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Exploration Extravehicular Mobility Unit (xEMU) Chamber B Thermal Vacuum "Suit 2" Pressure Garment System Test Article 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 results from the "Suit 2" Pressure Garment System (PGS) test article. The primary objective of the "Suit 2" PGS test article was to evaluate system-level suit heat leak and Environmental Protection Garment (EPG) thermal performance. 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 a heater cage surrounding the test article. This paper will principally focus on system-level thermal results from the "Suit 2" PGS test article. This paper will examine data collected from one-hundred and seventy thermocouples located in critical locations inside and outside of the suit, as well as seven resistance thermometers (RTDs) for calorimetry to determine total heat flux in and out of the suit. The test data will be compared against the system-level PGS thermal models for model validation. To conclude, this paper will address knowledge gaps presented by unmanned xPGS thermal vacuum testing and the current state of lunar xPGS thermal modeling and testing.

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 Design Verification Testing (DVT) in 2021, 2022, and 2023, culminating in thermal-vacuum (TVAC) testing of the xEMU spacesuit at Johnson Space Center's (JSC) Chamber B[1]. The xEMU thermal-vacuum test included two test articles: a short-xEMU (SxEMU) including the Exploration Portable Life Support System (xPLSS), and "Suit 2," which was 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. 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 shows both test articles with the Suit 2 test article installed inside of a custom heater cage[2] in the right side of JSC's Chamber B. 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[3], internal environment[3], and audio data[4]. Reference 3 should be treated as a companion paper and provides references to specific instrumentation and reference designators that will be helpful when interpreting the results presented here. Test support equipment was also developed to simulate the life-support functionality nominally provided by the PLSS. A detailed description of this test support equipment is provided in Reference 3. In particular, this paper will examine the system-level test results and data collected for the xPGS test article, also including Display and Control Unit (DCU) Liquid Crystal Display (LCD) performance, humidity analysis, xInformatics (xINFO)

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lighting band thermal effects on the xPGS, and an overview of boot thermal performance. To conclude, this paper will address forward work for the government reference design spacesuit and on-going thermal analyses.

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. Thermal data was gathered though a variety of sensors. One-hundred and seventy thermocouples were placed in critical locations both on the inside and outside of the test article. The internal and external thermocouples afforded the ability to measure crew touch-temperatures and heat transfer though the spacesuit materials in specific locations. Resistance temperature detectors (RTDs) were installed into the thermal loops and gas loop of the test article to assess the system-level heat leak of the xPGS. Four thermal cameras were also installed inside the chamber to gather thermal images of the test article while exposed to environmental thermal extremes. Test equipment was developed to power the DCU LCD screen and continuously scroll though display messages during the test. A video camera was positioned to view the DCU LCD screen on the Suit 2 test article to observe the LCD messages in cold and hot environments. The xINFO lights and camera thermal simulator were powered on or off during the test to isolate the thermal effect of those components on the xPGS. The boots of the spacesuit were placed in contact with the liquid-nitrogen chilled chamber floor to simulate the conduction pathway that will be experienced between the boots and the surface on the moon.

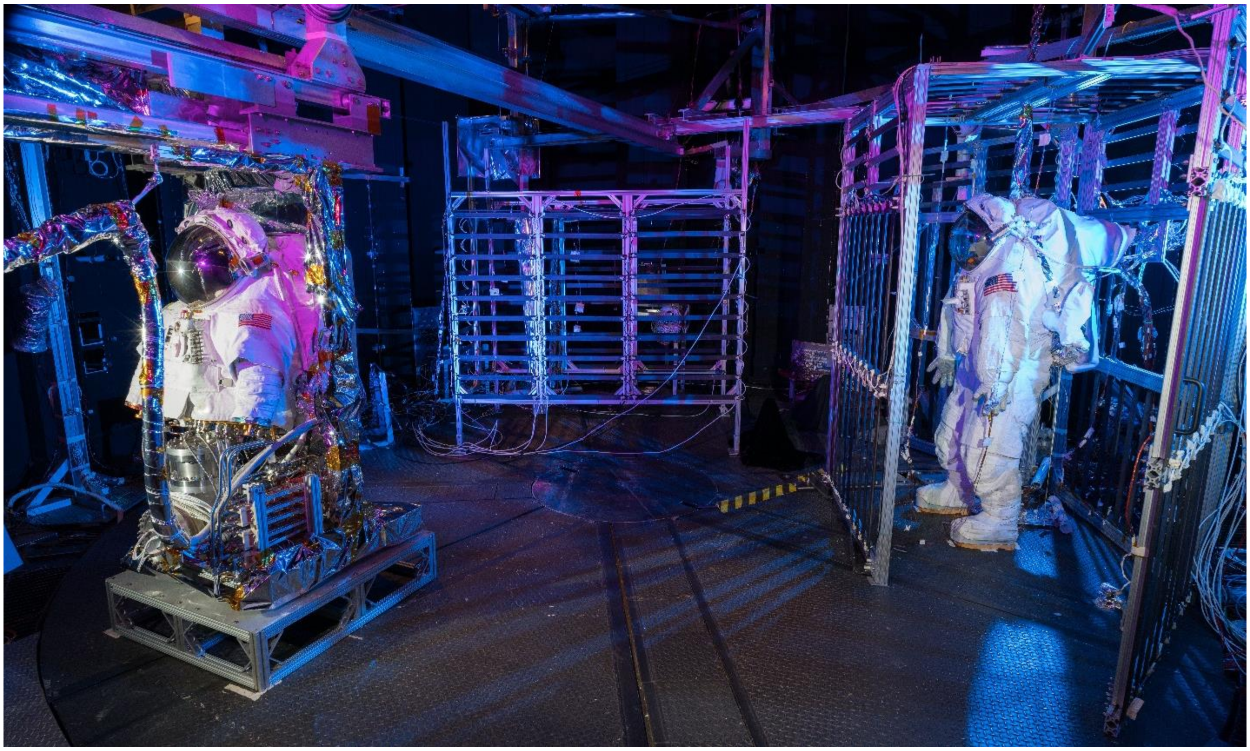

Figure 1. SxEMU (Left) and Suit 2 (Right) Test Articles Installed in Chamber B.

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. 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. The minimum temperature test point would be whatever the chamber could provide. For the hot environments, a custom heater cage, with independently controllable heater zones, was designed to surround Suit 2. Various thermal profiles were tested, and the test article internal and external temperatures were allowed to reach steady state with the environment temperature. The thermal performance of the xPGS was characterized and relevant test data can be used to validate xEMU thermal models.

Eleven thermal test profiles were chosen to test both thermally stressful environment cases at the maximum and minimum environments, as well as mixed thermal environments based on anticipated operational scenarios. These are detailed in Table 1. The custom heater cage designed for the Suit 2 test article, shown in Figure 2, included 14 independently controllable heater zones that afforded the ability to heat the suit in different configurations. The liquid-nitrogen flowing through the floor of the chamber was turned off in the hot environment test profiles. Additionally, the xINFO lights and camera thermal simulator was able to be turned off or on to isolate the thermal load provided by those components onto the Helmet/EVVA. The Suit 2 test article was allowed to reach steady state with the environment in most test profiles.

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

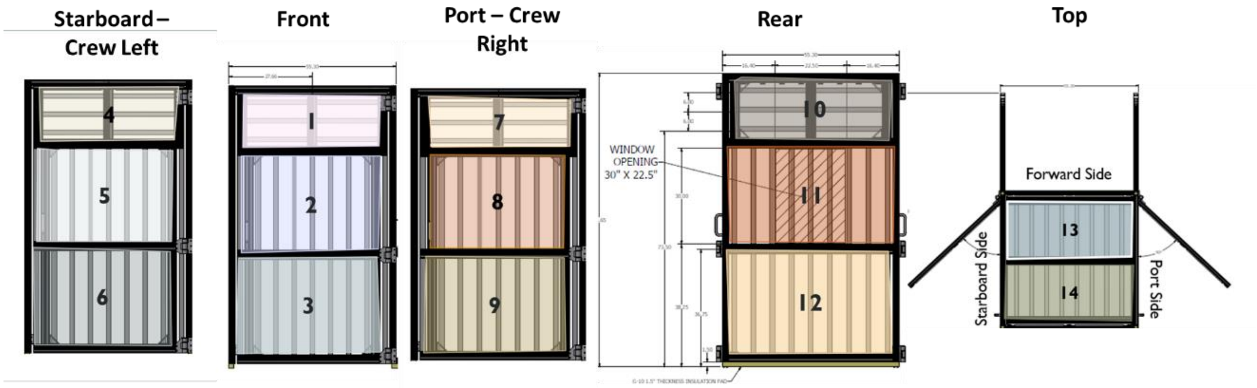

Figure 2. Suit 2 Heater Cage Control Zones

III. DCU LCD Performance

Suit 2 had a unique DCU for this test. It did have a flight-like LCD; however, several aspects of the unit were lower fidelity simulations of the xEMU design. It also did not include a flight-like Service Cooling Connector (SCC) where an Exploration Service and Cooling Umbilical (ESCU) would be mated during recharging operations that occur as part of airlock operations in between EVAs. Instead of using a flight-like SCC, which is a complex and expensive component, a stainless-steel block with pipe fluid ports was used instead. The water lines that would normally run through an ESCU were jumpered outside of the DCU using stainless steel tubing and then covered with insulation. Finally, the body of the DCU was made from 3D-printed Ultem instead of aluminum. The Ultem housing had been a concept which had been previously pursued, but ultimately was ended due to thermal concerns. The DCU is a

Figure 3. DCU LCD screen in ambient (Left) and cold (Right) environments.

thermally challenging component of the xEMU for a variety of reasons. It is located out in front of the spacesuit with a small footprint to mount it to the Hard Upper Torso (HUT). Water flows through the SCC as part of the thermal control system of the spacesuit, but this is just at the center of the unit. Switches and controls cannot be covered with EPG because it would inhibit operability. Testing this Ultem-based unit was an excellent verification of the thermal analyses that had previously ended pursuit of the concept. The test data was compared to the Ultem-based models and results from the aluminum bodies DCU, that was tested as part of the Short-xEMU (SxEMU) test article. Figure 3 shows video feed from the in-chamber cameras of the Suit 2 DCU during ambient operations and a cold test point. LCDs have a history of degraded performance at low temperatures and this unit performed in agreement with that reputation. Vacuum operations at nominal and/or hot temperatures appeared to be fine. The display was readable via the chamber camera. As the chamber got cold, the liquid crystals appeared to become sluggish with respect to changes and then eventually the messages washed out completely. As test points progressed to warmer thermal environments, operability and readability returned and no damage appeared to be sustained.

IV. Thermal Results

The following section summarizes the thermal performance results from the Suit 2 test. More detailed analyses are in work and will be presented in future papers. A general overview of the temperatures reached during testing is presented first, with subsequent sections focusing on specific analyses performed on the data. These include documenting ice buildup that occurred during the cold test points, evaluating the internal temperatures against bare skin touch temperature limits and assessing the energy balance between the suit and the environment. These provide a high-level overview and a first assessment from this test at the time of the writing of this paper. It is expected that the data produced from this thermal-vacuum test will be analyzed for many years to come.

Suit 2 was in test at vacuum conditions for 116 hours continuously, or approximately 5 days. Figure 4 shows all of the thermocouple readings across the suit for the duration of the test. Test points correlating to those documented in Table 1 are noted in the gray bars at the bottom. There are too many lines to easily pull data from the graph, however, they are shown in clusters to give a high-level assessment of performance of the system through the week of testing. Environment “Coupons” were small pieces of EPG-like layups with thermocouples attached to the back side of the coupon. The concept is that an adiabatic coupon with the same optical surface properties as the suit EPG would give an indication of the thermal environment that Suit 2 was experiencing. These were hung near the suit on all four sides and at different heights from the floor of the chamber. There was one coupon for each controllable heater cage zone. For the purposes of this graph, the suit EPG is bundled with the environment coupons. The suit EPG sensors are located on the outer layer of suit insulation and are expected to be most similar to the ambient thermal environment. Even though the EPG did have some heat flux passing through it, it was very small. This grouping of

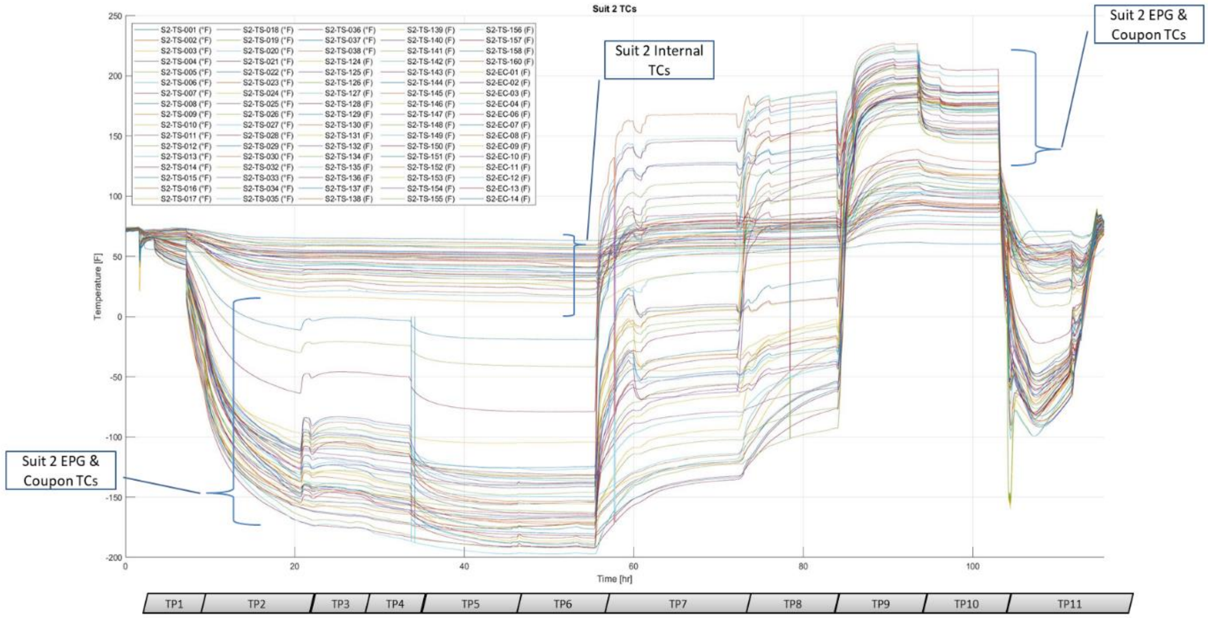

Figure 4. Suit 2 Temperature Summary

coupon and EPG temperatures is easy to track from cold test points to mixed environment test points to the hot test points. At time 0 hours from test initiation, the graph shows the chamber slowly cooling over about a day and the performance of cold test points 2 through 6. Test points 7 and 8 were mixed environment tests where the top and/or front of the heater cage was warmed to generate potentially mission-like thermal gradients on the suit that might represent an astronaut working in a cold location on the Moon with the sun overhead. This caused the coupon and EPG temperatures to spread based on whether they were located in a hot or cold zone of the heater cage. Test points 9 and 10 represented full hot environments and all of these temperatures followed that trend and rose up into the 200°F (367 K) range. On the far right of the graph, test point 11 was data during the end of testing while the chamber was warming and repressurizing. This data is interesting because the EPG is radiative thermal insulation that works best at chamber pressures below 10^{-4} Torr. As the pressure in the chamber rose, conductive and convective heat transfer mechanisms became viable through the atmosphere in the chamber, and bypassed the EPG radiative thermal insulation. Developing spacesuit thermal insulation for partial pressure atmospheres is a key technology need for performing EVAs on Mars. This was not an objective for this thermal-vacuum test and no additional analysis on data from the period of the test has been performed to date, but it is notable and could be of interest in the future.

Figure 4 shows that the coupon temperature and external EPG temperature followed the temperature profile of the test across the different test points. The other bundle of temperature readings noted are the Suit 2 Internal Thermocouples. These are a cluster that for the most part stay close together between 50°F (283 K) and 100°F (311 K). A top-level review of this data shows that the spacesuit and EPG generally performed well and maintained the inside of the suit to nominal temperatures that would be safe for a human across the wide range of environments tested. The internals of the Suit 2 test article were thermally anchored by a manikin wearing an LCVG, as described in Reference 3. More detailed discussion of specific locations, specific temperatures, and how the test design may or may not have performed well simulating a person wearing an LCVG inside of the suit are discussed in later sections of this paper.

Two of the eleven test points are presented in Figure 5 and Figure 7. These present bounding cases to give a overview of the system performance during this test. Test point 5 was a max-cold case with the xINFO hardware mounted to the helmet assembly turned on. In this test case, the heater cage was simply turned off and the suit got as cold is it could get via radiation to the chamber. Infrared imagery is also available for test point 5 and is shown in Figure 6. This test point was held for approximately 12 hours to let the system reach a steady state, which is significantly longer than an actual EVA would last. Suit internal temperatures were centered around 50°F (10°C) with some locations that dropped lower. These will be discussed in a later section on Bare Skin Touch Temperature limits. External temperatures (coupons and EPG) centered around -150°F (172 K) with some approaching -200°F (144 K) and a few significantly higher. It was understood before the test that the chamber could not reach the -292°F (93 K) requirement for a permanently shadowed lunar crater, however these temperatures do approach a cold thermal environment that might be seen on ISS. Lower temperatures were typically on the backside of Suit 2 which had a more direct view to the cold walls of the chamber. The front side of the Suit 2 test article had a large view to a Mylar curtain that was intended to minimize heat transfer between it and the SxEMU test article also included in the test, however the view to the chamber LN2 shroud was diminished. The warmer EPG temperatures were observed on or around the DCU on the front of the suit. Warmer temperatures were typically on the upper torso and helmet areas of the spacesuit. This is due to the overlapping view angles from the heater bars onto the torso and helmet, as well as thermal contributions from reflected heat from the mylar divider between the two test articles.

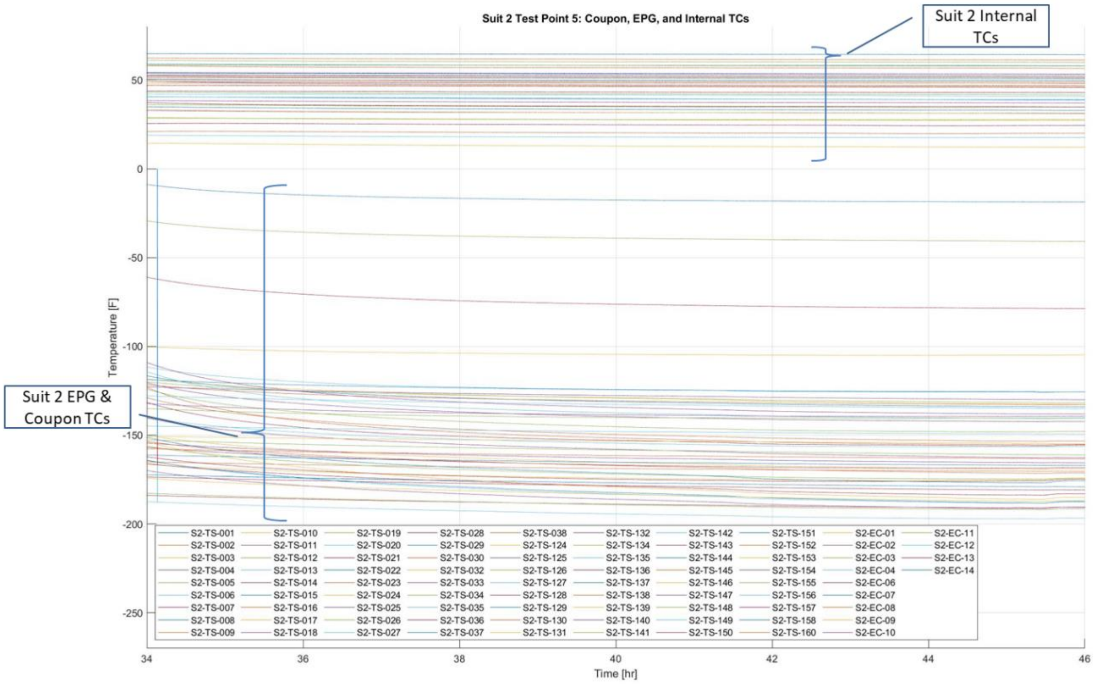

Figure 5. Test Point 5, Maximum Cold with xINFO On.

Figure 7 shows a similar graph for the maximum hot case performed. The xINFO lighting band and camera simulator were powered on during this test point also. Unfortunately, the infrared cameras overheated during hotter test points and automatically shut down, so no thermal pictures are available. The EPG and coupon temperatures are centered around 200°F (367 K), with many reaching the 220°F (378 K) hot lunar requirement. In general, the internal temperature were all between 50°F (10°C) and 100°F (38°C) with some excursions above. These will be discussed in a subsequent section as compared to bare skin touch temperature limits inside of the suit. This test point also provides an interesting assessment of the time constant of a spacesuit. It begins at the end of a mixed environment test point where the bottom portion of the suit was still very cold but the top was heated. A large change was made to the heater cage setting to shift to a fully hot test point and all of the temperatures can be seen rising around the 84 hour mark. Temperatures have approached steady state around hour 93, which is approximately 9 hours later after this large shift in the environment. Thermal modeling is typically carried out until the results provide steady state values. However, human in the loop tests seldomly achieve steady state because people typically are performing transient activities. In addition, it appears that the time constant of a spacesuit may be longer than a typical 8 hour EVA. Test point 5 stabilized for around 12 hours and this one was slightly faster, but still around 9. It should be noted that the manikin wearing an LCVG is significantly different than a human when assessing the transient aspects of the integrated system due to differences in mass, heat generation and heat storage. Even with this difference, this test series provides interesting data with respect to the transient thermal performance of a spacesuit that may be useful for future thermal analysis and EVA planning activities.

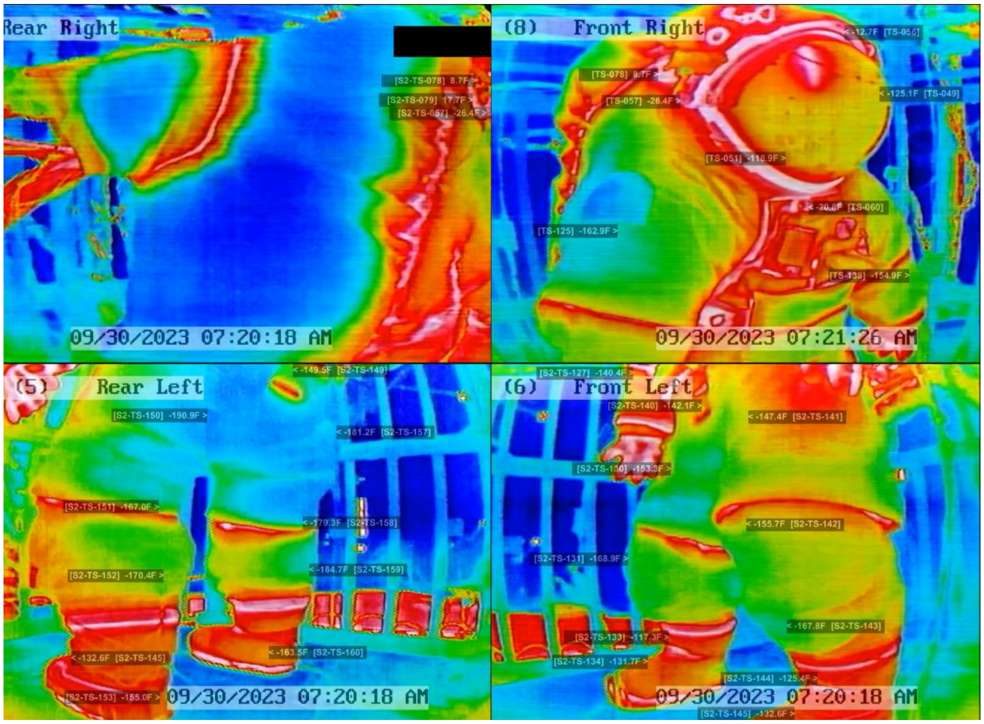

Figure 6. Test Point 5, Infrared Images

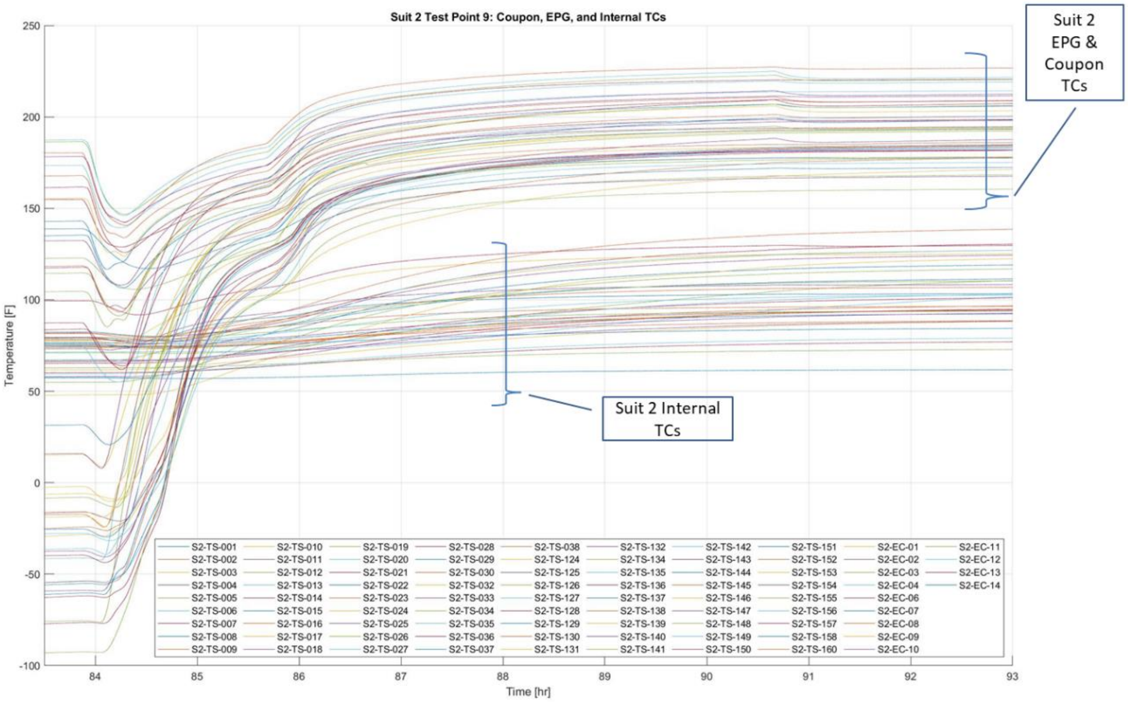

Figure 7. Test Point 9, Maximum Hot with xINFO On.

A. Suit 2 Humidity Analysis

The Suit 2 test article flowed ambient air from the exterior of the chamber though the spacesuit during the thermal vacuum test. During cold environments, there was the potential to condense water vapor present in the atmospheric air inside of the spacesuit on parts inside of the suit. Prior to the test, consideration was given to the likelihood of this event and the consequence of condensing water and/or forming ice inside of the spacesuit. Calculations were performed assuming that the air entering the Suit 2 ventilation loop was 75°F (24 °C), ambient pressure, and 60% relative humidity. This corresponded to a mole fraction of 0.018 for the air flowing through the suit. As the air flowed through the Suit 2 ventilation loop to the suit, it was throttled down to 4.3 psia (29.6 kPa), producing a partial pressure of water in the gas flow of 534 Pa. Since this is less than the triple point of water, condensation was not possible in this scenario, however frosting was possible on surfaces below 32°F (0°C). Anticipated internal surfaces that could reach below freezing inside the spacesuit during the thermal vacuum test were the helmet bubble, electrical passthrough adapter, and locations with high heat leak to the environment. Figure 8 shows predicted temperatures on the outside of the suit, but under the EPG for an ISS cold environment of - 210°F (139 K). Environment temperatures did not get this low during testing (~-180°F), but it was the closest point of comparison from previous thermal analyses. While ice formation inside of the spacesuit was certainly an unusual scenario, no failure modes were theorized that would result in damage to the hardware and the test design was deemed to be acceptable.

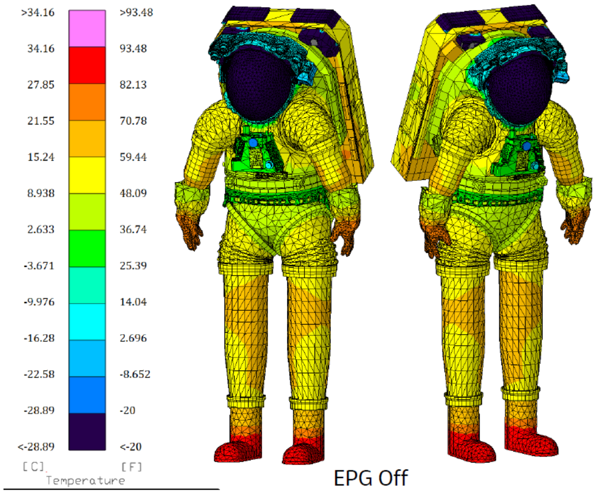

Figure 8. Suit Temperature Predictions for ISS Cold Environment, EPG Removed.

During the thermal vacuum test, ice formation on the helmet bubble was observed during cold environment test profiles. It should be noted that this was after operations in a cold environment that approached a duration of two continuous days, which is much more severe than a real EVA. This test demonstrated a very small frost buildup rate over a test that was extended for a very abnormal duration. xEMU thermal modeling (modeled with a subject inside the suit) predicted internal helmet bubble temperatures may approach the lower xEMU internal touch temperature requirement of 50°F. However, the Suit 2 test article did not attempt to simulate the thermal load provided by a crewmember's head on the helmet bubble. Prior modeling analyzing the effect of this thermal load indicated a possible 30°F (17°C) decrease in internal helmet bubble temperatures from the nominal case. Therefore, the anticipated internal helmet bubble temperature for the Suit 2 test article was near freezing in a cold environment. Figure 10 shows the internal helmet bubble temperature observed during the test reached steady state around 32°F (0°C). As expected, this internal temperature was low enough to allow for ice formation inside the helmet bubble. As the helmet began to warm in subsequent hot test profiles, the ice was seen sublimating or melting, until the two ice spots disappeared. Post-test inspections did not reveal any artifacts on the helmet bubble left by the ice formation. Should the

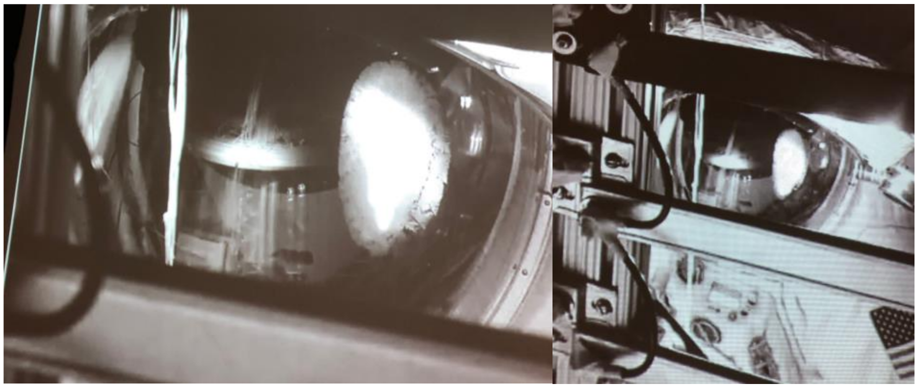

Figure 9. Ice Formation Inside of the Suit 2 Helmet

thermal load of a crewmember's head provide heat to the helmet, it is expected that the internal temperature of the helmet bubble would be close to 50°F (10°C) and prevented the frost build up seen in Figure 9.

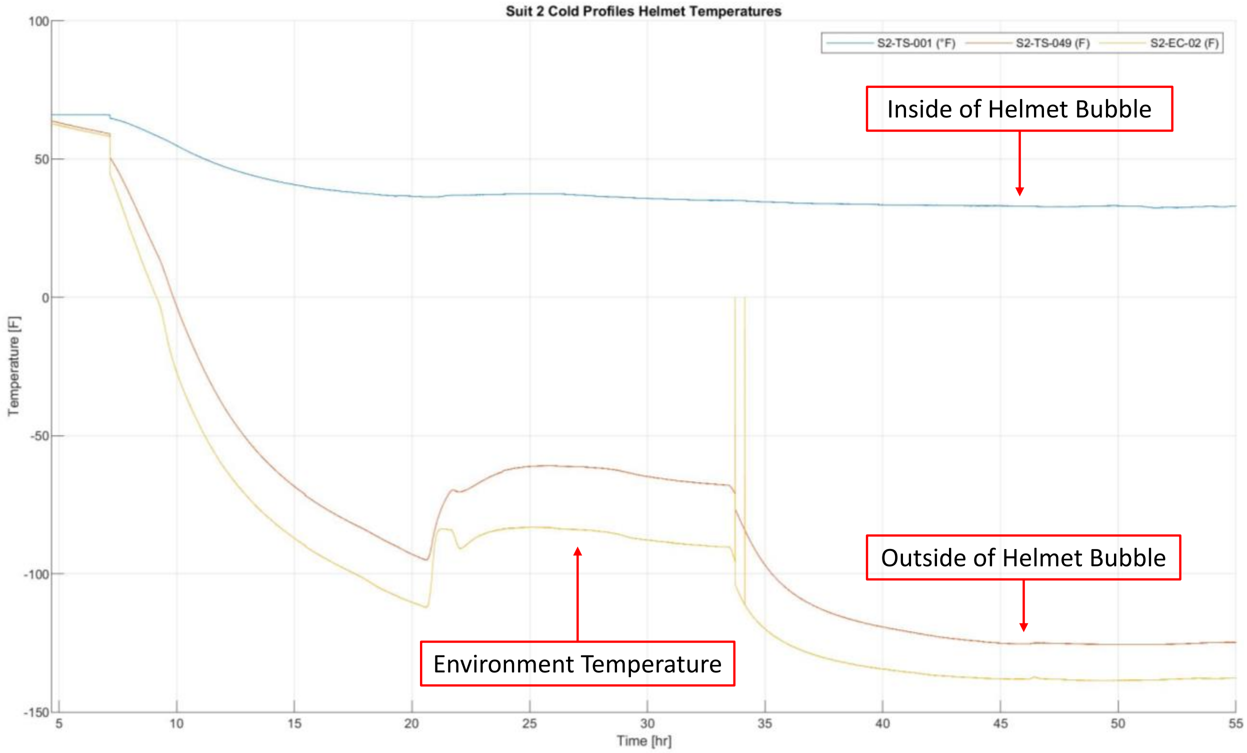

Figure 10. Helmet Temperatures During Cold Test Points

B. Bare Skin Touch Temperatures

One of the key aspects of evaluating the thermal performance of the xEMU is to assess the temperatures of internal surfaces that the crew might come into contact. Requirements for bare skin touch temperature direct that those surfaces must be between 50°F (10°C) and 111°F (44°C). As part of the xEMU project, thermal models were built to assess if these internal temperatures could be maintained over a wide variety of thermal environment. Figure 11 shows these predictions and indicates areas of potential temperature violation as either magenta for a hot case or dark blue in a cold case. Areas around the upper portion of the HUT, around the waist-brief-hip assembly, and the gloves were the areas of most significant concern with respect to these limits. This test was not able to achieve the lunar crater cold environment temperatures, but the test results presented indicate that the resulting cold environment test temperatures

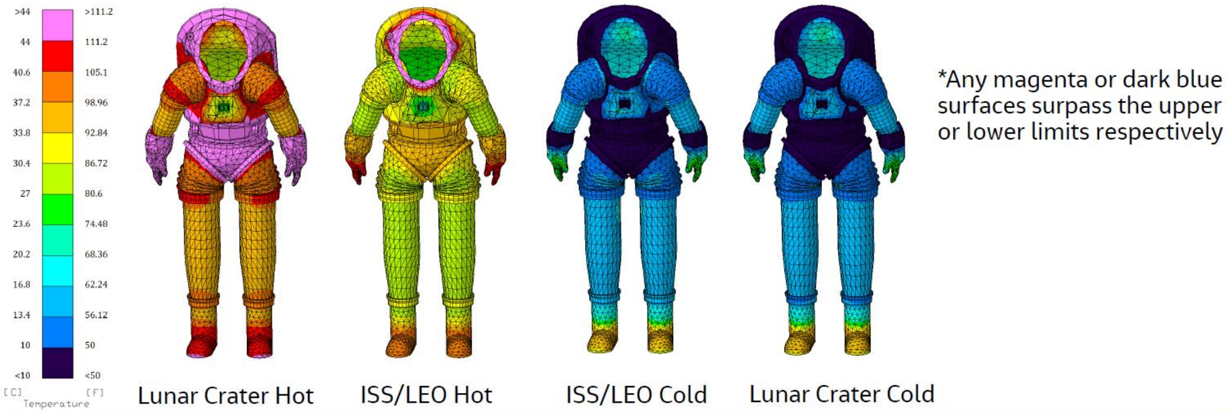

Figure 11. Bare Skin Temperature Predictions.

were similar to the ISS/LEO cold case. One important consideration in analyzing the internal crew touch temperatures is lack of a mobile crewmember inside of the spacesuit. While performing EVA tasks, it is expected that the LCVG will incidentally contact various internal surfaces of the spacesuit and help regulate internal temperatures. This interaction was not simulated during thermal vacuum testing and consequently provides a bounding case where internal spacesuit surfaces were allowed to reach thermal steady state without any conductive thermal regulation from the LCVG.

Figure 12 plots all of the internal thermocouple readings for the entire test and compares then to the touch temperature lines (shown as horizontal lines at 50°F and 111°F). This figure shows that many of these internal temperatures drop below the lower limit during cold test points. Several of the internal temperature also exceed the maximum limit on the hot points. The following locations never exceed either limit for the duration of the test: PLSS Interface Pad inside of the hatch (034), center of the hatch shell (036), left hip bearing (037), center of the brief in the crotch area (039), waist-hip-brief bladder between the hip and thigh bearings (040), and right boot bladder at the bottom center (047). The location with the largest extremes was the right boot bladder at the bottom-front (046).

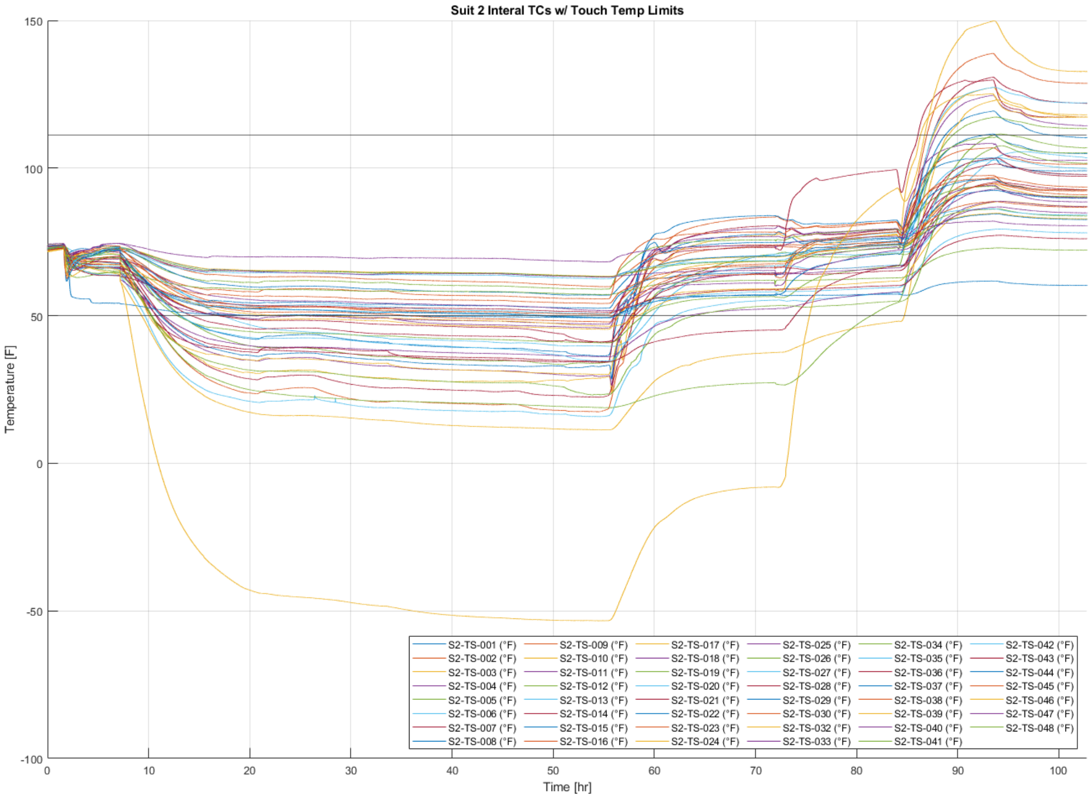

Figure 12. All Internal Temperatures.

These results were generally encouraging and as expected. Pre-test analysis had indicated the waist-brief-hip area might be a location with limit exceedances, but these were some of the areas showed acceptable temperatures throughout the test. Excursions with S2-TS-046 (basically the toe of the boot) had been noticed during testing. The toe area of the boot does not have the same type of EPG and the rest of the suit, which makes it an interesting location thermally. In addition to that, the test setup for this location could have also helped to impact these results. The LCVG water loop tubing was wrapped around a sock inside of the boot to provide a thermal boundary inside of that component. Also, the boots were in contact with the floor, which added another heat transfer mechanism to consider. Additional analysis of the boot data generated is forward work, with some analysis presented in Reference 5. Two additional plots were generated to provide more details with respect to bare skin touch temperatures.

Figure 13 plots temperatures of several locations in the HUT near the purge valve. These are also areas highlighted by pre-test thermal modeling and were expected to exceed the limits. It is important to note that the Suit 2 test article utilized a composite HUT, which does not transfer heat laterally through the structure as the aluminum one used in the SxEMU test article. Temperatures shown in this plot include: the integrated communication system ring near the center microphone (07), internal HUT surface between the neck ring and DCU interface plate (08), internal purge valve fitting (026), right speaker (027), internal HUT surface near the purge valve (028), the HUT purge valve outside of the suit (078), external neck ring near the purge valve (079), and an external HUT surface near the purge valve (080). The purge valve is located at a hole in the EPG to allow operation of the valve. In addition, the body is highly conductive and expected to be an area of heat leak from the inside of the suit. Temperature data is consistent with what is expected from this design. The external surfaces of the neck ring and HUT (079) and (080) in this area swing with the environment temperature due to the lack of EPG protection and the purge valve itself stays at a temperature that is closer to the internal environment of the suit. However, heat is being transferred out of the suit at this location and it becomes a relatively colder area as a result. The inverse is true in the hot case. Additionally, and as noted in the ice buildup analysis, no effort to simulate the thermal impacts of a crew's head were made for this test buildup. The audio manikin was not a good thermal representation. In this case, it is reasonable to expect that a human would help thermally anchor this area and help maintain the temperatures within the bare skin contact limits.

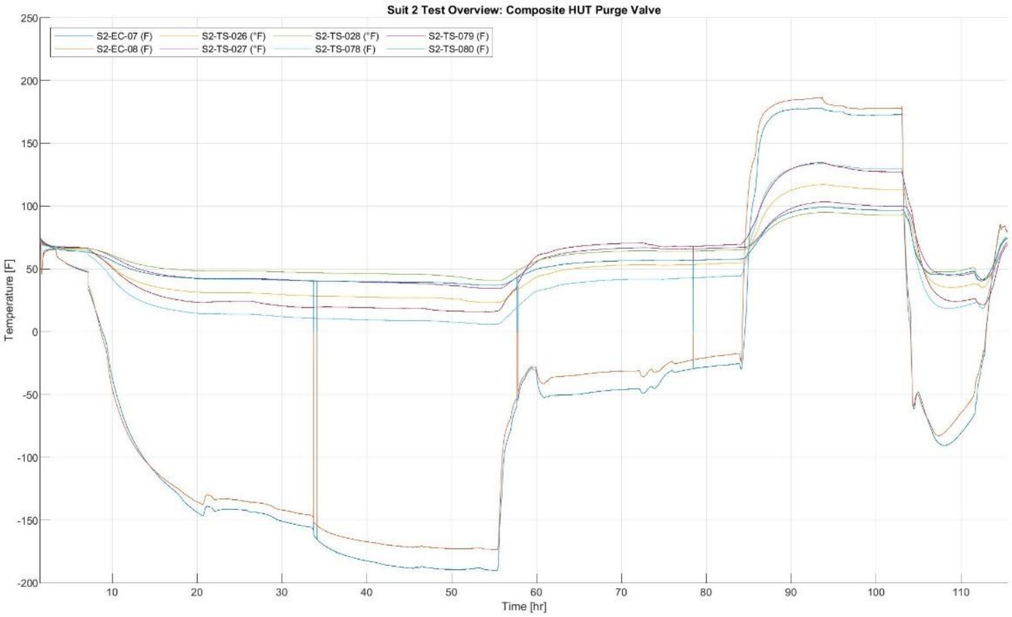

Figure 13. HUT Temperatures Near Purge Valve.

Figure 14 shows temperatures for other areas of interest inside of the Suit 2 test article. These include thermocouples inside of the Suit 2 test article located in the arms and gloves (numbers 12 through 19), in the hatch (34, 35, and 36), in the waist-brief-hip assembly (37, 38, and 39), legs (41 through 44), and boots (45 through 48). S2-TS-046 in the boot, as previously discussed, is the most extreme location in this figure also. The extremities of the suit (gloves and boots) followed the environment temperature the closest. After noting these locations where the temperatures on the inner surfaces of the suit does exceed the bare skin temperature limits, it should also be noted that a crew member would have several additional layers between this surface and their skin. This would likely include the LCVG and a comfort garment. Also, similarly due to S2-TS-046 on the boot, glove temperatures are likely dependent on tubing locations of the modified LCVG that tried to set an internal thermal boundary inside of the glove.

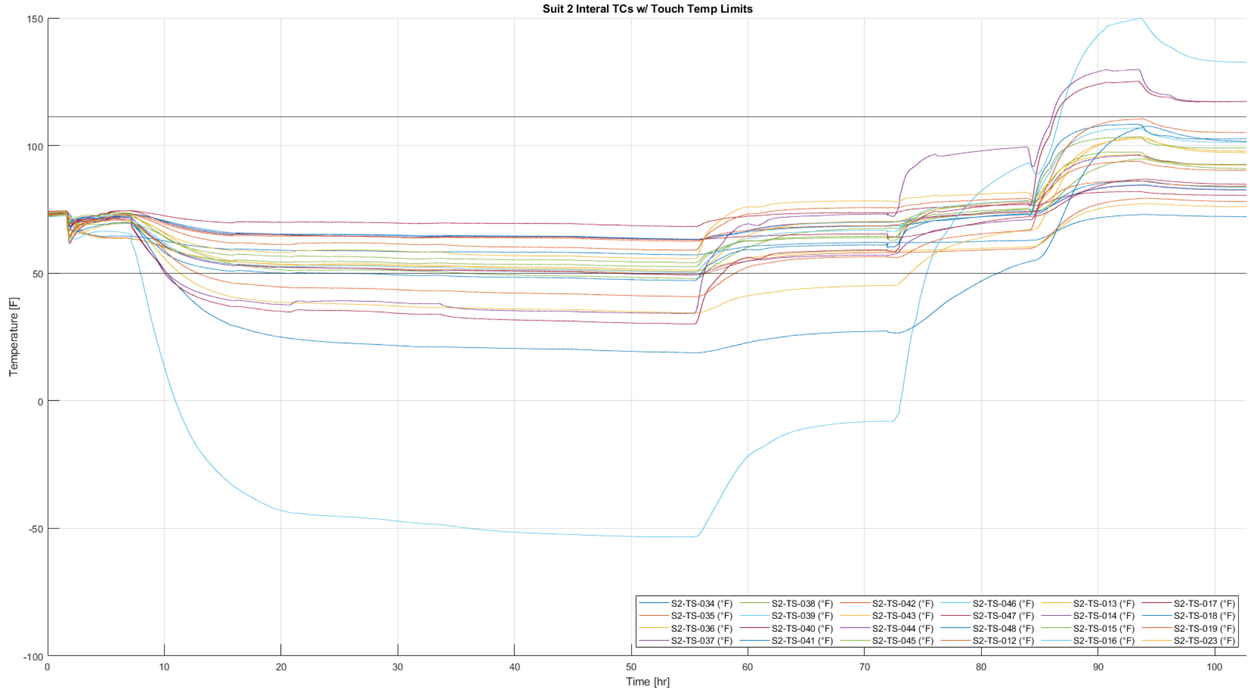

Figure 14. Internal Temperatures: Arms, Legs, Gloves, Boots, Waist Brief, and Hatch

C. Energy balance

An energy balance calculation was performed on the Suit 2 test article to estimate the total heat exchange between the spacesuit and the environment. Total heat lost or gained in a particular thermal environment is a key parameter needed to size the life support system. Based on the Suit 2 test configuration, the heat exchange to the environment was balanced against heat transferred in or out of the suit from the LCVG thermal loop (Primary Thermal Loop 1), the simulated xPLSS thermal loop (Primary Thermal Loop 2), the ventilation air flow, and the electronics inside of

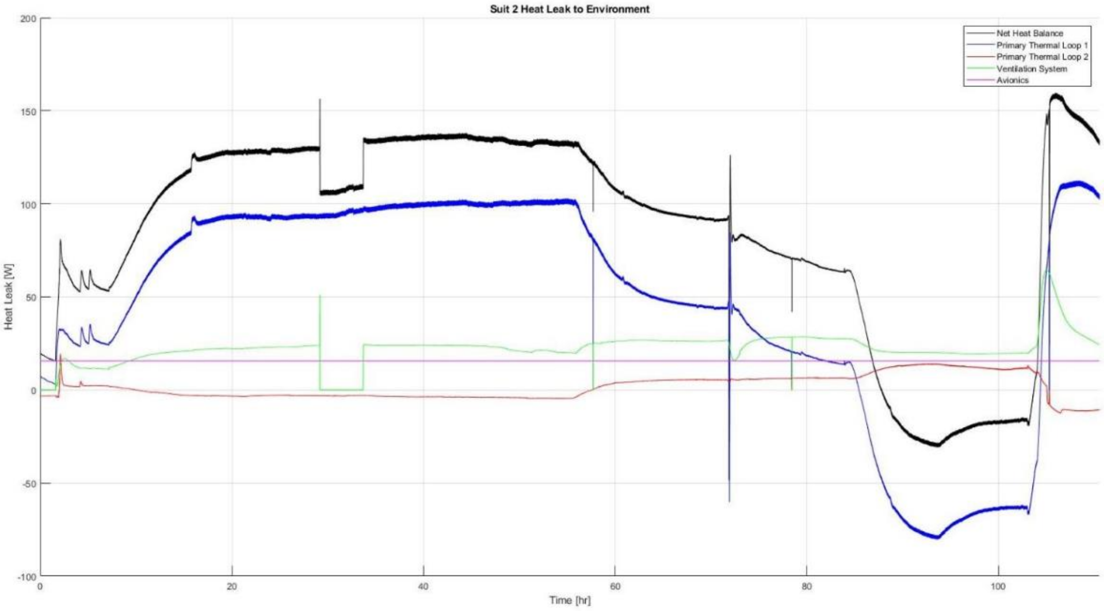

Figure 15. Suit 2 Energy Balance.

the suit, consisting of instrumentation, audio equipment, and the data system. Figure 15 graphs these calculated parameters through the duration of the test, although it is noted that the system was not at steady state conditions for all the times shown. Heat input from the electronics inside the suit was estimated to be approximately 15 W based on the power ratings of different equipment. This estimate is likely high, but this value is a fairly small component of the total energy balance. Primary Thermal Loop 2 and the suit ventilation flow are also very small components. Thermal Loop 2 sent water to select areas of the suit at 50°F (10°C) which consisted of the simulated PLSS on the back of the suit and the DCU on the front of the suit. This system lost a small amount of energy during cold test points and picked up heat during hot points but was a small contributor due to the small heat transfer area of the system. The low-density gas flowing through the suit had a limited heat capacity but appears to have continually made a small heat contribution to the system throughout testing. There is a drop out in the ventilation energy contribution at approximately 30 hours which was due to a data system issue.

As expected, the primary thermal contributor from the test system the Primary Thermal Loop 1 which fed warm water to the LCVG during testing. This water loop interacted thermally with the majority of the spacesuit and was configured to simulate the thermal boundary a crew member wearing an LCVG provides during an EVA. Fluid temperatures and the direction of flow were changed from cold environments to warm environments to better represent the temperature profiles that a crew member would have across their torso, hands, and feet. These results indicate that Suit 2 lost a maximum of approximately 140 W (475 BTU/hr) to the environment during cold tests and gained up to 75 W (250 BTU/hr) during warm tests. A positive heat leak indicates heat lost to the environment and a negative heat leak indicates heat gained from the environment.

These results were compared to previous xEMU thermal analyses. Figure 16 shows this comparison. Heat leak from Suit 2 in cold and hot thermal environments appears to better than the model predictions. Potential causes for the discrepancy could include the EPG performing better than expected, the internal temperatures being higher than realistic in Suit 2, the internal temperature boundaries in the model being too low, or potentially discrepancies in how key areas like boots or the helmet were either set up in the test or model. Further analysis will be performed to assess these differences.

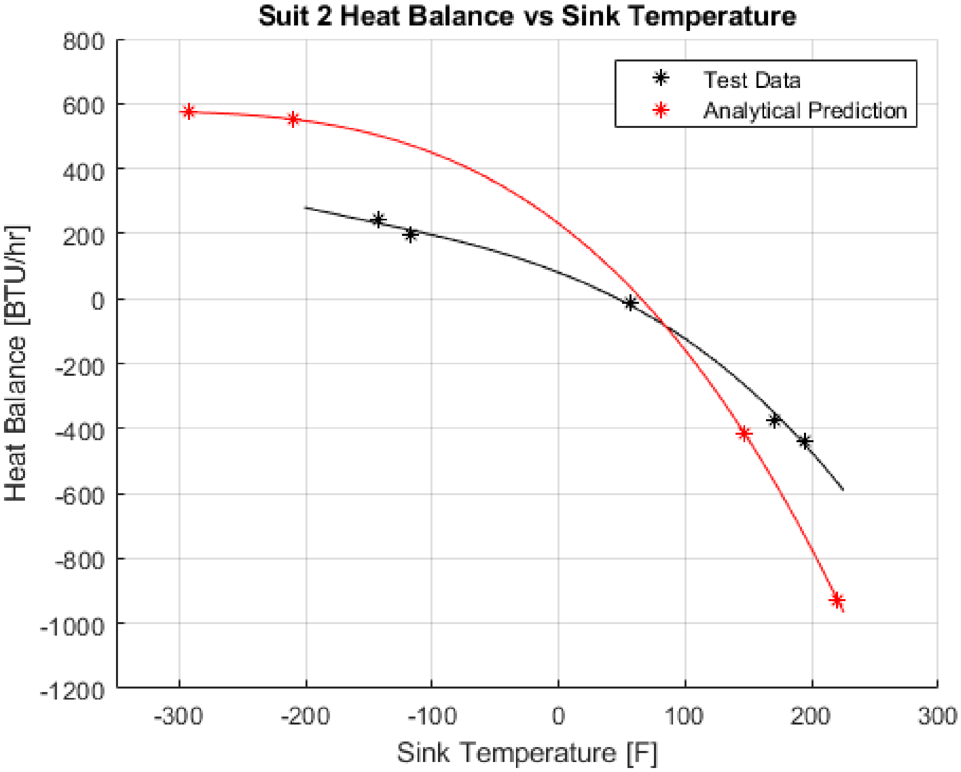

Figure 16. Environmental Heat Leak Comparison

V. Anomalies and Forward Work

As discussed previously, the largest anomaly observed on the Suit 2 test system was internal boot bladder temperatures reaching below -50°F (-46°C). While further investigation is needed, it is believed that a lack of mylar thermally protecting the toecap of the boots led to excessive heat leak near the toe-end of the boot. Post-test inspections of the boots did not reveal any damage to the hardware. Post-test structural and leaking testing were performed, and no anomalies were observed. Additionally in regard to the boots, the Suit 2 test article added a second thermal insert between the bottom of the boots and the chamber floor to slow the conductive heat transfer. With test data, the xEMU boot thermal model can be updated and better predict boot temperatures without this second thermal insert. Additional model validation work and possibly more testing is needed to fully characterize the performance of the xEMU lunar boots in Permanently Shadowed Region (PSR) temperatures of 40K (-387°F). The liquid-nitrogen chilled chamber floor in Chamber B was only able to reach 111K (-260°F). Finally, future work may consider the effects of flexing the boot softgoods at PSR temperatures to evaluate structural integrity of the bladder/restraint assembly.

Anomalies were observed with the EPG coupons used to measure the environment temperature. These 2” x 2” EPG coupons were place between the heater cage and the Suit 2 test article. The heater cage is constructed with heater bars spaced apart from one another. These heater bars and gaps between the heater bars were found to affect view angles from the heater bars and from the liquid-nitrogen shrouds onto the EPG coupons. Consequently, the placement of the coupons could impact the environment temperatures indicated. This was better on the Suit 2 test article than with the SxEMU, due to the simpler heater cage, but additional evaluation is needed to assess how accurately these instruments performed.

Another anomaly observed was the thermal effect of the mylar divider isolating the two test articles. It was observed during the test that the mylar divider reflected heat back onto the test articles from heater bars that had a view to the mylar divider. Specifically for Suit 2, the front of the spacesuit faced the mylar divider. When powering the heater cage zones on the front and back of the heater cage equally, the temperature of the front of the spacesuit with a view to the mylar divider would increase significantly. Thermal engineers were able to make real time adjustment to the power levels of the respective heater zones to evenly heat the front and back of the spacesuit. The effects reflected heat are an important consideration in design of future thermal vacuum tests.

Forward work remains in analyzing the thermal data gathered during the Suit 2 thermal vacuum test. Specifically, there is on-going component-level analysis of the Helmet/EVVA, Hard Upper Torso (HUT), and boots. Additionally, further analysis is needed to better understand the effects of the mylar divider on the test article and EPG coupon/heater cage design.

VI. Conclusion

The xEMU project produced high fidelity spacesuit hardware and successfully tested it in a space-like environment. An unmanned thermal test like this had never been performed on a developmental spacesuit. The hardware under test not only survived almost five continuous days in harsh space-like conditions, but it also appears to have performed well thermally. The xEMU design and this test series serve as an excellent reference for future spacesuit development efforts to build from.

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