Exploration Extravehicular Mobility Unit (xEMU) 11 Foot Vacuum Chamber Upgrades Test Results

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The Exploration Extravehicular Mobility Unit (xEMU) uncrewed 11 foot vacuum chamber testing evaluated the capabilities of the 11 foot vacuum chamber facility to support advanced spacesuit testing. The government reference design xEMU spacesuit provided a high-fidelity test article to demonstrate 11 foot vacuum chamber capabilities which included: gas loading of the chamber at varying simulated metabolic rates and open loop suit abort operations, Intravehicular Activity (IVA) vacuum access, consumables recharge, IVA vehicle-provided thermal loop cooling, and IVA vehicle-provided power. To demonstrate the xEMU airlock operations transitioning from IVA to EVA conditions without a test subject in the suit, test support equipment was developed to remotely actuate both the Exploration, Servicing, and Cooling Umbilical (ESCU) and the vacuum access umbilical. This test also evaluated the performance of the Exploration Portable Life Support System (xPLSS) at vacuum conditions. Data was collected and analyzed for carbon dioxide (CO2) scrubbing performance of the Rapid Cycle Amine (RCA) swingbed, for thermal regulation performance of the Suit Water Membrane Evaporator (SWME), and for sensor performance across the xPLSS. This paper will detail the findings of the testing performed with these upgrades which discussed previously laid out in ICES-2025-342.

Acronyms and Nomenclature

ACFM	=	Actual Cubic Feet per Minute
ATCL	=	Auxiliary Thermal Control Loop
BPV	=	Back Pressure Valve
CEM	=	Controlled Evaporator Mixer
CO_2	=	Carbon Dioxide
DAQ	=	Data Acquisition
DCU	=	Display and Control Unit
EMU	=	Extravehicular Mobility Unit
ESCU	=	Exploration, Servicing, and Cooling Umbilical
EVA	=	Extravehicular Activity
FSA	=	Feedwater Supply Assembly
GN2	=	Gaseous Nitrogen
H_2O	=	Dihydrogen Monoxide (water)
HITL	=	Human-in-the-Loop
HMS	=	Human Metabolic Simulator
ISS	=	International Space Station
IVA	=	Intravehicular Activity

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JSC	=	Johnson Space Center
lbm	=	Pound mass
MON	=	Monitor
O_2	=	Oxygen
OVL	=	Oxygen Ventilation Loop
POV	=	Primary Oxygen Vessel
pph	=	pound per hour
psig	=	Pounds per square inch – gauge pressure
PTCL	=	Primary Thermal Control Loop
RCA	=	Rapid Cycle Amine
SLPM	=	Standard Litres per Minute
SOV	=	Secondary Oxygen Vessel
SWME	=	Suit Water Membrane Evaporator
SxEMU	=	Short Exploration Extravehicular Mobility Unit
TBD	=	To Be Determined
UHF	=	Ultra High Frequency
UIA	=	Umbilical Interface Assembly
xEMU	=	Exploration Extravehicular Mobility Unit
xEVAS	=	Exploration Extravehicular Activity Services
xPLSS	=	Exploration Portable Life Support System

I. Introduction

The development of spacesuits has evolved significantly since the early days of human space flight/exploration, driven by advancements in materials, technology and mission requirements. Early spacesuits, such as those used during the Apollo program, were groundbreaking for their time, enabling astronauts to perform extravehicular activities (EVAs) on the Moon's surface. However, as space exploration expands beyond low earth orbit to destinations like the moon, Mars, and deep space, new spacesuit designs are required to provide greater mobility, durability, and functionality. These next-generation suits, such as those being developed by commercial partners in NASA's Exploration Extravehicular Activity Services (xEVAS) program, must withstand extreme environments while supporting the diverse needs of manned missions, from operating in microgravity aboard spacecraft to exploring planetary surfaces with complex terrains and varying atmospheric conditions.

To ensure the safety and effectiveness of these advanced spacesuits, NASA's Johnson Space Center (JSC) is leveraging its Apollo-era manned vacuum chambers, which are being upgraded to meet the rigorous testing demands of modern missions. These chambers, originally designed to simulate the vacuum of space for Apollo spacesuit and equipment testing, and since used extensively for Space Shuttle and International Space Station (ISS) Extravehicular Mobility Unit (EMU) testing, must now accommodate cutting-edge technologies and more extensive testing protocols. By updating these facilities, NASA can test the new spacesuits under both manned and unmanned conditions, replicating the harsh environments of low earth orbit, the lunar surface, and beyond. This critical step ensures that the suits will perform reliably in the challenging conditions of future exploration, paving the way for a new era of human spaceflight.

One of these vacuum chambers, the 11ft Chamber in JSC's Building 7, has long supported crewed, or human-in-the-loop (HITL) vacuum testing of both EVA and Intravehicular Activity (IVA) space suits and suit technologies. Although the 11ft Chamber includes support hardware for HITL Shuttle and ISS EMU testing, as shown in Figure 1, the next-generation xEVAS suits will have different facilities and hardware support needs to perform HITL suit checkouts (Acceptance testing, flight certification, etc.). Upgrades to the chamber test hardware were carried out by NASA JSC's Crew and Thermal Systems Division's Systems Test Branch (EC4) and Space Suit and Crew Survival Systems Branch (EC5) in order to make the 11ft Chamber compatible with expected xEVAS testing needs, and prevent potential damage or contamination from modifications to existing EMU test support hardware, which is still in use as the EMU is continued to be used on the ISS.

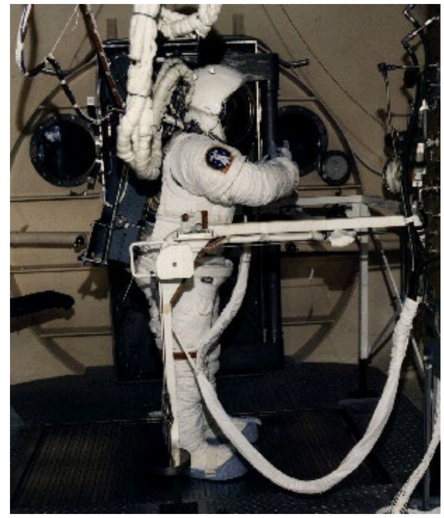


Figure 1: Manned EMU testing in NASA JSC's 11ft Vacuum Chamber

Prior to any crewed testing, the new facility upgrades were tested by performing a simulated HITL test in the 11ft Chamber using NASA's xEMU government reference design spacesuit as test support hardware. The xEMU is a high-fidelity analog of an xEVAS Spacesuit using many of the advanced technologies andTest hardware was installed to simulate the metabolic functions and some of the manual operations of a suited test subject.

II. Testing Objective

In order to support a full HITL spacesuit test run, the 11ft Chamber must be able to support a single crewed spacesuit starting with suit donning at atmospheric pressure, suit consumables (water (H_2O), oxygen, battery) recharge, pre-breathe, depressurization to vacuum with the suit connected to its servicing umbilical, simulated EVA with the umbilical's disconnected, chamber repress with umbilical reconnected, vehicle cooling, vehicle power, and finally suit doffing. Each of these functions are fully laid out in ICES-2025-342[3].

A. Extravehicular Activity Test Days

The purpose of the EVA test days was to stress the chamber vacuum system to characterize performance across a range of loads representing EVAs with a nominal metabolic profile, maximum-specification transient metabolic profile, single-purge valve operations, and dual purge valve operations. This sequence of test profiles represented an increasingly challenging gas and water vapor loading for the chamber's vacuum pumps. The suit was powered by the chamber's battery simulator supply to demonstrate that interface.

Additionally, on EVA days the IVA equipment was also tested. This enabled assessment of the capability of suit cooling via the umbilical, IVA vacuum access for CO_2 removal swing-beds, vehicle power, and procedural validity for running an IVA-EVA-IVA series of procedures as a HITL test would. The lowest priority of the altitude runs was to collect additional performance data on the Short Exploration Extravehicular Mobility Unit (SxEMU) test article, specifically the vacuum-dependent performance of the Rapid-Cycle Amine (RCA) and Suit Water Membrane Evaporator (SWME)[1,2].

B. Ambient Test Daysvehicular Activity Test Days

Due to the unmanned nature of the SxEMU test, several objectives required engineers to operate the suit and test hardware in the chamber in an ambient environment. On ambient test days the primary focus was demonstrating the following;

- Consumable recharge
- Serial telemetry output
- Ultra High Frequency (UHF) communication with control room
- UHF telemetry streaming
- Hardline communications
- Execution of a critical lift and installation of the SxEMU into upgraded facility donning stand interfaces

- Integration of Data Acquisition (DAQ) system with the EC4 facility
- Wi-Fi streaming of telemetry and video

These objectives are shown in Table 1. The level of fidelity for this test column represents the level of fidelity with respect to the manned xEVAS vendor HITL test. A grade of "high" indicates that the test replicated a manned test, "medium" indicates that the test realistically demonstrated interface for an Exploration Extravehicular Mobility Unit (xEMU) but may not perfectly mirror the To Be Determined (TBD) xEVAS vendor interfaces, and "low" indicates that the interface was verified, but not in a way that mirrors a manned test.

Objective	Fidelity
Verify Primary/Secondary Recharge to 3000 PSIA	Low
Verify Thermal Loop Cooling via ESCU	High
Verify Feedwater Recharge	Medium
Verify IVA Wastewater Drain/Sampling	High
Verify IVA Vacuum Access for Swing Beds	High
Verify 28 V Umbilical Power	High
Verify Serial Telemetry Output via ESCU	Medium
Verify Chamber Pressure and Quality with Gas and Water Loading	High
Demonstrate EVA Power with Primary and Secondary Power Simulators	Medium
Demonstrate UHF Telemetry Streaming	Medium
Demonstrate Wi-Fi Telemetry and Video Streaming	High
Demonstrate Hardline Communications with Control Room	Medium
Demonstrate Suit Provider DAQ Integration with EC4	Medium
Simulation Manned Chamber Depress/Repress Operations	High
Demonstrate Umbilical Cooling at Vacuum	High
Demonstrate Critical Lift/Installation to Facility Interfaces	Medium
Execute Fit Check of xEMU in Donning Stand	Medium
Execute Fit Check of xEMU in Chamber Weight Relief	Medium
Capture Additional SxEMU Performance Data	High

Table 1: 11 Foot upgrades Test Objectives

The sole low-fidelity was the verification of the Primary and Secondary tank recharge with the xEMU, as the xEMU is not rated for Oxygen (O_2). To remove flammability hazards, the xEMU is solely tested with nitrogen (GN_2). Testing with GN2 functionally demonstrates the chamber's high pressure O2 supply capability and associated instrumentation. Before a manned test, the High Pressure Gas Supply will be wetted with O2 as a final design and safety verification.

III. Test Day Overview/Anomalies

A. Test Day 1: Powered Functional

Test Day Goals:

i. Verify the functionality of all systems, integration and procedural flow minus vacuum chamber pump down
ii. Power on the SxEMU
iii. Verify Display Control Unit (DCU) simulator (outside the chamber and functional) switch positions
iv. Verify SxEMU DCU (attached to the suit and not functional) switch positions
v. Verify ESCU mating and demating and RCA vacuum access line actuator
vi. Vehicle cooling capability and SCU to BATT power transitions

Test Day Anomalies:

vii. None experienced

B. Test Day 2: EVA 1

Test Day Goals:

i. 11 Foot vacuum chamber depress with SxEMU
ii. Run a full 8hr SxEMU EVA with vacuum chamber at pressure
iii. RCA vacuum access actuator switching
iv. ESCU mating and demating actuator
v. 11 Foot vacuum chamber repress with SxEMU

Test Day Anomalies:

vi. RCA vacuum access line leaking. Prior to this valve opening, the IVA vaccum pressure was measured to be approximately 0.07 Torr. However, after that spike of the valve being opened, the pressure did not return down to the previous pressure levels; instead it stabilized around 0.6 Torr, which is roughly a factor of 8x the previous magnitude
vii. ESCU unsuccessful in mating to the DCU at the end of testing
viii. Vacuum appeared to be struggling more than a nominal depress of the chamber based on

previous runs. An inspection was carried out to determine if a leak was present. It was discovered that one of the chamber penetrations was improperly sealed which allowed ambient air leakage into the chamber at a significant rate.

With anomaly delays, an abbreviated test day was performed with 350, 683, 1025, 1332 and 1598 BTU/hr met rates

C. Test Day 3: Recharge

Test Day Goals:

i. Recharge consumables

ii. Fix all anomalies and update procedures as necessary

1. Vacuum chamber leaking was due to an improper sized B-nut. This was replaced and a flare saver added
2. ESCU was unable to mate with high-pressure O_2 poppets. Procedure change to depress lines prior to mating
3. RCA Vacuum access line fittings were replaced with barbed fittings

Test Day Anomalies:

iii. None

D. Test Day 4: EVA 2

Test Day Goals:

i. IVA testing at 400 BTU/hr with active vehicle cooling

ii. 11 Foot vacuum chamber depress with SxEMU

iii. Run a full 8hr maximum transient metabolic rate profile SxEMU EVA with vacuum chamber at pressure. Modified CO2 injection to account for the lack of water injection.

iv. RCA vacuum access actuator switching

v. ESCU mating and demating actuator

vi. Feedwater Supply Assembly (FSA) depletion and check valve cracking testing

vii. 11 Foot vacuum chamber repress with SxEMU

Test Day Anomalies:

viii. SWME (HX-440) back pressure valve (BPV) linear potentiometer went out of sync during valve position changes in the closing direction. No constraint to testing.

ix. Human Metabolic Simulator (HMS) controlled evaporator mixer (CEM) temperature probes, which measure the temperature of the humidity injection which was not used, read off-scale high. No constraint to testing.

E. Test Day 5: Recharge 2

Test Day Goals:

i. Recharge consumables

ii. Bypass RCA solenoid valves to pump directly to the IVA vacuum pumps

Test Day Anomalies:

iii. None

F. Test Day 6: EVA 3 and Recharge 3

Test Day Goals:

i. IVA testing at 400 and 600 BTU/hr with active vehicle cooling

ii. IVA Heat injection testing at 205W

iii. 11 Foot vacuum chamber depress with SxEMU

iv. Load the vacuum chamber to the maximum extent that the suit could reasonably do under conventional operations. Max CO2, Heat injection and both purge valves opened.

v. RCA vacuum access actuator switching

vi. ESCU mating and demating actuator

vii. FSA depletion and check valve cracking testing

viii. 11 Foot vacuum chamber repress with SxEMU

Test Day Anomalies:

ix. None

G. Test Day 7: IVA Vacuum Access Leak Detection

Test Day Goals:

i. Identify RCA vacuum access line leakage. Source determined to be possible O-ring crushed in the VAC_1003 to VAC_1004 connection as seen in Figure 2

Test Day Anomalies:

ii. None

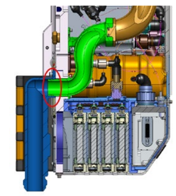


Figure 2: VAC_1003 to VAC_1004

H. Test Day 8 and 9: Communications, WI-FI, and Radio

Test Day Goals:

i. Verify communications, signal interfaces, and connectivity through EMU radio and the in-suit microphones

Test Day Anomalies:

ii. EV-701 communication through EMU radio unsuccessful

iii. Suit hardline testing no audio detected

iv. The required Linux laptop and software to access streamed telemetry and video from the suit over Wi-Fi was not present

I. Test Day 10: IVA Vacuum Access Testing and Water Drain and Fill

Test Day Goals:

i. Verify communications, signal interfaces, and connectivity through EMU radio and the in-suit microphones. Focused on hardline communications

ii. Fill and drain SxEMU water bladders using facility water drain port, recharge and degas

Test Day Anomalies:

iii. Facility side hardline audio connection to the chamber intercom system and that the SxEMU test article was the issue.

J. Test Day 11: IVA Vacuum Access Testing Re-Test

Test Day Goals:

i. Load various profiles on the IVA vacuum pumps using various Ballast Modes on the vacuum pumps

Test Day Anomalies:

ii. None

IV. Detailed Testing/Anomalies

A. EVA Vacuum Loading

The EVA vacuum system was challenged over a total of 3 EVAS. Due to the in leakage of ambient air seen on the first test day, EVA 1 was the largest loading on the vacuum system while EVA's 2 and 3 were nominal. The expected gas loading of a next-generation spacesuit is calculated by summing contributions from four pathways: RCA bed cycling, SWME water evaporation, suit leakage and purge valve flow (when activated). The RCA releases CO_2 and H_2O through desorption, water vapor is released by the SWME through evaporative cooling, suit leakage is conservatively assumed at the maximum allowable oxygen leak rate, and purge valves provide additional oxygen flow during contingency operations. Test Setups used simulators and mass flow controllers to replicate purge conditions, and gas loadings were computed across metabolic rates under standard temperature and pressure assumptions, with valves averaged per minute from hourly calculations while excluding environmental heat effects. Table 2 shows the xEMU Gas Loading, which used 0.5 Torr and 20°C to calculate mass flow from volumetric flow.

Metabolic Rate [BTU/hr]	CO_2 Loading [g/min]	CO_2 Loading [m^3/min]	Water Vapor Loading [g/min]	Water Vapor Loading [m^3/min]	O_2 Loading [g/min]	O_2 Loading [m^3/min]	Net Loading [m^3/min]	Net Loading [m^3/hr]
1200	1.820	1.512	8.023	16.297	0.415	0.475	18.284	1097.050
3000	4.550	3.781	17.973	36.507	1.052	1.202	41.489	2489.366
1200 w/ purge	1.820	1.512	8.023	16.297	13.267	15.159	32.969	1978.114
3000 w/ purge	4.550	3.781	17.973	36.507	13.904	15.886	56.174	3370.430

Table 2: VAC_1003 to VAC_1004

Post-test, the gas loading of the SxEMU into the chamber was directly calculated from the captured data. Each loading pathway was instantaneously calculated at the 2 Hz data acquisition rate, with the exception of the RCA which cyclically desorbs cardon dioxide (CO_2) and H_2O. SWME gas loading is equal to the mass needed to evaporate to achieve cooling across the SWME, and the equation used: $\dot{m}_{\boldsymbol{evap}} = \frac{\dot{m}_{\boldsymbol{flow}} * \boldsymbol{c_p} * \boldsymbol{\Delta T}}{\boldsymbol{h_v}}$

$\dot{m}_{\boldsymbol{evap}}$ is the mass flow of evaporated water (kg/s)
$\dot{m}_{\boldsymbol{flow}}$ is the bulk mass flow of water through the SWME (kg/s)
$\boldsymbol{c_p}$ is the specific heat of water, 4.184 kJ/kg-K at 10°C
$\boldsymbol{\Delta T}$ is temperature difference across the SWME (K)
$\boldsymbol{h_v}$ is the heat of vaporization of water, 2260 J/g at 10°C

The leakage rate for a given day was tested and documented in the procedures and used in calculating the transient gas load. The purge flow loading was measured at the mass flow controller. To accurately calculate the RCA gas loading of the adsorbed amount of CO_2, which corresponds to the removal rate of CO_2 across the RCA and half-cycle time for the previous cycle, was first calculated. Then the removed CO_2 was fit to the half cycle time and an average desorption load was applied for the half-cycle. It should be noted that this method is most accurate when the RCA is in cyclic steady state and is less accurate when the RCA is undergoing a transient step in metabolic load. Finally, during EVA 1 there was significant in-leakage to the chamber, which was quantified post-EVA 1 at ~62 g/min of ambient air, by doing a leak check. Once a mass flow rate of each constituent gas was calculated (CO_2, water vapor, N_2, and air), the volumetric gas loading at chamber pressure and temperature was calculated. The transient loading for each EVA is shown below in Figure 3, plotted along with chamber pressure.

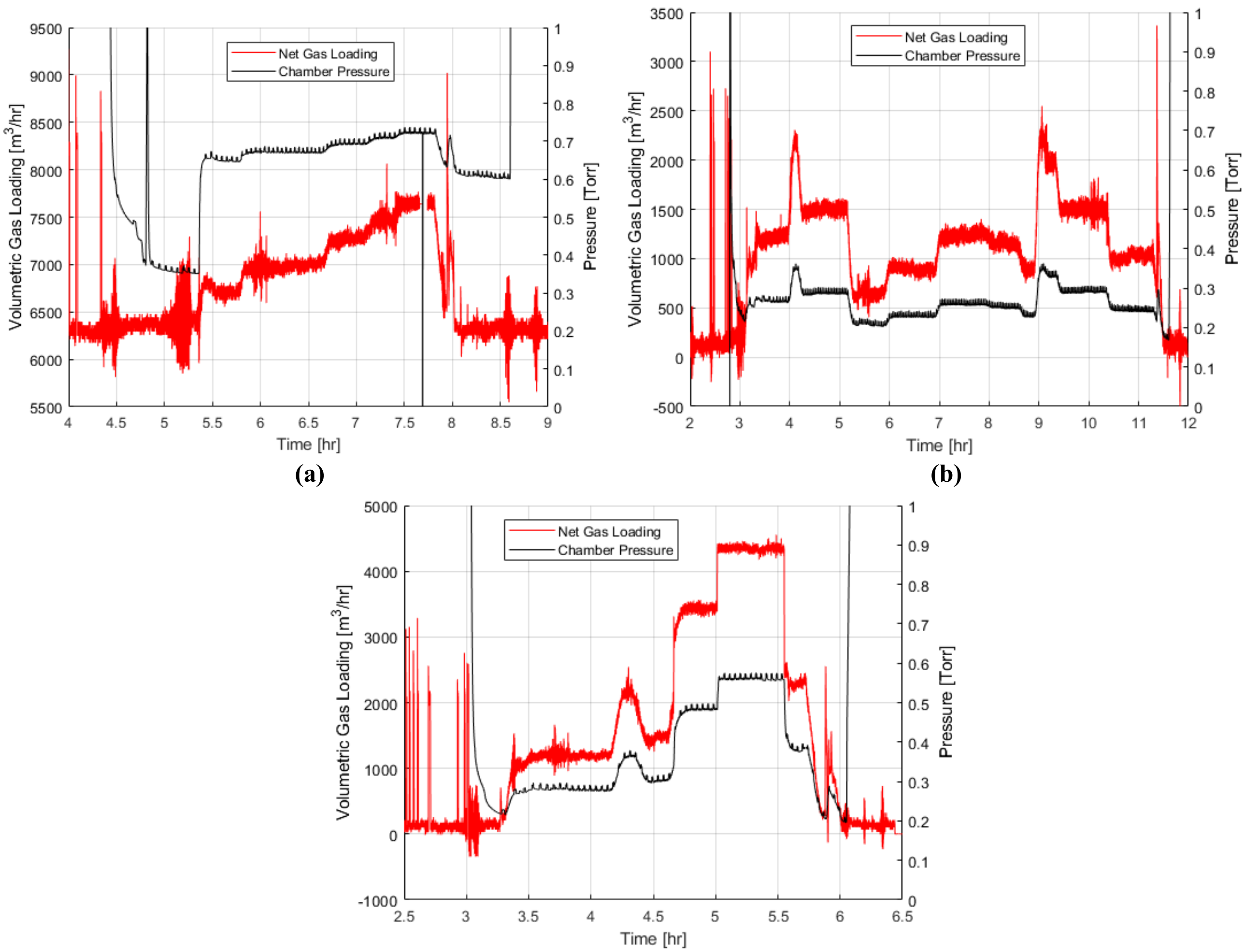
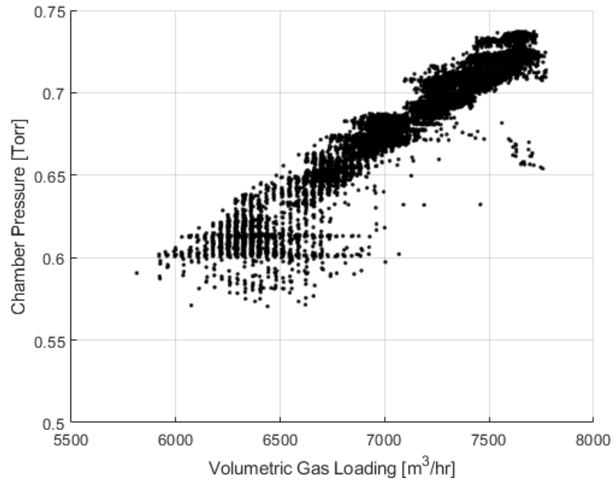
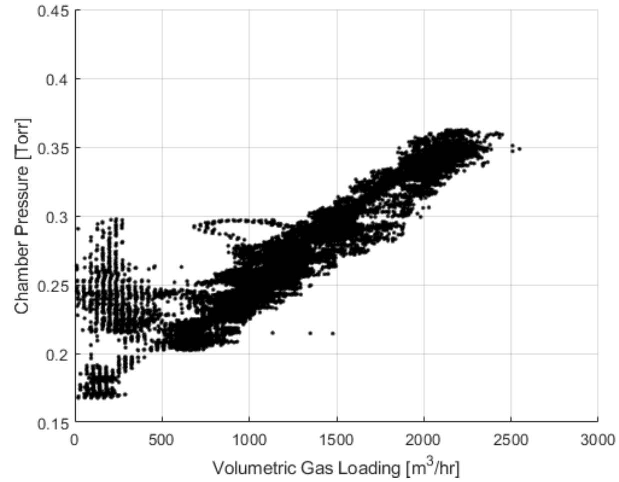


Figure 3: Volumetric Gas Loading and Chamber Pressure for EVA 1 (a), EVA 2 (b), EVA 3 (c)

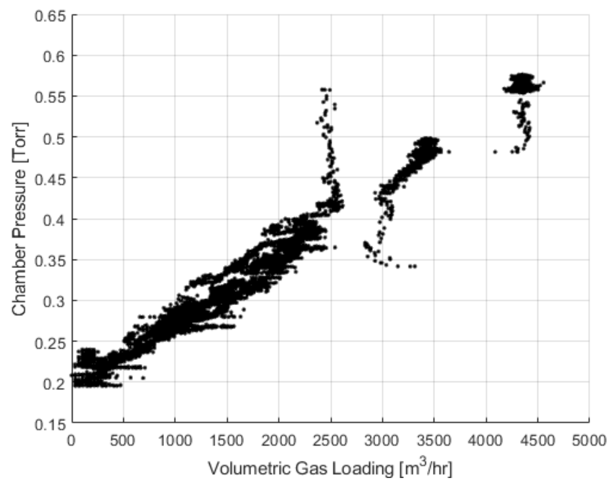
The following figure, Figure 4, plot chamber pressure as a function of the volumetric gas loading during EVA testing. These are instantaneous data points calculated (with the exception of the RCA) which led to noticeable noise in the data.



(a)



(b)



(c)

Figure 4: Chamber Pressure vs Gas loading for EVA 1 (a), EVA 2 (b), EVA 3 (c)

Figure 5 contains all of the data from Figure 4a, 4b and 4c, as well as vertical lines which represent the xEMU gas loadings under the four different operating cases. It should be noted that there is a significant vertical trend in the EVA 3 data, which is due to some data from the repress and depress being included into the post-processed data. For a next-generation spacesuit to operate nominally, two components must have suitable vacuum access, the SWME and the RCA. For maximizing the desorption of the RCA and the effectiveness of the SWME, the vacuum levels should be as low as possible. Previous testing of the xEMU shows acceptable CO2 desorption levels when exposed to vacuum of less than a Torr, however this does inhibit verifying the full range of metabolic loads as the maximum half-cycle time which the RCA can support decreases as vacuum pressure increases. For an xEMU the vacuum pressure observed during the EVA portion of this test would be sufficient, but providers of new systems should be aware of their predicted hardware performance under the now-known 11-ft vacuum environment or communicate as early as possible that changes need to be made to successfully execute a manned test in the chamber.

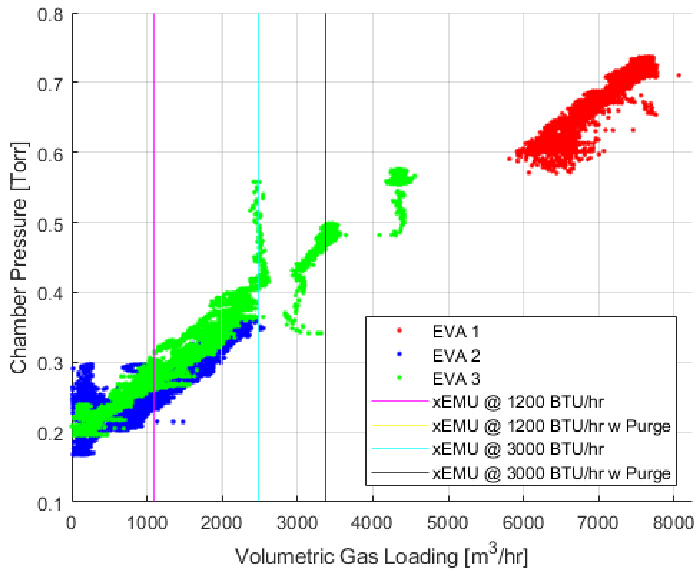


Figure 5: Comparison of xEMU Loading with Tested Loadings

B. IVA Cooling

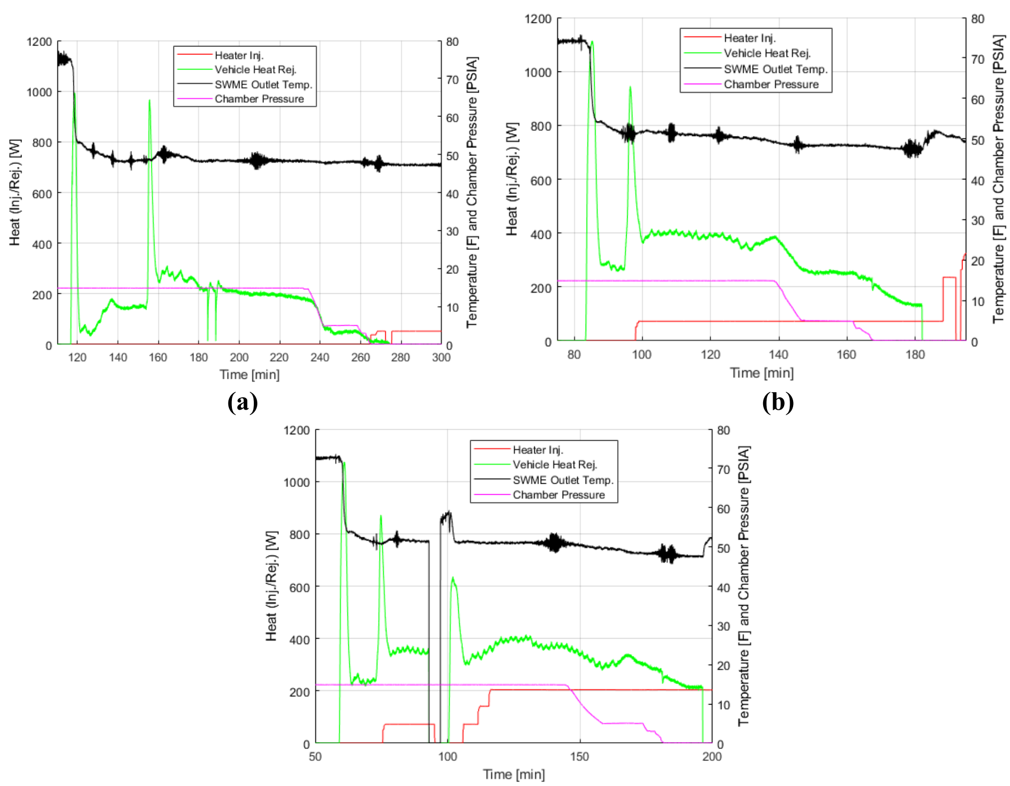


Figure 6: (a) IVA Cooling Day 1, (b) IVA Cooling Day 2 and (c) IVA cooling Day 3

While the crewmember is in the airlock prior to going out for their EVA they receive their cooling from the vehicle heat exchanger rather than the SWME. IVA cooling was tested by injecting controlled heat via the test systems cold plate heaters. The vehicle chiller cart was set to 45°F (7.22°C) and not adjusted throughout all IVA test days. The outlet temperature was monitored to have the outlet temperature of 50°F +/- 1.5°F (10°C +/- 0.3°C). Figure 6 shows the IVA cooling of all three EVAS. As the figures show, there was an initial spike in temperature upon startup but then leveled off to the SWME outlet temperature requirement, this proved that the IVA cooling system was proven effective.

C. IVA Vacuum Access

Vacuum access testing was composed of 2 days testing, the first with the RCA attached directly to the IVA vacuum access system and the second when the pressure transducers were updated and retested. Both test days were performed with dry gas loading and therefore was adjusted until the RCA cycle time hit 15 seconds as see in Figure 7. Next, the HMS system was plumbed directly to the IVA vacuum pumps, bypassing the SxEMU, to fully load the system with CO2 and H2O rations equivalent to 400 BTU/hr. This testing showed that the IVA vacuum pump was unable to maintain less than 1.7 Torr when just half the water vapor of the 400 BTU/hr equivalent was injected, Figure 8.

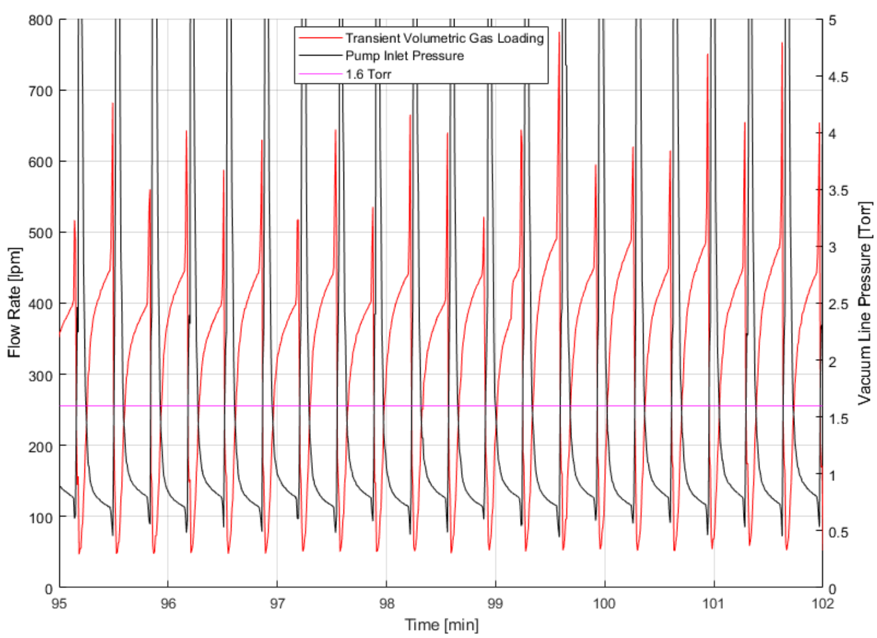


Figure 7: RCA loading of IVA Vacuum Access

The second test day was carried out after a faulty pressure sensor on the vacuum access line was changed out to mitigate the impact of injected water vapor. The HMS was installed near the vacuum access panel and an 1/8th inch line about 8 inches long was installed and the various Ballast Modes of the vacuum pumps were tested. Table 3 shows the test points while Figure 9 shows the various responses in the different Ballast Modes. Ultimately the 11 foot Chambers IVA vacuum access system met the governing requirement of maintain vacuum line pressure below 1.6 Torr under 400 BTU/hr equivalent loading which is the required EHP metabolic rate. The only exception that was found is that the vacuum pumps needed to be run in Ballast Mode 1 or Ballast Mode 2, but as Table 3 shows, Ballast Mode 1 gives the best performance.

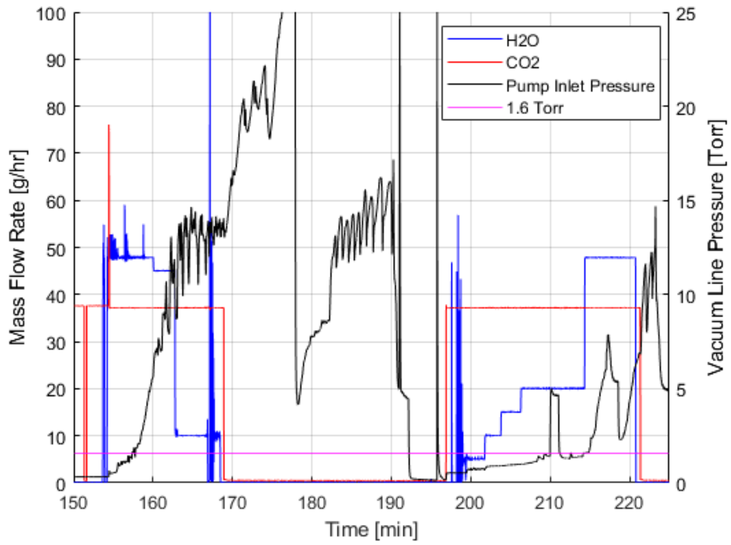


Figure 8: HMS Loading of IVA Vacuum Access System

Case #	CO_2 [g/min]	H_2O [g/hr]	Notes	Average Pressure [Torr]
1	0	0	Baseline Isolated Ballast 1	0.08
2	0	0	Baseline Connected Ballast 1	0.12
3	0.276	0.000	~1/2 CO_2 Loading, 400 BTU/hr	0.187
4	0.552	0.000	Full CO_2 Loading, 400 BTU/hr	0.288
5	0.552	11.600	~1/5 H_2O Loading, 400 BTU/hr	0.45
6	0.552	23.200	~2/5 H_2O Loading, 400 BTU/hr	0.575
7	0.552	34.800	~3/5 H_2O Loading, 400 BTU/hr	0.72
8	0.552	46.400	~4/5 H_2O Loading, 400 BTU/hr	0.85
9	0.552	55.455	Full 400 BTU/hr Loading, Ballast 1	0.94
10	0.828	64.549	Full 600 BTU/hr Loading, Ballast 1	1.125
11	1.104	73.644	Full 800 BTU/hr Loading, Ballast 1	1.3
12	0	0	Ballast 0 Baseline Connected	0.094
13	0.552	55.455	Ballast 0 400 BTU/hr	FAIL, reached 5 torr at 400 BTU/hr loading
14	0.828	64.549	Ballast 0 600 BTU/hr	
15	1.104	73.644	Ballast 0 800 BTU/hr	
16	0	0	Ballast 2 Baseline Connected	0.135
17	0.552	55.455	Ballast 2 400 BTU/hr	1.05
18	0.828	64.549	Ballast 2 600 BTU/hr	1.25
19	1.104	73.644	Ballast 2 800 BTU/hr	1.43
20	1.656	91.833	Ballast 1 1200 BTU/hr	1.65

Table 3: HMS Direct Loading of IVA Vacuum Access System

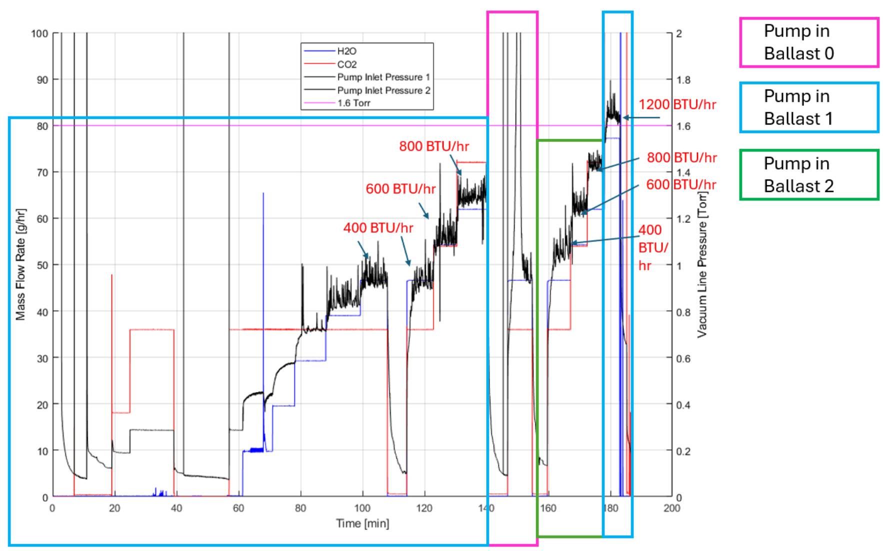
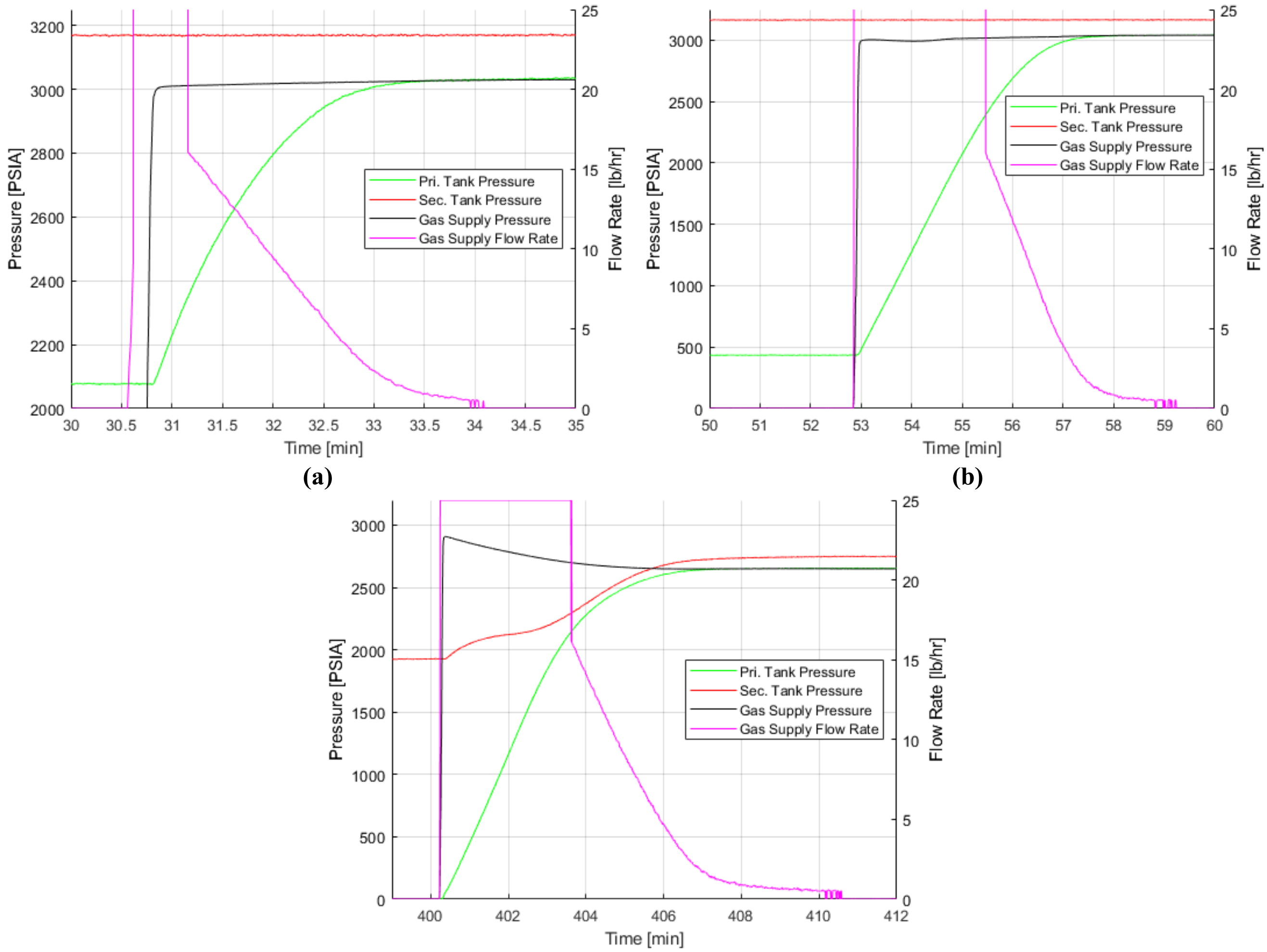


Figure 9: HMS Loading of IVA Vacuum Access System

D. Primary Oxygen Vessel (POV)/Secondary Oxygen Vessel (SOV) Recharge

There were a total of three recharge days, only recharge day 3 fully recharged the POV as it was completely depleted on that day of testing. All three recharge days successfully flowed high pressure GN2 through the High Pressure Gas Supply, its associated flow meter and pressure transducer, the Umbilical Interface Assembly (UIA) panel, the ESCU, and then into the POV and SOV. During recharge, the gas flow meter initially read off scale high and then recovered



(a) (b)

(c)

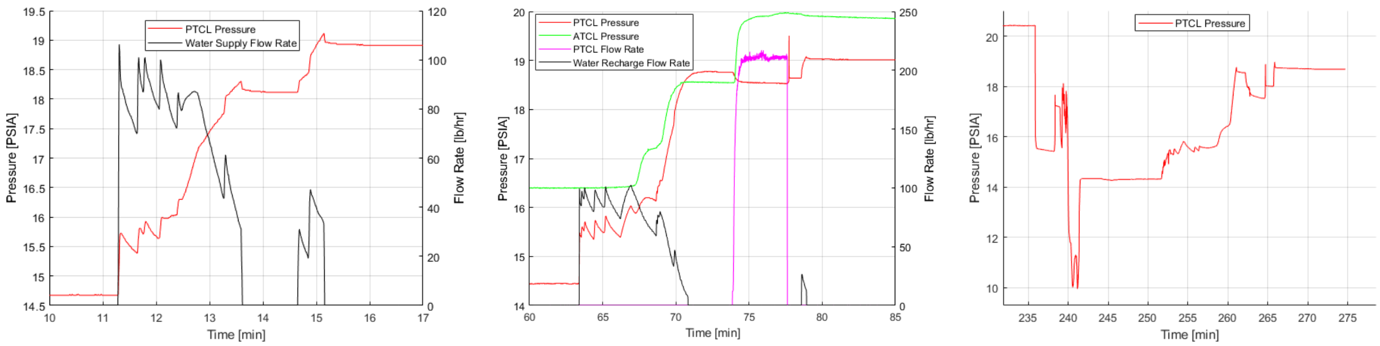
Figure 10: (a) POV/SOV recharge day 1, (b) POV/SOV recharge day 2 and (c) POV/SOV recharge day 3

at approximately 16 lbm/hr, which was higher than expected as the SxEMU should have limited the flow to around 14 lbm/hr or less. Post test analysis confirmed the flow restriction orifeces were installed and the reading was due assumed to be an incorrect flow meter reading/calibration error. Figure 10 shows the tanks recharge time an pressure, it is worth noting that the off-scale high reading (which read 99999 lbm/hr) was changed to 25 lbm/hr to allow for the axes were scaled appropriately.

E. FSA Fill and Drain

The recharge of the FSAs was carried out three times, once on test day 3, once on test day 5, and once at the conclusion of test day 6. The recharges on test days 3 and 5 were carried out on dedicated recharge days, however the recharge on test day 6 was post-draining of the SxEMU test article to verify that the chamber supported fill and drain operations of a next-generation space suit. Figure 11a and 11b show the first two recharges. When degassing of the Primary Thermal Control Loop (PTCL) was carried out, as shown in Figure 11b, the pressure in the ATCL rises due to the water loops being connected via the ESCU, this pressure recovers during chamber depress.

The last verification of chamber capabilities carried out was the drain and fill test of the SxEMU, where a chamber side drain valve was opened in the water loop (located outside of the chamber), which allowed water to escape into a bucket. This was carried out on test day 10 and was successful. The bucket gained 10.116 lbm over the approximately 4 minute drain time, which is equivalent to the amount drained out of the SxEMU. This drain operation was immediately followed by a refilling of the SxEMU water. Figure 11c shows the primary water loop pressure during the drain and subsequent refill.



(a) **(b)** **(c)**

Figure 11: (a) Day 2 Water Recharge, (b) Day 4 Water Recharge, (c) SxEMU PTCL Drain

F. Battery Simulators and Vehicle Power

During this test series two power supplies to the SxEMU were tested: one simulated vehicle power, and and the other powered battery simulators. Both showed good performance. There was an accidental disable of vehicle power by a technician while the SxEMU was operating off of vehicle power, however once power was restored, the SxEMU recovered from the power loss exactly as intended and gave the expected faults and warning messages. Additionally, the ESCU was disconnected during the end of EVA 3 (during attempts to get a good mate for high-pressure gas flow while at vacuum), while the SxEMU had been set to operate off vehicle power post-EVA in preparation for repress. This was a hot-demate of the ESCU which was off-nominal and led to a second loss of power to the SxEMU. Once again, after power was restored to the SxEMU, the suit recovered from the power loss as expected. Other than these two unintentional power resets, the battery simulators and vehicle power supply operated nominally with no other anomalous behavior.

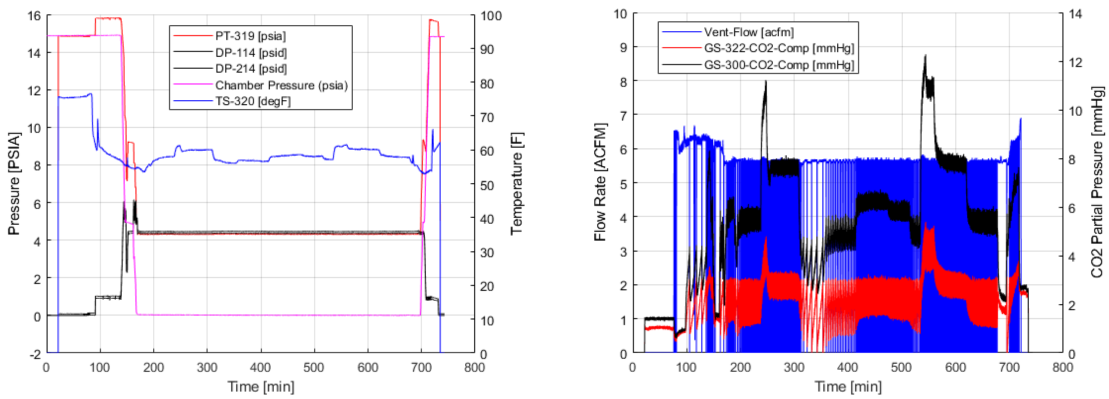
G. Suit Telemetry and Communications

Ambient test days were used to verify suit communication and telemetry. Engineers removed the SxEMU helmet and verified radio communications to the control room. While the SxEMU software was not configured for communication over the ESCU hardline, engineers were able to inject audio signals into the ESCU and verify connectivity to the control room. These tests verified the infrastructure for safety-critical communications between a suited test subject and the test team.

WiFi connectivity was confirmed between a test engineer's laptop and the SxEMU's informatics box via command terminal. Suit telemetry was successfully transmitted via the serial connection in the ESCU umbilical and via the suit radio.

H. SxEMU Performance

Overall, the SxEMU performed well during this test series with minimal anomalous behavior. All figures in this section are from EVA 2, as it was the only full length 8-hour EVA. Additional analyses for all EVA's was performed but since they were not the full 8-hr EVA's they were not included in this paper. The Oxygen Ventilation Loop (OVL) performed as expected during this test series, providing continuous flow through the suit volume and maintaining a habitable pressure during simulated EVAs. Figure 12 below shows the OVL pressure sensors, temperature, flow rate, and CO_2 concentrations during EVA 2. GS-322 goes high for higher metabolic rates due to

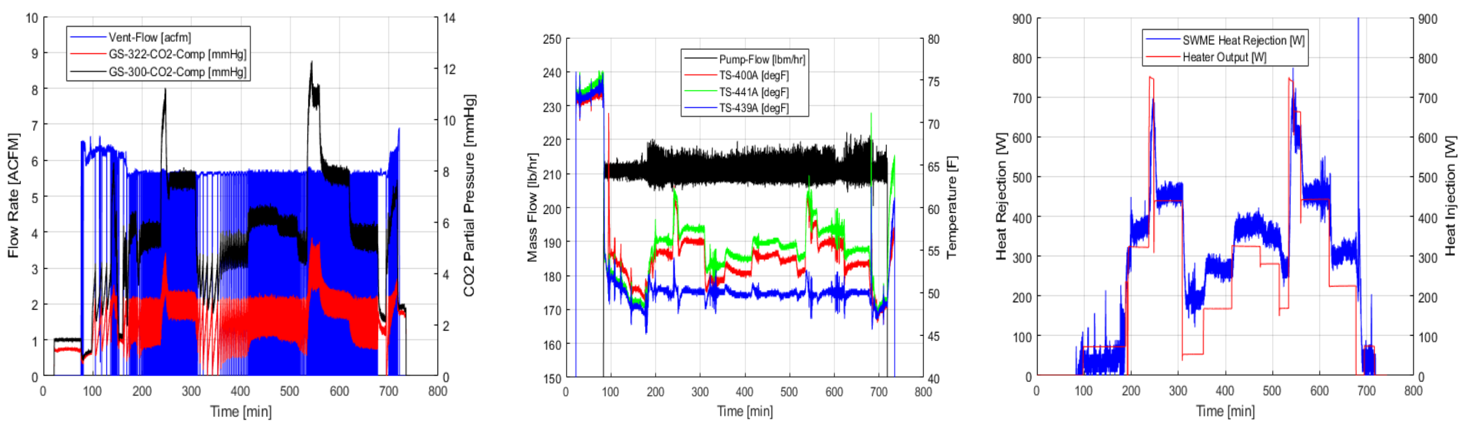


(a) **(b)**

Figure 12: (a) EVA 2 OVL Pressures and Temperatures, (b) EVA 2 OVL Flow Rate and CO2 Concentrations

the RCA degradation, this is discussed in ICES-2026-402.

The PTCL operated nominally during this test series, providing cooling flow to the SxEMU test article during simulated EVAs. Figure 13 below show the PTCL flow rate, temperature, heat rejection, coldplate heater output, and pressure during EVA 2. The Auxiliary Thermal Control Loop (ATCL) was checked out during pre-EVA operations, however it remained in monitor mode (MON) during the simulated EVAs**.**



(a) **(b)** **(c)**

Figure 13: (a) EVA 2 PTCL Flow Rate and Temperatures, (b) EVA 2 PTCL Heat Balance, (c) EVA 2 PTCL Pressures

I. Anomalies

During this test series anomalous performance of the SWME BPV was noticed. When the valve self-adjusted in the closing direction, it appeared that the measured position and the commanded position became misaligned. This is shown below in Figure 14, which plots the BPV measured and commanded position, along with heat rejection of the SWME during a portion of EVA 2. Post-test an inspection of the SWME BPV is planned to identify what caused this anomalous behavior.

During the simulated EVAs there was also anomalous behavior on both water loop pressure sensors on the SxEMU. There was an unexpected spike in pressure on all water loop pressure sensors (both

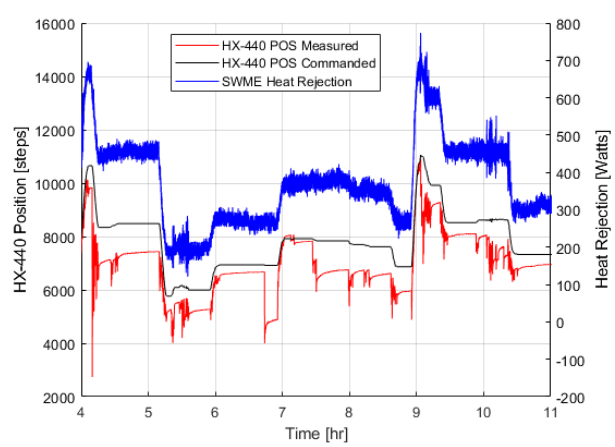
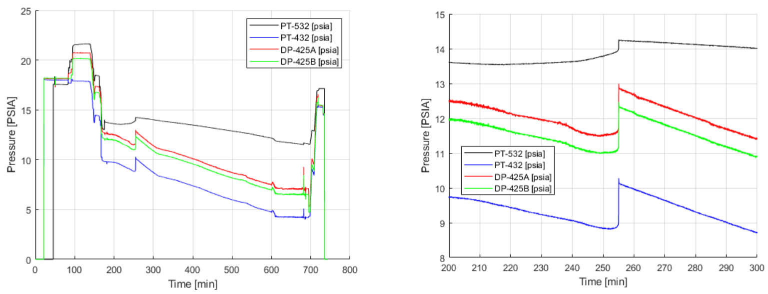


Figure 14: EVA 2 SWME BPV Anomaly

PTCL and ATCL), additionally the water loop absolute pressure did not follow the suit absolute pressure as expected during depress. Figure 15 below shows the entirety of EVA 2, which is followed by Figure 15, which specifically shows the anomalous spike in pressures. At the time of writing, the spike in the pressure sensors has yet to be suitably explained, however the prevailing hypotheses are FSA shifting, or entrained gas or bubble interactions in both water loops.

V. Conclusion



(a) **(b)**

Figure 15: (a) EVA 2 Water Loop Pressures, (b) EVA 2 Water Loop Pressures (zoomed)

The SxEMU 11-ft Chamber Test was successful, verifying that the chamber is capable of testing an advanced spacesuit in preparation for a planned manned test in 2026. A key finding of the test was that the IVA vacuum pumps must be operated in Ballast Mode 1 or Ballast Mode 2, preferably Mode 1 as it gives the best performance. If the pumps are operated in Ballast Mode 0, the pumps will fail to provide adequate vacuum to the CO_2 removal component and therefore the component will be unable to remove the CO_2 from the ventilation loop. Overall, the chamber was successful at maintaining acceptable vacuum levels under anticipated EVA loadings, as well as providing the needed interfaces and plumbing to safely carry out a manned test. Radio, Communications, and Wi-Fi functionality were verified, but future work is necessary verify full functionality for a given xEVAS suit, however these are not safety critical systems. Supporting interfaces for high-pressure gas and water fill and drain operations were successfully tested, with only minor anomalies in the flow meters of each system, which were on the test system side and had no effect on suit performance so not mentioned.

Acknowledgments

The authors would like to acknowledge the EC5 test team who designed, built, and upgraded all the test systems required to test spacesuits and performed the test. The authors would also like to acknowledge and thank the EC4 test team who operated all of the vacuum and facility systems. Additionally the authors would like to acknowledge all the EC4 test directors, EC5 test requestors, EC5 test system operators, and many others not mentioned here to allow for a successful unmanned SxEMU chamber checkout test.

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