Short xEMU Pressure Garment Thermal Vacuum Test Results

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NASA performed a thermal-vacuum test of the Exploration Extravehicular Mobility Unit (xEMU) to demonstrate the performance of the government reference design in a relevant space-like environment. One of the spacesuit test articles was configurated as a Short-xEMU (SxEMU). This unmanned configuration provided an excellent test to evaluate the Exploration Portable Life Support System (xPLSS), however it posed some challenges with the Exploration Pressure Garment (xPGS) components involved due to the lack of a human wearing a Liquid Cooling and Ventilation Garment (LCVG), which significantly contributes to the thermal performance of the suit. This paper provides an overview of the pressure garment components that made up this portion of the test article, the test configuration, test results, and lessons learned from this very unique spacesuit test.

I. Introduction

A THERMAL-Vacuum test was performed at the NASA Johnson Space Center to demonstrate the design of the Exploration Extravehicular Mobility Unit (xEMU). This demonstration was the culmination of over a decade of internal government spacesuit development. Reference 1 provides an overview of the test, including references to other detailed papers on specific results on components of the Suit 2 test article. Two xEMU test articles were tested in Chamber B at the Johnson Space Center for approximately a week in the fall of 2023. Figure 1 shows both suits as installed in Chamber B with the Short xEMU (SxEMU) in the heater cage on the left and the Suit 2 test article on the right. This paper focuses on the Exploration Pressure Garment Subsystem (xPGS) components on the SxEMU test article. Exploration Informatics Subsystem (xINFO) components including the lighting band and camera were installed on the helmet assembly. This SxEMU test configuration was originally intended to close the thermal and ventilation loops for the Exploration Portable Life Support Subsystem (xPLSS), but even though it was not the original focus of the test article it provides an interesting set of data for xPGS thermal performance and from the standpoint of being a uniquely designed test. Testing was performed "unmanned" and the xPLSS operated with nitrogen as its internal atmosphere instead of oxygen to avoid the risk of


Figure 1. xEMUs in Chamber B.

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fire. This paper will document the design of the xPGS portion of the test article, summarize test data, and document lessons learned from this activity.

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: demonstration in relevant thermal environments, demonstration in a relevant pressure environment, and demonstration at a high level of spacesuit integration.

The SxEMU xPGS demonstrated a sub-set of xPGS components in relevant thermal environments. The SxEMU did not include a waist brief hip, legs, boots, gloves, or a Liquid Cooling and Ventilation Garment (LCVG), therefore calculating a suit level heat exchange with the environment at different temperatures was not a feasible objective. In addition, a crew member wearing an LCVG was absent from the SxEMU. These represent a relatively massive, self-regulating thermal input to the spacesuit system. Instead of a crew member, the SxEMU housed an instrumentation package to help assess the performance of the xPLSS and audio system. These did not behave similarly to a crew member wearing an LCVG and provided additional limitation to the potential testing operations of the xPGS portion of the SxEMU. Understanding these caveats, the xPGS components were still exposed to a wide range of environment temperatures and different aspects of the performance were assessed. Numerous thermocouples were included on the hardware at varying levels within the layup of the xPGS component. 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 nominally consists of multiple layers of Mylar separated with layers of scrim material. Hot or cold spots could be observed across the xPGS components where higher areas of heat leak could be identified. Data can be used to verify thermal models. Finally, simply surviving the temperature extremes that the hardware and softgoods were 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).


Figure 2. SxEMU Test Article.

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 (< $1x10^{-5}$ Torr) and the internals were 4.3 psia (30 kPa). Simply surviving these space-like pressure conditions was significant demonstration for this xPGS hardware.

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 relief valves and water bladders) and also supported use of the Display and Control Unit (DCU), which is mounted to the front.


Figure 3. SxEMU Test Article Traversing into the Manlock.

III. Test Configuration

The SxEMU test configuration includes the test article (with specific xPGS components), an internal instrumentation package that resided in the Hard Upper Torso (HUT)[2], numerous type T thermocouples, and a specially designed heater cage to simulate the target thermal environments[3]. Figure 2 shows the test article inside of heater cage and inside of the chamber. The SxEMU performed simulated EVAs where the test article would travel between the manlock and main chamber. This consisted of simulated airlock operations in the chamber manlock, pumping down the manlock, transporting the SxEMU into the main chamber via a rail system and chain drive, performing an EVA, returning the SxEMU to the manlock, re-pressurizing the manlock, and then repeating that sequence. Figure 3 shows the SxEMU going into the manlock using the rail system and chain drive.

A. SxEMU Overview

The SxEMU test article included a stand that interfaced to the crew transport system rails, a human metabolic simulator (located under Mylar insulation below the SxEMU, and internal instrumentation package to monitor the life support system performance, the xPLSS, xINFO, and the xPGS suit hardware. The focus of this paper is the performance of the xPGS components. A key aspect of the test design was that it was an unmanned test without a human or Liquid Cooling and Ventilation Garment (LCVG). These provide a significant thermal boundary on the inside of the xPGS components that was not present during these tests. A person is a massive thermal sink that self regulates to approximately 98.6°F (37°C). In the xEMU, the LCVG water temperatures are actively controlled by the xPLSS to 50°F (10°C). Both the human and LCVG would cover the majority of the surface area inside of the suit in a real configuration. These were not well represented by the instrumentation package that was used inside of the HUT.

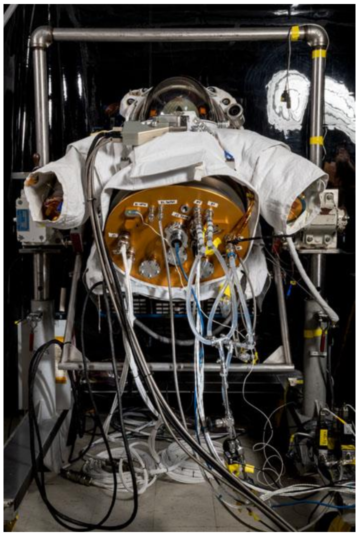

Figure 4. SxEMU Waist Plug.

B. xPGS Components

The xPGS components in the SxEMU were obviously missing the waist-brief-hip, legs, and boots. Custom thermal insulation utilizing a 7-layer mylar layup was developed to provide thermal protection for the wrist plugs. An aluminum HUT and hatch were used in the SxEMU. The HUT was fully populated with the Integrated Communication System (ICS) speakers and microphones, purge valve, and relief valves. The helmet assembly included a full EVA Visor Assembly (EVVA) that included the xINFO lighting band and high-definition camera. The upper torso included shoulders and lower arms. 2.25" and 3" tall waist sizing rings were used to provide more space for the internal instrumentation package and increase the free volume of the xPGS to something close to that of a full suit. Plugs were used at both wrists and for the waist. Figure 4 shows the waist plug and all of the fluid and electrical passthroughs for the internal instrumentation and human metabolic simulator. The DCU was mounted to the front of the HUT and several electrical harnesses and fluid lines were used, consistent with the xEMU design, to connected components across the suit. Flight-like EPG was used to cover all of the components. It typically consisted of seven layers of aluminized mylar separated by a scrim with an outer covering of ortho-fabric.

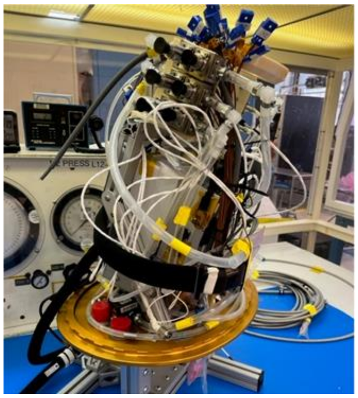

Figure 5. Internal Instrumentation Package.

C. Suit Internals

Because the SxEMU included a fully functioning xPLSS, an internal instrumentation package was installed inside of the HUT to monitor life support system aspects of the suit performance[2]. Figure 5 shows the majority of the of this instrumentation package. Sensors included CO2, pressure, ventilation loop pressure drop, humidity, temperatures, flow rates, and an ammonia sensor. Water lines exited the bottom of the waist plug and flowed through electrically heated coldplate to simulate metabolic heat input to the SxEMU. Flow controllers for water vapor and CO2 were also located underneath the SxEMU and were injected through the waist plug. An internal line routed these gasses from the waist plug to the crew-right arm. There was a concern with the humidity condensing and forming liquid water inside of the SxEMU due to the configuration of the Human Metabolic Simulator (HMS). Therefore, an attempt to control the gas input (which was heated to minimize condensation) and to get those metabolic byproducts back to the xPLSS. A bracket was made to support the

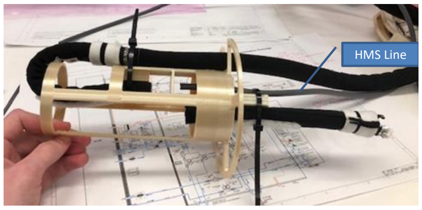

Figure 6. HMS and Vent Line Locating Bracket

Table 1. Internal Thermocouple Reference Designators

Subsystem	ID	Description
Hatch	ST-TS-00	PLSS Interface Pad
Hatch	ST-TS-01	FSA (between hatch cover and FSA)
Hatch	ST-TS-02	AFSA (between crew right AFSA and side of hatch)
Hatch	ST-TS-03	F-548
HUT	ST-TS-04	WHRM (on PTCL)
HUT	ST-TS-05	Speaker (On HUT, left)
HUT	ST-TS-06	HUT Vent Loop (oro-nasal)
HUT	ST-TS-07	Neck Ring (Near ICS)
HUT	ST-TS-08	Neck Ring (Top)
HUT	ST-TS-09	ICS Ring (near a mic)
HUT	ST-TS-10	ICS connector
HUT	ST-TS-11	DCU Interface Pad
HUT	ST-TS-12	NPRV
HUT	ST-TS-13	PPRV (RV-346A)
HUT	ST-TS-14	HUT Surface (PPRV- Shoulder)
HUT	ST-TS-15	HUT Surface (NPRV - Shoulder)
HUT	ST-TS-16	Speaker Wedge (Left)
HUT	ST-TS-17	Speaker Wedge (Right) similar to HUT-purge
HUT	ST-TS-18	Purge Fitting
HUT	ST-TS-19	Manikin Internal
Shoulders	ST-TS-20	Scye Bearing (Left)
Shoulders	ST-TS-21	Scye Bearing (Right)
Shoulders	ST-TS-22	Shoulder Bladder (left)
Shoulders	ST-TS-23	Shoulder Bladder (right)
Shoulders	ST-TS-24	Arm Bearing (left)
Shoulders	ST-TS-25	Arm Bearing (right)
Arms	ST-TS-26	Left Arm Bladder
Arms	ST-TS-27	Right Arm Bladder
Arms	ST-TS-28	Wrist Disconnect (Left)
Arms	ST-TS-29	Wrist Disconnect (Right)
Helmet	ST-TS-30	Helmet Pressure Bubble
Instrumentation	ST-TS-31	Manikin Forehead

ventilation duct assembly and the HMS injection line and to prevent heated gasses from directly impinging on the arm bladder. Figure 6 shows this bracket. This was installed inside of a comfort glove and then inside of a pink poly bag to contain any condensate. A flight-like ventilation tree was used in the internal instrumentation package. Since the legs of the suit were not used, those ducts were also routed into the arms on the proper side of the suit. In addition to the life support test equipment, audio test equipment was part of this instrumentation package. This includes an audio manikin, three measurement microphones, and two accelerometers[4].

D. Thermocouple Placement

In the spirit of this test being a thermal evaluation of the xEMU, 128 type T thermocouples were placed at key locations inside and outside of the spacesuit. Tables 1 and 2 give a summary of the thermocouples on the inside (pressurized) and outside (exposed to vacuum) of the SxEMU xPGS components. Key locations included areas that were not well insulated with EPG like the neck ring or valves. An effort was also made to take temperature measurements across the different layers of the suit lay-up. An example would be measuring the inside of the arm bladder, the outside of the arm bladder, and the outer EPG temperature all at approximately the same location.

E. Heater Cage Overview

Reference 3 provides detailed background on the design and analysis of the heater cage that is used to control the thermal environment that the SxEMU experienced during testing. In addition to simulating the thermal environment of the test article, the heater cage had two additional and unique requirements. First, due to the nature of the test where the SxEMU was entering and leaving the chamber, the heater cage had to be open on the side next to the chamber manlock. This made controlling to a uniform thermal environment extra challenging. A design where the cage was extended away from the SxEMU like a hallway was adopted. Movement of the SxEMU in and out of the chamber also made it difficult to put heaters on the top of the cage. A few heaters were able to be fit in between the rails of the crew transport system and up above the test stand supporting the test article, however they did not provide a thermal environment that was as uniform as the side panels.

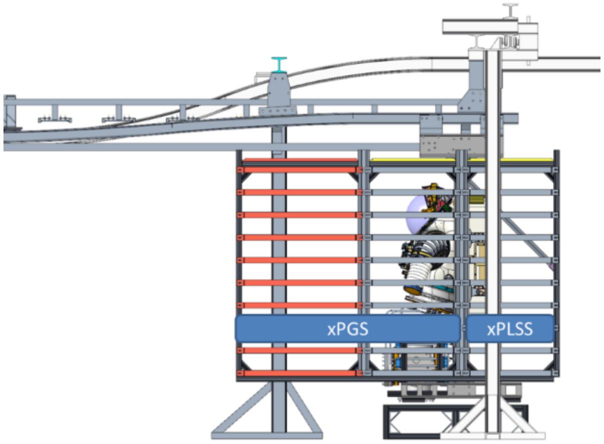

Figure 7. SxEMU Heater Cage.

Second, because the xPGS did not have a flight-like thermal sink inside of it, there was concern that those xPGS components would follow the temperature environments more closely than the xPLSS. This led to separating the heater cage into a xPLSS control zone and a xPGS zone. With this design, the xPLSS could be exposed to a wider range of environments and the xPGS components could be closely monitored and the heaters could be adjusted to maximize the temperature range while protecting the hardware. Figure 7 shows the heater cage, SxEMU test article, the crew transport system railing, and identified the xPGS and xPLSS heater zones. The manlock is located to the left of the figure and the SxEMU backs into the heater cage with the xPGS facing the manlock door. As documented in Reference 3, a series of thermal analyses were performed to assess the design of the heater cage. Figure 8 provides examples of the results of a hot case and cold case. These predictions indicated uniform temperature distributions across the xPLSS, but some colder areas on the top of the xPGS based on the sparse heater arrangement above the SxEMU.

Table 2. External Thermocouple Reference Designators

Subsystem	TC Lookup ID#	Description
xPGS	TS-T21-001	PGS - Helmet Top Center
xPGS	TS-T21-002	PGS - Helmet Bubble Lower Left
xPGS	TS-T21-003	PGS - Helmet Bubble Lower Right
xPGS	TS-T21-004	PGS - Helmet Right Shade
xPGS	TS-T21-005	PGS - Helmet Sun Visor Center
xPGS	TS-T21-006	PGS - Neck Ring Front
xPGS	TS-T21-007	PGS - Neck Ring Back
xPGS	TS-T21-008	PGS - EVVA Top
xPGS	TS-T22-001	PGS - Hatch Latch Front Face
xPLSS	TS-T22-003	PLSS - DCU Front
xPGS	TS-T22-004	PGS - HUT Under Left Arm
xPGS	TS-T22-005	PGS - HUT Under Right Arm
xPGS	TS-T22-006	PGS - HUT Top Above Purge Valve
xPGS	TS-T23-001	PGS - Arm Left Upper
xPGS	TS-T23-002	PGS - Arm Left Lower
xPGS	TS-T23-004	PGS - Arm Right Upper
xPGS	TS-T23-005	PGS - Arm Right Lower
xPGS	TS-T23-006	PGS - RC Ring Right
xPGS	TS-T24-001	Hatch - Bottom, Between Hatch and PLSS
xPGS	TS-T24-002	Hatch - Right, Between Hatch and PLSS
xPGS	TS-T24-003	Hatch - Left, Between Hatch and PLSS
xINFO	TS-T31-005	INFO - Light Capsule #1
xINFO	TS-T31-006	INFO - Light Capsule #2
xINFO	TS-T31-007	INFO - Light Capsule #3
xINFO	TS-T31-008	INFO - Light Capsule #4
xINFO	TS-T31-009	INFO - Lighting Band PCB
xPLSS	TS-E22-001	EPG, PGS - Hatch Latch Front Face
xPGS	TS-E22-002	EPG, PGS - HUT Under DCU
xPLSS	TS-E22-003	EPG, PLSS - DCU Front
xPGS	TS-E22-004	EPG, PGS - HUT Under Left Arm
xPGS	TS-E22-005	EPG, PGS - HUT Under Right Arm
xPGS	TS-E22-006	EPG, PGS - HUT Top Above Purge Valve
xPGS	TS-E23-001	EPG, PGS - Arm Left Upper
xPGS	TS-E23-002	EPG, PGS - Arm Left Lower
xPGS	TS-E23-004	EPG, PGS - Arm Right Upper
xPGS	TS-E23-005	EPG, PGS - Arm Right Lower
xPGS	TS-T22-020	Waist Sizing Ring - Front
xPGS	TS-T22-021	Waist Plug - Away From Water Lines
xPGS	TS-T22-022	Waist Sizing Ring - Rear

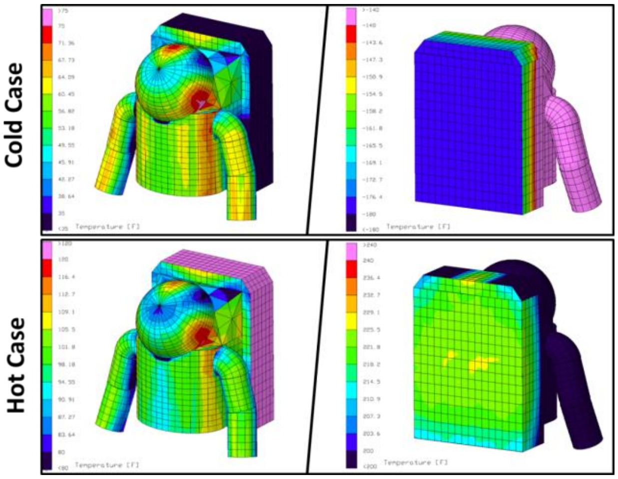

Figure 8. SxEMU Heater Cage Analysis.

IV. Results Summary

Five simulated EVAs were performed with the SxEMU from September 28th through October 3rd, 2023. The first EVA was performed in a cold environment with the sunshades on the EVVA deployed. Since this was the first simulated EVA a significant amount of uncertainty existed on the xPGS component temperatures, the environments were managed conservatively. For the second EVA the sun visor and shades were stowed. It also consisted of a cold environment; however, the environment temperature was decreased slightly because EVA 1 had shown that the xPGS components could handle colder environments. EVA 3 was the first hot case for the SxEMU. In this test the sun visor and shades were deployed. Again, a conservative approach was taken to ensure that temperature limits of xPGS components were not exceeded. EVA 4 was another hot case with the sun visor and shades stowed. EVA 5 was also a hot case, this time with the sun visor and shades deployed. EVA 5 also included testing the suit at different operating pressures: 4.3 psia (30 kPa), 5.0 psia (34 kPa), 6.2 psia (43 kPa), and 8.2 psia (57 kPa). All other tests were performed at 4.3 psia (30 kPa). Each hot test point had slightly more extreme environment temperatures as the test team gained comfort that hardware temperature limits would not be exceeded. The following section will summarize highlights of temperature data from the test. At the time of this paper, additional analysis was underway to future assess the performance of the xPGS components.

Figure 9 and Figure 10 show all of the temperature reading on the SxEMU xPGS during one of the cold EVAs and one of the hot EVAs. Both graphs have too many readings to easily pull out individual data, but the groupings provide a high level, general assessment of the thermal performance of the xPGS. Temperatures are organized to be part of a group of “Internal TCs,” “EPG TCs,” or “Coupon TCs.” Coupons were pieces of materials that were similar to the suit EPG, that had thermocouples attached, and were hung in the heater cage around the test article. The concept of an environment coupon is that if there is an adiabatic object with the same optical properties as the test article, it can be used to “measure” the environment temperature. These are the most extreme temperatures in each graph. Coupons were used to set the environment in the heater cage while the SxEMU was in the manlock. Unfortunately, due to the motion of the SxEMU in and out of the heater cage, these coupons were hung out of the path of motion of the suit and ended up being significantly closer to the heater cage than the suit. Because of the difference in the distance between the coupons to the heater cage and the relatively small size of the coupons, it is believed that the view factor to the heater cage and the cold walls of the chamber could have been significantly different than that of the SxEMU. Therefore, these values are used as a reference, but with the knowledge that they may not be an accurate representation of the thermal environment that the xPGS was exposed to.

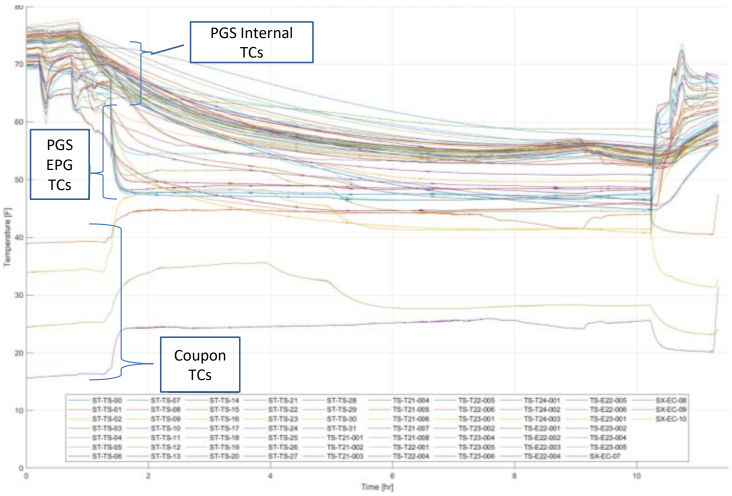

Figure 9. All Temperatures EVA 2 (Cold).

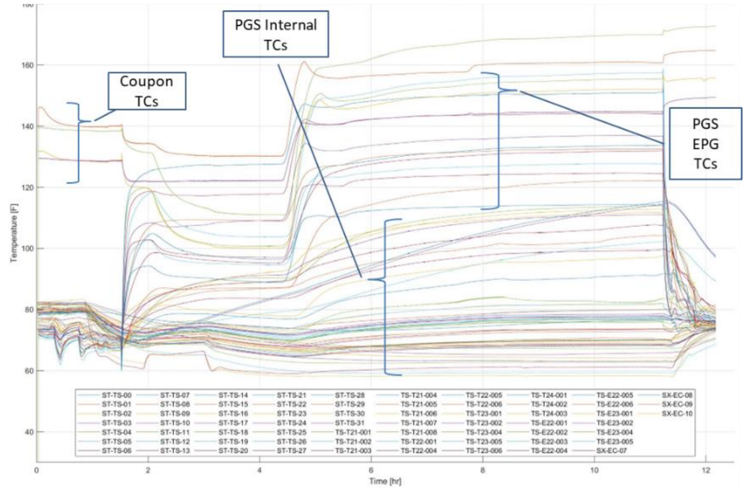

Figure 10. All Temperatures EVA 4 (Hot).

Next, the EPG thermocouples show the temperatures on the outer layer of the spacesuit insulation. These temperatures are also indicative of the environment temperature; however, the EPG is not totally adiabatic. Some heat is leaked into or out of the SxEMU through the EPG for each test point. The effective environment temperature can be inferred to be between the EPG and coupon temperatures. For the cold test point in Figure 9, this would be between approximately 25°F (269 K) and 50°F (283 K). In the hot test shown this is likely between 110°F (317 K) and 190°F (361 K). It should be noted that some non-uniformity in the environments was expected due to the heater cage design. Also, in the hot case, a coupon that was much closer to a heater bar would read significantly hotter than an EPG temperature that was significantly farther away and had a larger view to the cold chamber walls in-between each heater. Across all five test points, the minimum EPG temperature recorded was 40°F (278 K) and the maximum was 180°F (355 K).

Finally, the Internal thermocouples are shown in a group. These are the most moderate grouping of temperatures, which is expected. Even though there was not a human or LCVG inside of the xPGS, the EPG still provided significant thermal insulation and the test equipment inside of the suit and ventilation gas flowing through the xPGS provided some temperature control.

These summary graphs also provide interesting information about the time constant of the SxEMU as a thermal system. The y-axis for each graph is the number of hours after the EVA began. EVAs began while the SxEMU was still in the manlock. The coupon temperatures have approached a steady target temperature prior to the SxEMU being transferring into the chamber and the heater cage. As the SxEMU enters the heater cage, the EPG temperatures change quickly to reflect the change from the room temperature environment in the manlock to the chamber. The presence of the SxEMU also impacts the readings of the environmental coupons. In the cold test point, the radiative heat from the room temperature SxEMU appears to warm the coupons. In the hot case, the coupon temperatures drop. From this point all of the temperature on the SxEMU begin to drift towards what would be a steady state temperature. SxEMU test points were limited by consumables in the xPLSS and were not continued until a steady state was reached. That noted, the SxEMU was at vacuum for 10.6 hours during EVA 2 and for 11.4 hours during EVA 4. Both of these are significantly longer than a maximum EVA duration of 8 hours that the system was designed to achieve. This would indicate that the time constant for a spacesuit is likely longer than the 8 hour duration for which they are usually planned. Having a human in the suit would impact this transient as they are a large and fairly constant temperature mass that was not included in the system during this unmanned test.

Infrared (IR) cameras were mounted at each corner of the heater cage to qualitatively monitor the SxEMU for hot and cold spots. Figure 11 shows views captured during EVA 2. IR images were only captured during cold test points because the cameras overheated during the hot test points and shut off. These images indicate that performance similar to what was anticipated was achieved. Arms of the suit were warmer from being closer to the heater cage. Upward facing surface on the helmet and shoulder were cooler due to limited overhead heaters. The crew left side of the suit is partially obstructed by the test umbilical which was hanging vertically near the crew-left should of the suit. The neck ring did not have EPG covering and appears to be warmer (or closer to the internal temperatures), which was expected. The visor and sunshades were stowed during this test profile, so the transparent and reflective nature of helmet bubble may be leading to interesting profiles on that component that may not be indicative of the temperature distribution.

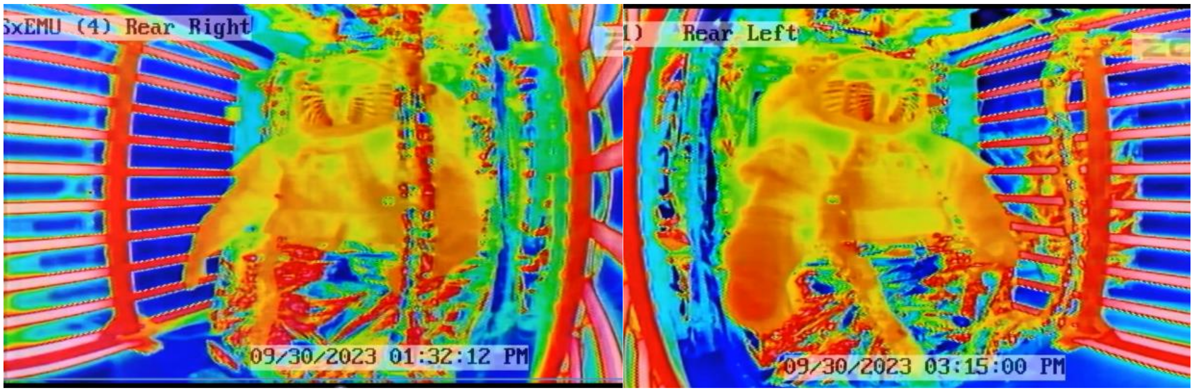

Figure 11. Infrared Images During EVA 2 (Cold).

Next internal touch temperatures were checked. Figure 12 plots all of the internal temperatures through all five EVAs. Horizontal lines are present to indicate the minimum and maximum temperatures that an astronaut would be able to contact while performing an EVA inside of the spacesuit. Bare skin touch temperature limits are 50°F (10°C) to 111°F (44°C). Each simulated EVA can be seen as a temperature valley or peak in the graph, with airlock operations consisting of the hardware returning to room temperature in between. All the temperatures during this test series stayed with these bounds with two exceptions. ST-TS-27 is the right arm bladder and ST-TS-29 is the right arm wrist disconnect. Both of these temperatures appeared to respond in a more extreme manner to the test environments than the other internal temperature. This is surprising because they were both covered in EPG and they were expected to

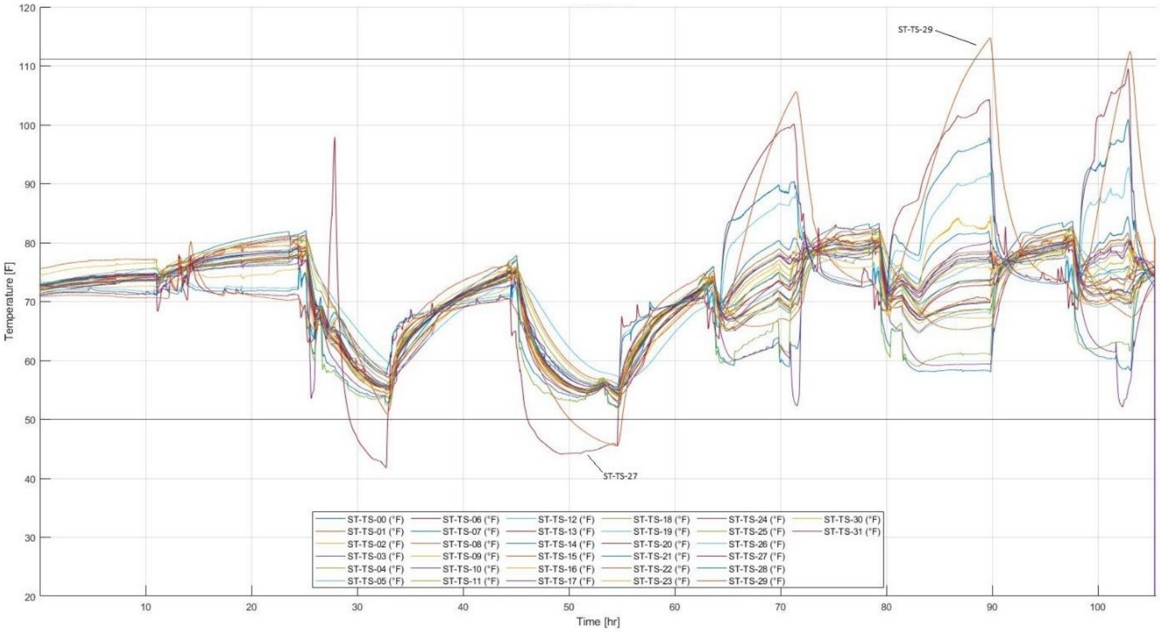

Figure 12. Internal Temperatures.

be symmetrical with the left arm. In fact, Figure 11 shows that the EPG in this area was generally warmer than the rest of the EPG which contrasts these lower internal temperatures. Potential causes for these extremes could be due to the HMS injection line and supporting bracket that were installed in the crew-right arm, or potentially due to exhaust from the xPLSS CO2 scrubber which vented on that side of the SxEMU for EVAs 2 through 5. The Rapid Cycle Amine (RCA) vacuum vent line had been reconfigured after EVA 1 in an attempt to troubleshoot performance issues with the RCA. During the first EVA, issues with the HMS puddling water in the right arm were present and that water may have never fully evaporated or may have impacted heat transfer in the arm. Water injection also caused the temperature spike at approximately hour 27. The water vapor was heated to avoid condensation, however this hot gas unexpectedly and rapidly heated the arm bladder. Concern over the peak bladder temperatures reached and the condensate generation led to the termination of humidity injection for the remainder of the test profile. CO2 scrubber exhaust from the xPLSS may have provided enough of a local pressure environment to decrease the effectiveness of the EPG, however, this would not apply to EVA 1 due to the scrubber exhaust line configuration for that test point.

A few additional notes are important when assessing these internal bare skin touch temperature excursions. First, the external thermal environments were not as extreme during this test as the xEMU requirements. This is especially true in the cold case where the minimum temperature were barely below the cold touch temperature. On the hot end, even though the hot lunar environment temperatures were not reached, testing was in the range of a hot environment on ISS. Next, bare skin would not touch either of these two areas where the extremes were recorded. The wrist plug would be replaced with a glove and the LCVG would be between the crew member's skin and these suit parts. Finally, the crew member and LCVG would also help maintain the internal temperatures within safe limits. This test was unconservative in how much the suit components were impacted by the environment temperature due to the lack of a crew member with an LCVG. Temperature variations from this test are expected to be larger than in a real EVA.

No quantification of heat leak between the inside of the xPGS to the environment has been performed at the time this paper was written. For the SxEMU, a full energy balance on the test article is very dependent on the heat rejection from the Suit Water Membrane Evaporator (SWME) in the xPLSS. With respect to xPGS components, it is possible to get an assessment of the performance of the EPG by evaluating the temperature gradient through the different layers of the suit assembly. Thermocouples were purposefully located across the suit layup at several places to evaluate this heat transfer. These temperature profiles are shown in the following section at the left arm and on the right chest underneath the arm as examples. Data from cold and hot tests are shown to provide a comparison.

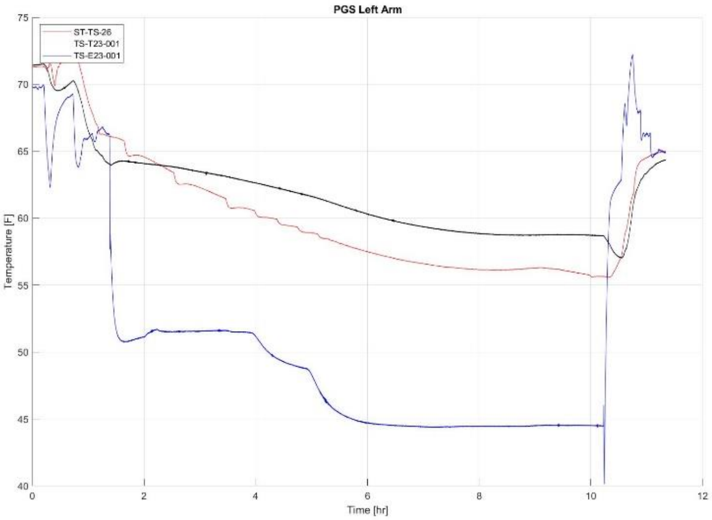

Figure 13. Left Arm EVA 2 (Cold).

Figure 13 and Figure 14 show the temperatures across the layers of the left arm assembly for a cold test and a hot test, respectively. The cold test, EVA 2 shows that the arm had approached steady state by the end of the test point. The EPG temperature (TS-E23-001) was steady at slightly below 45°F (280 K). Because this temperature is so close to the internal temperatures of the SxEMU, the remaining two temperatures show unexpected values. As a point of reference, the gas flowing through the suit during this test point was approximately 55°F (286 K). No water lines ran through the left arm, so the gas flow is the primary temperature boundary on the inside of the suit. ST-TS-26 is the internal bladder temperature, and it matches the gas temperature closely. TS-T23-001, the external bladder temperature, is strangely even warmer than this internal temperature. This thermocouple is physically located on the outside of the restraint next to the inner surface of the EPG. A mechanism for this temperature to be hotter than the internal bladder temperature is not obvious. They are within approximately 2°F and this could potentially be due to uncertainties in the sensor or some error in the data acquisition system. Slightly different locations from the inner surface to the outer surface could also potentially be a source of this difference. If the sensors were at different radial positions on the arm, locations that were facing upward saw colder environments than those facing the heater cage more directly. Regardless of the source of these unexpected temperatures, the two bladder readings are close together compared to the external EPG temperature. In these test conditions, where the heat exchange should be very small due to how close the environment temperature is to the internal suit temperature, the EPG takes almost of the temperature gradient, which is about 11°F (6 K).

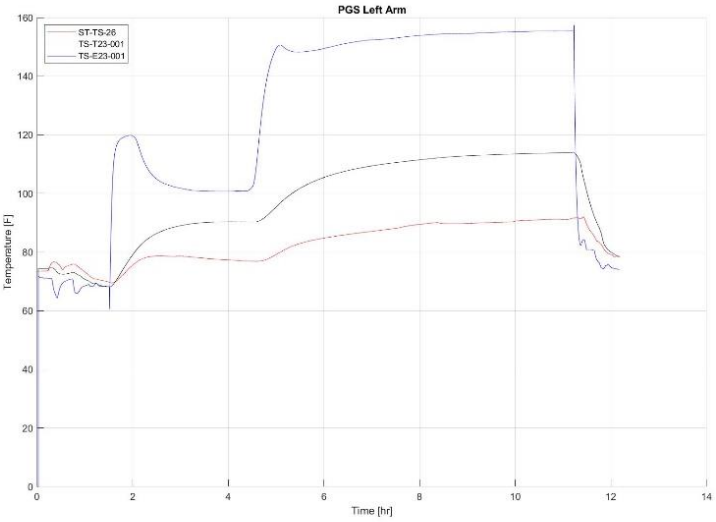

Figure 14. Left Arm EVA 4 (Hot).

The hot test point, in this case EVA 4, provides an expected temperature gradient over a wider temperature range. The EPG temperature approached 155°F (342 K), with the external restraint temperature at approximately 115°F (319 K), and the inner bladder slightly above 90°F (305 K). This profile is much closer to what was expected with the lowest temperature being inside of the suit and the hottest on the outer layer that is exposed to the hot thermal environment. The difference from the inside of the arm bladder to the outside is slightly larger than expected for such a thin material, which may be additional reason to believe that the thermocouples were not directly across the bladder from each other. If this sensor, (TS-T23-001, external bladder) was closer to the heater cage and reading slightly hotter than ST-TS-14, it would be consistent with the results on both Figure 13 and Figure 14.

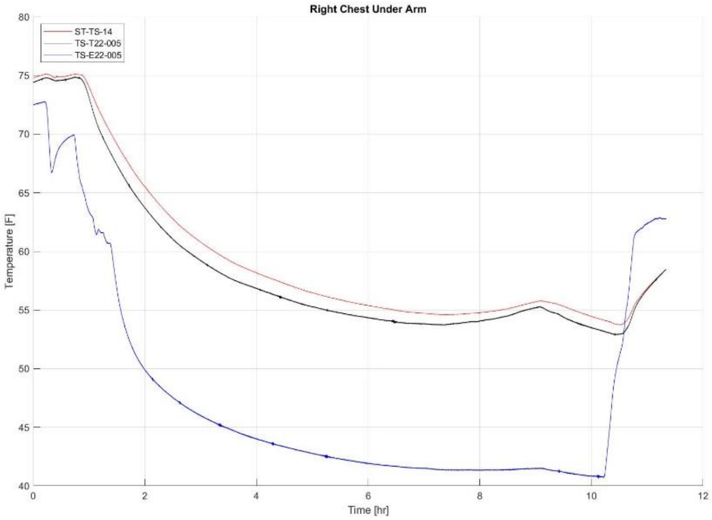

Figure 15. Right Chest Under Arm EVA 2 (Cold).

A second location, the right chest under the arm, is shown in Figure 15 and Figure 16 for a cold and hot case, respectively. ST-TS-14 is the thermocouple inside the pressurized volume of the suit. Similarly, to the arm, the inner temperature approaches 55°F (289 K) which corresponds to the gas temperature flowing through the suit. This is also close to the water loop temperature which is flowing through the tubing shown in Figure 5 and also along the inner wall of the aluminum HUT. TS-T22-005 in on the outer surface of the HUT and matches very closely, with only being slightly cooler. The EPG temperature, TS-E22-005, drops down almost to 40°F (278 K), which was as cold as the test article was allowed to go per the test procedures. Clearly, the majority of the temperature gradient is across the EPG, which is expected.

In the hot case, the EPG temperature is significantly higher that the HUT hardware temperatures. In this case, the inner HUT temperature is slightly higher than the outer temperature, which is unexpected. However, this difference is very small and again could be due to instrumentation uncertainty or slightly different placement from between the two locations. TS-E22-005 approached 125°F (325 K), which is a gradient of almost 55°F (31°C) from the hardware temperatures. This shows the EPG providing effective insultation to the HUT in this environment.

V. Lessons Learned

This thermal-vacuum test of the SxEMU was the first test of its kind. It demonstrated key aspects of the xEMU design in a relevant environment and provides a special reference point as a unique spacesuit test. Important lessons learned, especially with respect to the xPGS hardware, are documented here.

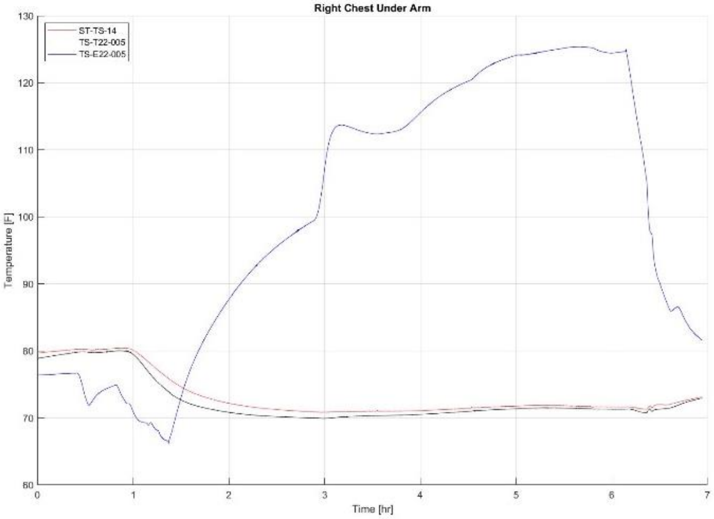

Figure 16. Right Chest Under Arm EVA 5 (Hot).

First, the lack of a person wearing an LCVG inside of the suit did restrict the potential test environments that could be performed due to the hardware following the environment more closely than in a manned test. Test points were run in an experimental fashion where an environment was set, hardware temperatures were evaluated and then the environment would be taken to a more extreme temperature if the hardware was still within safe limits. These limits likely could have been pushed a little bit farther, but especially on the cold cases, the internal hardware temperatures started much closer to the freezing temperature of water than they would have in a human in the loop style test, so there was less room to work with.

With that in mind, the EPG did work very well as an insulator. When looking at the temperature gradients across the suit layup, almost all of the temperature gradient is through the EPG. Multi-layer mylar insulation is the standard for spacecraft applications and its effectiveness was demonstrated again in this test.

Steady state conditions are a key aspect of thermal analysis and testing. Most modeling efforts are run until they reach a steady state. Typically, tests are too. In a spacesuit application, this may be additionally challenging in a real life application. The data presented in this paper indicate that the time constant for the SxEMU was likely longer than an 8 hour EVA. This was without the crew member, which is a significant mass and energy source not being included in the system. In addition, in a real EVA, a crew member will change their metabolic heat input into the system based on their activities and they rarely stay in one place without moving for extended periods. Reaching steady state conditions is unlikely and that needs to be considered when performing thermal analyses on spacesuits.

Two lessons learned are particularly applicable to the test setup. First, the infrared cameras used were low cost, commercially available units that were not actually rated for vacuum operations. That said, they worked just fine until they overheated in the hot tests. They were mounted directly onto the heater cage and minimal effort was made to provide temperature management. A few layers of mylar were wrapped around the back of the cameras, but otherwise, they were bolted directly to the heated aluminum framing. It was good news that they worked as well as they did, but more effort should be made in future tests to prevent overheating. Second, the environment coupons were problematic for this test article. Due to the nature of how the SxEMU moved in and out of the heater cage, there was not a good way to have them installed in the optimal locations. If they had been mounted on the stand close to the test article, they would have had to travel in and out of the heater cage also. This would not have given the team any insight to set the environment temperature prior to each simulated EVA. In this test configuration, where they were suspended in the heater cage, they ended up being too close to the heater bars so they would be out of the path the test article traveled as it moved in and out of the chamber.

VI. Conclusion

The xEMU project produced high fidelity spacesuit hardware and successfully tested it in a space-like environment. The focus of this paper was on the thermal performance of the SxEMU xPGS hardware, which was one of the major objectives. Other objectives included operations at a sub ambient pressure environment and also operating the SxEMU at a high level of integration. Although specific results for these objectives are better documented in companion papers, the simple fact that the system was able to successfully perform five simulated EVAs shows general success. 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] Whalen, P., Gazzara, S., Marsch, R., Nasser, M., and Moore, A., "Short Exploration Extravehicular Mobility Unit Testing Setup: Evaluation Under Realistic Pressure and Thermal Conditions," International Conference on Environmental Systems, ICES, Louisville, KY, 2024.

[3] 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

[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.