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Short Exploration Extravehicular Mobility Unit Testing Setup: Evaluation Under Realistic Pressure and Thermal Conditions

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The purpose of Short Exploration Extravehicular Mobility Unit (SxEMU) thermal vacuum testing was to verify the functionality of the Design Verification Testing (DVT) prototype xEMU (SxEMU for this test) at vacuum pressures and extreme space and lunar surface temperature conditions. The SxEMU Thermal Vacuum Test was the culmination of the DVT xEMU project. This paper's focus is on the pre-Extravehicular Activity (EVA) test setup, and general performance of the SxEMU Portable Life Support Subsystem (xPLSS), with focus on the performance of the Primary Oxygen Assembly (POA) and Secondary Oxygen Assembly (SOA), including Secondary Oxygen Regulator (SOR) takeover and the POA and SOA low-setpoint change inhibit. The initial pre-EVA test preparation included recharging the batteries and replenishing consumables, including test-system water, oxygen assemblies (with gaseous nitrogen), and the integrated thermal loops, including the Feedwater Supply Assemblies. xPLSS functionality testing included carbon dioxide (CO_2) removal via the Rapid Cycle Amine swingbed system, thermal loop temperature control, and monitoring of suit ventilation loop pressure, temperature, and CO_2 percentages. Testing evaluated automatic takeover of suit pressure control by the SOR after the primary oxygen supply is depleted. The Primary Oxygen Regulator and SOR low-setpoint change inhibit function prevents the crewmember from inadvertently setting the primary regulator to a low pressure setpoint during an EVA.

Nomenclature

AC = Alternating Current
ATCL = Auxiliary Thermal Control Loop
CO_2 = carbon dioxide gas
DC = Direct Current
DCU = Display and Control Unit
DVT = Design Verification Testing
ESCU = Exploration Service and Cooling Umbilical
EVA = extravehicular activity
FSA = Feedwater Supply Assembly
FPUIRD = Fluid Pumping Unit Interfaces Requirements Demonstrator
GN_2 = nitrogen gas

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HMS = Human Metabolic Simulator
HUT = hard upper torso
ISS = International Space Station
K = Kelvin (temperature)
mmHg = millimeter of mercury (pressure)
O_2 = oxygen
POA = Primary Oxygen Assembly
POR = primary oxygen regulator
POV = primary oxygen vessel
pp = partial pressure
pph = pounds per hour
psi = pounds per square inch
psia = pounds per square inch, absolute
psid = pounds per square inch, differential
psig = pounds per square inch, gauge
PTCL = Primary Thermal Control Loop
SOA = Secondary Oxygen Assembly
SOR = secondary oxygen regulator
SOV = secondary oxygen vessel
SxEMU = Short Exploration Extravehicular Mobility Unit (test article)
TVAC = thermal vacuum test
UIA = umbilical interface assembly
VI = vehicle interface
xBMS = Exploration Battery Management System
xEMU = Exploration Extravehicular Mobility Unit
xPLSS = Exploration Portable Life Support Subsystem

I. Introduction

THE xEMU thermal vacuum test in Chamber B at NASA's Johnson Space Center was the culmination of over a decade's worth of work and development. In the test, the Short xEMU (SxEMU) test article was placed inside Chamber B in Building 32 at Johnson Space Center and subjected to extreme temperatures and vacuum quality mimicking the conditions of space.[1] The SxEMU was tested in both hot and cold cases ranging from 116 K (–250°F) to 355 K (180°F). The temperature testing bounds were set to mirror the thermal extrema found during normal xEMU EVA environments. The temperature range encompass the thermal conditions of environments, such as the lunar surface, within a lunar shadow, areas of direct sunlight, and outside of the International Space Station (ISS). The pressure in the chamber was capable of being decreased to 9×10^{-6} Torr using large cryogenic pumps that removed the air from the chamber and a double-cold-wall system that trapped stray particles. The inner wall of the vacuum chamber featured internal channels for liquid nitrogen (at a temperature of 77 K or -321 °F) to flow through to cool the walls and floor of the chamber. The outer wall of the chamber had a similar channeled wall that allowed the flow of liquid helium (4 K or -452 °F). The double-wall system trapped stray particles and prevented unwanted particles from entering the chamber. In doing so, the partial pressure of contaminants within the chamber was minimized, while simultaneously maximizing the vacuum quality. Furthermore, the low temperatures characterized by the double-cold-wall system setup enabled the xEMU to reach low enough temperatures to perform lunar shadow testing. In addition to the main vacuum chamber, Chamber B also provided a personnel airlock, or crew-lock, that allowed for ingress and egress while the main chamber remained at vacuum.

SxEMU testing consisted of five separate simulated Extravehicular Activities (EVAs) into the space-like vacuum chamber environment. Prior to each test EVA, the test article consumables were replenished. The consumables included spacesuit battery power, cooling water, and gaseous nitrogen (GN_2) (in place of oxygen (O_2) in the high pressure O_2 tanks), as well as test system water for the Human Metabolic Simulator (HMS). To recharge the test article consumables, two separate setups were designed: the Vehicle Interfaces (VI) Test Cart and the Exploration Battery Management System (xBMS). These assemblies were maintained outside of the chamber during the EVAs and were connected to the SxEMU between EVAs. Inside the chamber, an umbilical interface assembly (UIA) panel stand-in connected to the Exploration Service and Cooling Umbilical (ESCU). The ESCU was mated on the front of the SxEMU Hard Upper Torso (HUT) and allowed for water and gas recharge and the use of vehicle power. The xBMS and the Alternating Current (AC)/Direct Current (DC) power supply were stored on a separate cart and were wheeled into the crew-lock when required. The electrical connector of the xBMS was directly connected to the xPLSS.

II. Pre-EVA Test Setup

A. Airlock Operations Overview

Although the SxEMU test article did not have a human in the loop, in between test EVAs the SxEMU was brought back into the crew-lock from the vacuum chamber on a remote-controlled rail system managed by the test team. The crew-lock to chamber door was then closed behind the suit and sealed, which allowed the test team to repressurize the crew-lock prior to entry, to allow personnel to perform recharge operations. During recharge operations, the SxEMU was connected to the ESCU via the Display and Control Unit (DCU), which supplied the xPLSS with iodinated water to fill the thermal loop FSA and high pressure GN_2 to fill the O_2 tanks. The ESCU was connected to a UIA panel simulator which served as a stand-in for the ISS panel used for EMU spacesuit recharge functions prior to ISS EVAs. The UIA simulator was connected to piping, which led outside of the chamber to the VI Test Cart. The VI test cart consisted of a high pressure GN_2 Charging Rig, the Fluid Pumping Unit Interfaces Requirements Demonstrator (FPUIRD), and a heat exchanger to simulate the active cooling on the ISS. The xBMS test unit was then connected directly to the xPLSS to recharge the on-board batteries. The DCU Simulator, located outside of the test chamber, allowed control of xPLSS functions during both EVA and airlock operations and allowed the test team to operate switches on the DCU that would normally be operated by the crewmember in a crewed test or real EVA.

B. Battery Recharge

Battery recharge was one of the critical tasks between EVAs. The batteries outperformed initial expectations and lasted longer than the 8-hour design requirement for EVA time; however, the batteries did not perform well-enough to last two full EVAs. Like most batteries, if the voltage of the xEMU battery cell dropped below a certain threshold, then the battery would be considered damaged and not safe to be recharged.

Battery charging was performed using the xBMS shown in Figure 1 and was supplied by a 120V DC power supply. The xBMS connected to the xPLSS via the J4 connector and synchronously charged all 10 primary batteries (BATT-690) as well as the independent Auxiliary Thermal Control Loop (ATCL) battery (BATT-590). Once the xBMS was connected and charging, the system indicated charging status, including charge completion and faults for each individual battery via indicator lights. Once all batteries were fully charged to 32 V and all indicator lights indicated complete, the supply power was disconnected from the xBMS and the charge cable was disconnected from the xPLSS J4 connector.

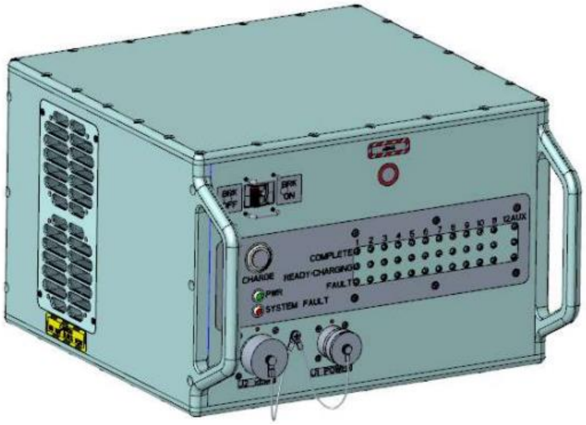

Figure 1. Exploration battery management system (xBMS). *The xBMS includes indicator lights to provide the charging status of each of the 10 primary batteries and one auxiliary battery on the xEMU.*

Full charging of the batteries from an “empty” state of 22 V to full charge of 32 V took approximately 6 hours. In practice, each battery’s voltage did not fall below 25 V during EVA operations. As expected, the BATT-590 ATCL battery had a higher starting voltage at charging when compared to the other batteries due to the minimal load on the auxiliary loop during a normal EVA. Thus, when comparing charging times, the BATT-590 completed charging well before the other batteries, while the ten primary batteries generally completed charging within 15 minutes of each other. Given the ten primary batteries are power loaded evenly during xPLSS operation, comparing the xBMS charging completion times of each provides surface-level insights into battery health.

C. O_2 Assembly Recharge

The xPLSS O_2 tanks nominally hold 3,000 psi O_2. However, for xEMU DVT testing, GN_2 was used as the working fluid with the same pressures, as it effectively made no difference as there was no human in the loop for this test. Furthermore, using GN_2 eliminated flammability hazard concerns. The GN_2 was stored at roughly 6,000 psi in four large pressure vessels on the 6K GN_2 Charging Rig (Figure 2). The four pressure vessels were configured to open either synchronously or asynchronously as isolated vessels. The GN_2 was then regulated down from 6,000 psi to 3,000 psi, before flowing through the VI Test Cart, the ESCU and SxEMU DCU, and, ultimately, into the xPLSS O_2 tanks. The 6K Charging Rig protected the downstream hardware via a 3,500 psi relief valve set at or below the Maximum Allowable Working Pressure of all downstream hardware.

Figure 2. 6K GN_2 charging rig photo. *The 6K GN_2 charging rig provides nitrogen gas stored in four tanks as well as pressure control valves and gauges to supply the SxEMU O_2 tanks with 3,000 psi gas.*

When charging the Primary Oxygen Vessel (POV) and Secondary Oxygen Vessel (SOV) during crew-lock operations, two off-nominal situations occurred. The first occurred during the Oxygen Vessel fills performed after the Powered Functional test, prior to each EVA. The POV pressure transducer, PT-112, did not indicate the full 3,000 psi fill pressure that the regulator on the 6K Charging Rig supplied. The anomaly was further verified by comparing the PT-112 readout to the pressure transducer on the VI cart charge line. As seen in Figure 3 showing the nominal POV fill during the Powered Functional Test, these values should match closely at completion of fill. During subsequent tank fills, the POV tank pressure reading would either fail to reach 2,750 psi or quickly reach equilibrium at around 2,750 psi, despite 3,000 psi being applied through the recharge line. For crew-lock operations, when refilling the POV/SOV, where the indicated pressure did reach above the approximately 2,750 psi mark, indicated readings dropped to approximately 2,500 psi, again, despite the higher pressure in the recharge line upstream. An example of the decay and stabilization of readings below the expected value can be seen in Figure 4, representing tank pressures and temperatures during crew-lock and EVA 1. An example of initial failure of the pressure transducer to indicate full charge can be seen in Figure 5, representing tank pressures and temperatures during crew-lock and EVA 4. After completion of charging, the indicated pressure rose independently of temperature, as the crew-lock pressure was decreased in preparation for the EVA. In summary, the anomaly analysis indicates an error with the high pressure O_2 pressure transducer and not of a leak or failure of pressurization hardware.

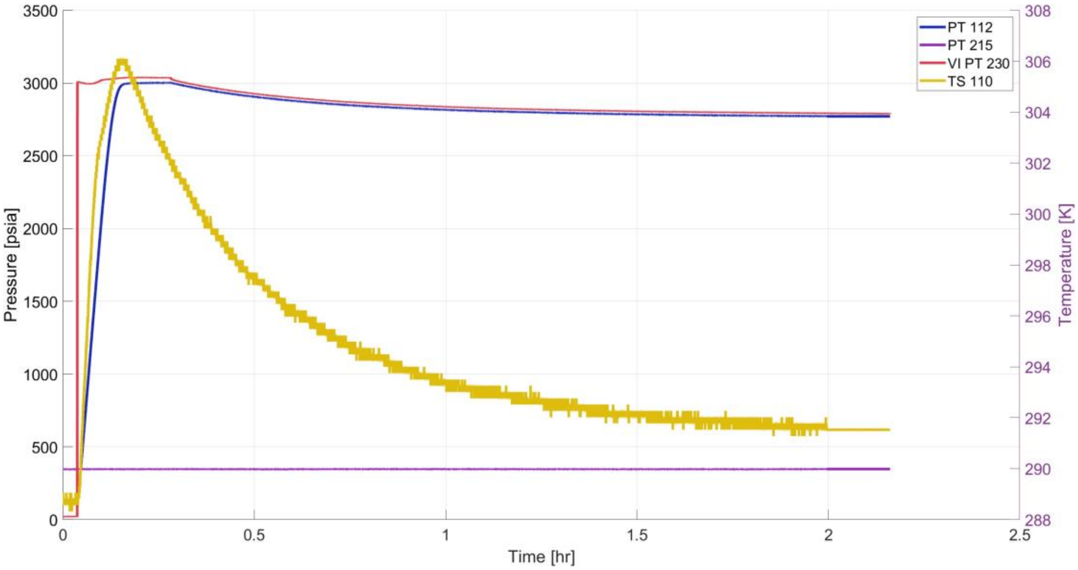

Figure 3. Powered functional pressures and tank temperatures (nominal POV fill). *The indicated POV pressure, PT-112, shown in blue, increased to approximately 3,000 psi, matching the supply pressure shown in red. The POV temperature, orange, increased during pressurization, then was allowed to stabilize. SOV pressure PT-215, shown in purple, did not increase with supply pressure.*

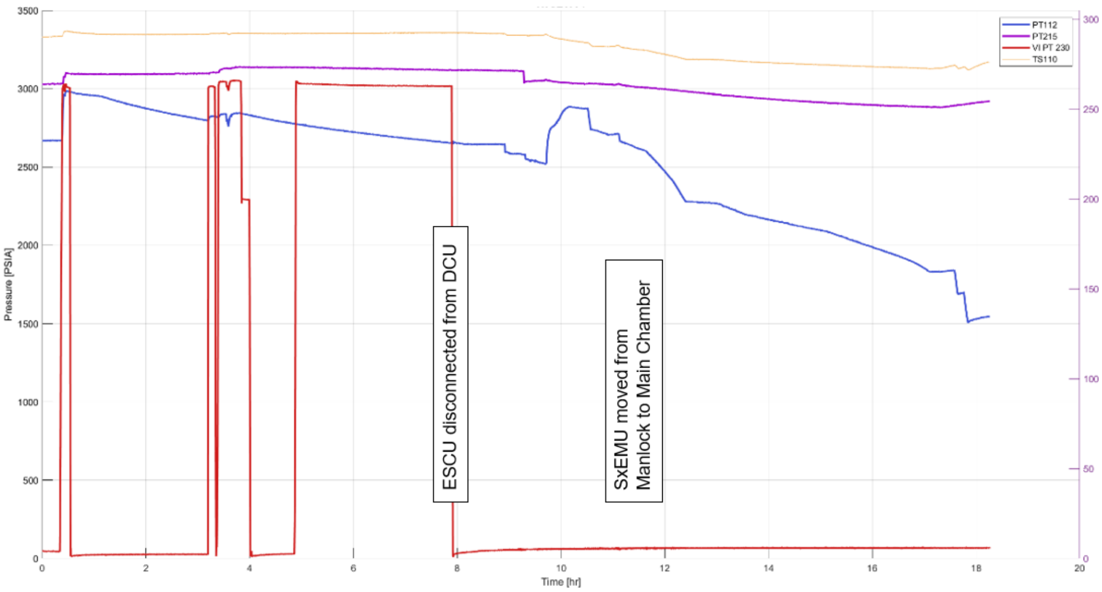

Figure 4. Crew-lock and EVA 1 pressures and tank temperatures (PT-112 decay and low stabilization). *POV pressure PT-112 (blue) appeared to decrease after initial fill and would not increase back to full pressure even after supply pressure (red) was reapplied. During crew-lock depressurization, indicated PT-112 pressure increased with supply pressure disconnected.*

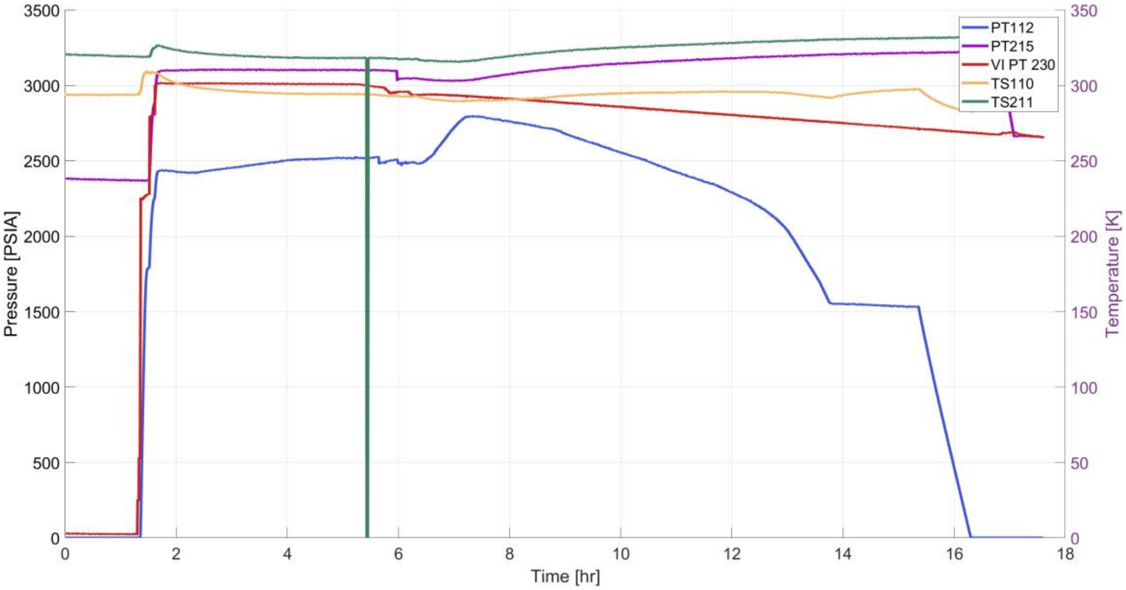

Figure 5. Crew-lock and EVA 4 pressures and tank temperatures (consistently low PT-112). *POV pressure indicated by PT-112 (blue) did not reach the high-pressure supply of 3,000 psi, as indicated by VI-PT-230 (red), and reached a peak indicated pressure of about 2,500 psi during fill operations even as the SOV indicated pressure exceeded 3,000 psi, as shown by PT-215 (purple). Supply pressure was shut off and disconnected and the airlock depressurization was begun. PT-112 indicated pressure increased during depressurization to a maximum around 2,800 psi.*

The second off-nominal operation was the inability to charge the SOV in accordance with the standard fill operations. Standard operating procedure required 3,000 psi to be applied instantly when the high-pressure fill line was opened. However, prior to the first test EVA, it was found that while the POV increased in pressure as described above, the SOV stopped filling at approximately 100 psi. Subsequent troubleshooting efforts found that by incrementing the supply pressure in 250 psi steps, SOV pressure increased as expected with supply pressure. All further EVAs implemented the adjusted step-up fill procedure, as seen in Figure 6. Initial investigations indicate the anomaly may be due to a poppet valve not operating as expected in the SxEMU DCU where the ESCU connects to the suit.

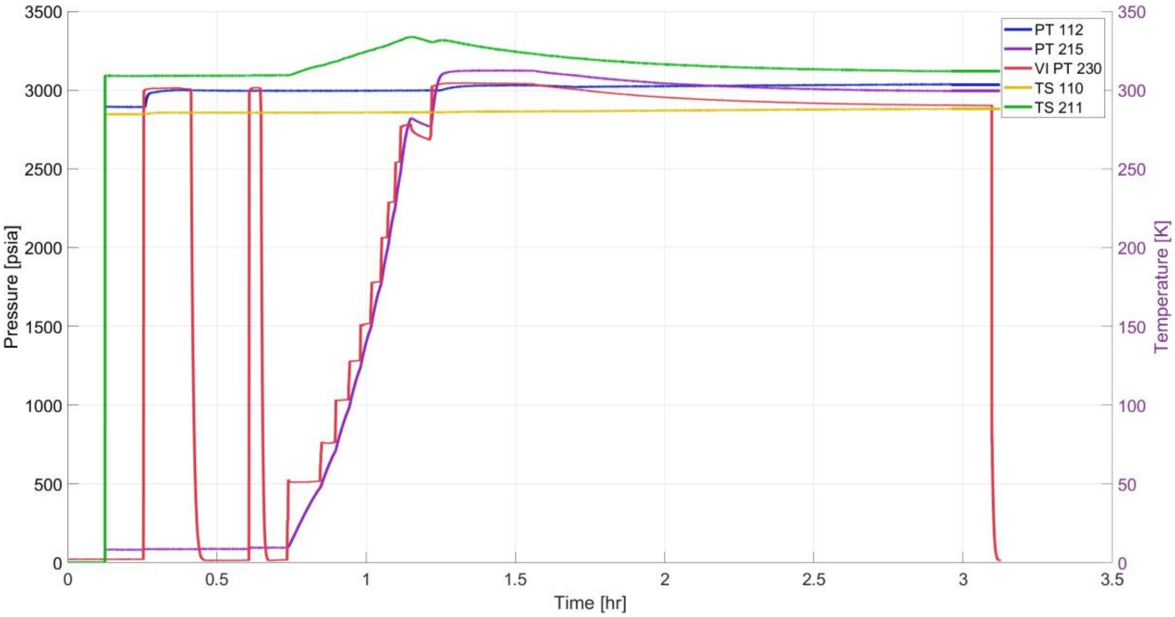

Figure 6: O_2 recharge troubleshooting pressures and tank temperatures (step up method). *SOV pressure PT-215, shown in purple, did not initially increase with the 3,000 psi supply pressure, red. When supply pressure was set at 500 psi, SOV pressure began to increase. Supply pressure was then stepped up in 250 psi increments, which allowed SOV pressure to reach the full supply pressure of 3,000 psi. SOV temperature, in green, began to increase once the SOV began to charge effectively. It was then allowed to stabilize after completion of the fill.*

D. Thermal Loop FSA Fill

The xPLSS FSAs, which contain the cooling loop water, were filled via the FPUIRD seen in Figure 7. The FPUIRD mirrors the ISS Airlock fluid pumping unit to fill the FSAs. The iodinated water was stored in the stainless steel Millipore can on a scale that allowed the test team to measure water usage in and out of the system. The water was pumped out of the Millipore can by the FPUIRD and flowed through the chamber penetration. From the chamber penetration, the water flowed through the ESCU into the FSAs. The FPUIRD had three integrated pressure transducers, as shown in the schematic in Figure 8, which continuously measured the pressure in the fill water line to prevent FSA over-pressurization. The FPUIRD controlled the fill rate depending on the measured fill pressure. Feedwater was supplied at a rate of 50 pounds per hour (pph) until the pressure reached 0.75 psi below the set fill pressure, as measured at the FPUIRD, at which point the flow rate was decreased to 5 pph. The flow rate reduction was designed to decrease the pressure drop through the ESCU fill water line to ensure the water pressure reaching the suit was as close as possible to the water pressure supplied and measured at the FPUIRD.

For TVAC testing, the maximum fill pressure was set at 2 psig, which was less than the nominal FSA fill pressure of 5 psig. The test team reduced the maximum pressure to avoid over-pressurizing the FSAs, as the ambient pressure was reduced to ~0 psia and suit internal pressure to 4.3 psia in the vacuum chamber. Given the FSAs were stored in the pressurized xEMU hatch volume, FSA external pressure matched the suit internal pressure and would drop from 14.7 psia atmospheric pressure to 4.3 psia during depressurization. Thus, the differential pressure in the FSAs could be expected to increase by this difference of 10.4 psi during depressurization. The FSAs used during TVAC had a maximum operating pressure of 15 psid, and an initial fill pressure of 5 psig could result in a final FSA pressure of 15.4 psid. Hence, fill pressure was reduced to 2 psig to ensure the 15 psid limit would not be exceeded.

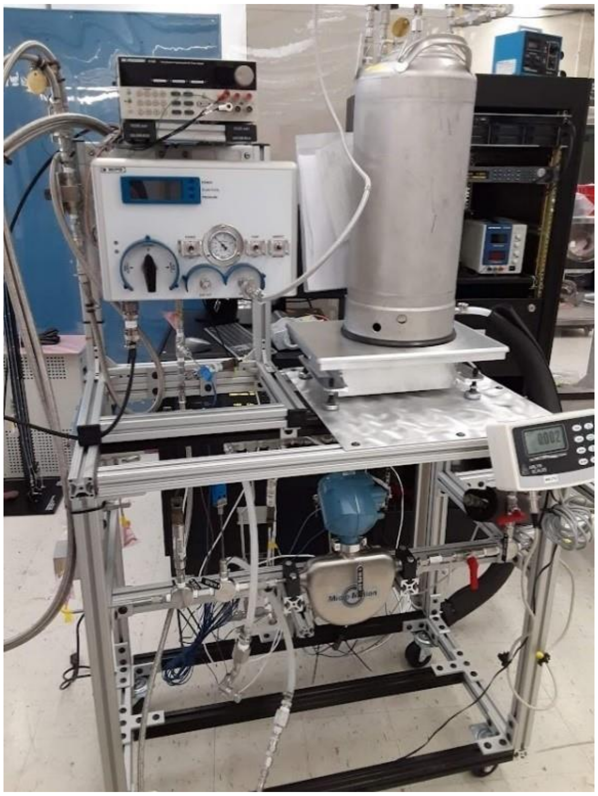

Figure 7. Fluid pumping unit interfaces requirements demonstrator (FPUIRD). *The FPUIRD was mounted on the Vehicle Interface Cart for TVAC, which provided and monitored the water and gas consumables used by the xPLSS.*

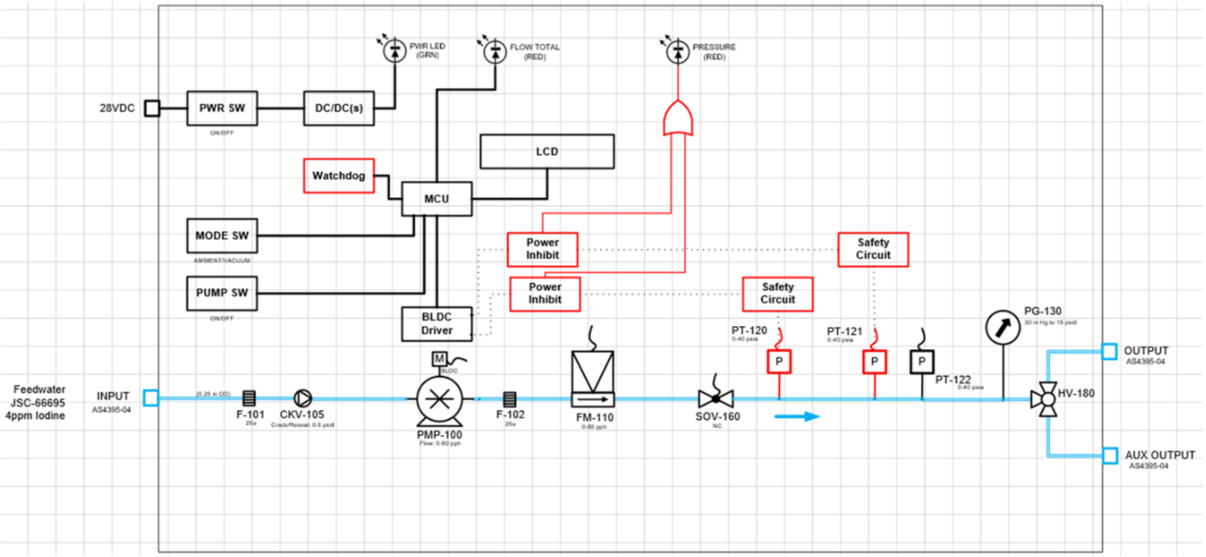

Figure 8. FPUIRD pneumo-hydraulic schematic. *The FPUIRD includes a pump, flow meter, and redundant pressure sensors to control water fill rate and cutoff pressure.*

Plots of the FSA pressures during water fill prior to EVA 3 are shown below in Figure 9 and Figure 10. Supply pressure is shown by VI-PT-401 (blue line) in Figure 9, which reads slightly higher than the FPUIRD fill pressure due to its location about a foot below the FPUIRD on the VI cart. The xPLSS pressures and xEMU internal instrumentation package pressures read slightly lower than the fill pressure, due to line losses and elevation differences of the sensors. The PT-532 auxiliary pump inlet pressure reads lowest due to its position at the top of the xPLSS. This pressure only outputs a reading when the auxiliary loop is powered on, in Monitor or On modes, as demonstrated in Figure 10.

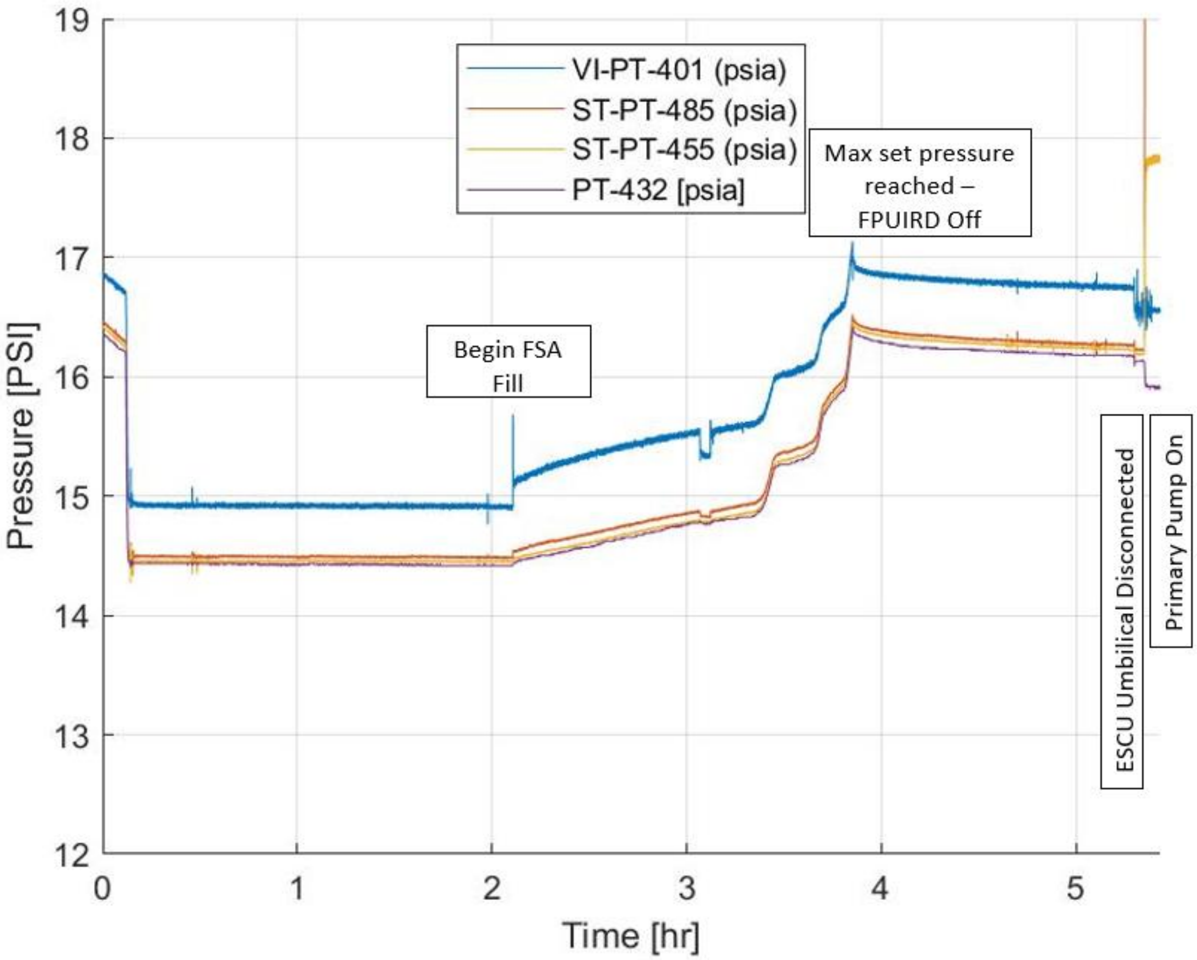

Figure 9. IVA 3 Primary thermal loop water recharge pressures. *Supply pressure VI-PT-401 increased to just above 17 psia during FSA fill before the FPUIRD shut off. The xPLSS and SxEMU internal pressures peaked at about a half a psi lower, due to line losses and elevation differences. When the xPLSS pump is turned on, the SxEMU internal test loop pressures (ST-PT-485 and ST-PT-455) increase due to flow, while the PT-432, which is located inside the PLSS at the inlet to the pump, decreases due to pump suction.*

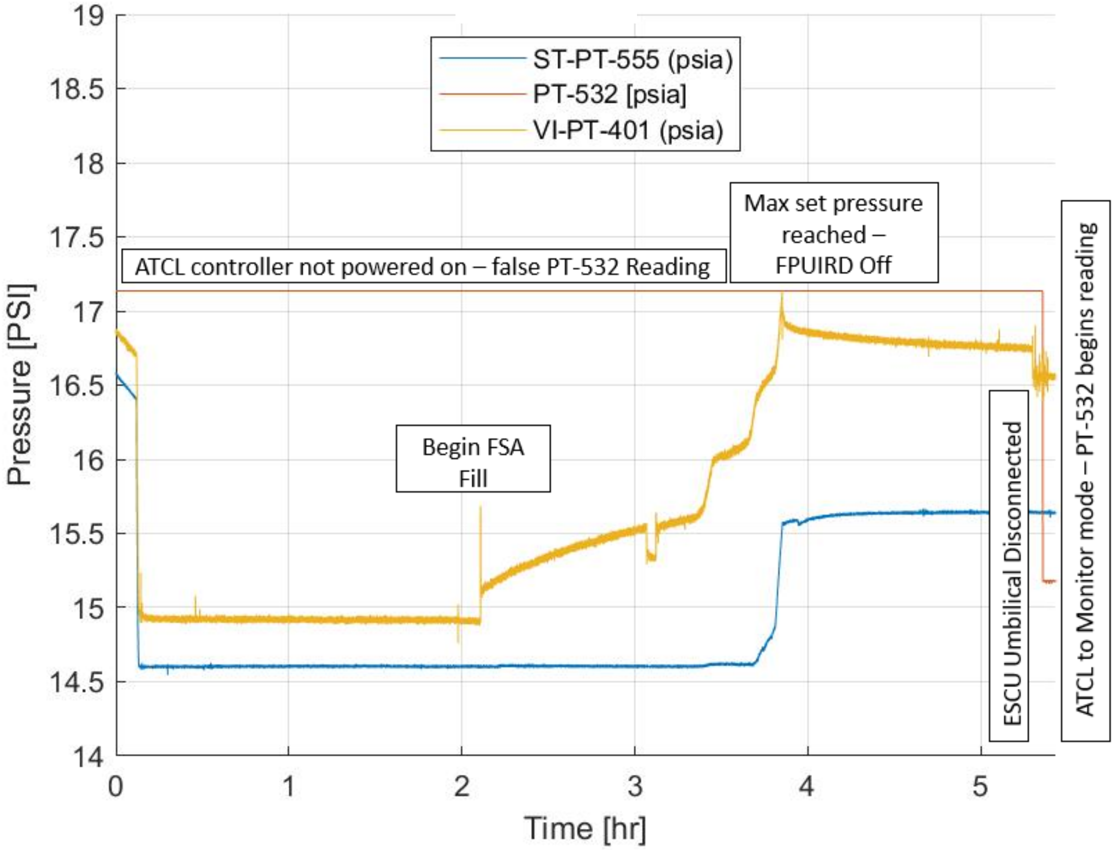

Figure 10. IVA 3 Auxiliary thermal loop water recharge pressures. *While supply pressure VI-PT-401 increased to just above 17 psia during FSA fill, SxEMU internal ATCL test system pressure ST-PT-555 peaked at about 15.6 psia, due to line losses, check valves inside the ATCL, and elevation differences. The xPLSS auxiliary pump inlet pressure did not begin to read accurately until the ATCL was powered on to Monitor mode.*

E. Test System Water Fill

In addition to the xPLSS consumables, the test system itself required consumables to be refilled. Prior to test EVAs, the water supply for the Human Metabolic Simulator (HMS) was refilled. The water was vaporized by the HMS Controlled Evaporator Mixer (CEM) and injected into the SxEMU suit volume along with CO_2 at a controlled rate to simulate the products exhaled by an astronaut during crewed operations. While the CO_2 was supplied to the HMS by hoses into the vacuum chamber, the liquid water was carried in two tanks along with the suit and test system into the chamber by the test stand and chamber rails. The positioning was chosen to minimize the tubing length between the water supply tanks and the HMS to prevent boiling or freezing of the liquid water in the lines during high- and low-temperature thermal testing. The water tanks, as well as the entire HMS test package, were insulated with multilayer insulation to minimize radiative heat transfer to and from the chamber.

III. Portable Life Support Subsystem Performance

A. xPLSS Functionality Testing Summary

1. *Rapid Cycle Amine CO_2 Removal*

The Rapid Cycle Amine (RCA) is a new technology for spacesuits that aims to make CO_2 removal no longer dependent on a consumable. The current EMU suits use a Metal Oxide canister that can last the duration of an 8-hour EVA and then needs to be baked out in an oven on-board the ISS before further use. The RCA design uses two beds and space vacuum to continually refresh the CO_2 removal capability. Trapped CO_2 is removed via off-gassing the inactive bed to the vacuum of space, and once the active bed is saturated with CO_2 and water vapor, the two beds switch and the freshly off-gassed bed enters the vent loop stream while the saturated bed begins its desorption to space.[2] During the thermal vacuum test, the partial pressure of CO_2 ($ppCO_2$) inside the suit began to rise, indicating a potential anomaly. This occurred when the HMS CO_2 injection rate was set higher than a 1,200 BTU/hr simulated metabolic rate. The RCA should be able to keep the $ppCO_2$ at a level of 3 mmHg up to 2,000 BTU/hr, based on requirements and previous tests. However, the unit performed below these levels and further investigation is necessary to determine the causal factors.

2. *Thermal Loop Temperature Control*

During simulated EVAs, a series of heat exchangers fixed with heater pads were used to heat up the cooling loop water in the Primary Thermal Control Loop (PTCL) and Auxiliary Thermal Control Loop (ATCL). The heat was injected into the water loops by the test system to simulate the crew member's body heat under different simulated metabolic loads (Met Rates). The PTCL and ATCL, while conceptually similar, are separate cooling loops with independent controllers, pumps, and evaporator setups. The PTCL has a Spacesuit Water Membrane Evaporator (SWME) and the ATCL has a Mini Membrane Evaporator (Mini-ME). Functionally, the evaporators are identical; however, as Figure 11 shows, the SWME features three evaporative cartridges, while the Mini-ME uses only one. The design of the cartridges allows for liquid water to flow throw the hollow fiber membrane bundles while, orthogonally, water is vaporized by exposure to vacuum. The resulting phase change rejects heat from the water loop and maintains appropriate temperatures within the spacesuit system.[3] The SWME and Mini-ME both performed as anticipated, and in fact, the SWME kept the cooling water within thermal limits at a higher Met Rate than its design specification.[4] The PTCL was tested from 0 to 900 W and the ATCL from 0 to 300 W heat loading. The PTCL and ATCL both demonstrated their capability to maintain water temperature control through their full range of test points. The SWME was able to maintain an outlet temperature of 50°F (±2°F) throughout the full range of heat loads as seen in Figure 12.

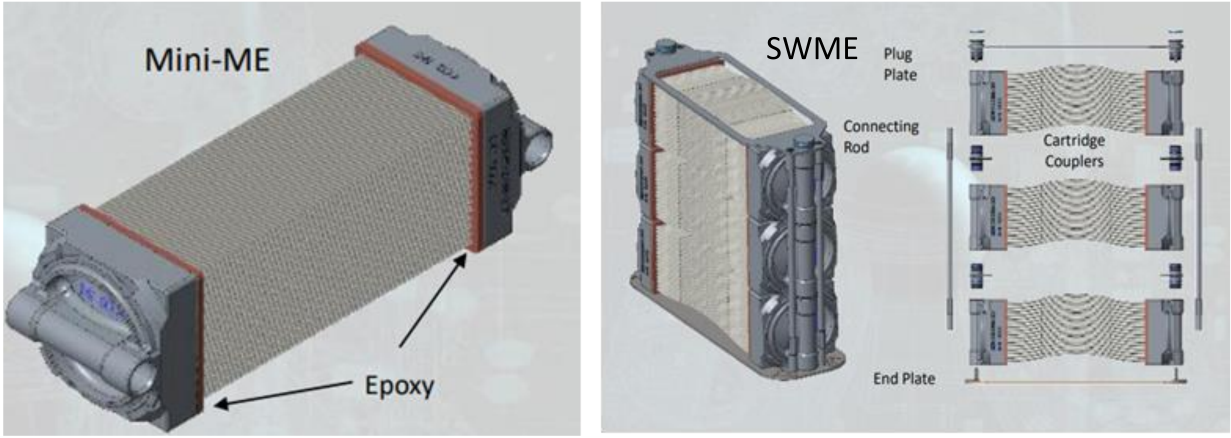

Figure 11. SWME and Mini-ME internal membrane models. *The SWME and Mini-ME consist of cartridges of hollow fiber membrane bundles.*

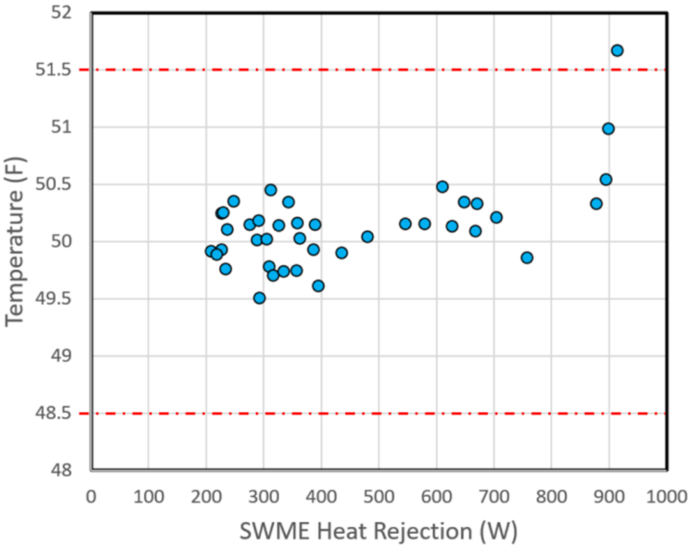

Figure 12. SWME heat rejection versus outlet water temperature. *The SWME was able to maintain the outlet temperature withing the required band at all but the highest input heat.*

3. Pressure, Temperature, and CO_2 Concentration Monitoring

The xPLSS, in addition to providing life support and communication functions, must also monitor these functions through metrics such as suit pressure, POV/SOV pressure, thermal loop pressures, a wide variety of temperatures, and internal CO_2 monitoring. The SxEMU test system allowed for comparison of many of these xPLSS instrumentation readings to test instrument readings to validate their accuracy. During each depressurization and EVA, all the functionalities worked seamlessly, apart from the POV pressure transducer (PT-112) readings during airlock depress and early stages of the EVAs. The test team constantly monitored the data through the xPLSS telemetry and test system data acquisition system at the control station. Although xPLSS instrument readings had been independently validated at the subsystem level during xPLSS pre-integration acceptance (PIA) testing at vacuum and ambient conditions, the TVAC testing was the first check of these functions in thermal vacuum conditions, while connected to a Pressure Garment System suit.

As evidenced by the variable sawtooth graph in Figure 13, the CO_2 sensor continuously collected data throughout the EVA and captured the different CO_2 injection rates and RCA swing rates. This is especially impressive as the type of sensor used in the xPLSS utilizes Non-Dispersive Infrared technology in its sensor head, which is not intrinsically pressure compensated. Thus, the xPLSS itself must perform the pressure compensation calculation in order to determine the actual ($ppCO_2$) in mmHg given the actual suit pressure.

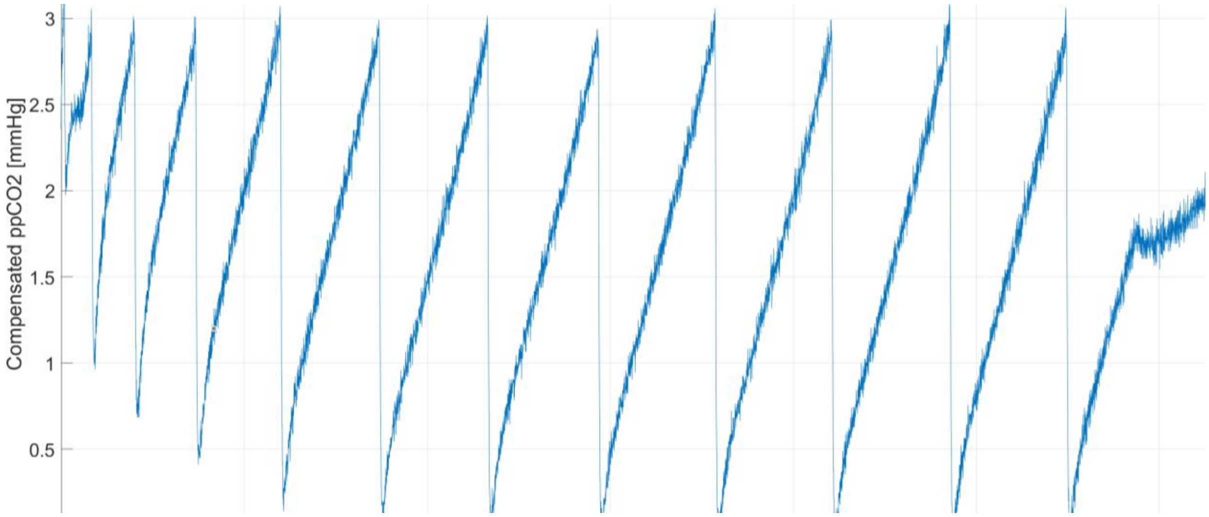

Figure 13. ppCO2 over time during EVA. *The CO_2 sensor was able to continually monitor CO_2 percentage during the course of the approximately 8-hour EVA, at different CO_2 injection and RCA swing rates, as indicated by the variations in the saw tooth pattern of the plot.*

The PT-112 POV pressure transducer displayed inconsistent and unexpected behavior during airlock depressurization prior to each EVA. The PT-112 indicated pressure had failed to reach the full nominal 3,000 psia charge pressure during fill operations, as described above in Section II C while in the airlock with an ambient pressure of 14.7 psi. However, as the airlock was depressurized and approached full chamber vacuum, the indicated PT-112 pressure increased. This is believed to be due to an error with the PT-112, which has a sealed vacuum reference and should not be affected by surrounding air pressure conditions. PT-112 appeared to perform as expected after depressurization. Figure 14 shows a plot of PT-112 performance during a representative EVA, including the unexplained pressure increase during airlock depress and nominal steady decrease during the EVA. As shown in Figure 14, the indicated pressure increase did not correlate to increasing POV temperature.

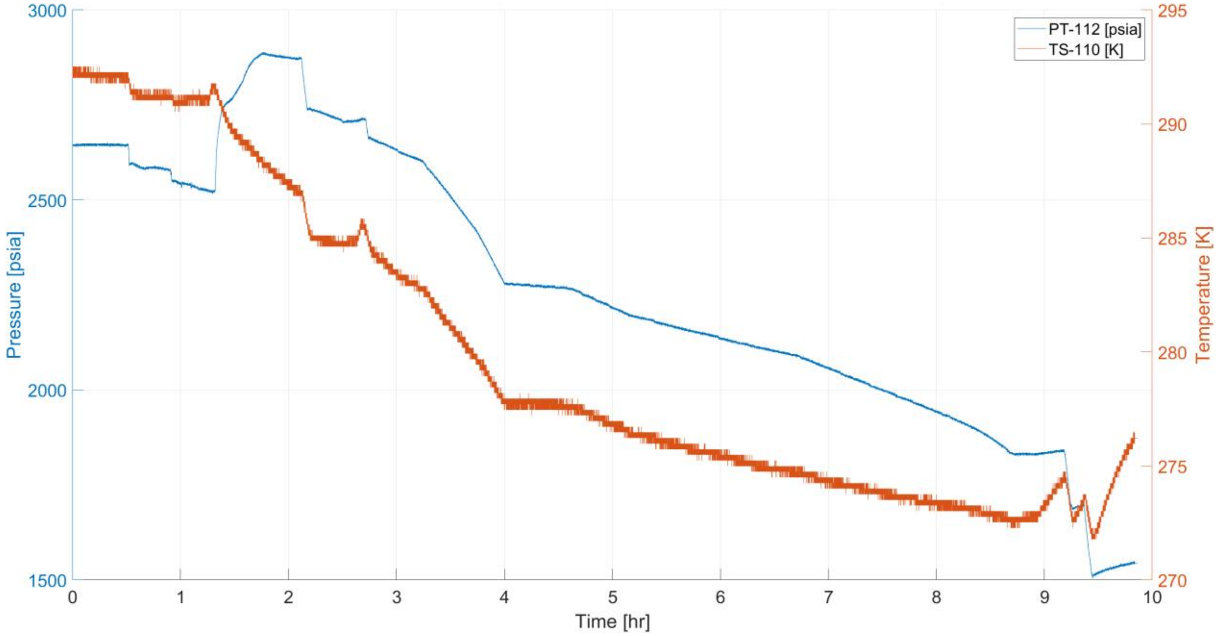

Figure 14. POV pressure and temperature during EVA 1. *The indicated POV pressure (PT-112, blue) increased during the final stages of airlock depress after the high-pressure supply had been disconnected. This was not caused by a rise in temperature (TS-110, red). POV pressure decreased as expected during the course of the EVA, once the SxEMU had left the airlock and entered the main vacuum chamber.*

B. Secondary Oxygen Regulator Takeover

An additional TVAC test objective was to demonstrate the xPLSS's backup capabilities that afford the system additional layers of fault tolerance and make EVAs safer for the crew. One of the important xPLSS backup functions that was tested was the SOR takeover. Once the pressure from the Primary Oxygen Regulator (POR) dips below 3.6 psia, the SOR should start flowing and keep the suit pressure stable at 3.6 psia to give the astronaut time to abort the EVA and make their way towards the airlock and doff the suit safely. The SOR takeover is performed automatically through mechanical means and does not require a physical input from the crew member, provided the SOR was enabled at the start of the EVA. During the test, the SOR takeover worked as anticipated. As seen in Figure 15, the suit pressure, shown on the right axis, dropped from 4.3 psia to 3.6 psia and held there as the pressure in the secondary tank (left axis) started to decline after the POV was depleted. After a short period of holding the suit pressure using the secondary regulator the suit was then brought back into the crew-lock where it was repressurized back to ambient.

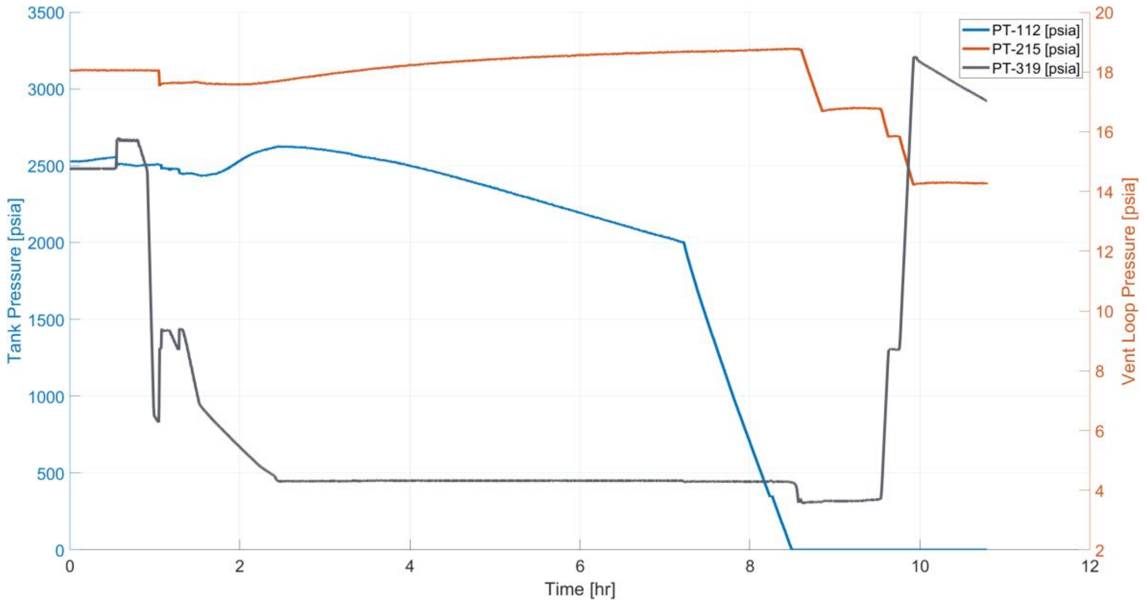

Figure 15. POR-SOR takeover demonstration. *As the POV pressure (in blue, left axis) is depleted to near-zero the SOR takes over suit pressure control, as indicated by the decrease in suit pressure (gray) from 4.3 psi to the 3.6 psi SOR setpoint and the corresponding decrease in SOV pressure (orange).*

C. POA and SOA Low Setpoint Change Inhibit

Another major safety function of the xEMU is known as the Low Setpoint Change Inhibit. The purpose of this feature is to prohibit the crewmember from inadvertently setting the suit pressure below a safe operating pressure while in a vacuum environment. Specifically, the POA controller induces a lower set limit of 4.3 psid for the POR and the SOA controller prohibits the "OFF" position on the SOR when the surrounding pressure, as measured by built-in controller pressure transducers, is less than 4 psia. Thus, the pressure requirements required this functionality to be verified at vacuum as done in the TVAC test. The Low Setpoint Change Inhibit was demonstrated during the Thermal Vacuum test to work as expected. To test the functionality, the POR pressure setpoint was set to 0.9 psid and then 0.0 psid (OFF position). As expected, the xPLSS telemetry showed the POR position neither changed, nor did suit pressure begin to reduce from 4.3 psia during the second test EVA. The xPLSS telemetry also showed a Low Setpoint Change Inhibit fault, indicating that the xPLSS recognized anomalous behavior. The same test was performed with the SOR by setting the SOR switch to OFF on the DCU Simulator. Again, as desired, the SOR position did not move to closed/off, and xPLSS telemetry displayed a corresponding fault.

Although the Low Setpoint Change Inhibit functioned as expected, for both the POR and SOR, anomalies were encountered with regards to the fault messages. The xPLSS fault indications did not clear after the POR and SOR switches were returned to the appropriate positions of 4.3 psid setpoint and 3.6 psid setpoint, respectively. The faults eventually cleared once the EVA was completed and the xPLSS was power cycled. However, the POR and SOR switches could be set to lower pressures or to OFF once the Inhibit State was cleared following completion of the EVA and repressurization of the airlock pressure to above 4 psia, even with the faults still indicated. Evidence points to this anomaly being correctable with POA and SOA controller software updates.

IV. Conclusion

The success of the SxEMU testing is a monumental accomplishment for the xEMU team and NASA as an organization. The thermal vacuum test demonstrated the xEMU's ability to perform in the most extreme environments the ISS and Moon have to offer. The SxEMU test setup and equipment played an equally important role in the test itself. It allowed the suit to be recharged to perform five separate test EVAs, one more than originally scheduled. The test equipment also allowed the test team to monitor real time telemetry of the xEMU and record that data for future use and verify xPLSS sensor data against independent test instruments. Dozens of gigabytes of sensor telemetry were collected during this test and will be used to analyze and help further future spacesuit projects for many years to come. While not every part of the xEMU worked perfectly, data recorded for every sensor will assist in determining root causes of any discrepant data or off-nominal performance to allow for continuous hardware improvement. Even with these sub-par aspects, the overall test is seen as a massive success and will live on as being the highest fidelity uncrewed spacesuit test in American spaceflight history.

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