Space Suit Portable Life Support System (PLSS) 2.0 Pre-Installation Acceptance (PIA) Testing

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Following successful completion of the space suit Portable Life Support System (PLSS) 1.0 development and testing in 2011, the second system-level prototype, PLSS 2.0, was developed in 2012 to continue the maturation of the advanced PLSS design. This advanced PLSS is intended to reduce consumables, improve reliability and robustness, and incorporate additional sensing and functional capabilities over the current Space Shuttle/International Space Station Extravehicular Mobility Unit (EMU) PLSS. PLSS 2.0 represents the first attempt at a packaged design comprising first generation or later component prototypes and medium fidelity interfaces within a flight-like representative volume. Pre-Installation Acceptance (PIA) is carryover terminology from the Space Shuttle Program referring to the series of test sequences used to verify functionality of the EMU PLSS prior to installation into the Space Shuttle airlock for launch. As applied to the PLSS 2.0 development and testing effort, PIA testing designated the series of 27 independent test sequences devised to verify component and subsystem functionality, perform in situ instrument calibrations, generate mapping data, define set-points, evaluate control algorithms, evaluate hardware performance against advanced PLSS design requirements, and provide quantitative and qualitative feedback on evolving design requirements and performance specifications. PLSS 2.0 PIA testing was carried out in 2013 and 2014 using a variety of test configurations to perform test sequences that ranged from stand-alone component testing to system-level testing, with evaluations becoming increasingly integrated as the test series progressed. Each of the 27 test sequences was vetted independently, with verification of basic functionality required before completion. Because PLSS 2.0 design requirements were evolving concurrently with PLSS 2.0 PIA testing, the requirements were used as guidelines to assess performance during the tests; after the completion of PIA testing, test data served to improve the fidelity and maturity of design requirements as well as plans for future advanced PLSS functional testing.

Nomenclature

A	=	amplitude of oscillation
a	=	cylinder diameter
C_p	=	pressure coefficient
Cx	=	force coefficient in the x direction
Cy	=	force coefficient in the y direction

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I. Introduction

The Advanced Extravehicular Mobility Unit (AEMU) Portable Life Support System (PLSS) technology development effort led by NASA's Johnson Space Center (JSC) continues to progress with increasing sophistication as exemplified by recent integrated PLSS test beds. The first integrated AEMU PLSS test bed, denoted PLSS 1.0 and decommissioned after testing was completed in 2011, comprised five key PLSS technology development components and extensive commercial-off-the-shelf hardware to provide PLSS functionality[1]. Successful PLSS 1.0 testing facilitated the study of PLSS subsystem interactions and furthered performance characterization, experimental and analytical, of the individual PLSS 1.0 technology developments components.

Given PLSS 1.0 was a breadboard ted bed occupying approximately 3.6 m³ (128 ft³), it was a natural objective of the follow on integrated AEMU PLSS test bed, PLSS 2.0, to package the hardware within a volume and geometric form factor representative of a flight-like PLSS design concept occupying approximately 0.1 m³ (4 ft³). PLSS 2.0 objectives also included furthering experimental characterization of key technologies with PLSS 2.0 hardware representing first generation or later prototypes for all components less instrumentation, tubing, and fittings. Another PLSS 2.0 objective was to investigate a new contingency cooling method intended to extend the operational capacity of the emergency systems and add robustness via backup thermal control. The concept is predicated on relieving the Secondary Oxygen Loop (SOL) of crew cooling requirements during purge flow operations and involves a new subsystem, the Auxiliary Thermal Control Loop (ATCL). The ATCL was designed to cool the crew and purge flows can be lowered while still providing adequate helmet carbon dioxide washout[2].

PLSS 2.0 was designed and developed from late 2011 through early 2013. Following assembly of the prototype, testing commenced in March 2013 with Pre-Installation Acceptance (PIA) testing[3]. Pre-Installation Acceptance is carryover terminology from the functional acceptance testing that was performed on the EMU PLSS prior to its installation into the Space Shuttle. With respect to PLSS 2.0, PIA was a test series comprising 27 individual test sequences designed to functionally evaluate component performance as installed in the integrated system. PLSS 2.0 PIA testing was completed in March 2014, at which point the PLSS prototype was disassembled in order to repair, modify, or upgrade several items. This activity is referred to as PLSS 2.0 R&R, or repair and reassembly. After PLSS 2.0 was reassembled, a select set of PIA test sequences was repeated in order to verify functionality of the items that had been changed or for which previous interface verifications had been invalidated. Several component performance characterization tests were also completed in preparation for follow-on test series.

Plans for unmanned PLSS 2.0 testing, including PIA testing, involved the use of specialized hardware to simulate the crew. While this approach enables a rigorous, quantitative characterization of the PLSS performance, it fails to capture critical qualitative aspects of a PLSS that a human test subject would experience and sense. PLSS engineers always considered human evaluation of the AEMU PLSS necessary and, fortunately, an opportunity to conduct the first such evaluation arose earlier than expected. The idea was to extend the long history of Mark III space suit human testing to evaluation of PLSS 2.0. This test configuration became known as the Integrated PLSS 2.0/Human-in-the-Loop (HITL) test configuration and commonly referred to as PLSS 2.0/HITL or HITL for short. Test objectives identified for this test series focused on aspects of PLSS 2.0 performance that directly impacted the comfort of a suited subject including smells, noise levels, thermal comfort, as well as the small pressure and flow fluctuations induced by the RCA as it cycled. HITL test results are summarized in the Reference 4.

Finally, an extensive series of unmanned test points was performed at JSC from January 9 to July 9, 2015. The majority of this test series was completed with the PLSS 2.0 assembly operating in a vacuum environment, although several test sequences were conducted at ambient pressure. The test series included numerous independent tests such as RCA mapping, SWME mapping, and RCA IVA vacuum desorb evaluations, and culminated with 25 simulated EVAs[5].

II. An Overview of the Advanced Portable Life Support System 2.0

The advanced PLSS schematic has evolved over the past several years based on lessons learned from PLSS 1.0 development and testing, analytical models, insights gained through considerations of failure modes, and other assessments of the design. When the PLSS 2.0 schematic was developed in 2012-2013, it was reflective of the thoughts at that time for an advanced PLSS design that could be used for future flight operations. The pneumo-hydraulic schematic is illustrated in Figure 1 and the as-build assembly is shown in Figure 2.
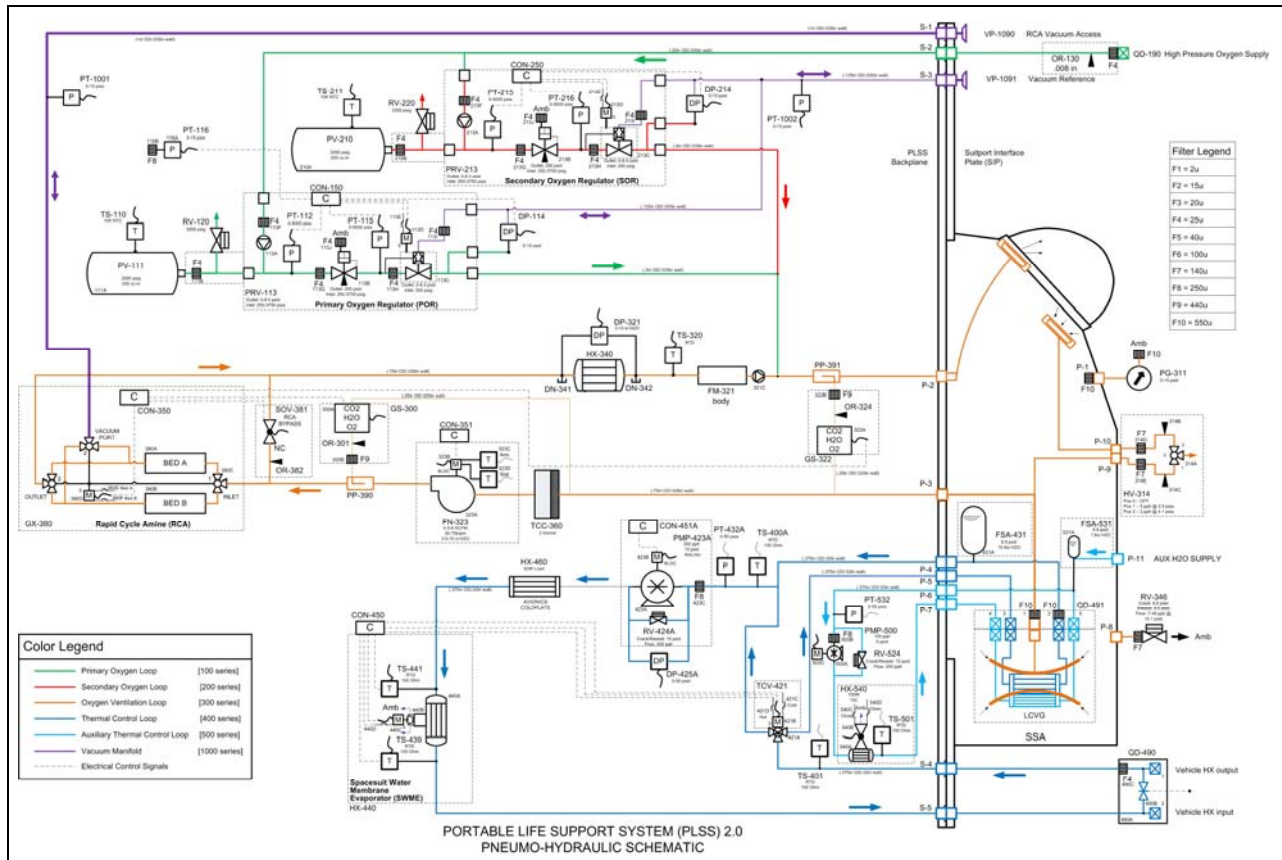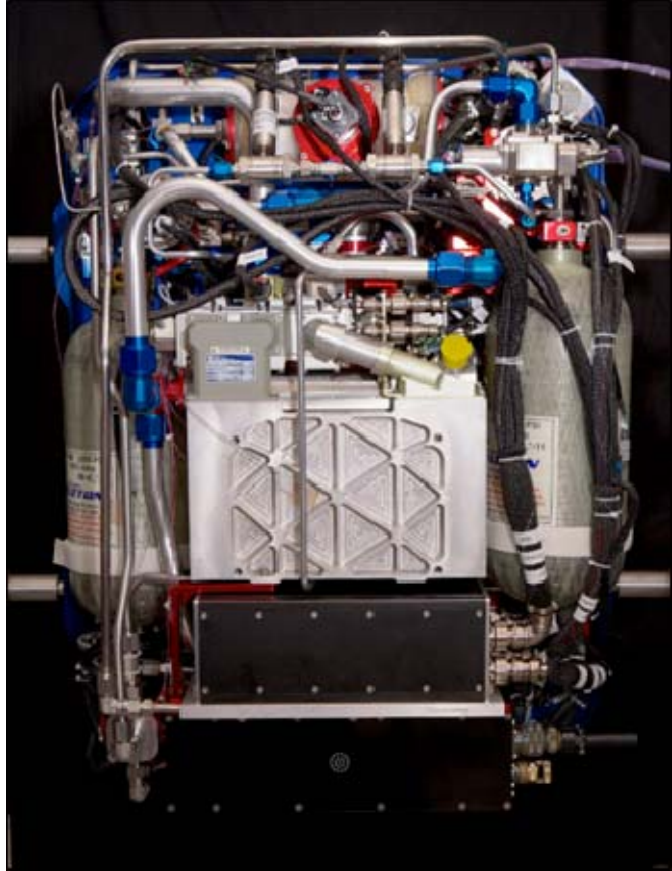
Figure 1. PLSS 2.0 Pneumo-Hydraulic Schematic.

The PLSS 2.0 pneumo-hydraulic design comprises the Primary Oxygen Loop (POL), Secondary Oxygen Loop (SOL), Oxygen Ventilation Loop (OVL), Thermal Control Loop (TCL), and Auxiliary Thermal Control Loop (ATCL). The POL and SOL are identical in design and serve the critical life support functions of replacing consumed oxygen and maintaining the space suit at habitable pressures. They differ in purpose with the POL providing nominal oxygen flow over a large range of suit-to-environment delta pressures of 0.4 to 8.2 psid (2.8 to 56.5 kPa), while the SOL provides contingency oxygen flow should the space suit pressure drop to 3.7 psid (25.5 kPa) for any reason. The OVL serves the critical function of controller CO_2 inspired by the crew and does so by providing to the helmet gas flow of sufficiently high flow rates and low CO_2 partial pressures. Expired CO_2 is carried away by the OVL gas flow and removed from the gas stream before flowing back to the helmet. In addition, the OVL removes trace contaminants from the gas stream, provides convective cooling of the crew, and contributes to crew comfort and cooling by carrying water vapor, expired by breathing and evaporated from the skin, away from the crew and removing it from the gas stream. Whereas POL, SOL, and OVL requirements specify oxygen as the working gas and many aspects of the hardware were designed accordingly, it was never intended to operate PLSS 2.0 with 100% oxygen. PIA testing used gaseous nitrogen as the working fluid for the majority of testing, although a few evaluations used the ambient laboratory air.

The critical life support function provided by the TCL is to acquire crew heat and reject that heat while maintaining the crew at a safe and comfortable temperature. The TCL also acquires heat from the avionics. The ATCL represents a new approach to contingency purge flow operations, high flow operations triggered by OVL failures or significant space suit leakage. Traditionally, as in the Apollo and Shuttle/ISS EMU PLSS designs, contingency oxygen purge flows provide crew cooling and makeup oxygen with the former requiring much higher flow rates than the latter in many situations. The advanced PLSS design offloads this contingency cooling to the ATCL, which will allow the oxygen stored in the SOL to last significantly longer in many contingencies.

Interfacing with all of the PLSS 2.0 loops is the onboard Caution, Warning, and Control System (CWCS). The CWCS was responsible for power distribution, and control of most PLSS 2.0 components, and facilitating two-way communication between PLSS 2.0 components (instrumentation, motor controllers, etc.) and the PLSS 2.0 Test System Data Acquisition and Control System (DACS). Namely, the CWCS provided control of the Primary and Secondary Oxygen Regulators (POR/SOR), fan, RCA, pump, TCV, and SWME. The Mini-ME or ATCL pump were powered and controlled via the test system DACS.

Figure 2. PLSS 2.0 Assembly.

Technology development components are the critical, enabling building blocks of the AEMU PLSS and merit emphasis. PLSS 2.0 contained numerous technology development components with a large range of technology readiness levels including the Primary and Secondary Oxygen Regulators (POR, SOR) in the POL and SOL. Key OVL technology development components include the RCA swingbed CO_2 and water vapor (H_2O) scrubber, fan, and gas/water heat exchanger. TCL technology development components include the SWME, pump, Thermal Control Valve (TCV), and Feedwater Supply Assembly (FSA). Whereas included in the technology development count are the ATCL Mini-Membrane Evaporator (Mini-ME) and Auxiliary FSA (AFSA), which are smaller versions of the TCL SWME and FSA, respectively. Perhaps more important is the idea that the ATCL represents a technology development system and new way of handling select contingencies. The PLSS 2.0 onboard avionics, the CWCS, was also a notable first generation technology development prototype.

III. PIA Tests

As previously stated, PIA testing was a test series comprising 27 individual test sequences designed to functionally evaluate component, and in some cases sub-system, performance as installed in the integrated system. These tests were performed at periods of time throughout the life of the PLSS 2.0 test article and ranged in complexity and functionality from leak checks and electrical harness continuity checks to integrated OVL or TCL performance characterization. Many tests were repeated after test article upgrades were made including: replacing the CWCS emulator (CWCS-E) with the actual CWCS, upgrading the RCA controller, and after the PLSS 2.0 R&R activity. The objectives of these tests range from verifying proper workmanship, to figuring out how to operate certain components, to component calibrations, to requirements verification.

1	Pretest Leakage Checks	POL, SOL, OVL, TCL, ATCL	Verify workmanship of fluid loops
2	Pretest Cleanliness Verification	POL, SOL, OVL, TCL, ATCL	Verify system cleanliness levels
3	Instrumentation Checks	PLSS 2.0	Harness continuity, measure electrical characteristics of the integrated PLSS and CWCS
4	PLSS 2.0 to CWCS-E Integrated Calibration Checks	PLSS 2.0 and Test System DAQ	End to End Instrument Calibration
5*	Gas to Water Side Leakage	PLSS 2.0 and Test System	Quantify leakage between TCL and OVL (test not performed due to known leaks in LCVG)
6	Operating Voltage, Power Consumption, and Voltage Brown Out	PLSS 2.0	Measure power draw of different PLSS components at different system voltages
7.1	POL/SOL Recharge	POL, SOL and Test System	Measure oxygen tank recharge time
7.2	TCL Feedwater Storage Characterization	TCL and Test System	Measure FSA capacity, characterize the low level alarm, measure recharge time
8	PRV-113 Mapping, Regulation and Flow	POL	Map specific stepper motor settings against pressure setpoints, demonstrate the ability maintain setpoint control at a variety of flow rates
9	PRV-113A/PRV-213A Back Flow	POL and SOL	Verify operation of the check valves in the regulators
10	PRV-113 Flow Limiting	POL and SOL	Verify regulators limit gas flow rate to the suit
11	PRV-213 Mapping, Regulation, and Flow	SOL	Map specific stepper motor settings against pressure setpoints, demonstrate the ability maintain setpoint control at a variety of flow rates
12	FN-323 Performance/FM-321 Calibration Check/SOV-381 Flow	OVL	Characterize vent loop flow performance in multiple configurations
13	FM-321 Check Valve Leakage and Flow	FM-321 Check Valve	Measure check valve leakage in different orientations
14	GS-322/GS-300 Calibration Check and Performance	GS-322 and GS-300	Calibrate gas sensors with respect to CO_2 and humidity
15	HV-716 Setting	Test System	Simulate vehicle loop pressure drop
16	Dry LCVG Degassing	TCL	Demonstrate ability of the TCL to degas the loop after installing an empty LCVG
17	Thermal Control Valve (TCV) Mapping	TCL	Map flow rates to valve position
18	Thermal Control Valve (TCV) Internal Leakage	TCL	Measure water leakage between the bypass and LCVG sides of the valve
19	PMP-423/RV-424 Flow Verification	TCL	Generate pump curves and verify RV-424 cracking pressure
20*	PMP-500 Flow Mapping/RV-524 Verification	ATCL	Generate pump curves and verify RV-424 cracking pressure
21*	Auxiliary Thermal Control Loop Dry LCVG Degass	ATCL	Demonstrate ability of the ATCL to degas the loop after installing an empty LCVG
22*	Auxiliary Feedwater Quantity Verification/Low Level Detection	ATCL	Measure AFSA capacity, characterize the low level alarm, measure recharge time
23	Primary Oxygen Regulator (POR) Controller Check	POL, CWCS	Verify that the regulator still achieved the desired setpoint control with fully integrated avionics and software
24	Secondary Oxygen Regulator (SOR)	SOL, CWCS	Verify that the regulator still achieved the desired setpoint control with fully integrated avionics and software
25	Fan Controller Check	FN-323	Verify that the fan still achieved the desired setpoint control with fully integrated avionics and software
26	RCA Controller Check	OVL	Verify the ability of the fully integrated system (including avionics and software) to cycle the RCA based on an input time cycle or based on a CO_2 reading
27	SWME Controller Check	TCL	Verify the ability of the fully integrated system (including avionics and software) to control the SWME exit temperature

Table 1. PIA Test Sequences.

In many cases these tests performed early in the life of the PLSS 2.0 test article turned out to be entry points for trouble shooting activities where engineers first discovered that the components or integrated systems were not

working as originally envisioned. In many cases, these tests also helped to mature the supporting test systems that were required to complete the larger PLSS 2.0 testing program.

Table 1 summarizes these 27 test sequences. Test sequences denoted with a "*" where not performed due to hardware limitations. Leaks in the Mini-ME during the initial installation prevented testing of the ATCL at that time. Mini-ME was repaired during PLSS 2.0 R&R, however, these tests were not performed afterwards based on time constraints and other testing priorities. In addition, the LCVG had known leaks, making section 5 (Gas to Water Side Leakage) irrelevant.

The remainder of this paper document results from specific PIA test sequences that provide valuable data in the characterization of certain PLSS 2.0 components and subsystems. Each section outlines the objective of the test performed, the test setup and procedures used, the data and results, and finally a conclusion that often consists of comparing the measured performance against the latest applicable development requirements. Test results for PIA test sequences not documented in this report can be found in Reference 3.

A. Section 8: PRV-113 Mapping, Regulation and Flow

1. Objective:

This set of tests had two primary objectives. First, the regulator was mapped to determine how the number of steps commanded to the stepper motor on the regulator translated into a set pressure for the ventilation loop. This test was performed multiple times to evaluate repeatability and hysteresis. These tests successfully demonstrated that regulator was controllable and repeatable. A correlation between the motor steps and set point pressures was generated and successfully used for all of the remaining PLSS 2.0 testing. Further details with the results of this portion of the Section 8 testing can be found in the final report[3]. Next, the regulator was commanded to different set points and the demand was varied to measure how well the regulator could maintain set point control across the required range of flow. Results from this portion of Section 8 testing are discussed here.

2. Test Configuration:

PLSS 2.0 was used for this test in conjunction with the "Ventilation Loop Jumper." This jumper connected to the ventilation loop at the P-2 interface and provided flow measurement capability, a metering valve to vary the demand on the system, and a connection to a lab vacuum system when needed. Tests were performed with the regulator controlling to super-ambient and also to sub-ambient pressures. An additional vacuum reference line was connected to the regulator via the S-3 port to perform the sub-ambient pressure tests.

During the test, PRV-113 set points ranged from 0.4 to 8.2 psid (2.8 to 56.5 kPa). Flow rates between 0.1 and 5.6 lb/hr (0.05 to 2.5 kg/hr) were set by adjusting the metering valve and read on two TSI flow meters in the Ventilation Loop Jumper. Each of these pressure and flow rate points was also tested at tank pressures of approximately 2700, 2000, and 1500 psia (18,616, 13,790, and 10,342 kPa). An attempt was made to perform the tests with a tank pressure of 250 psia (1724 kPa), however, the tank pressure decreased too rapidly to perform meaningful test points.

3. Test Results:

The following figures show a sample of the results from this series of tests. Graphs with step counts of 4524 were intended to set the system to 4.1 psid (28.3 kPa) above the ambient pressure (lab or vacuum) and the tests at 7421 steps were intended to hit a pressure of 7.8 psid (53.8 kPa). It should be noted that during this early phase of PLSS 2.0 testing, there were some difficulties associated with counting steps and re-zeroing the step counts on the regulator. These tests helped to refine the methodology for controlling the regulators, but these difficulties explain why each of the lines on these graphs did not start at the same pressure even though the regulator was set to the same
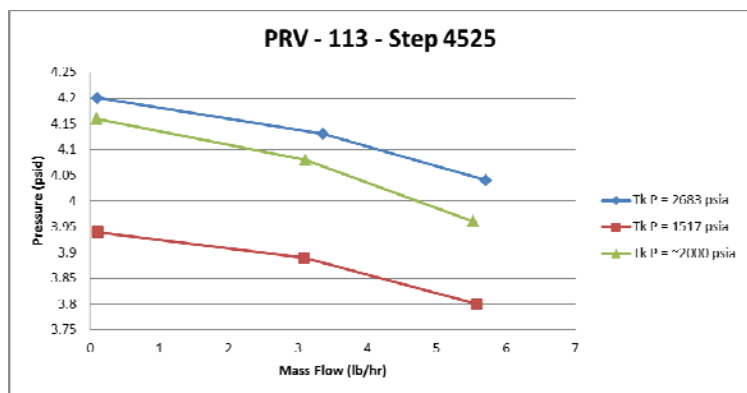

Figure 3. PIA 8.2 Super Ambient POR Pressures and Flows with Motor Stepped to 4525 Steps.

number of steps. The key aspect of the performance to observe in these graphs is the decrease, or droop, of the regulator set pressure as the flow rates were increased.

4. Comparison to Development Specification:

Regulator performance requirements include the ability to regulate to a range of set points between 0 and 8.2 psid (0 to 56.5 kPa), with an ambient reference environment of 0 to 14.7 psia (0 to 101.4 kPa). It was also required to be able to control to a specific set point within ±0.2 psid over a range of flow rates from 0.02 lb/hr to 5.6 lb/hr (0.009 kg/hr to 2.5 kg/hr). The graphs presented in this section indicate that the regulators met these requirements for the set points around 4.0 psid (27.6 kPa), but the droop exceeded the 0.2 psid at the higher pressure set points. As a result of these tests, it was determined that this requirement could be relaxed at the higher pressure settings and was expanded to an acceptable band of +0.2/-0.4 psid across the range of flow rates for a regulator set point of 8.2 psid (56.5 kPa). This piece of equipment, used for PRV-113 in PLSS 2.0, still narrowly missed this expanded requirement. This will be revisited in future PLSS regulators.

It should also be noted that PIA Section 11 repeated a very similar test series using the SOR (PRV-213). These regulators were identical pieces of hardware and performed almost identically.

B. Section 9: PRV-113A/PRV-213A Back Flow
1. Objective:

The objective for Section 9 was to verify the POR and SOR check valve operation (PRV-113A and PRV-213A). The PLSS tanks are charged from a vehicle high pressure supply (normally oxygen but it was nitrogen for PLSS 2.0 testing) through a port in each regulator. Check valves are built into this port in each regulator, denoted PRV-113A and PRV-213A in the schematic, and allow gas to enter the primary and secondary oxygen subsystems. During PLSS 2.0 testing, once tank charging was completed, the line was vented and the check valve sealed to keep the gas from leaking back out of the tanks. Since these check valves are a potential leak path for oxygen to leave a future PLSS and vent to space, their performance is essential to performing a safe EVA.

Figure 5. PIA 8.2 Super Ambient POR Pressures and Flows with Motor Stepped to 7421 Steps.

Figure 4. PIA 8.2 Sub-Ambient POR Pressures and Flows with Motor Stepped to 4525 Steps.

Figure 6. PIA 8.2 Sub-Ambient POR Pressures and Flows with Motor Stepped to 7421 Steps.

2. Test Configuration:
A specific test was not performed to meet this objective. However, during the regular mapping and flow test in PIA Section 8, leakage back through the check valve was unexpectantly observed.
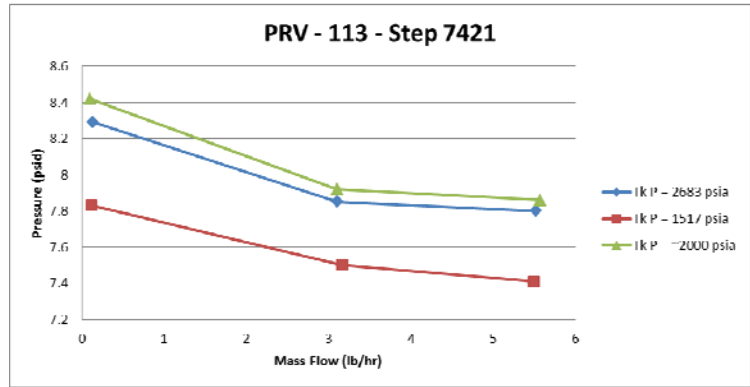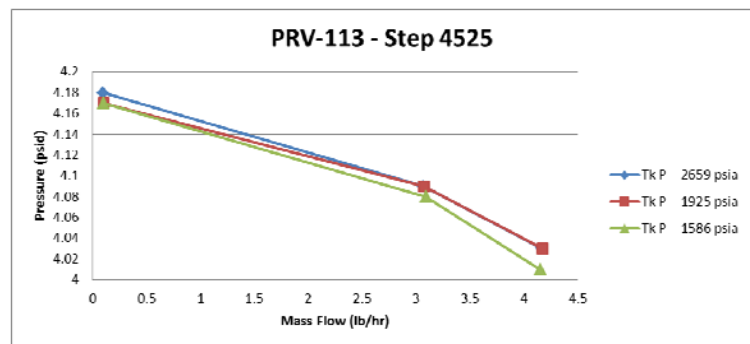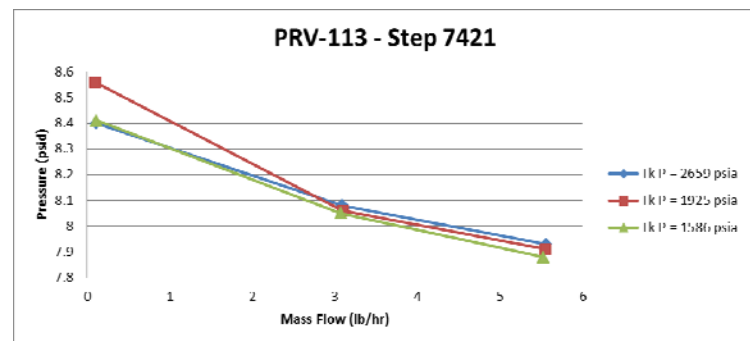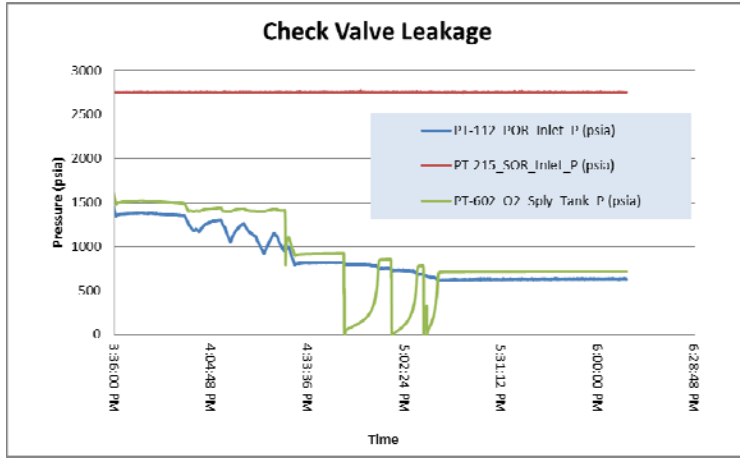
3. Test Results:

During the PRV-113 Flow and Regulation test, it was noted that the GN2 supply line pressure are read on PT-602 was tracking with the Primary Oxygen Vessel (POV) pressure as read on PT-112. The GN2 supply line was

Figure 7. PRV-113A Check Valve Leakage.

isolated from the GN2 supply at this time. At the end of the PRV-113 regulation and flow test, the supply line was vented. Shortly after the vent valve was closed the pressure in the line returned to the approximately the POV pressure. It should be noted that PT-112 and PT-215 had not yet been calibrated at the time when this test was performed, which can explain why the pressures do not appear to be the same once the system had reached equilibrium conditions. This was repeated two additional times and the pressure in the line returned to the approximately the same pressure as the POV each time (see Figure 7). The POV tank pressure dropped slightly with each attempt at venting starting at 813 psid (5605 kPa) before the first attempt

to 625 psi (4309 kPa) after the final attempt. This data suggested that the check valve was leaking from the tank into the recharge line (PT-602). The system was left in this state overnight. The next day the check valve appeared to reseat and operate as expected after the tank pressure above 2,500 psia (17,237 kPa). This phenomena was observed many times throughout PLSS 2.0 testing. These occurrences were typically at lower tank pressures, because the pressure helped to seal the check valve closed.
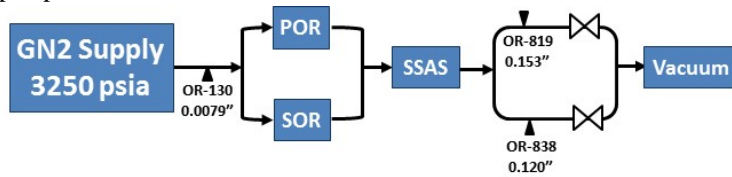
4. Comparison to Development Specification:

The PLSS development specification (CTSD-ADV-780, Sections 3.3.3 and 3.4.3) has requirements for the POR and SOR (PRV-113/PRV-213) of no more than 1 sccm of leakage with 3750 psia (25,855 kPa) bottle pressure and ambient pressure at the fill port. As previously stated, the purpose of the requirement is to prevent back flow from the PLSS into the charging system or back into space during an EVA.

As the testing discussed above was not conducted at those conditions the test does not show non-conformance behavior to this specific requirement. The check valve has been demonstrated to hold pressure at the conditions detailed in the PLSS development specification requirement. However, the tendency of the PRV-113 check valve to leak at lower tank pressure merits further investigation and has led to the separation of the high pressure gas recharge lines within the PLSS 2.5 so that a leaky check valve would not allow the POV and Secondary Oxygen Vessel (SOV) to pass gas between each other due to a check valve failure.

C. Section 10: PRV-113 Flow Limiting

1. Objective:

The object of Section 10 was to verify that the POR and SOR limit gaseous nitrogen flow to the equivalent of 7.49 lb/hr (3.4 kg/hr) oxygen flow. Flow limiting from the regulators is important from a system design perspective because this maximum flow into the suit cannot exceed the flow rates capable of the relief valve that

Figure 8. Simplified Schematic of PIA 10 POR/SOR Flow Limiting Test Configuration and Flow Paths with Orifices Identifier and Diameter Listed.

protects the suit from over pressurization.

2. Test Configuration:

Figure 8 presents a very simplified schematic of the POR/SOR flow limiting test configuration highlighting the orifices used to simulate suit purge flow and calculate flow through the system. Orifice flow rates are calculated assuming the Perry sharp edge orifice flow coefficient[6] and

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knowing upstream pressure and temperature and downstream pressure. Not shown in Figure 8**Error! Reference source not found.**, but fully detailed in JSC drawing SEN36155701, are the many pressure and temperature measurements required to calculate flow rates through the orifices. Simulating suit purge flow was accomplished by the opening and closing of solenoid valves in lines connecting the Space Suit Assembly Simulator (SSAS, "suit") to the vacuum system. Each line contained a sharp edge orifice that would limit flow under steady state choked flow conditions. The larger orifice line, OR-819, is referred to as the high flow purge line while the line with OR-838 is referred to as the low flow purge line. Orifice OR-130, a sharp edge orifice that protects the POL and SOL from rapid pressurization, is also highlighted because it yielded a simultaneous mass flow calculation.

Maximum purge flow testing methodology was the same for the POR and SOR and consisted of the following steps: 1.) Verify gaseous N_2 supply equal to or greater than 3000 psia (20,684 kPa), 2.) Set POR or SOR to maximum pressure control setting of 8.4 psid (57.9 kPa), which required respective stepper motor to be stepped 7857 and 7244 steps, 3.) Open low and high purge flow solenoid valves and allow pressures to stabilize, and 4.) Close low flow purge valve and allow pressures to stabilize.
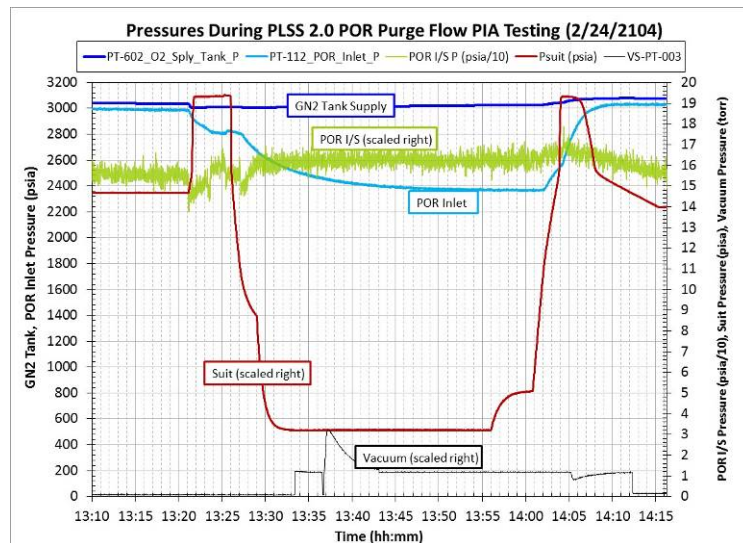
3. Test Results:

Figure 9 presents calculated gaseous N_2 flow rates through each orifice for the two test configurations, first with both purge valves open and then with only the high flow purge valve open starting at 13:56:30. Total steady state purge flow was 6.5 lb/hr (3.0 kg/hr) with a split of 4 and 2.5 lb/hr (1.8 and 1.1 kg/hr) for the high and low purge flow lines, respectively. Calculated flow rates using the high pressure orifice took longer to stabilize, but did so at 6.55 lb/hr (3.0 kg/hr) at the end of the dual open purge line test run. The two total mass flow calculations differed by less than 1%, showing excellent agreement between the two independent measurements.
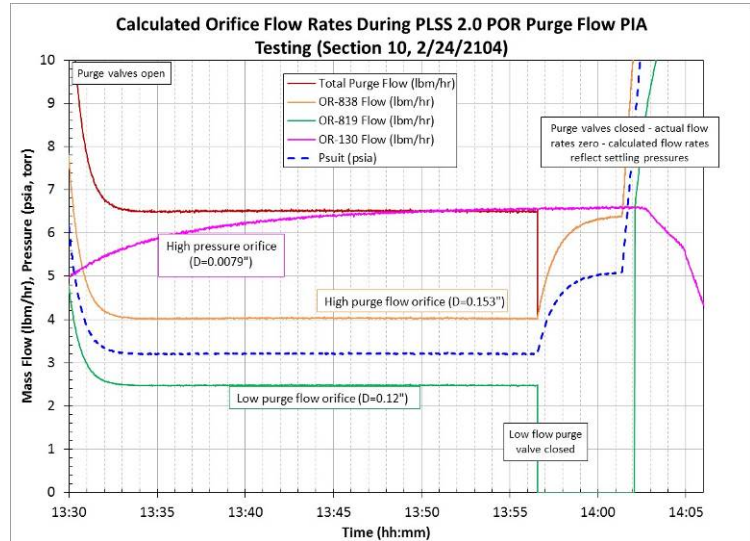
Figure 9.   Calculated Flow Rates During POR Purge Flow Testing.

After the low flow purge valve was closed, the suit pressure naturally rose in response to increased flow restriction and flow through the high flow purge line increased proportionately. At the end of the high flow purge test run, calculated flow rates per the purge line and high pressure orifices were respectively 6.4 lb/hr (2.9 kg/hr) and

Figure 10. Pressures During POR Purge Flow Testing.

6.6 lb/hr (3.0 kg/hr), differing by 3% and again showing good agreement. It is believed the suit pressure and consequently high flow purge line flow rate would have stabilized at a slightly higher pressure had the test run been extended.

The fact that the suit pressure rose until purge flow stabilized at 6.4 lb/hr (2.9 kg/hr), essentially the same flow rate as measured during the dual purge line configuration, strongly indicates the choking point in this system was upstream of the suit. A review of the pressures, plotted in Figure 10, shows that the second stage of the POR proved to be the flow path limiting point. First, note the OR-130 upstream and downstream pressures, GN_2 tank and POR inlet, respectively, demonstrate the flow through OR-130 was subsonic during the purge flow test as the pressure ratio across OR-130 was

0.78 or higher, remaining well above the critical flow pressure ratio of 0.528 for nitrogen. Next, consider the POR first stage with flow characterized by its upstream and downstream pressures, the POR inlet and POR inter-stage (I/S) pressures, respectively. The latter was divided by 10 so that it could be scaled with the suit pressures and allow visibility of small changes. As expected, the POR stage flow is very much choked with pressure ratio of 0.1 or less. The POR I/S pressure transition from zero flow to purge flow provides critical insight. Initially the POR I/S pressure was at 155 psia (1069 kPa) with minimal demand and then reached a steady 165 psia (1138 kPa) during the purge flow phase. Had the POR first stage been the choking point of this system, POR I/S pressure droop would have been observed. Instead the POR first stage opened as required to maintain a steady downstream pressure that was slightly greater than the low demand flow pressure. Downstream droop was captured by the suit pressure measurements, which combined with the steady upstream pressures demonstrates the POR second stage proved to be the system choking point. Finally, vacuum pressure measurements confirm the vacuum system capably handled

the requisite mass flow while maintaining acceptable vacuum pressures of ~1.2 torr during steady state flow.

SOR purge flow testing results, plotted in Figure 11, show that calculated purge flows reached 6.4 lb/hr (2.9 kg/hr) with both purge lines open and 6.3 lb/hr (2.9 kg/hr) with only the high flow purge line, respectively. Flow rates calculated using OR-130 reached 5.6 lb/hr (2.5 kg/hr) at the end of SOR purge testing, differing from the purge line flow rate calculations by 11%. SOR purge flow testing was completed in less than 17 minutes, which was not enough time for the SOR inlet pressure to reach steady state. Additional SOR purge flow testing that lasted 25 minutes showed calculated OR-130 flow rates attaining 5.9 lb/hr (2.7 kg/hr), differing from the purge line total flow of 6.4 lb/hr (2.9 kg/hr) by 8% (see Figure 12).

Pressures measurements during the first, short SOR purge flow test (see Figure 13) demonstrated the same behavior exhibited by the POR in that the SOR second stage proved to be the choking point. Flow through OR-130 was again subsonic as the pressure ratio across this orifice reached a minimum of 0.85, well above the critical pressure ratio of 0.528 for nitrogen. While transitioning from low flow to high flow the SOR I/S pressure increased from ~110 psia (758 kPa) to ~130 psia (896 kPa), thus demonstrating the ability of the SOR first stage to open sufficiently to maintain constant downstream pressures. As in the POR testing, droop was observed in the suit pressure measurements as the purge configuration was changed from dual open purge lines to high flow purge line only. The fact that both the POR and SOR attained 6.4 lb/hr (2.9 kg/hr) nitrogen flow, but with respective I/S pressures of 160 psia (1103 kPa) and 130 psia (896 kPa) is interesting and is attributable to adjustments or instrumentation uncertainties or instrumentation error.
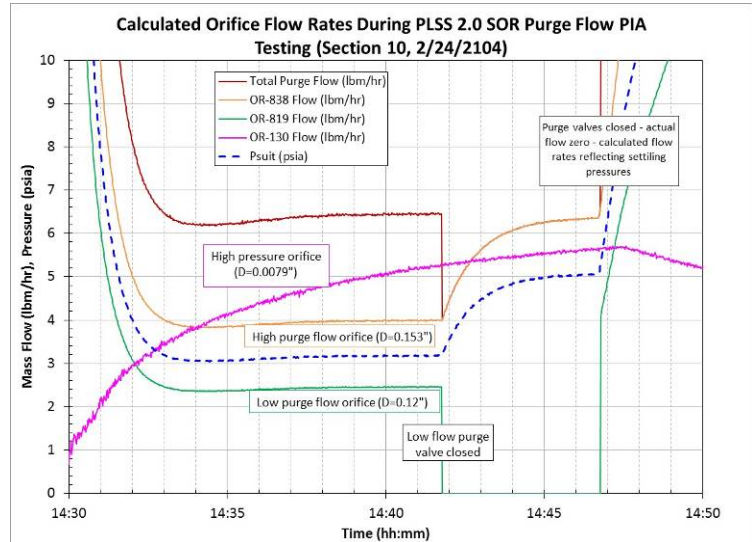
Figure 11.   Calculated Flow Rates During SOR Purge Flow Testing.
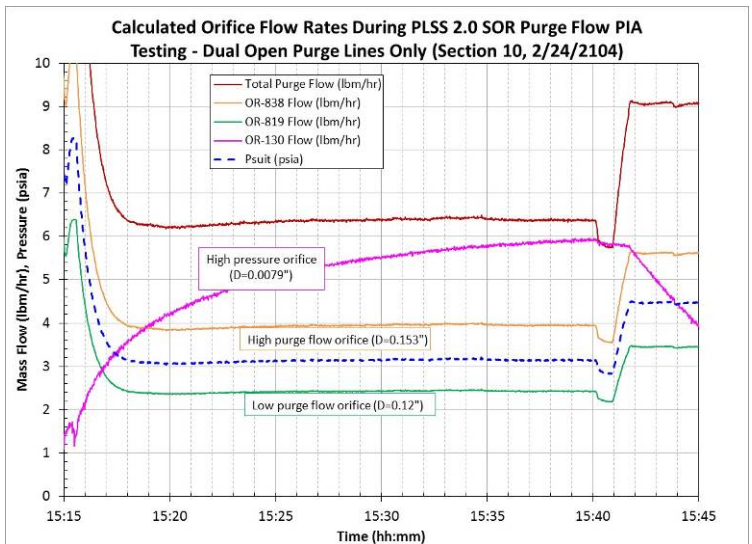
Figure 12. Calculated Flow Rates During Additional SOR Purge Flow Testing with Both Purge Flow Lines Open for the Entire Test Run.

4. *Comparison to Development Specification:*

A final step in the applicable detailed PIA procedure is to scale the calculated maximum nitrogen flow rates to an equivalent flow rate for comparison with the oxygen limiting flow rate requirement. While the scaling methodology was not specified, the project has commonly referred to 6.5 lb/hr (3.0 kg/hr) nitrogen flow as an appropriate scaling of the oxygen limit. This value of nitrogen flow, derived by simply scaling the 7.49 lb/hr (3.4 kg/hr) oxygen flow rate limit by the ratio of the N_2/O_2 molar masses (molecular weights), has two issues with one pertaining to the nature of choked gas flow and the other leading to question whether this test can ever be confidently performed at a pressure lower than the requirement.

First, given the O_2 limiting flow requirements assure choked flow through the regulator, it is reasonable to assume the ideal choked gas flow equation would serve as a foundation for developing an appropriate scaling factor. Gas choked flow rates are proportional to the upstream total pressure and the square root of the gas molar mass.
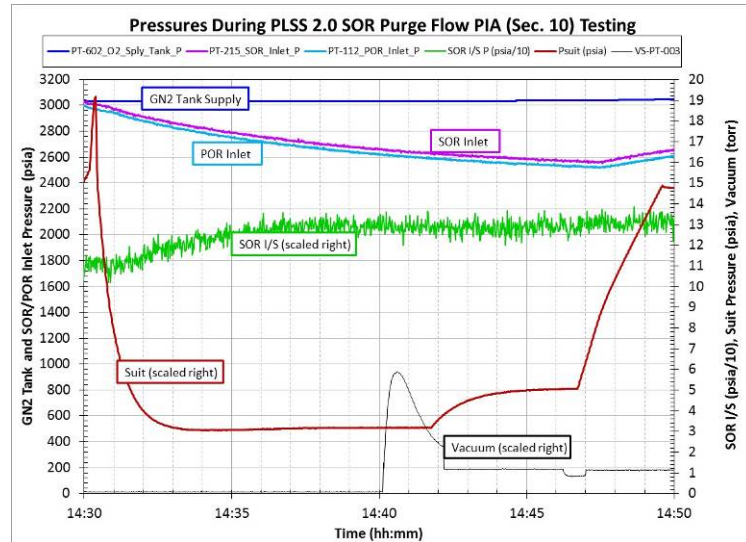

Figure 13. Pressures During SOR Purge Flow Testing.

Treating the regulator as an orifice and assuming equal upstream and downstream conditions yields an equivalent nitrogen flow requirement of 7.01 lb/hr, not 6.55 lb/hr per the simple ratio of molar masses.
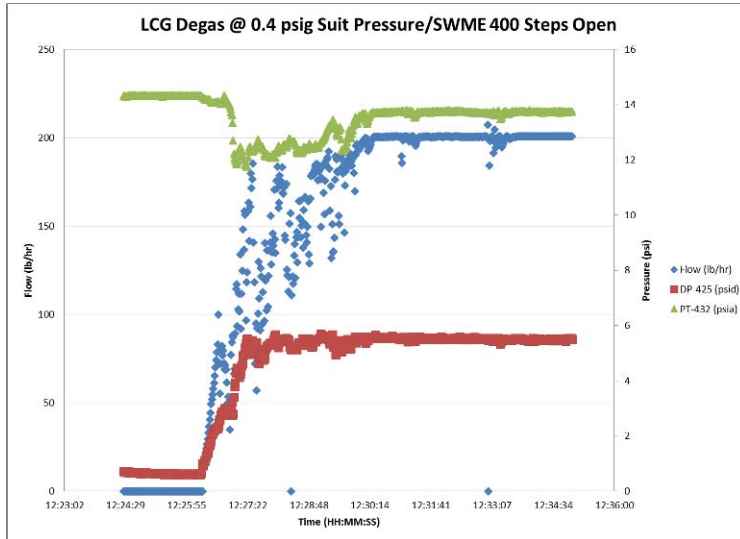
While further investigation is needed, this test data shows that the regulator first stage performed well enough to provide a relatively constant inter-stage pressure and the second stage was actually the flow limiting portion of the system. Consequently, it is concluded the POR and SOR properly limited flow to less than an appropriate limit of 7.01 lb/hr over a range of tank pressures.

However, the second consideration pertains to whether treating the regulator as an orifice is a viable approach since the regulator employs mechanical linkages. Consequently, questions arise including: Is it physically possible for a larger inlet pressure to "overcome" the first stage and, thus, resulting in greater I/S pressures? What would happen if the first stage failed open? Is it possible higher pressures cause low I/S pressures due to mechanism counteraction? Therefore, would a conservative test involve reducing the inlet pressure lower? If so, how much lower as it is expected there would be a trade-off between conservatism for the mechanical case, but not too low so that the gas has maximum pressure energy? These questions are being asked and have initiated additional analysis and testing to further characterize the flow limiting performance of the regulators.

D. Section 16: Dry LCVG Degassing

1. *Objective:*

Section 16 was intended to characterize the ability for the thermal loop, using the pump and SWME, to prime a fully dry LCVG. The PLSS specification denoted references the requirement for the system to be able to remove a slug of gas which is representative as a fully dried Liquid Cooling and Ventilation Garment (LCVG). No time is associated with the requirement.

2. *Test Configuration:*

While operating the PLSS on the EMU Ground Test Fixture (EGTF), a thermal loop jumpers was connected to the PLSS to close the TCL. This jumper contained a metering valve, a flow meter, and a Millipore can to supply additional water. The Millipore can was pressurized to about 0.4 psia to simulate Inter-Vehicular Activity (IVA) conditions in the suit. A LCVG was purged and completely dried of water by flowing dry nitrogen through it over a few hours. Once the LCVG was dried, it was connected to the loop with the pump off. The SWME back pressure valve was then opened to 2000 steps, which was approximately 50% open, and pump set to flow 200 lb/hr (91 kg/hr).

3. Test Results:

Figure 14 shows one of these tests in which the thermal loop was effective at degassing a fully dried LCVG. Flow rate was measured 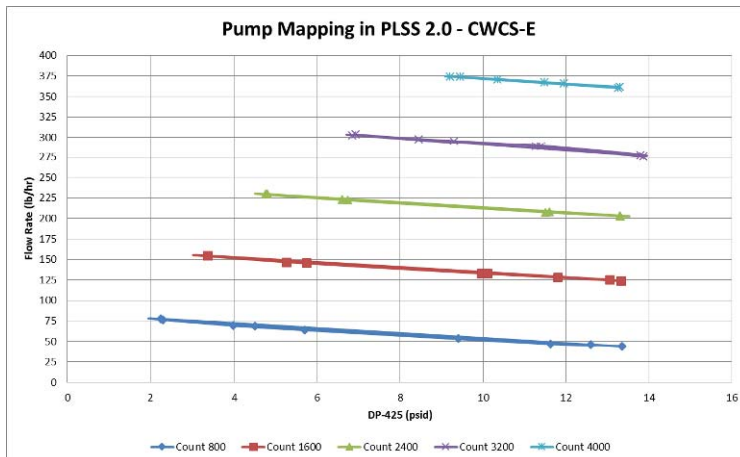by an independent flow meter in the thermal loop jumper. DP-425 is the head rise across the pump and PT-432 is the inlet pressure to the pump. Once the pump was turned on, as shown in the increase in flow rate, the pressures and flow rates experienced an initial period of instability due to the LCVG induced bubble being circulated through the loop. Over time, this air bubble passed through the hollow fiber membranes in the SWME and the pressures and flow rate stabilized at normal operating conditions for the loop. The time it took to fully degas was approximately 4 minutes.

Figure 14.   Results from PIA 16 Thermal Control Loop Degassing Testing.

4. Comparison   to   Development Specification:

The system was able to remove the gas bubble from the thermal loop induced by a dry LCVG and return to stable flow rates and pressures in a relatively short amount of time, therefore it was considered to have met the intent of the design. The requirement did not specific an amount of time, but this 4 minute period has been demonstrated, it did not appear to cause any damage to the system, and provides specific system performance that can be evaluated in the future as the system and operations are further defined.

E. Section 19: PMP-423/RV-424 Flow Verification

1. Objective:

The objective of PIA 19 was to characterize thermal loop pump across operating conditions and verify bypass relief valve set point pressure. This paper documents the pump curve generated. The bypass relief valve was verified and additional information is available in Reference 3.

Figure 15.   PIA 19 Pump Mapping Test Results with PLSS 2.0 and CWCS-Emulator Configuration.

2. Test Configuration:

The PLSS pump was characterized during the PLSS in the EGTF configuration using the thermal loop jumper. The set up was similar to that for Section 16. For this sequence the pump speed was varied through a 0-5 Vdc signal voltage and at each set point, a metering valve simulating the LCVG leg pressure drop used to vary the differential pressure of the loop. Similar tests were performed throughout the PLSS 2.0 testing period in slightly different configurations. These subsequent tests provided additional system characterizations, but did not always have the necessary instrumentation or valving to repeat the generation of pump curves.

3. Test Results:

Pump mapping in all of the different configurations showed the expected pump performance. Figure 15 shows the pump curve generated during the EGTF configuration testing. These results were also similar to previous tests

on earlier version of this pump[7]. Due to the use of the CWCS-E, the pump speed was input as "counts," as opposed to RPM.

4. *Comparison to Development Specification:*

These results show the minor decrease in flow performance associated with the increasing resistance across the thermal loop. Per the PLSS development specifications, the thermal loop will nominally operate with a 200 lb/hr (91 kg/hr) flow rate and require a head rise from the pump between 5.3 psid (6.5 kPa) for the PLSS only loop and 9.8 psid (67.6 kPa) for the PLSS integrated with the vehicle interface loop. The data produced through PIA testing, once the speed was converted from counts to RPM, indicate that with a pump speed of 3820 RPM, the flow rate will vary from approximately 202 lb/hr and 188.72 lb/hr across these different pressure drop configurations. Based on the allowed flow rate range of the thermal loop of 170-220 lb/hr, the pump performance was determined to be adequate.

## F. Section 27: SWME Controller Check

1. *Objectives:*

The objectives of PIA 27 were to 1.) Verify proper functioning of the Spacesuit Water Membrane Evaporator (SWME) Back Pressure Valve (BPV) controller by visual confirmation of BPV poppet movement, 2.) Verify SWME controller automated outlet temperature control, and 3.) Verify functionality of Thermal Loop Thermal Control Valve (TCV) via DCM input. The remainder of this section will focus on Objective 2. Objective 1 was simply confirmed by watching the valve move and objective 3 is not as relevant due to changes in TCV design that have occurred since this test was performed.

2. *Test Configuration:*

The PLSS 2.0 assembly was completed prior to this test sequence and attached was to the Space Suit Assembly Simulator (SSAS) for this test with a 2 inch diameter vacuum line connected to the SWME BPV via a custom tubing adapter. Additional details on this test configuration can be found in reference 3.

3. *Test Results:*

Controlling SWME heat rejection is achieved by the opening and closing of the BPV until the desired outlet water temperature is attained. Opening the valve increased heat rejection rate and closing the valve decreases the rate. The heat rejected by the SWME is dependent upon the heat load on the PLSS Thermal Loop and characterized by the SWME inlet water temperature. Test results from the SWME with vacuum access phase are summarized in
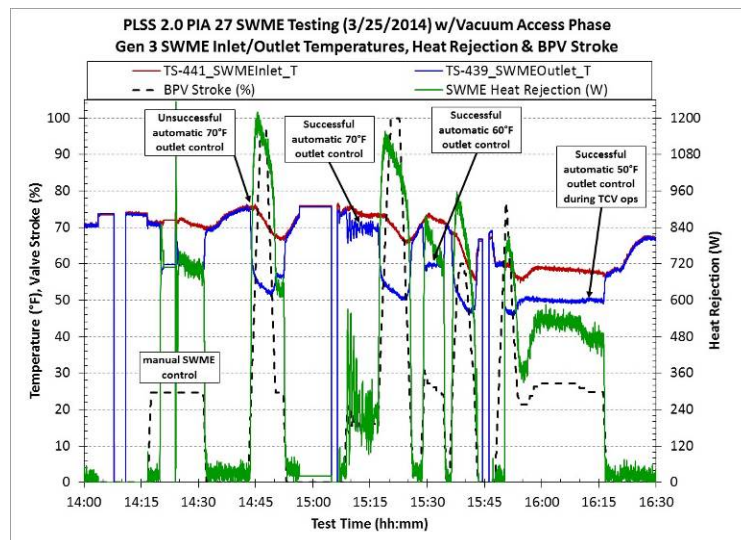
Figure 16. PIA 27 SWME Inlet/Outlet Temperatures, BPV Stroke, and Heat Rejection During Vacuum Testing.

Figure 16, which plots SWME inlet/outlet temperatures, BPV step counts (valve stroke) in percentage terms, and SWME heat rejection. An initial attempt to control the SWME outlet temperature to 70°F (21°C) using the algorithm programmed into the DACS failed leading to changes in the algorithm that consisted of increasing the time delay between subsequent BPV adjustments. The second attempt to control to 70°F (21°C) succeeded with scatter up to ±2°F, while the following 60°F (15.5°C) and 50°F (10°C) test points succeeded with much smaller scatter.

The two fully open BPV test runs at 14:50 and 15:20 test time yielded valuable data regarding SWME heat rejection performance at the design condition 50°F (10°C) outlet temperature. In particular, heat rejection from these two transient test runs can be used to approximate SWME

heat rejection at 50°F (10°C) outlet temperature. PLSS team thermal analysts have significant experience scaling transient SWME performance, as well as accounting for performance changes over time. SWMEs typically have a "glory day" where they perform better at the beginning of life, drop off to a nominal level, and then slowly degrade

over time. This set of tests was performed at the beginning of life, so the "glory day phenomena was considered. Additional details can be found in reference 3, but it was estimated that this unit provide approximately 1000 W of heat rejection at steady state with an exit temperature of 50°F (10°C) based on this set of testing. Additional SWME performance data from PLSS 2.0 testing can be found in reference 5.

4. Comparison to Development Specification:
This series of tests could be compared to development requirements for the SWME that define a total heat rejection of at least 810 W and the TCL had the ability to control the outlet temperature of the SWME to 50°F (10°C) ±2°F at a variety of inlet temperatures. Based on this test series, it was determined that PLSS 2.0 met these requirement. Figure 16 notes periods where the CWCS successfully controlled the SWME outlet temperature to 50°F, as well as set points of 60°F and 70°F. In addition, there are several points where the heat rejection exceeds 810 W and this data lead to an estimate of 1000 W for steady state performance.

IV. Conclusion

The overarching conclusion gleaned from PLSS 2.0 testing, and specifically PIA testing, is that building and testing hardware and systems is essential to developing complex systems for spaceflight applications. PIA testing produced information, capabilities, and experience that enabled the successful demonstration of PLSS 2.0. This series of tests verified important characteristics of components like: cleanliness, workmanship, calibration, or control points and then used that information to evaluate portions of PLSS 2.0 in more and more complex ways that culminated with the entire integrated system performing simulated EVAs. Without these early PIA tests, this would not have been possible.

In addition, the data produced provides a valuable characterization of different components and well as subsystems. In many cases results of these tests provided direction on future hardware or system design iterations. Many of the tests were also able to provide an indication of how well the technologies and system designs were meeting requirements, or in some cases brought light to requirements that needed to be revised.

The data produced during PIA testing and subsequent PLSS 2.0 testing is a tremendous step towards developing the next PLSS that can be used to explore space, the Moon, or Mars. Technical details from these tests that are not documented in this paper can be found in Reference 3 and can be provided by contacting any of the authors listed. In addition, this test program is a good reference for technology developers or systems engineers as an example of how a test program can start with functional checks and incrementally build into a complex integrated system being demonstrated through high fidelity simulated operational scenarios.

Acknowledgments

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