

# Space Suit Portable Life Support System Test Stand Overview

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The Space Suit Portable Life Support System (PLSS) must meet stringent requirements during testing prior to any Human in The Loop (HITL) activity on the ground or in space. The PLSS Test Stand (PTS) is intended to fully test an Exploration PLSS either with or without the Hard Upper Torso (HUT) and Display and Control Unit (DCU). It can test the system at either ambient pressure or at vacuum. This test stand shall bridge the gap between basic component level testing and a HITL test. The stand will be able to test the system level integration of all components in the PLSS. The PTS will be able to simulate human metabolic functions using a vent loop and thermal loop and provide suit recharge operations. It can operate with 100 percent nitrogen for preliminary testing, 100 percent oxygen for final testing, and heliox (99.5 percent O<sub>2</sub>, 0.5 percent He) for leak checking. This report will provide a design overview of the test rig. It will also review lessons learned, future upgrades, and potential test capabilities.

## Nomenclature

AFSA	=	Auxiliary Feedwater Supply Assembly
ATCL	=	Auxiliary Thermal Control Loop
DCU	=	Display and Control Unit
ESCU	=	Exploration Service and Cooling Umbilical
EVA	=	Extravehicular Activity
CEM	=	Controlled Evaporative Mixer
CDR	=	Critical Design Review
CO <sub>2</sub>	=	carbon dioxide
CWS	=	Caution and Warning System
DP	=	Delta Pressure
FSA	=	Feedwater Supply Assembly
GSE	=	Ground Support Equipment
HITL	=	Human in the Loop
HMS	=	Human Metabolic Simulator
HUT	=	Hard Upper Torso
IVA	=	Intravehicular Activity
JSC	=	Johnson Space Center
LCVG	=	Liquid Cooling and Ventilation Garment
NPRV	=	Negative Pressure Relief Valve
N <sub>2</sub>	=	nitrogen
O <sub>2</sub>	=	oxygen
OVL	=	Oxygen Ventilation Loop
PLSS	=	Portable Life Support System
PIA	=	Pre-Installation Acceptance
PIPA	=	PLSS Interface Pad Adapter
POA	=	Primary Oxygen Assembly
PPRV	=	Positive Pressure Relief Valve

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- PTCL = Primary Thermal Control Loop
- PTS = PLSS Test Stand
- RCA = Rapid Cycle Amine
- RV = Relief Valve
- SCC = Service Cooling Connector
- SOA = Secondary Oxygen Assembly
- SWME = Spacesuit Water Membrane Evaporator
- SxEMU = Short Exploration Extravehicular Mobility Unit
- xEMU = Exploration Extravehicular Mobility Unit

## I. Introduction and Background

### A. Introduction

The Portable Life Support System (PLSS) Test Stand (PTS) in Figure 1 is intended to test integrated system level capabilities of space suits prior to running a Human in the Loop (HITL) test and certifying the unit for flight. It shall test the suit in two distinct environments and two distinct configurations. It shall test the suit at ambient pressure for initial checkouts, and then in a vacuum chamber to simulate the space environment. It is intended to test a PLSS by itself, or a PLSS with a Hard Upper Torso (HUT) and Display and Control Unit (DCU). This second configuration is commonly referred to as the Short Exploration Extravehicular Mobility Unit (SxEMU) as it does not include the legs or the helmet assemblies. In the SxEMU configuration, the stand can test all electrical and pneumatic functions minus the lights & audio included on the helmet. The electronic functions shall be tested at the component level with subsequent integrated HITL tests.

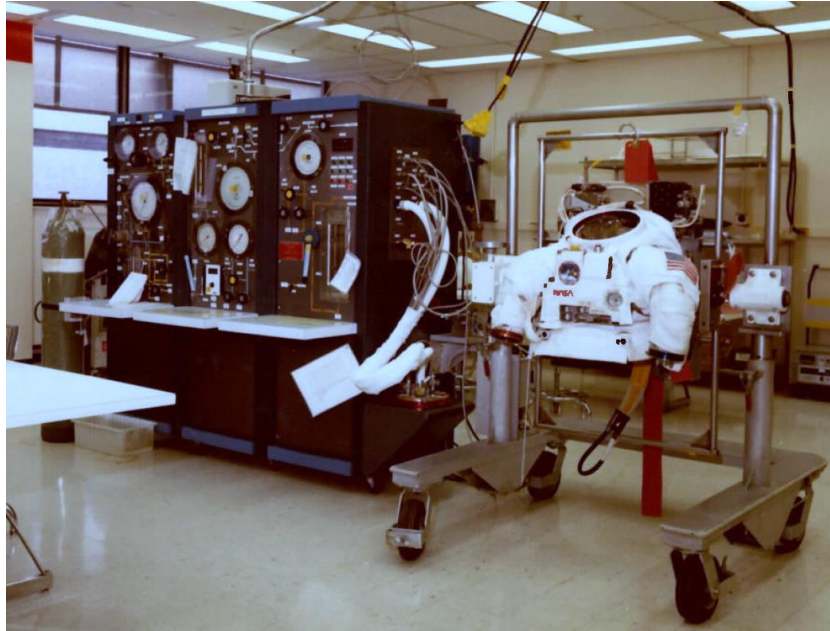
This PTS is considered a system level test rig which can test the entire PLSS or SxEMU. At a verification step level lower, there are component level test rigs for testing components of the PLSS such as CO2 sensors, fans, pumps, regulators and more. While the PTS may be able to be configured for testing some components, it is intended for system level testing. Component level testing is more suited for dedicated and simpler rigs for each application. In conjunction with developing the PTS, there are also three other component level high fidelity rigs in work to test components for flight, the Water Flow Delta Pressure Rig (WFDP), the Oxygen Gas Sensor Test Stand (O2GSTS), and the High-Pressure Oxygen Test Stand (HPOTS). These are being developed as separate efforts but follow similar build processes as the PTS.



**Figure 1. PLSS Test Stand (PTS)**

## B. History and State of the Art

The PTS design is based on the EMU Test Stand II design.<sup>7</sup> The main gas and water loops follow similar design schemes as the EMU Test Stand II. The PTS has additional capability to test at vacuum and simulate metabolic loads. It also integrates modern sensors for increased accuracy as well as additional sensors for increased functionality for testing. Furthermore, it adds modern software-based logging of data with a near complete set of electronic based sensors. This stand is also specifically designed to be able to test the new advanced Exploration Extravehicular Mobility Unit (xEMU) design as well as other advanced suit designs. The previous EMU Test Stand is pictured for reference in Figure 2.



**Figure 2. EMU Test Stand**

For xEMU, ambient and vacuum state of the art N<sub>2</sub> test system level test systems were developed by the PLSS team that have also influenced the PTS design. Chamber C and the Pre-installation Acceptance (PIA) test systems are designed to test the PLSS at vacuum or ambient respectively with nitrogen. These systems have been used to test the PLSS & SxEMU and have helped the team learn of gaps and design improvements for both the suit and the test system. Compared to those systems, the PTS is designed to combine the vacuum and ambient capability, add the capability to test with oxygen, and ultimately certify the suit for human testing and flight.

## C. High Level Capabilities

At a high level, the PTS can simulate the load from a human crewmember, provide system level measurement, verification, and calibration, perform leak checks, and provide fluid charge/recharge. It can simulate the crewmember by capturing the vent and thermal loop lines from the PLSS, adding heat, humidity, and carbon dioxide (CO<sub>2</sub>), and passing it back into the PLSS. It also can provide recharge or simulation capability for the oxygen (O<sub>2</sub>), water, and power for the suit. While the thermal and vent loop fluids are passing through the PTS, they are measured and compared with expected values to verify that the suit is operating correctly. The stand also connects to the avionics system, including the Caution and Warning System (CWS), to read internal suit systems while testing the PLSS or SxEMU.

## D. Requirements

The PLSS test stand requirements were written during suit development and have evolved as the design of the suit has evolved. The original test requirements were to perform all the checkouts in the PLSS pre-installation acceptance test matrix, local document number PLSS-0006, which references the various test objectives, requirements, criteria,

and the associated procedures.<sup>1</sup> Beyond PLSS-0006, there are a few NASA-wide and JSC-specific requirements documents that defines the requirements for documentation, certification, and commissioning of Ground Support Equipment (GSE). This included drawings, certifications of compliance, a full manual including Familiarization, Operations, Maintenance, Test Service and Calibration (FOMTSC), Hazard Analysis (HA), Failure Mode Effects Analysis (FMEA), Oxygen Compatibility Assessment (OCA), Pressure Systems Design Review (PSDR), LabVIEW code, and a Software Design Document (SDD). The design space was very open due to not having a full test article designed/ready at the inception of this project. Therefore, the EMU test stand was reviewed as a starting point to base design on and iterated on from that point as the test article became more mature. After delivery, a delta Critical Design Review (CDR) was conducted to address some of the forward work required on the original design to ensure it met all base requirements and NASA safety guidelines.

## E. Ground Support Equipment (GSE) Description

This system shall test Class 1 hardware for spaceflight, so this system is classified as Ground Support Equipment (GSE). The purpose of GSE is to ensure hardware and software traceability and to provide a high level of confidence in all components and material that interface with flight hardware. This GSE hardware being developed is compliant with both NASA-STD-5005, “Standard for The Design and Fabrication of Ground Support Equipment” and CTSD-ADV-1540 “Test Equipment Requirements for the Exploration Extravehicular Mobility Unit (xEMU).”<sup>2</sup> While the overall PTS assembly will be GSE, it is only the critical elements that control a hazard or interface with the flight hardware that will maintain this traceability and fidelity. This includes things like electrical connectors that mate to the flight hardware, structure that holds the flight hardware, the fluid loops passing fluid into the flight hardware, and sensors that record data. Non-Critical GSE elements like panels and panel screws are exempt from the level of pedigree typically required for GSE, as allowed by CTSD-ADV-1540.

## II. Capabilities

### A. Overview

The PLSS Test Stand capabilities are primarily assessed on a loop-by-loop basis. A simplified piping and instrumentation diagram of the stand is shown in Figure 3. For this simplified graphic, internal regulation, safety, and support components have been removed for clarity to highlight major functional systems. Each loop shall be discussed individually in separate sections.

- The “**Water Loop**” serves to charge the Feedwater Supply Assembly (FSA) and Auxiliary Feedwater Supply Assembly (AFSA) in a SxEMU assembly and evaluate the performance of the PLSS Primary Thermal Control Assembly (PTCL) and Auxiliary Thermal Control Loop (ATCL).
- The “**Low-Pressure Oxygen Loop**” provides the equipment to evaluate the Oxygen Ventilation Loop (OVL) in a PLSS or SxEMU assembly including the suit system’s ability to provide flow and carbon dioxide scrubbing. This loop also includes the metabolic simulation system including water and carbon dioxide injection using Controlled Evaporative Mixers (CEMs)
- The “**High-Pressure Oxygen Loop**” provides the capability to charge and test the PLSS Primary Oxygen Assembly (POA) and Secondary Oxygen Assembly (SOA), both of which are nominally charged to 3000 PSIA with 100% oxygen.
- The “**Vacuum Loop**” includes a chamber & pumping system capable of being pulled down to sub-ambient conditions to test the SxEMU/xPLSS at vacuum pressures and provide metabolic simulation and purge capabilities.
- The “**Power Simulation, Software, & Data System**” is provided to simulate the batteries of the PLSS if needed, and record data from all the sensors & readouts both on the stand and within the PLSS.

The stand can be used to test individual loops on a PLSS, or the test stand can be used to perform system level functionals to evaluate the performance of a fully built PLSS or in preparation for HITL. The PTS also provides the ability to recharge & monitor the suit avionics via the Exploration Service and Cooling Umbilical (ESCU) for water and gas and a battery simulator system. The PTS provides the capability to test a spacesuit life support system at both vacuum and ambient pressure.

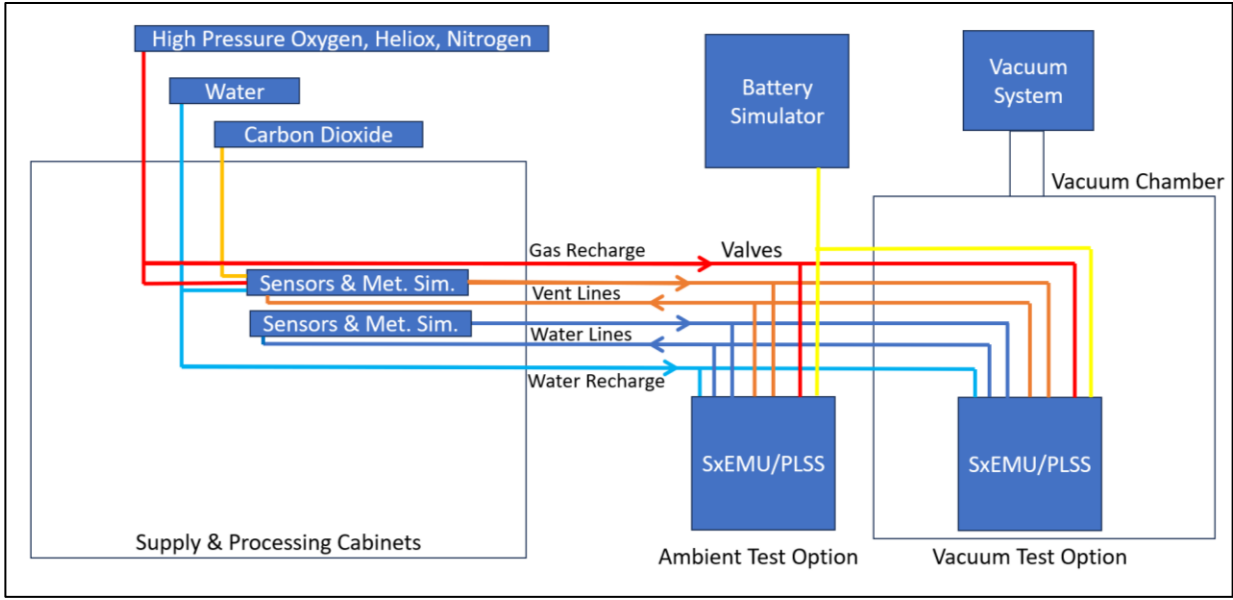


Figure 3. Simplified PLSS Test Stand combined schematic.

### B. PTS Demonstration Capabilities

As NASA received the rig from KBR an assessment was made on the type of tests it could run to meet the goals in PLSS-0006.<sup>4</sup> There are many tests in PLSS-0006 that may be verified at component level, but to be complete, the list in Table 1 was made to show the entire list of tests that could be verified.<sup>5</sup> They are either listed as direct, indirect, or no. If it is direct, then that means the PLSS test stand can directly demonstrate the capability. If it is indirect, then it is expected to be able to be verified but only in an indirect manner such as functional verification of controllers operating on the PLSS. Some items are not able to be verified and may be intended for lower-level component testing like logic flow of controllers, though others may be potential future upgrades of the rig such as CO<sub>2</sub> calibration. Note some of the identities in the descriptions in the table below has been simplified for clarity.

Table 1. PLSS-0006 PLSS Test Stand Demonstration Capability<sup>4,5</sup>

Type	SEQ	Test Description	PTS Demonstration Capability
Avionics	1.0	CWS Logic Flow Verification	No*
Avionics	1.1	CWS Post-Installation Functional Verification	Indirect
Avionics	2.0	POA Controller Logic Flow Verification	No*
Avionics	2.1	POA Controller Post-Installation Functional Verification	Indirect
Avionics	3.0	SOA Controller Logic Flow Verification	No*
Avionics	3.1	SOA Controller Post-Installation Functional Verification	Indirect
Avionics	4.0	OVL Controller Logic Flow Verification	No*
Avionics	4.1	OVL Controller Post-Installation Functional Verification	Indirect
Avionics	5.0	PTCL Controller Logic Flow Verification	No*
Avionics	5.1	PTCL Controller Post-Installation Functional Verification	Indirect
Avionics	6.0	ATCL Controller Logic Flow Verification	No*
Avionics	6.1	ATCL Controller Post-Installation Functional Verification	Indirect
Avionics	7.0	DCU Performance Detailed Verification	Indirect

Avionics	7.1	DCU Functional Verification	Indirect
Avionics	7.2	DCU Flow, Actuation Force Verification, Calibration Check	Indirect
Avionics	8.0	Telemetry Functional Verification Tones/Communication	No <sup>†</sup>
Avionics	9.0	PLSS Power up, display, tones, and telemetry verification	Indirect
O2 Loop	10.0	Primary Oxygen Servicing and Leakage and Calibration check	Direct
O2 Loop	11.0	Secondary Oxygen Servicing and Leakage and Calibration check	Direct
O2 Loop	11.1	Temperature Sensor Calibration Check	No <sup>•†</sup>
O2 Loop	12.0	Ventilation Loop Gas Structural Leakage and Calibration Check	Direct
O2 Loop	13.0	POA/SOA Flow Verification and Regulation	Direct
O2 Loop	13.1	SOA Flow Verification and Regulation	Direct
O2 Loop	14.0	Gas Sensor Calibration Check	No <sup>•†</sup>
O2 Loop	15.0	Gas Sensor Calibration Check	No <sup>•†</sup>
O2 Loop	16.0	Check Valve Seating and Back-Leakage	Direct
O2 Loop	17.0	Fans Functional Check, and Flowmeter Calibration Check	Direct
O2 Loop	18.0	PPRV Crack, Reseat, Flow	Direct
O2 Loop	19.0	NPRV Crack, Reseat	Direct
O2 Loop	20.0	RCA, Heat Exchanger, & Temperature Sensor Functional Verification and Cal Check	Indirect
O2 Loop	21.0	Ambient pressure Sensor Functional Verification	Direct
Thermal Loop	22.0	Thermal Loop Servicing/Structural/Leakage and Calibration check	Direct
Thermal Loop	23.0	Pump Functional Check, and Check Valve back-flow leakage, and Filter Flow Verification	Direct
Thermal Loop	24.0	Pump Outlet Check Valve Crack	Direct
Thermal Loop	25.0	Pump Outlet Check Valve Back-leakage	No <sup>•†</sup>
Thermal Loop	26.0	RV Crack, Reseat, Flow Verification – Static (Pump OFF)	No <sup>†</sup>
Thermal Loop	27.0	RV Crack, Reseat, Flow Verification – Dynamic (Pump ON)	Direct
Thermal Loop	28.0	Thermal Control Valve Flow and Flow Control	Direct
Thermal Loop	29.0	Thermal Control Valve Shut-off Leakage	No <sup>•†</sup>
Thermal Loop	30.0	Temperature Sensor Calibration Check	No <sup>•†</sup>
Thermal Loop	31.0	Temperature Sensor Calibration Check	No <sup>•†</sup>
Thermal Loop	32.0	SWME Degassing Verification	Direct
Thermal Loop	33.0	ATCL servicing/Structural/Leakage and Pressure Transducer Calibration check	Direct
Thermal Loop	34.0	Pump Functional Check and Filter Flow Verification	Direct
Thermal Loop	35.0	RV Crack, Reseat, and Flow	Direct
Thermal Loop	36.0	ATCL Temperature Sensor Calibration Check	No <sup>•†</sup>
Thermal Loop	37.0	Heat Exchanger Degassing Verification	Direct
Power	38.0	Power Draw, Operating Voltage, Internal Power Quality Verification	Indirect
Power	39.0	In-Situ Charging Verification with Battery Management System	No <sup>§</sup>
Power	39.1	Battery OCV and Loaded Voltage Verification	Indirect
Power	39.2	Battery OCV and Loaded Voltage Verification	Indirect

Avionics	39.3	PLSS Integrated telemetry output verification, Comm check	Indirect
Avionics	39.4	PLSS Integrated telemetry output verification, data-logging verification	Indirect
Avionics	39.5	SxEMU Lighting and Video Verification	No <sup>‡</sup>
Thermal Loop	40.0	FSA Servicing, Charge/Discharge Verification	Direct
Thermal Loop	41.0	FSA Servicing, Charge/Discharge Verification	Direct
Other	42.0	Crew Interfaces Force/Torque Measurement	No <sup>‡</sup>
Integrated	43.0	SWME Performance Mapping	Direct
Integrated	43.1	ATCL Heat Exchanger Performance Verification	Direct
Integrated	43.2	RCA Performance Mapping	Direct
Integrated	43.3	PLSS Vacuum Performance Verification	Direct
Integrated	44.0	SxEMU Vacuum Performance Verification	Direct
Integrated	45.0	xEMU Pre-EVA Check (in-flight)	No <sup>‡</sup>

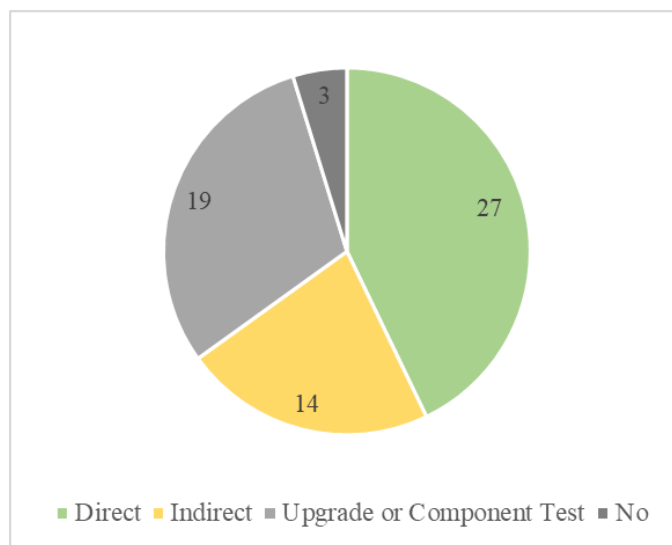
\*Could be addressed with component level testing

†Could be addressed as future PTS upgrades

‡Cannot be addressed with the PTS due to needing to a more complete suit or involve a crewmember

§The Battery Management System (BMS) is separate, but could be brought it to test while suit is connected to PTS

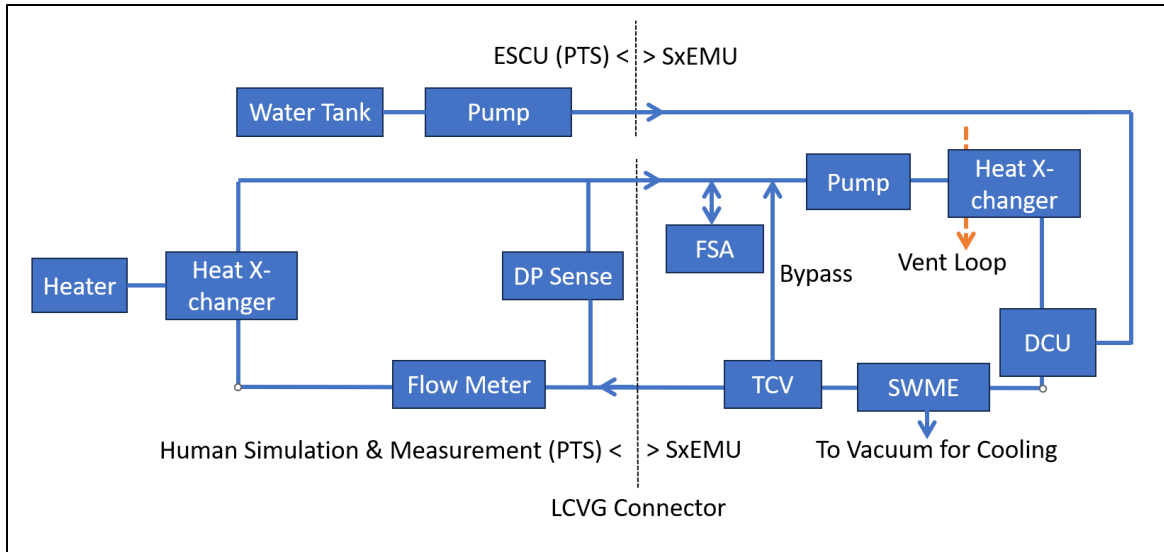
To better quantify the requirements for verification, Figure 4 demonstrates the capabilities able to be verified, both directly and indirectly and requirements that are not verified but may be verified at the component level or given an upgrade to the rig.



**Figure 4. PLSS-0006 PTS ability to verify requirement.**

### C. Water Loop

A SxEMU or PLSS water loop is a partially closed loop system providing re-circulating pumping, water cooling, sensing, Thermal Control Valve (TCV) for cooling control, and feedwater supply to support water loss through the water-cooling process. Water is cooled and a portion is expelled using a vaporization process with the vacuum environment using the Spacesuit Water Membrane Evaporator (SWME). A diagram showing a simplified view of water loop for the SxEMU and the PTS is shown in Figure 5. Note this is a simplified diagram only showing major elements; many details are not included such as pressure sensors, temperature sensors, RVs, and valves.



**Figure 5. Simplified water loop testing diagram**

A SxEMU connects to the PLSS Test Stand water loop through a PTCL and ATCL connector, like those that would be connected to a Liquid Cooling and Ventilation Garment (LCVG) water loops in a nominal xEMU configuration. The water loop provides a single loop to test both the PTCL and ATCL systems with valves used to select which loop should be tested. This means that when testing a NASA PLSS, only one loop can be run at a time as not to introduce water contamination or flow issues. The testing loop contains a flow meter to verify pump flow in either loop. It also contains a pressure transducer to verify the fluid loop pressure and perform structural leakage evaluations by verifying that the pressure is maintained during prescribed holding leak check periods.

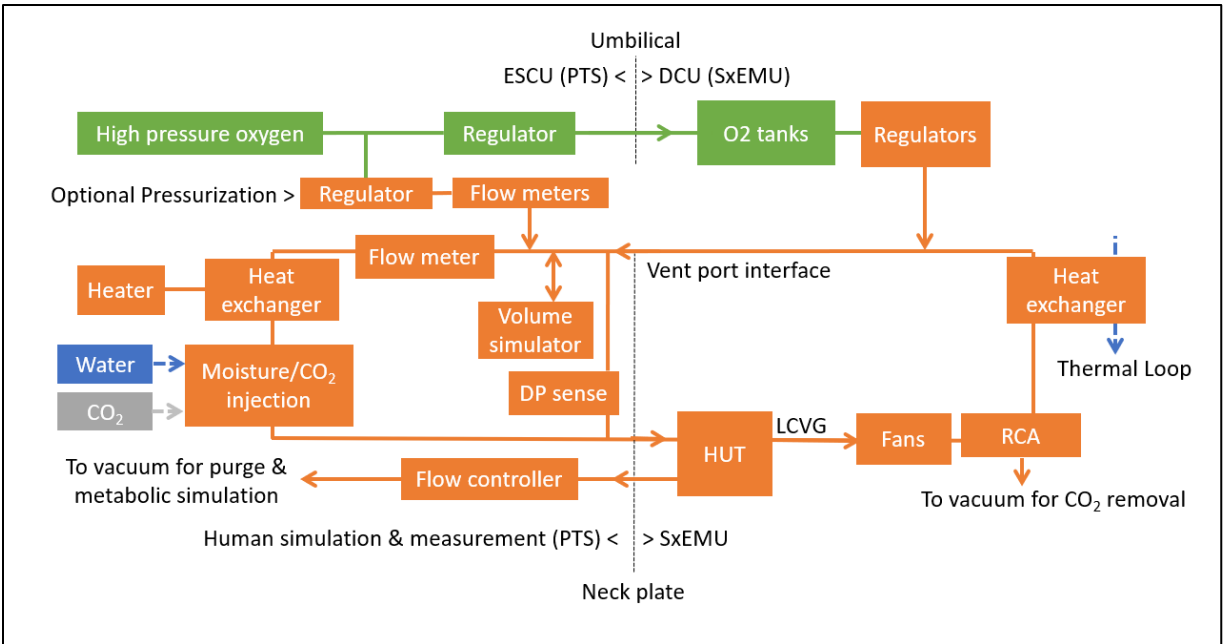
Beyond telemetry verification, the water loop contains two systems designed to challenge the SxEMU and verify its ability to meet objectives. The first of these is a heat exchanger that can be used to heat the water- something nominally accomplished by a crew member in an LCVG. Heat exchanger temperature set points can be programmed and verified using data from the inlet and outlet temperature sensors to achieve varying thermal loading on the suit. This allows the test team to verify the performance of the suit's cooling devices such as the SWME on the xEMU in maintaining the required outlet temperature across the required crew loading conditions. A second test can use the thermal bulkheads to inject gas to verify a suit's ability to meet the degassing requirement. The degassing performance can be monitored through an operator observing the water in the loops through a sight glass.

In addition to evaluating the thermal control loops, the PTS also provides the capability to perform a recharge of the FSA and AFSA in a SxEMU. The recharge lines are connected through a GSE umbilical and a Service Cooling Connector (SCC), like the ESCU that is nominally used for recharge operations of the xEMU. The SCC is connected to the Display and Control Unit (DCU) on the SxEMU allowing for nominal recharge of these loops.

The PTS test loop interfaces through PTCL and ATCL connectors mounted in the neck plate and the recharge interfaces through the DCU. Both the neck plate and DCU require the Hard Upper Torso (HUT), so the water loop can currently only be utilized with the SxEMU. Furthermore, the FSA and AFSA are packaged inside the hatch, so they are only available in an SxEMU configuration. To test at the PLSS level, the PTS would need FSA/AFSA stand ins or a similar reservoir.

#### **D. Low-Pressure Oxygen Loop**

A SxEMU or PLSS OVL is a partially closed loop system providing re-circulating gas flow from fans, cooling via heat exchanging with the water loop, carbon dioxide removal, sensing, and oxygen supply to account for CO<sub>2</sub> removal, metabolic consumption, and leakage. Carbon dioxide is removed using the Rapid Cycle Amine (RCA) swing bed. A diagram showing a simplified view of the high- and low-pressure oxygen loop for the SxEMU and the PTS is shown in Figure 6. Note this is a simplified diagram only showing major elements; many details are not included such as pressure sensors, temperature sensors, RVs, and valves.



**Figure 6. Simplified high & low-pressure oxygen loop testing diagram.**

The PTS low-pressure oxygen loop contains systems to validate and challenge the SxEMU OVL as well as flow controllers to perform loop pressurization in place of the regulators in the POA or SOA and characterize suit and PLSS leakage. All these functions interface to the suit through its neck plate. A duct coming from the hatch outlet terminates in at the neckplate. The neckplate seals with the duct to capture gas leaving the PLSS and gas is returned from the PTS into the suit cavity where normal intake back to the PLSS occurs through the open vent loop port on the LCVG connector. Because of the use of neck plate interfaces, the low-pressure oxygen loop can currently only be used to evaluate a SxEMU; however, the test stand contains the necessary instrumentation to test a PLSS-only configuration, so with the addition of a PLSS Interface Pad Adapter (PIPA) mating fixture like those used in Chamber C and PIA testing, the PTS could perform PLSS-only vent loop testing.

Flow meters and a pressure transducer allow the verification of PLSS telemetry for flow rates and loop pressure. The pressure transducer can also be used to verify pressure levels during a structural leakage evaluation. To simulate the metabolic inputs of carbon dioxide and water vapor, three Controlled Evaporative Mixers (CEMs) are installed that functionally make up the Human Metabolic Simulator (HMS). Each CEM has an inlet for CO<sub>2</sub> and water vapor. The CO<sub>2</sub> is sourced from an external bottle connected to the stand and the water is sourced as a liquid from a Millipore canister pressurized by a facility low pressure panel. The operator can control the flow rate of CO<sub>2</sub> and water into the CEM to match various metabolic rates to achieve a desired metabolic profile. Inside the CEM, the water and CO<sub>2</sub> are heated to a commanded temperature (normally 100°C) to evaporate the water into a mixture that is fed into the OVL. The return lines to the suit are heat traced to mitigate cooling and condensing of the water. Injection of this CO<sub>2</sub> and water vapor is important to challenge and test the performance of a suit's carbon dioxide and humidity removal system (an amine swing bed in the xEMU) and provide varying CO<sub>2</sub> levels to verify performance of the suit's carbon dioxide sensors.

The low-pressure loop has a volume simulator that can be toggled open or closed. This provides the approximate suit volume of an xEMU to verify the PLSS ability to pressurize the suit volume without being in a SxEMU or xEMU configuration.

Three lines with flow controllers and one with a flow meter and a metering valve are also installed in the low-pressure oxygen loop. They take gas regulated down from the high-pressure oxygen loop and feed it into the OVL or through bulkheads that can be connected via flex hoses to other suit locations or components. Each flow controller or meter has a different range allowing the operator to select the line most suited to the desired activity or work through levels of granularity for characterizing leak rates. The highest range may be used as an alternative method for pressurizing the OVL rather than through the POA or SOA. The medium ranges may be used for measuring the flow required to off-set leakage to calculate the leakage rate for a SxEMU level leak check and the smallest range may be used to do the same for a PLSS level leak check. The option of connecting though bulkheads with flex hoses, however, allows the test operator the option to use this loop with a variety of components for any number of tests.

## E. High-Pressure Oxygen Loop

The high-pressure oxygen loop is used to charge and evaluate the POA and SOA on the PLSS. It also provides high-pressure gas to the low-pressure oxygen loop for the flow controller/meter lines described in Section D. Despite its name, the high-pressure oxygen loop can supply high-pressure oxygen, nitrogen (N<sub>2</sub>), and heliox (0.5 percent He and 99.5 percent O<sub>2</sub> mixture) to the suit under test. Oxygen and nitrogen would nominally be used for suit testing while heliox would be used for leak checks. The heliox can be used to charge a bottle prior to flight to verify it is leak tight before shipping it and used in service with an astronaut with the very low concentration of helium. An air-operated valve tied into the facility emergency management system (EMS) sits between the high-pressure gas inlets and the rest of the PTS (including the test article) and isolates the gas if facility oxygen levels are too high or low or the EMS is otherwise activated.

The high-pressure oxygen loop interfaces to the suit through the SCC and DCU, and thus, can currently only be used to evaluate a SxEMU. Before the umbilical, it contains two shut-off valves, one for the primary oxygen line connected to the POA and one to the secondary oxygen line connected to the SOA. With this valve, the test operator can choose to evaluate the POA and SOA charging and evaluating performance individually or simultaneously. A pressure transducer upstream of this valve verifies the inlet pressure provided to the POA and/or SOA.

## F. Vacuum Loop

A vacuum chamber large enough to accommodate a HUT and PLSS provides the environment required for vacuum testing. The vacuum vessel as shown in Figure 7.a is a semi-custom unit made by LACO. The vacuum pump system as shown in Figure 7.b is located across a wall from the vacuum chamber for noise concerns. The vacuum system was designed in-house and at the heart of the system is an Edwards vacuum pump with a nitrogen purge system and a captured exhaust. The purge system prevents the water vapor emitted from the PLSS from damaging the pump components. The captured exhaust prevents the oxygen in the room being displaced by the purge nitrogen. The chamber can be isolated from the vacuum system via a gate valve mounted directly to the vessel outlet flange. The pump can lower the pressure in the chamber to < 0.01 Torr and the chamber has a leak rate of 0.13 Torr/hr. when isolated from the pump.

The PLSS interfaces with the vacuum chamber via the PLSS holding frame, the frame is mounted on rails to allow the frame to slide in and out of the chamber like a drawer. The frame can support up to 500 lbs. and can be rotated to hold the PLSS in either a vertical or horizontal orientation.



a) Vacuum Chamber



b) Vacuum Pump System

Figure 7. Vacuum System

## G. Power Simulation, Software & Data System

A separate battery simulator cart is intended to be coupled with the PTS to simulate the batteries in lieu of batteries being installed on the PLSS. Wires can be hooked directly inside the PLSS battery ports from the battery simulator. PLSS batteries can also be installed on the PLSS and charged using the Battery Management System (BMS) designed for test article charging in-situ.

The computer attached to the PTS can display all the pressure and flow transducer data, control select flow controllers, and display the information being sent from the PLSS. It also has the capability to record the data streams from all the instrumentation and test article on the rig. The rig utilizes LabVIEW as the software language. Since the rig is intended to test flight hardware, the rig will be classified as Class C, non-safety critical per 7150.2 “NASA Software Engineering Requirements”. Class C software requires additional detailed documentation for design, requirements, verification, and version control that will be created to manage the software on the rig.

### **III. Lessons Learned**

Building this test stand has been a long endeavor taking multiple years of design and development. It has not been without issue, although each one is being addressed and closed before testing later in the year. The stand is in work to meet JPR 1710.13 “Design, Inspection, and Certification of Ground-Based Pressure Vessels and Pressurized Systems” and NASA-STD-5005 “Standard for The Design and Fabrication of Ground Support Equipment” and CTSD-ADV-1540. Paramount to all, ensuring safety is a critical function especially with O<sub>2</sub> which has introduced some unfamiliar requirements requiring some additional attention to detail to be added. This following section shares some specifics of the rework in the hope that future systems may learn and adapt appropriately.<sup>3</sup>

#### **A. Specification Additions and Certification**

The following additions and certifications are listed to show the changes currently being implemented to meet requirements and certify the system.<sup>3</sup>

- After an Oxygen Compatibility analysis review, a selector valve was removed, and a check valve was added upstream of where the three gas options are combined. The heliox/nitrogen combined line originally connected to the HMS water can is now being fed off a lower pressure nitrogen source to reduce complexity and improve oxygen safety from the original design.
- Upon an audit of the rig at delivery, there were some cleaning concerns. Parts of the rig are being recleaned to reduce oxygen fire risks. The rig will be sampled during functional checks with nitrogen to verify cleanliness of the lines.
- After a pressure system design review, several regulators, RVs, and orifices were found to be insufficient for flowrate requirements and are being replaced to meet pressure systems requirements. Some RVs replaced were oversized and could lead to chatter creating an oxygen hazard. For the primary high-pressure RVs an upstream orifice was added to restrict flow to help with oxygen safety for the test article; however, it made it near impossible to size a standard RV. Therefore, the plan is to move the orifice downstream of the RV before the test article. Other RVs were undersized and had to be replaced to meet minimum flowrate requirements.
- Metabolic Consumption testing, Suit Leakage and Purge testing, and vacuum chamber depressurization operations require a purge system to allow the unit under test to dump gas to prevent over-pressurization inside the HUT. This system is being added to the PTS to meet these requirements. A flow controller is being added to flow gas from the internal suit volume to vacuum system to simulate both high flow for purge and low flow for leak and metabolic simulation.
- An electrical feedthrough for connectors for a DCU simulator is being added to the chamber.

#### **B. Improvements for a Future Design**

The following suggestions reflect an idealized scenario if the rig was to be built again. These summarize some of the lessons learned from above, coupled with some ways the rig could have been built to mitigate concerns and simplify design process and certification. While the rig does not currently reflect any of these changes, and functions adequately without them, a future rig could implement them to potentially reduce complexity and improve function.<sup>6</sup>

1. Remove or reduce custom welds. In many or all cases there exists Commercial off the Shelf (COTS) systems that could be configured to work without welding pieces together. Certification of custom welds is a complex process that is costly and time consuming.
2. Use a Millipore can for the water system. This can reduce the need for a custom tank with custom welds and could use a scale to check capacity. The water can also be pressurized or use a pump.
3. Tie the HMS Bronckhorst controllers into the data system directly instead of a custom controller.
4. Reduce electrical valve control and avoid and software safety critical electrical valves. Introducing complex software systems can be difficult to certify for flight hardware testing.

5. Use an open frame easily reconfigurable structure. This would allow for easier maintenance and upgrades. It also reduces oxygen hazard risk and controls.
6. Place calibration ports close to the sensor. This avoids excess tubing to clean and sample and can reduce any pressure drop concerns between sensor location and measurement point.
7. Increase control station capability. For a complex test with the SxEMU/PLSS, many views and tables can accommodate the technicians and engineers required.
8. Remove dedicated sense lines on the ventilation system and water systems and add pressure transducers directly on vent lines out of neck plate. Direct sense lines add extra complexity and do not increase accuracy.

## IV. Testing Plans

### A. SxEMU Testing Plan

Once the rework is implemented, the next step for the PTS is to support the execution of SxEMU tests. The government reference unit xEMU is currently not O<sub>2</sub> rated, so the testing will utilize the PTS N<sub>2</sub> capability. For an initial assessment of the test system, the team plans to perform simulated Intravehicular Activity (IVA) and Extravehicular Activity (EVA) test procedures. IVA includes all the operations to prepare the suit and prior to going into vacuum, such as recharge and functional verification at ambient. EVA includes all operations going into and including vacuum testing and metabolic simulation. This would utilize all PTS loops as well as the vacuum system.

First, consumable recharge is performed using the PTS version of the ESCU. SxEMU batteries are recharged with the attached xEMU Power Simulator, primary and secondary oxygen tank levels are topped off to 3000 psia using the high-pressure oxygen loop, and the FSA and AFSA are recharged using the water loop. These recharge activities constitute the “IVA” portion of the test sequence. Next, the testing moves into simulated airlock and EVA operations. Unlike a crewed EVA, the ESCU must be either disconnected before depressurization or left connected for the entirety of the EVA. The PLSS Test Stand has the appropriate passthroughs that would allow the ESCU to stay connected at vacuum, so the decision will be based on operator discretion. If the goal is to test airlock operations, then it is recommended to leave it connected; however, if the goal is to test the EVA, then it should be disconnected. These tests could be run separately, however, a de-mate at vacuum is not planned capability for the PTS. The same is true for the vacuum access line that provides vacuum access to the RCA during airlock depressurization. The test operator can either choose to use the RCA during depress and have vacuum access line connected for the duration of the EVA or to not use the RCA during depress and have the vacuum source be the chamber itself. Once the SxEMU is configured in the desired state, pump down will occur. Normal pump-down protocols including the 5 psia hold will be followed with a few exceptions. First, the PTS does not currently have a purge valve simulator that can be accessed by an operator outside of the chamber. This means that the Positive Pressure Relief Valve (PPRV), suit leakage, and RCA ullage will be the only method of reducing suit differential pressure once chamber depressurization begins. The suit pressure may take some time to reach the nominal 4.3 psid set point. Second, normal operating procedure has the ATCL turned on around 200 torr to avoid freezing and sticking of the ATCL heat exchanger. Because only one thermal loop (primary or auxiliary) can be run at a time as described in Section III subsection C, this will not be possible. The test director must decide prior to pump down if they would like to test the PTCL or ATCL in that run.

After pump-down, the simulated EVA will move into the running of metabolic profiles. PLSS-0039 defines various metabolic profiles including chamber run, aft-loaded, and max transient. The test director makes the determination as to which profile to run. To run a profile, the test operator commands the CEMs on the low-pressure oxygen loop to a specific set point to inject the amount of CO<sub>2</sub> and water vapor corresponding to each met rate and holds those values for the prescribed amount of time. On the water loop, the heat exchanger temperature set point is set so that the required Watts of heat are being injected into the thermal loop for each metabolic rate. When it is time to move to the next rate in the profile, the values on the CEMs and heat exchanger are adjusted. This is repeated until the profile has been completed. During the execution of the profile, operators will be monitoring telemetry from the SxEMU and PTS to validate sensor values and PLSS operation. This includes monitoring the flow rate of the thermal loop through the water loop flow meter, the OVL pressure through the pressure transducer on the low-pressure oxygen loop, and, if the ESCU is connected, monitoring for any back-leakage from the POA or SOA using the pressure transducer on the high-pressure oxygen loop.

At the conclusion of the vacuum test objectives, the chamber will be repressurized, and suit systems monitored to verify the function of the Negative Pressure Relief Valve (NPRV) if required and monitor PLSS health. Once the chamber is at sea level, the SxEMU will be shut down, and the test director can opt to do another IVA recharge.

The test procedure outlined above performs a high level check out of both the PTS and SxEMU. Once the rig has matured or if a new SxEMU unit is built, PLSS loop level tests may be performed if desired in accordance with the capabilities described in Section III.

## **B. Future Testing**

The PLSS Test Stand has a couple options for future testing that are either planned or anticipated as part of operation. After the SxEMU test with N<sub>2</sub>, an O<sub>2</sub> wetting test will be conducted later to verify the rig operation with oxygen. The SxEMU could potentially be rated for oxygen and re-tested using the more dangerous gas. Once the rig is verified with oxygen, it is expected the rig will be ready to test flight hardware. In which case it is anticipated that commercial space vendors such as Axiom Space may use this rig to test the Space Suit they are developing prior to running a HITL test and certifying it for flight.

## **V. Forward Work & Potential Improvements**

### **A. Future Upgrades**

The PTS has been configured for a SxEMU test at the time of writing; therefore, some future upgrades for testing a PLSS only configuration and verifying other systems and test points may be required. This list below indicates anticipated upgrades.

For PLSS only tests there are several key safety systems and test systems that will need to be added including:

1. PPRV and NPRV stand ins: need to be added since these are normally contained on the HUT which will not be present in this case.
2. Throttling valves on the vent, ATCL, and PTCL loops: will be required to simulate the delta pressure drop caused by the ventilation lines and thermal lines including the LCVG in the HUT
3. High pressure refill orifice: needs to be added to protect the PLSS from a rapid pressurization with oxygen that can be a fire hazard.
4. A PIPA mating fixture will need to be sourced to connect standard fluid lines fittings from the PTS to custom PLSS fixturing.

A couple of “nice to have” features that could test other things on the PLSS or SxEMU and complete more of the PLSS-0006 matrix would be the following:

1. Structural leak check capability on vent loop – Addresses verification capability on Table 1: SEQ#12
2. Throttling valve on the thermal loop - Addresses verification capability on Table 1: SEQ#26
3. Relative Humidity Sensor for the vent loop – Improves verification capability on Table 1: SEQ#20
4. Temperature insight on the charging line – Addresses on Table 1: SEQ#11.1
5. Temperature insight on the inlet and outlet of the vent loop – Addresses verification on Table 1: SEQ#20
6. Temperature insight on the inlet and outlet of water loop – Addresses verification Table 1: SEQ #30,31,36
7. Carbon dioxide sensor on the vent loop – Addresses verification on Table 1: SEQ #14,15
8. Radio pass through in chamber for vacuum test – Addresses on Table 1: SEQ #8

For a PLSS only test it would be nice to add a feedwater supply assembly stand in and an improved volume simulation pass through solution. Although these may require more review.

### **B. Component Level Testing Options**

Outside of testing a SxEMU or a PLSS, the PTS could potentially conduct many advanced component level tests with minor modifications, upgrades, and/or interface plates. The rig could test CO<sub>2</sub> removal systems such as the RCA inside or outside a vacuum chamber with some tubing adapters, a fan, and some wiring/controllers. The SWME could be tested inside the chamber with a pump, an interface plate, and some wiring and controllers added. Many other thermal loop or vent loop components could also be tested, although many may be easier to test in a dedicated component rig. For many of these tests, the needs will need to be evaluated on a case-by-case basis; however, this rig should be able to support most, if not all tests at a component level with only minor upgrades.

## **VI. Conclusion**

The PLSS Test Stand was built to do full system testing for PLSS units, certify PLSS units for HITL testing, and certify PLSS units as ready for flight. It was built to quality level required for NASA Ground Support Equipment, with some exceptions as allowed by a local document.

The test stand uses the fluid loops inside to charge the suit with water and oxygen; to inject moisture, CO<sub>2</sub>, and heat into the ventilation loop to challenge the scrubbing and cooling functions of the PLSS; and to measure the pressures and flow rates to verify performance in the PLSS is nominal.

There were many challenges when building this rig, both technical and systematic that led to rework on this rig. Most of the rig is perfectly functional, but though the examples learned here are intended to share to assist with any future similar system builds.

Current testing plans, after an extensive calibration run, are to simulate EVA and IVA activity using nitrogen in place of oxygen, and then to simulate EVA and IVA activity using oxygen after the SxEMU prototype has been oxygen rated or a commercial space suit vendor requires using the stand for certification. These tests will require operation of the PLSS on the SxEMU through its entire operational envelope. The oxygen tests will also provide data to certify the PLSS for a HITL test.

Future plans for the PLSS Test Stand include the addition of some component test capabilities, after the required rework. The test stand will also be available to outside groups for testing of their PLSS, although some modification is likely required before the stand is fully compatible with another PLSS. The rig could also test individual components if needed.

## **Acknowledgements**

The PLSS team would like to thank KBR and their lead, Jeremy Szydowski, for their work developing this rig.

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