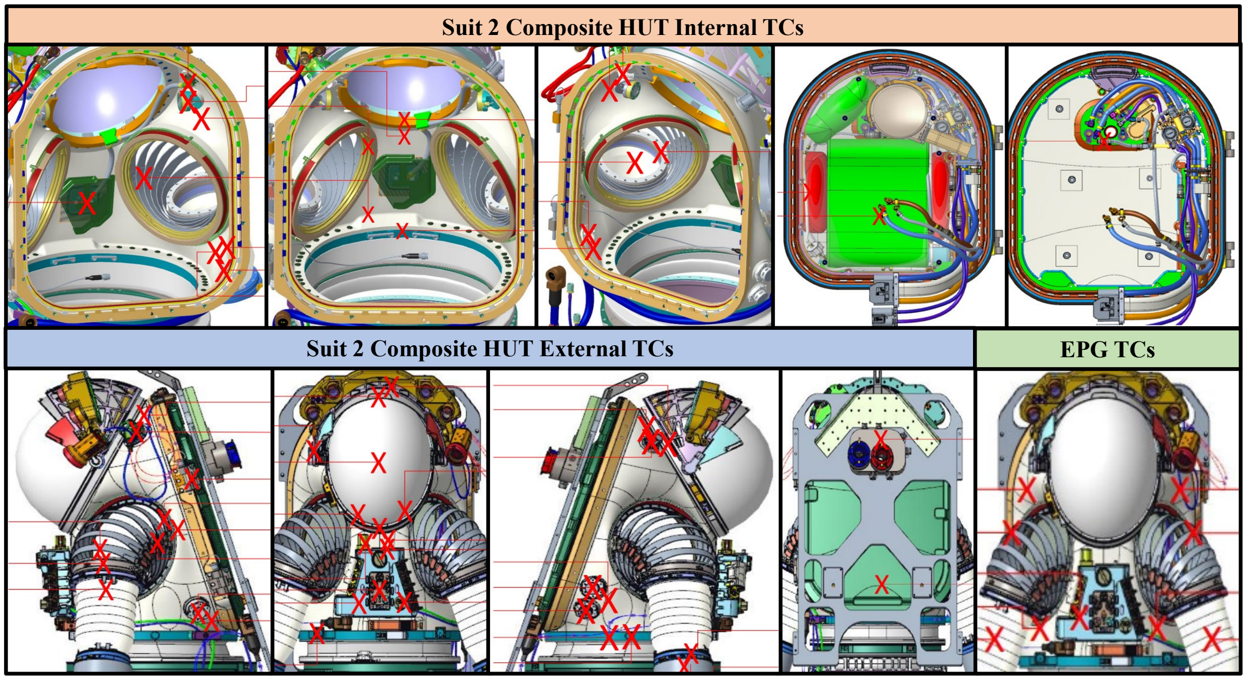

Figure 7. Suit 2 Composite HUT TC Locations. (EPG not shown)

IV. Results Summary

A. SxEMU Aluminum HUT Results

The SxEMU test article performed five simulated EVAs, returning to ambient temperatures between each EVA. This test methodology simulated a realistic time exposure of eight to ten hours with the thermal environment. The cold environment test profiles were quite mild with minimum environment temperatures kept above 40°F while the hot environment test profiles were more aggressive with maximum environmental temperatures reaching up to 170°F. Figure 8 illustrates the aluminum HUT shell temperatures on the SxEMU test article for the entire duration of the thermal vacuum test, with indications of EVA and IVA phases. It is difficult to derive conclusions about the aluminum HUT assembly performance in the cold case as environment test temperatures deviated significantly from expected ISS or lunar cold environment temperatures. However, in the hot environment testing, the EPG temperatures reached up to 130°F in EVAs #3 and #4 and up to 160°F in EVA #5. These temperatures are in the range of the 147°F ISS hot environment temperature assumption and useful analysis can be conducted. In summary, analysis for the SxEMU aluminum HUT will only consider the ISS hot environment.

Throughout the five simulated EVAs, the temperatures of the aluminum HUT shell did not extend beyond 50°F in the cold environments and 80°F in the hot environments. These temperatures, especially in the hot environment test profiles are within in the xEMU internal crew touch temperature requirement range of 50°F to 115°F. While this data is promising, the heat flux capacity of the internal instrumentation package was not characterized or mapped to the performance of an LCVG, so firm conclusions about the thermal performance of the aluminum HUT can only be inferred. However, the large temperature difference that exists in EVA #5 between the EPG at 160°F and the HUT shell at round 80°F indicates excellent performance of the EPG thermal insulation. Unlike the composite HUT on the Suit 2 test article, the aluminum HUT on SxEMU is expected to conduct heat through the HUT shell material efficiently. The aluminum HUT shell is expected to see more evenly distributed temperatures across the entire HUT shell as compared to the composite HUT. This expectation is confirmed in Figure 8 and Figure 15 where the aluminum HUT shell temperatures are grouped much more closely together than the composite HUT shell temperatures. However, it is recognized that it is unknown whether increased differentiation between aluminum HUT shell temperatures would be seen if the SxEMU test article was allowed to reach thermal steady state with the environment.

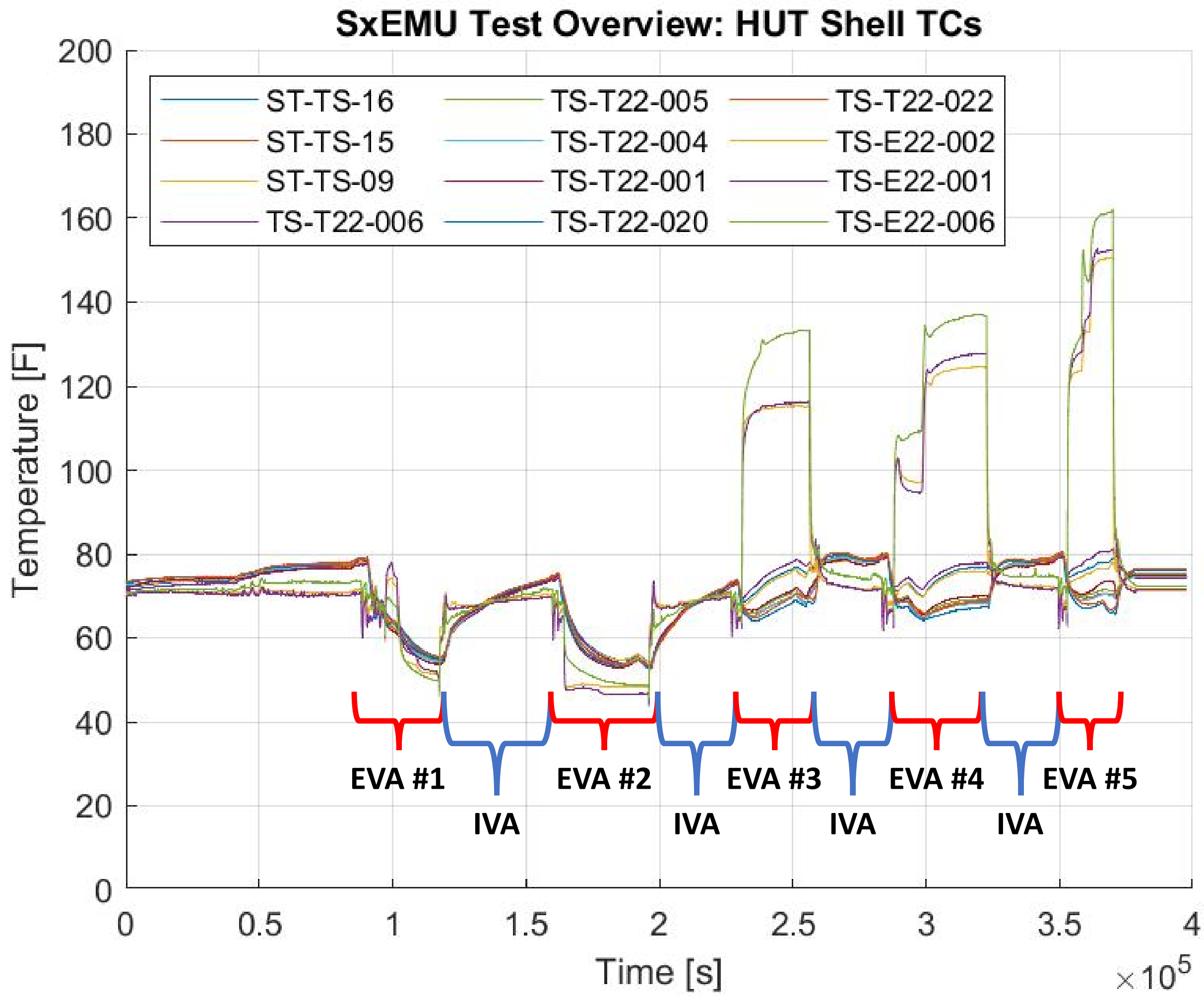

Figure 8. SxEMU Aluminum HUT Shell Temperatures.

Overall, the SxEMU test article performed well and produced encouraging results with respect to thermal performance in ISS hot environments. The xEMU aluminum HUT thermal model predicts HUT shell temperatures to generally be around 70°F to 90°F in an ISS hot environment temperature of 147°F. Surprisingly, the nominal xEMU HUT thermal model predictions (including a crewmember inside the HUT) match well with the test data for HUT temperatures in ISS hot conditions, despite not simulating the crewmember inside the spacesuit. Figure 9 illustrates the thermal model temperature predictions for an eight-hour exposure in an ISS hot environment. Figure 13 depicts two thermal images of the SxEMU test article in cold environment test profiles.

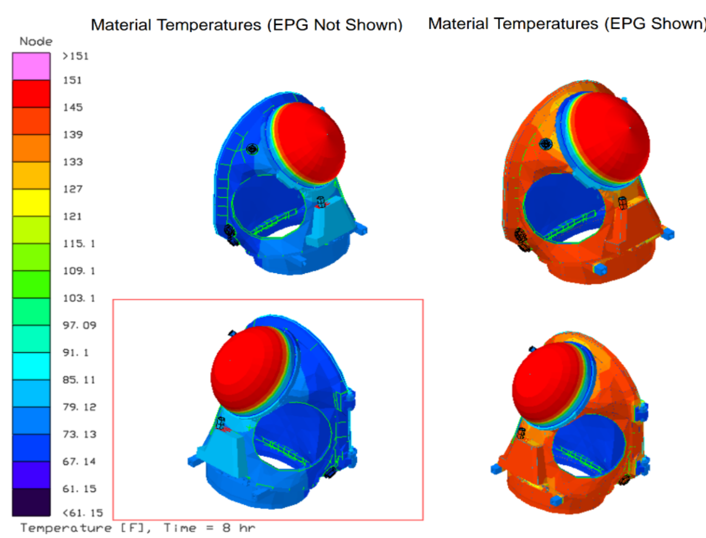

Figure 9. xEMU Aluminum HUT Thermal Model Results for an ISS Hot Environment.

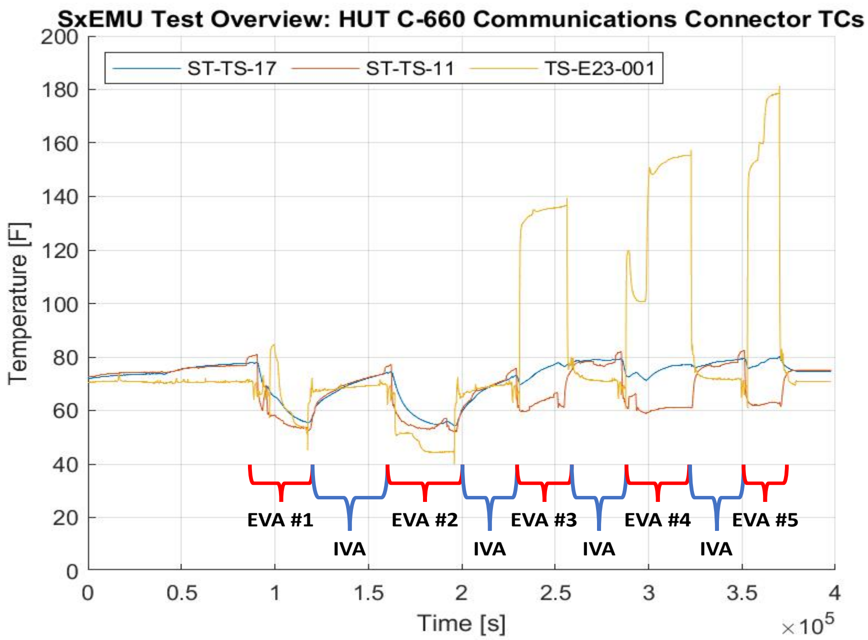

Figure 10. SxEMU C-660 Communications Connector Temperatures.

Figure 10 depicts the temperatures of the C-660 communications connector and the aluminum HUT shell on the inside of the suit. Unlike the C-660 connector results on Suit 2, which will be discussed later in this section, the C-660 connector and aluminum HUT shell temperatures on SxEMU are closely coupled together and do not significantly swing with the environment temperature (TS-EA-001). Interestingly in the hot environment testing, the C-660 connector (ST-TS-11) is colder than the HUT shell (ST-TS-17), whereas the reverse is observed on the composite HUT. The EPG covering the C-660 connector appears to perform well, accounting for a 100°F temperature delta in EVA #5.

The Negative Pressure Relief Valve (NPRV) is a thermally interesting component as it was not covered with EPG on the SxEMU test article, seen in Figure 11. The external temperature of the NPRV was read by TS-T22-004 and the internal temperature was read by ST-TS-13. ST-TS-16 read the internal HUT shell temperature near the NPRV, and SX-EC-10 read the temperature of a nearby environmental coupon. As illustrated in the hot environment cases in Figure 12, the internal, external, and aluminum HUT shell temperatures did not significantly change as the environment temperature increased to 150°F and 170°F. This is an interesting finding, as designing EPG to cover the NPRV while not restricting the gas flow rate was not achieved during the xEMU project. While further investigation is needed, the thermal data gathered during this test may indicate that the NPRV can remain uncovered by EPG. However, it is important to consider that only the ISS hot environment temperature was tested, and future testing should envelope lunar hot environment temperatures at +220°F before drawing firm conclusions. It is also possible that the NPRV had reduced view factors with the heater cage and did not experience the full range of temperatures expected in the ISS hot environment test profile.

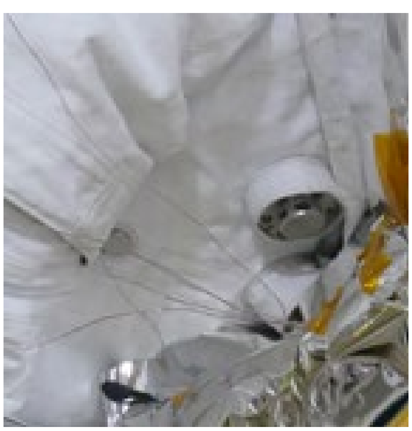

Figure 11. EPG around NPRV.

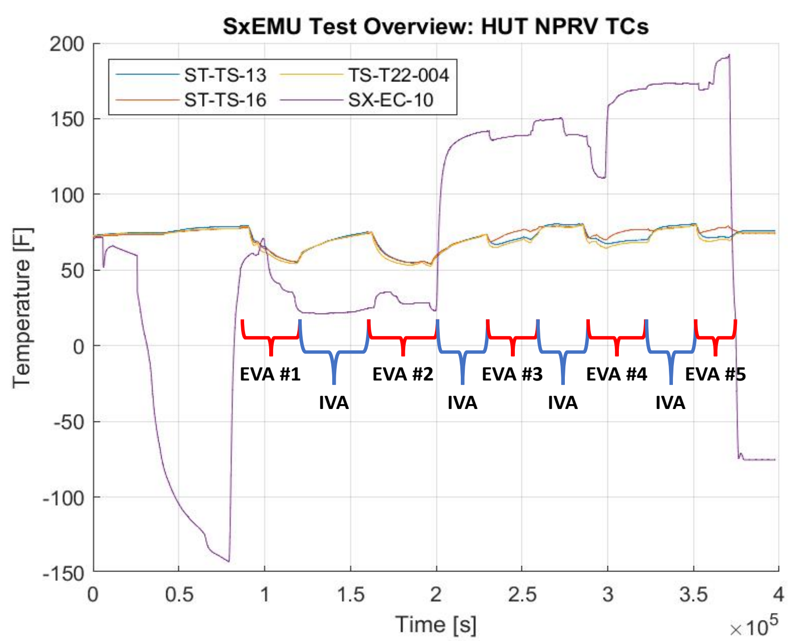

Figure 12. SxEMU Aluminum HUT NPRV Temperatures.

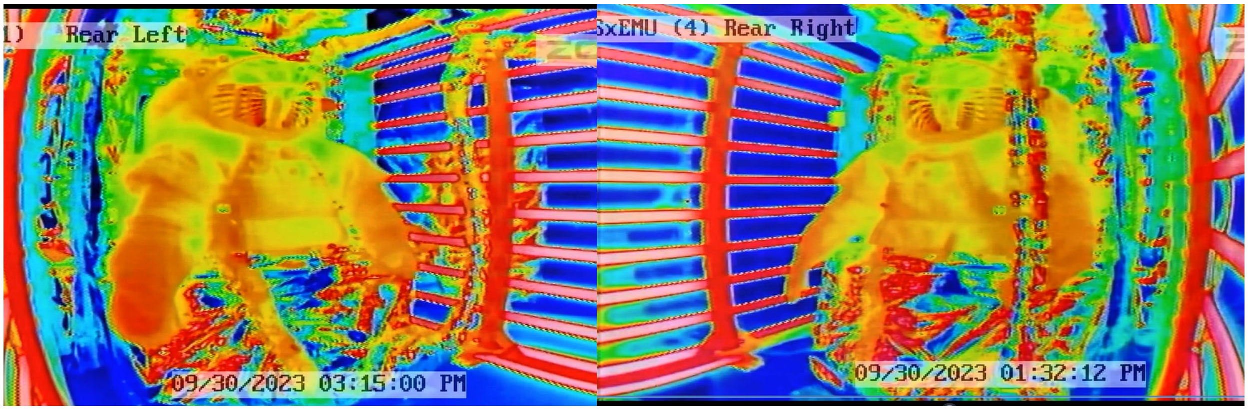

Figure 13. SxEMU Thermal Image.

B. Suit 2 Composite HUT Results

While the Suit 2 cold thermal radiation environment was not quite as cold as ISS or lunar environments, the minimum cold environment reached for the composite HUT ranged between -150°F and -170°F. This temperature range is cold enough to draw useful comparisons to the performance of the HUT in LEO and lunar cold environments. As Figure 14 illustrates, the EPG performed well as a thermal insulator, and the temperatures of the HUT shell underneath the EPG were generally around 50°F. As the composite HUT material is expected to be thermally insulating, it was anticipated that potentially high heat-leak areas like exposed metallic components not covered with EPG would not transfer heat well to the HUT shell, and vice versa. Figure 14 includes locations on the HUT shell near and far away from exposed metallic components, yet the HUT shell temperatures are all grouped closely together. This tight grouping indicates a lack of significant heat transfer to exposed metallic components from the HUT shell. One negative effect of this behavior is that not inputting heat from the HUT shell to the exposed components, leads to higher temperature extremes observed for the exposed components. Conversely, an aluminum HUT will transfer heat efficiently through the HUT shell and will potentially provide a better heat transfer pathway from the HUT shell to the heat leak location, reducing the temperature extremes expected for the exposed component. This finding will be discussed in more depth later on in this section.

With respect to internal crew touch temperatures, the composite HUT performed well. The HUT shell temperatures are grouped around 50°F, the lower limit of the xEMU internal crew touch temperature requirement. It is necessary

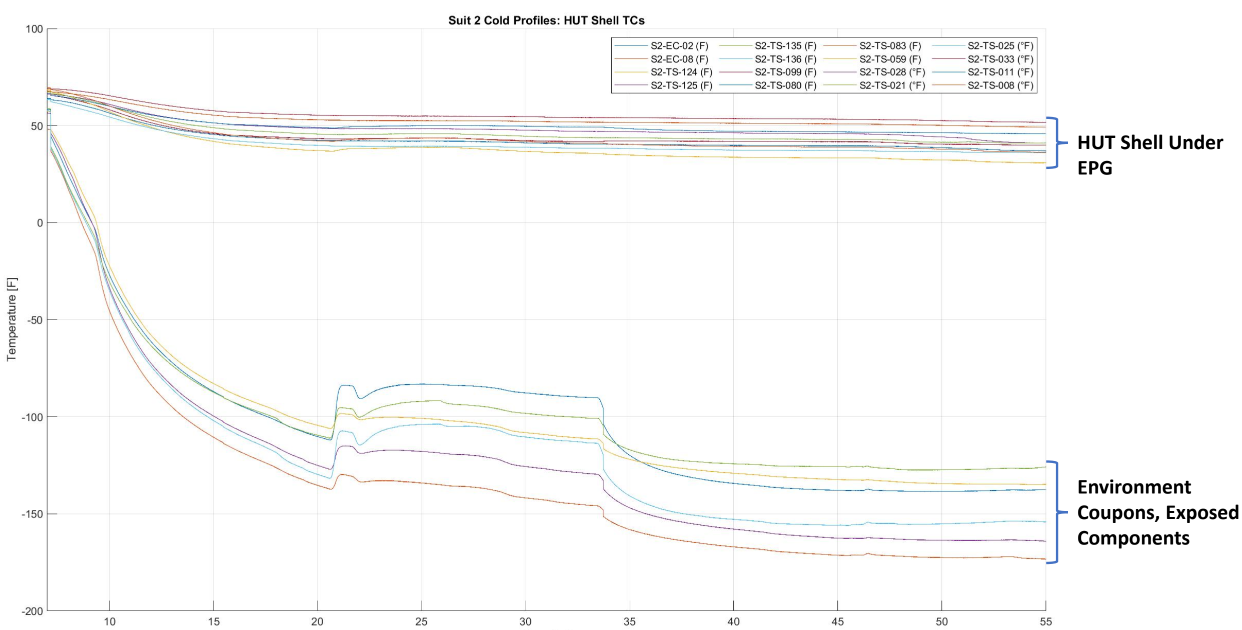

Figure 14. Suit 2 Composite HUT Shell Cold Environment Temperatures.

to consider that the thermal effects of the astronaut's head on the temperatures of the upper half of the HUT was not simulated. Prior modeling indicates an approximate 30°F temperature decrease without the thermal mass and heat generation of a suited subject's head. Taking this 30°F into account gives confidence in the performance of the HUT shell with respect to internal crew touch temperatures.

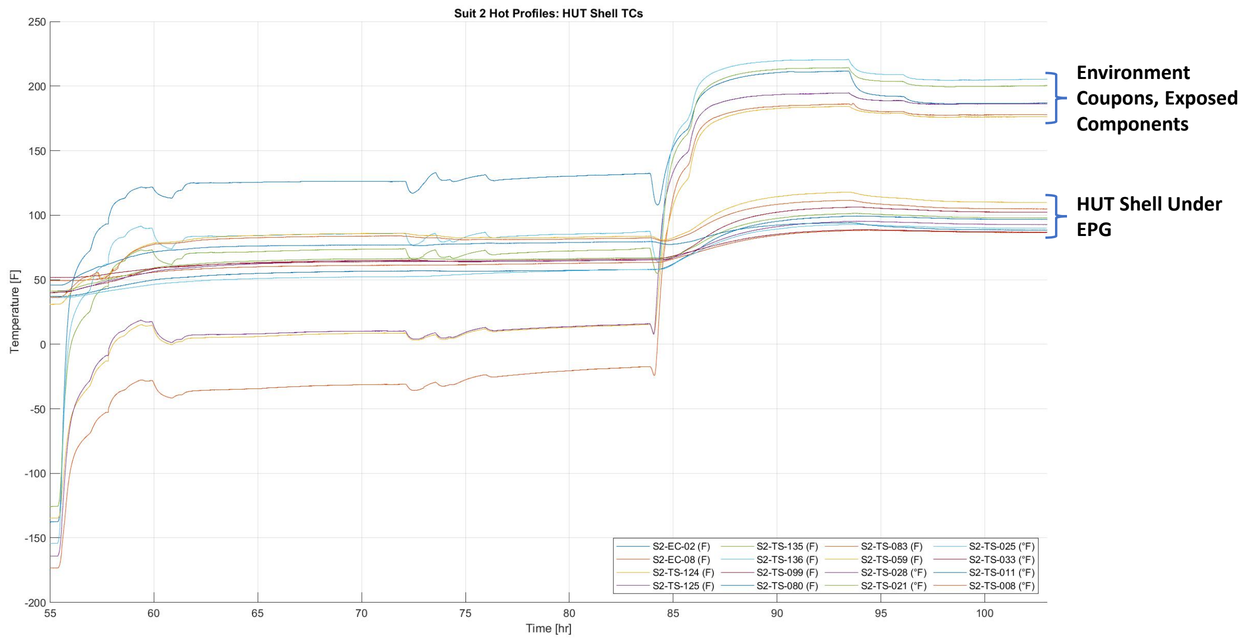

Figure 15. Suit 2 Composite HUT Shell Hot Environments Temperatures.

Figure 15 depicts three thermal profiles. After hour 85, two maximum hot radiation environments that were tested: the first focused on a +220°F temperature on the center of the helmet, and the second focused on a more evenly distributed +200°F temperature across the entire Suit 2 test article. Similar to the cold environment test results, the EPG performed well. Again, the HUT shell temperatures are grouped closely together slightly above +100°F. The upper limit for the xEMU internal crew touch temperature requirement is 115°F, and the majority of HUT shell temperatures were below this threshold value. A 10°F to 15°F decrease in the temperatures of the upper half of the HUT shell would be expected with a crewmember inside the suit. Satisfactory performance of the EPG and HUT shell in both hot and cold environments is a positive indicator that an astronaut could comfortably perform a LEO or Lunar EVA with the xEMU composite HUT design.

The composite HUT thermal data collected matches well with the anticipated temperatures of the HUT shell from the xEMU HUT thermal model. As seen in Figure 16, the thermal model predicts in a lunar hot environment, composite HUT shell temperatures will generally be in the range of 90°F to 120°F, with locations near exposed metallic components, such as the neck ring, seeing higher temperatures. The HUT shell temperature test data collected simulating lunar hot environments, plotted in Figure 15, fall within the range predicted by the thermal model. Similarly in the cold case, Figure 16 estimates the HUT shell temperatures from the thermal model in a lunar cold environment to be in the range of 40°F to 70°F, with areas near exposed metallic components reaching lower temperatures. Again, the HUT shell temperature test data collected from the cold environment simulation, plotted in Figure 14, are close to this range. A high-level correlation illustrated in Table 3 between

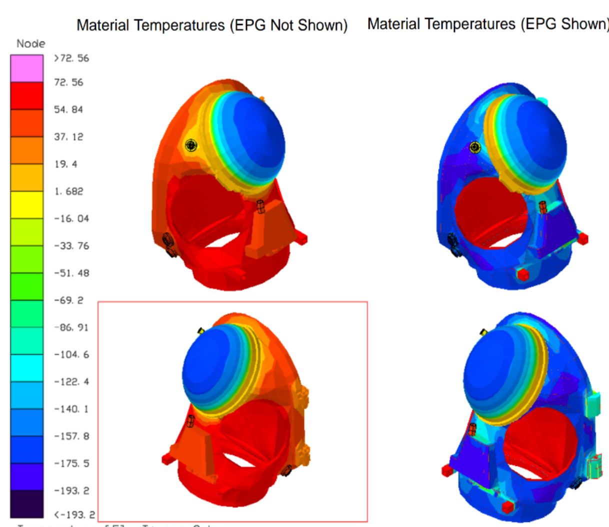

Figure 16. xEMU Composite HUT Thermal Model Results for a Lunar Cold Environment.

the model temperature predictions and the test data provides confidence in the xEMU HUT thermal model's accuracy and assumptions.

The C-660 Communications Harness interfaces with the HUT on the top crew-left side of the HUT. The connector is covered by EPG, however Figure 18 illustrates that the external connector saw higher temperature extremes than expected. In the cold environment testing, the external connector temperature reached as low as -50°F, and in the hot environment testing, reached as high as 170°F. Interestingly in the cold case, with the composite HUT material acting as a thermal insulator, the warmer HUT shell did not transfer a significant amount of heat to the connector. The internal connector actually saw higher temperature extremes than the internal or external composite HUT shell near the connector interface. This test data indicates that the EPG design covering the C-660 connector should be examined for future spacesuit development. Though probably not a significant contributor to system-heat leak due to the small amount of surface area the connector possesses, improving the insulation scheme for this connector is an easy area of improvement.

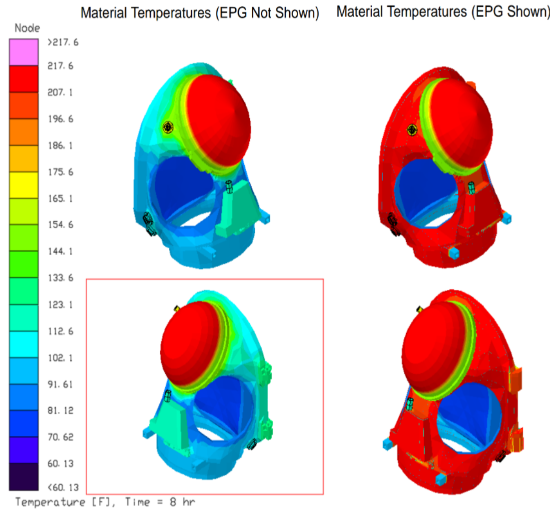

Figure 17. xEMU Composite HUT Thermal Model Results for a Lunar Hot Environment.

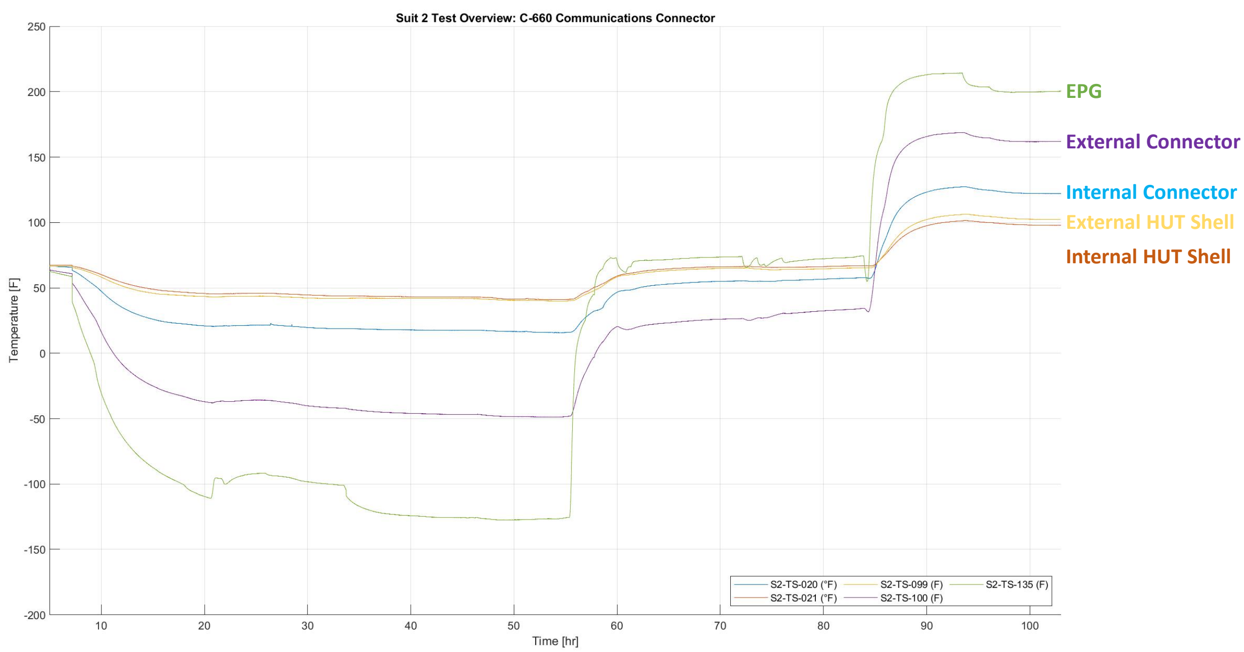

Figure 18. C-660 Communications Harness Connector on Composite HUT.

Several thermocouples were placed near and on the HUT purge valve located at the top crew-right side of the HUT. The HUT purge valve is a thermally interesting location because the purge valve is an exposed metallic component penetrating though the HUT shell to the interior of the spacesuit. While the purge valve has low surface area, the efficiency of the heat transfer though the barrel of the purge valve into the spacesuit was cause for investigation. Figure 19 depicts the purge valve test data. In the maximum cold environment, the external purge valve temperature reached down to 10°F. In the maximum hot environment, the purge valve temperature reached up to 140°F. The internal and external composite HUT shell temperatures did not equalize with the purge valve temperatures and an approximate 30°F temperature delta was observed in the cold environment test profiles and an approximate 40°F temperature delta was observed in the hot environment test profiles. This indicates the path of least thermal resistance was through the purge valve and into the suit, rather than transferring heat with the composite HUT shell.

However, similar to the C-660 communications connector, the purge valve has a low amount of thermal mass and contact area with the HUT so the total heat leak contribution to the system is expected to be low.

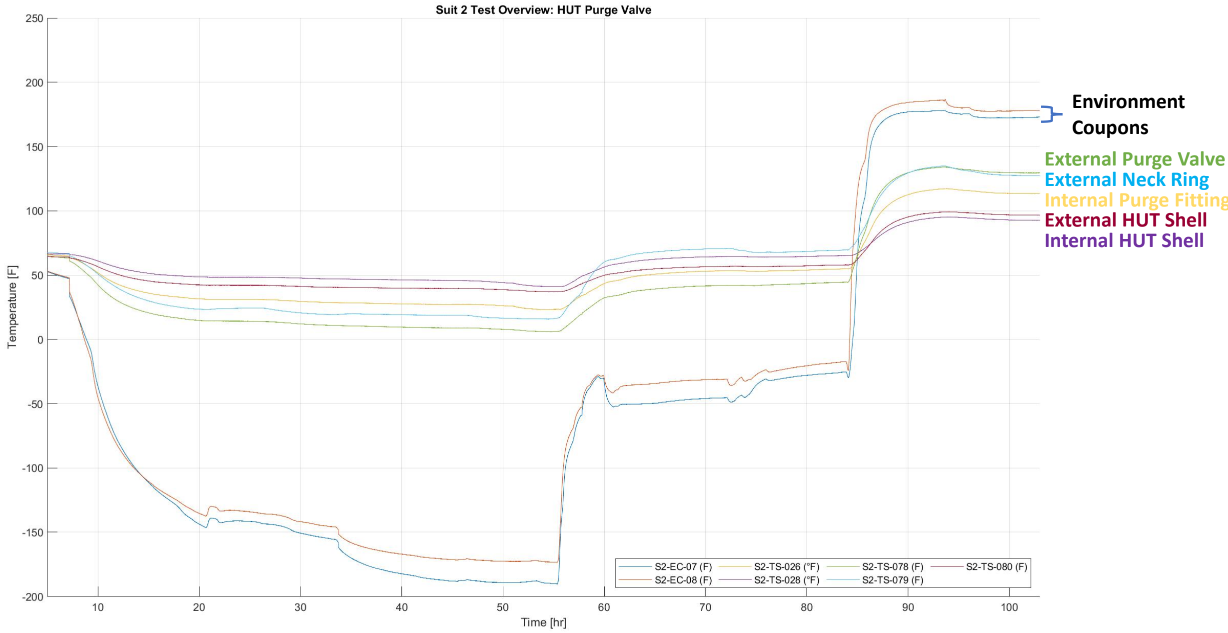

Figure 19. HUT Purge Valve on Composite HUT.

Figure 21 plots the temperatures of the neck ring, integrated communications ring (ICS), and the HUT shell over the entire duration of the thermal vacuum test. As the neck ring is not covered with EPG and is considered an exposed metallic component, it was expected to be a thermally interesting component warranting analysis. The neck ring is manufactured with a white polyurethane coating to decrease the absorptivity. While the neck ring was exposed to environmental temperatures ranging from -185°F to +220°F, a significant temperature difference between the temperature of the neck ring and the temperature of the environment was observed. The minimum temperature of the neck ring was around 20°F and the maximum temperature of the neck ring was around 135°F. In consideration of these temperatures, it is necessary to account for the lack of a thermal load that an astronaut's head would nominally provide with respect to the neck ring. Neck ring temperatures are expected to slightly increase in the cold case and decrease in the hot case. In a comparison of neck ring temperatures and the composite HUT shell, while a temperature delta exists between the two components of an estimated 25°F, this difference is less than the difference observed for the C-660 communications connector and the purge valve. This is explained by the significant increase in contact area between the neck ring and the composite HUT shell. Overall, the neck ring performed well. Figure 20 illustrates two thermal images of the front side of the Suit 2 test article, where the neck ring color gradient indicates a warmer temperature than the EPG in the cold case and a cooler temperature than the EPG in the hot case. While specific temperature values cannot be determined from the thermal images, the temperature color gradients match with the thermocouple data.

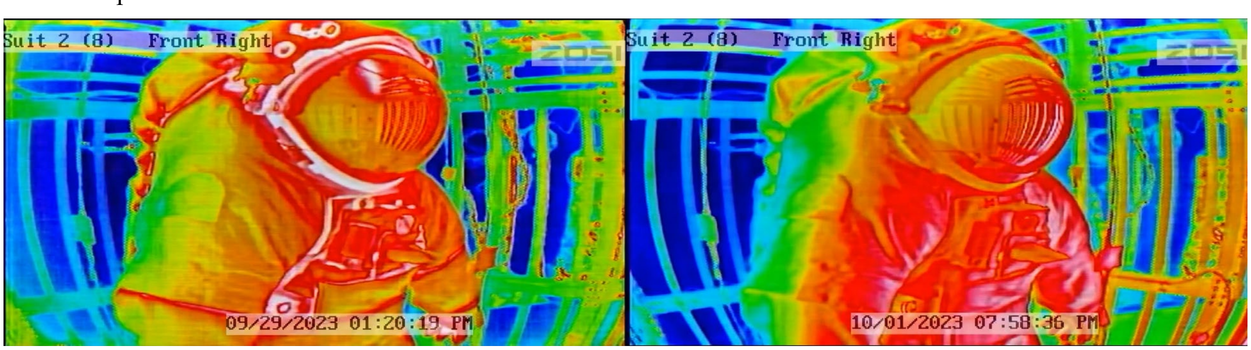

Figure 20. Suit 2 Thermal Images: Cold Environment (Left), Warming Front of Suit (Right).

The ICS ring is located inside the suit, mounted to the internal surface of the neck ring. As an internal component, the xEMU crew touch temperature requirement range of 50°F to 115°F applies. The ICS ring temperatures did exceed these limits in both the cold and hot environment test profiles. However, as aforementioned, the thermal effects of an astronaut's head were not simulated in the Suit 2 test article and the temperature of the ICS ring is estimated to increase by 30°F in the cold case and decrease by 15°F in the hot case. Applying these temperature correction assumptions to the observed test data brings the ICS ring minimum and maximum temperatures within the xEMU internal crew touch temperature requirement range. Additionally, it is important to note that while the temperatures of the ICS ring did exceed expectations, no degradation of audio performance was observed. Reference 7 discusses the audio testing results in more detail.

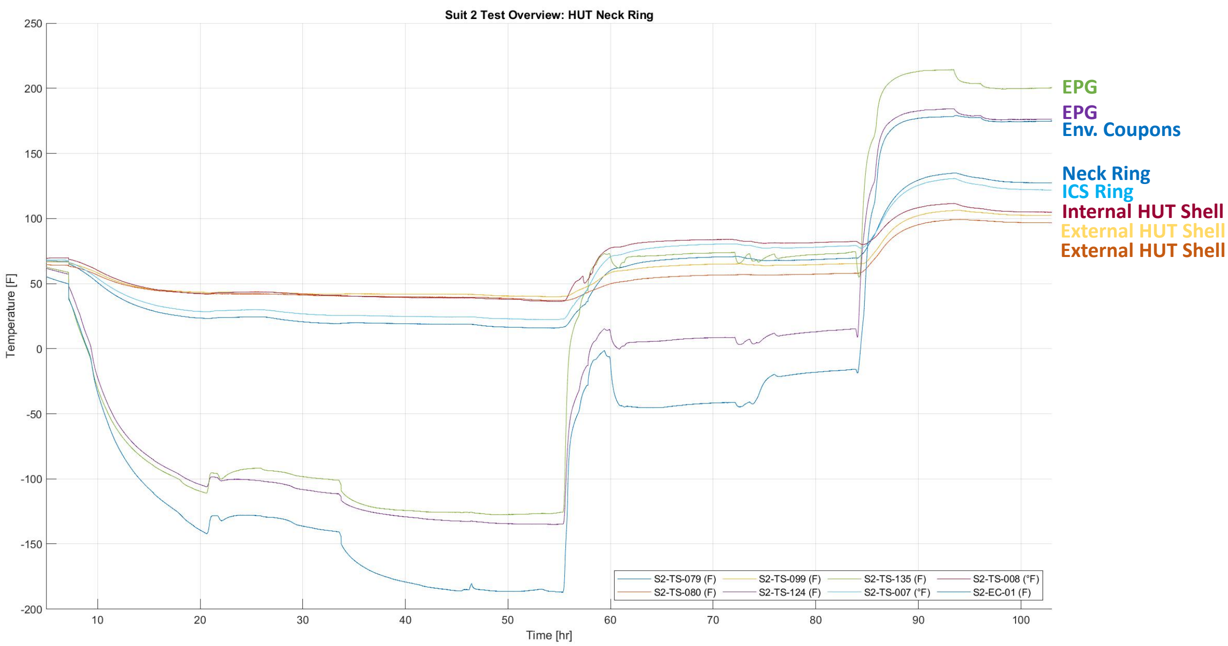

Figure 21. Neck Ring on Composite HUT.

Table 3 compares the temperature test data with the predicted temperatures of different components of the HUT assembly. While the hot environment test profiles reached +220°F and matches with the hot environment temperature assumed in the xEMU HUT thermal model, the cold environment test profiles, at a minimum -185°F, did not reach the same cold environment temperature that is assumed in the thermal model, at -292°F. However, the logarithmic function of radiative heat transfer and historical data from Apollo and EMU suggest system heat leak does not change significantly between an environment temperature of -200°F and -300°F. While this relationship remains to be proven for the xEMU spacesuit, a similar multi-layer insulation (MLI) lay up to the current EMU spacesuit is used on xEMU, and therefore a small difference in heat leak between the tested environment temperature and the anticipated lunar cold environment temperature is considered a fair assumption. Another difference between the model assumptions and the test conditions is the thermal soak duration. The Suit 2 test article was allowed to steady state with the environment, whereas the xEMU HUT thermal model was ran assuming an eight-hour exposure to the thermal environment. As demonstrated on the SxEMU test article, it is unlikely the spacesuit will thermally steady state with the environment in eight hours and consequently, the maximum and minimum temperatures of the Suit 2 test article are likely to be more extreme than the temperatures expected during a LEO or lunar EVA.

In the lunar hot test case, observed temperatures of the HUT assembly were significantly lower than predictions from the thermal model. This finding tracks with the finding presented in Reference 3, that the overall system heat leak in the hot environment test profiles was substantially lower than model predictions. The test data gathered indicates superior thermal performance of the HUT assembly in hot environments. In the cold case, only two components experienced temperatures lower than temperatures predicted by the thermal model: the positive pressure relief valve at 46.7°F and body seal closure at 45.8°F. Both of these temperatures are close to the lower internal crew touch temperature requirement of 50°F and the temperatures would likely remain above the requirement threshold value if exposed to thermal vacuum conditions for only eight hours, rather than the approximate forty-six-hour cold soak experienced during this test. In regard to the HUT shell temperatures, it is notable that in the hot test case, an approximate 60°F delta exists, and in the cold case, an approximate 45°F delta exists between the observed test temperatures and the model predicted temperatures. The composite HUT shell performed much better than expected. The C-660 communications connector is not currently accounted for in the xEMU HUT thermal model and is an area where improvements can be made in the future.

Table 3 . Suit 2 Composite HUT Temperatures Model Comparison.

Component Name	Composite HUT Model Lunar Hot	Composite HUT Test Data Lunar Hot	Composite HUT Model Lunar Cold	Composite HUT Test Data Max Cold
Hatch Shell	130°F	76.3°F	29°F	49.7°F
HUT Shell	168°F	105.4°F	-9°F	36.5°F
Hatch Hinge	133°F	87.3°F	28°F	41.9°F
HUT Purge Valve	169°F	130°F	-10°F	7.6°F
Neck Ring	153°F	130°F	9°F	16.4°F
PPRV	108°F	88°F	50°F	46.7°F
BSC	102°F	100°F	58°F	45.8°F
C-660 Connector	N/A	122.5°F	N/A	16.6°F

V. Discussion

A. Objective 1

The primary objective of this thermal vacuum test was to expose the xEMU spacesuit hardware to vacuum conditions and LEO/Lunar thermal environments. A chamber vacuum pressure of < 1×10^{-5} Torr and a spacesuit internal pressure of 4.3 psia (30 kPa) were achieved during this test. Table 4 compares the driving environments temperatures with the maximum/minimum thermal environments tested during this TVAC test. The SxEMU aluminum HUT produced useful data with respect to the ISS hot case. The Suit 2 test article produced excellent data in both the hot and cold environments, despite the tested cold environment not fully reaching ISS or Lunar requirements.

Table 4. Thermal Environments and Test Profiles Comparison.

Driving Environment Temperatures		SxEMU Environment		Suit 2 Environment	
Hot (Lunar/ISS)	Cold (Lunar/ISS)	Hot	Cold	Hot	Cold
+220°F (8 hr) +147°F (8 hr)	-292°F (8 hr) -210°F (8 hr)	+170°F (6 hr)	40°F (10 hr)	+220°F (10 hr)	-170°F (20 hr)

B. Objective 2

Surviving exposure to vacuum conditions and thermal environments without damaging the HUT hardware was an important objective. Post-test inspections of both the SxEMU aluminum HUT and Suit 2 composite HUT did not yield any anomalies from the pre-test conditions of the respective HUTs. Additionally, spacesuit gas leakage was test before and after the TVAC test and neither test article experienced an increase their respective leak rates. Standard maintenance procedures were performed on both HUTs after the TVAC test and have been returned to service to support other testing.

C. Objective 3

A high level of spacesuit integration was demonstrated during this thermal vacuum test. The SxEMU aluminum HUT provides interfaces for many PGS-located PLSS components such as the purge valve, relief valves, and the PLSS. Many of these interfaces were validated during this TVAC test series. Additionally for the SxEMU test article, significant test hardware was developed and integrated to the aluminum HUT, including the internal instrumentation package and human metabolic simulator. The composite HUT on the Suit 2 test article also housed a much smaller internal instrumentation system and also integrated test hardware to simulate PLSS functionality. This test series was a significant demonstration of airlock operations for the xEMU spacesuit and of chamber interfaces for planetary spacesuits.

VI. Conclusion

The xEMU project produced high fidelity spacesuit hardware and successfully tested it in a space-like environment. This test series serves as an excellent reference design for future spacesuit development efforts to build from. Not only did the hardware perform well, but this unique spacesuit test can be a reference for future demonstrations.

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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]Swartout, B., and Westheimer, D., "Exploration Extravehicular Mobility Unit (xEMU) Chamber B Thermal Vacuum "Suit 2" Pressure Garment System Hardware and Test Design," 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]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.

[5]Westheimer, D., Sladek, C., and Swartout, B., "Short xEMU Pressure Garment Thermal Vacuum Test Results," International Conference on Environmental Systems, ICES, Louisville, KY, 2024.

[6]Meginnis, Ian, Richard Rhodes, Daniel Kim, NASA Advanced Space Suit xEMU Development Report - Hard Upper Torso Assembly. 51st International Conference on Environmental Systems, St. Paul, Minnesota, New Mexico, July 2022.

[7]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.