Space Suit Portable Life Support System Oxygen Regulator History, Development, & Testing Results

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An oxygen regulator has been in development for the Exploration Extravehicular Mobility Unit (xEMU) Portable Life Support System (PLSS). The regulator provides the necessary oxygen pressure control for the crew member during prebreathe, Extra-Vehicular Activity (EVA), post EVA airlock operations, and Decompression Sickness (DCS) treatment. It has been over four decades since a new spacesuit oxygen regulator has been designed. The regulator and EMU that is presently used on the International Space Station (ISS) was developed for the space shuttle program without any significant changes made throughout its service life. The xEMU spacesuit oxygen regulator is based on the previous EMU Secondary Oxygen Pack (SOP). The new design integrates numerous improvements and changes including an innovative approach to regulator architecture, a more robust first stage pressure sensing mechanism, digital actuation control, and electronic pressure sensing. These upgrades replace manual control linkages, physical gauges, and enable infinitely variable pressure set points. The new setpoints can decrease prebreathe time and make in suit DCS treatment possible. Throughout its four iterations design concerns have been addressed, safety features have been added, and the envelope of the regulator designed to fit inside the xEMU PLSS package. This paper will review the history, design, testing, and lessons learned during the development of the xEMU PLSS Oxygen Regulator.

Nomenclature

DCS	=	Decompression Sickness
DP	=	Delta Pressure
DVT	=	Design Verification Test
EMU	=	Extravehicular Mobility Unit (current/previous generation – Shuttle/ISS)
EVA	=	Extravehicular Activity
ISS	=	International Space Station
IVA	=	Intra-Vehicular Activity
MEOP	=	Maximum Expected Operating Pressure
NVR	=	Non-Volatile Residue
O_2	=	Oxygen
OCA	=	Oxygen Compatibility Assessment
OPS	=	Oxygen Purge System (Apollo Secondary Oxygen Supply)
ORU	=	On-orbit Replacement Unit (ORU)
PLSS	=	Portable Life Support System

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POR = Primary Oxygen Regulator
PRV = Pressure Regulating Valve (POR/SOR)
RV = Relief Valve
SOR = Secondary Oxygen Regulator (xEMU)
SOP = Secondary Oxygen Pack (Shuttle/ISS EMU Secondary Oxygen Supply)
WSTF = White Sands Test Facility
xEMU = Exploration Extravehicular Mobility Unit (next generation)

I. Introduction

THE exploration External Mobility Unit (xEMU) Portable Life Support System (PLSS) is designed to provide all the necessary functions to keep the crewmember alive. One of the most critical functions is providing a pressurized Oxygen (O_2) environment in the suit for metabolic consumption. A Primary O_2 Regulator (POR) and Secondary O_2 Regulator (SOR) provide pressurized oxygen to the crewmember sourced from separate O_2 tanks for each regulator. The POR is designed to provide variable pressure setpoints for the crewmember for Extravehicular Activity (EVA) operations, prebreathe, leak checks, and DCS treatment. The SOR is a backup that provides pressurization support, carbon dioxide washout/removal, trace contaminant removal, and limited convective cooling in case of power failure, suit leaks, system failure, or POR failure via an open loop operating mode where one of the suit purge valves is opened and flowing to space. The regulators are designed to operate in vacuum and provide pressure at 4.3 psia for nominal EVA operations. This lower pressure is made possible by providing 100% O_2 instead of the typical 21% in ambient in the normal Earth atmosphere.

A. Regulator Design Safety

One of the most critical design points of these regulators is O_2 safety. 100% O_2 is extremely reactive and has caused multiple failures at NASA including Apollo 1, Apollo 13, and a fire during laboratory testing of the Shuttle External Mobility Unit (EMU). It is critical to learn from these failures to not repeat mistakes of the past. The most relevant failure to the regulator was from laboratory testing during the original development of the EMU for shuttle in 1980. The regulator failed and caused a catastrophic fire destroying the unmanned EMU. The probable causes were ‘dead end” particle impact in aluminum passages, adiabatic compression, and compression heating or rupture of thin aluminum sections(8). This led to design changes that can still be seen in the latest evolution of O_2 regulators, changing material of the high-pressure regulator body from aluminum to Monel, removing dead end passages and thin sections, eliminating rapid actuation upstream pressure valves, and specific inspection and finishing standards which remove burrs and other features which provide a high surface area to volume ratio.

The regulator, to provide needed reliability, includes a two-stage design. Two stage setup refers to the fact that this regulator is composed of two regulators tied together in series so that the outlet from the first stage is feeding the inlet to the second stage. This two-stage regulator is designed such that if the first stage fails, the second stage functions meet all functional requirements and if the second stage fails, suit regulation for the specific regulator assembly is lost but the first stage limits the flow such that the suit relief valve prevents over-pressurization and subsequent suit rupture.

Lastly, the regulator must incorporate re-compression safety into its design. To prevent damage to ear drums and lungs the regulator pressure must not increase at a faster rate than 13.5psi/min (NASA-STD-3001 V2 6007)

B. Prebreathe and Decompression Sickness (DCS) Treatment [6]

The regulator must also consider decompression sickness (DCS) safety while regulating pressure. To obtain a suit working pressure of 4.3 psia setpoint, the crewmember must go through prebreathe protocols which slowly acclimates the body to the lower pressure at 100% O_2. Depending on the vehicle pressure, this can vary from no time (Apollo with 100% O_2) to four hours when transitioning from a 14.7 psia 21% O2 cabin. The prebreathe period with pure O_2 ensures that enough nitrogen is purged from the crewmember’s body before the suit pressure is reduced to the 4.3 psia setpoint to reduce the risk that the crewmember will experience DCS, like the phenomenon deep sea divers experience when ascending to the surface of the ocean too rapidly and experience release of nitrogen gas from the bloodstream. For space suits, the risk of DCS occurs during the initial depress before initiating EVA and increases the longer the exposure at low pressure. For the ISS EMU, DCS is treated by taking the suit to 8 psid above a 14.7 psia cabin to provide an in-mission hyperbaric treatment. With a variable regulator capable of setting the suit pressure to 8.2 psid during the EVA, DCS treatment can begin immediately and continue through repress to full cabin pressure.

II. History

To contextualize the current design, it is useful to reflect on the history to understand the beginning and evolution of regulator design. There are only a handful of regulators designed for Apollo, EMU, and now xEMU in the United States and additional ones used in the Russian Orlan suits. Table 1 below shows a comparison between these regulators.

A. Apollo Regulators [2][6][14]

The Apollo mission had two regulators: a primary O_2 regulator and Oxygen Purge System (OPS) regulator. The primary O_2 system operated at a lower pressure during EVA at 3.85 +/- 0.15 psid and a tank pressure of 1,410 psia with a maximum flowrate of 0.5-0.62 pph. The OPS, which acts as a secondary O_2 supply loop, provides either a 4 pph or 8 pph purge flow at 3.7 +/- 0.3 psid with a 5,880 psia tank pressure and must be manually enabled by the crewmember in case of a primary failure. This purge flowrate is much higher than its successors which is advantageous for maintaining pressure with larger leaks and necessary for addressing thermal control for the 1,200 BTU/hr design metabolic rate during an EVA abort. Both the primary and the OPS regulator are single stage. Apollo also had a longer purge duration requirement at 1.25 hrs to return to the vehicle in case of a lunar rover failure in which case a Buddy Secondary Life Support System (BLSS) could connect to another suit through an umbilical for auxiliary cooling. The Apollo command capsule operated in a 5 psia 100% O_2 environment which meant prebreathe was not required for EVA, however this increased the cabin flammability risk as experienced in the fire with Apollo 1. In addition to this, manual actuation of the OPS imposed high risk if the crewmember loses consciousness before it can be enabled. In lieu of these challenges, future missions and suits have adopted a lower percentage O_2 operating pressure with higher vehicle pressures and a staged supply pressure. This enables a scenario in which the secondary regulator can take over in case of primary failure or depletion without the risk of causing hypoxia.

Table 1. Historical Regulator Comparisons

	Apollo	**EMU (Shuttle/ISS)**	**Orlan-M**	**xEMU**
Nominal EVA Pressure (psid)	3.85	4.3	5.8	4.3 nominal EVA (0-8.2 variable)
Secondary/Emergency Pressure (psid)	3.7	3.7	3.9	3.6
Primary MEOP (psia)	1,410	1,080	6,172	3,750
Secondary MEOP (psia)	5,880	7,400	6,172	3,750
Regulator Stages (Pri.)	1	1	3	2
Regulator Stages (Sec.)	1	2	2	2
Max Flowrate Available (pph)	8	5.6	4.4	5.6
Time to return to vehicle with purge (min)	30 75 (with BSLSS)	30	30	54
Vehicle Pressure (psia) / %O_2	5.0/100% (Apollo) 5.0/72% (Skylab)	10.2/26.5% (shuttle) 14.7/21% (ISS)	14.7/21%	14.7/21% (ISS) 8.2/34% (Artemis)

B. ISS EMU Regulators [1][2][3]

The Shuttle/ISS extravehicular mobility unit (EMU) includes a primary & secondary O_2 system. The primary regulator is composed of two single stage mechanical regulators which share a common housing. One regulator pressurizes the feedwater circuit commonly referred to as the water regulator while the other regulator pressurizes the ventilation loop and is commonly referred to as the dual mode regulator. The primary regulator assembly has an inlet operating pressure range from 45 to 1080 psia of pure O_2. The water regulator has an outlet pressure of 14.75 – 15.55 psid with flow rates between 0.01 to 0.04 pph. At flow rates above 0.04 pph, pressure is maintained at 15.55 psid or less. The dual mode regulator has two different regulation setpoints based on the operational mode required. The first, denoted as Intravehicular Activity (IVA) mode, has an outlet setpoint of 0.4 - 1.4 psid while the second, denoted as EVA mode, has an outlet setpoint of 4.2 – 4.4 psid. IVA mode can support flows from 0.02 to 0.33 pph from 0.4 – 0.9 psid with flows up to 5.6 pph at 0.2 – 0.9 psid above ambient, while EVA mode can support flows from 0.02 to 0.33 pph. The IVA mode is used for crewmember prebreathe in the airlock prior to starting the EVA as well as depress/repress operations. Mode changes are performed using two sets of mechanical springs. When IVA mode is required, the inner spring is lifted off the Belleville spring via a cam actuator driven by a cable and slide actuator on the front of the spacesuit.

The secondary O_2 system is commonly referred to as the Secondary O_2 Pack (SOP). The active component of the SOP is a two-stage mechanical regulator known as the secondary O_2 pressure regulator assembly. The first stage outlet and second stage inlet area are known as the interstage. Inlet operating pressures range from 365 to 7,400 psia of pure O_2. The first stage regulator reduces inlet pressure to 220 +/- 60 psia into the interstage. The second stage regulator further reduces this inlet pressure to 3.45 – 3.8 psid for flow requirements from 0.02 to 5.6 pph.

C. Orlan-M [15][16]

The Orlan-M suit has identical primary and secondary O_2 tanks at 6,172 psia with identical pressure reducing valves on each tank. Each reducing valve is a two-stage regulator with the first stage reducing to 176 psia and the second stage reducing to 64 psia. The O_2 is then fed from the primary tank and reducing valve to two identical third stages, a primary and a backup. The Orlan is set to an operating pressure of 5.8 psid nominal with a maximum flowrate of 0.56 pph. If the pressure drops below 3.9 psid, a second higher flow setting is automatically engaged to supply flow up to 3.4 pph within the third stage regulator. In the event a backup or purge is needed, there is either a backup injector setting or an emergency supply setting. For the backup injector setting, flow continues to use the primary supply but bypasses the third stage regulator directly into an injector and opens a dump valve. The emergency supply setting sources oxygen from the secondary O_2 tank and reducing valve then flows into both the injector and a separate dedicated backup port that enters the helmet through a calibrated orifice.

III. Advanced Regulator Design & Analysis

A. xEMU Regulator Advancements and Architecture

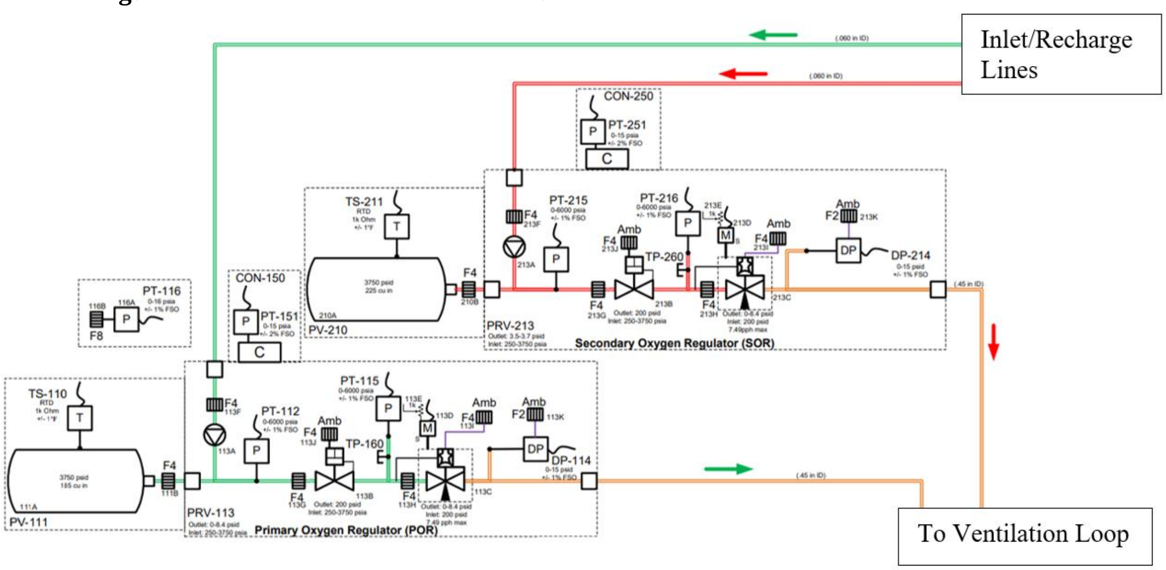


Figure 1. PLSS O_2 Assemblies Pneumatic Diagram

Since the development of the EMU there have been many new technologies and advancements that have contributed to the current regulator design. Two major advancements emerged from a better understanding of prebreathe and DCS treatment in conjunction with more modern actuator design and avionics. Modern actuator capabilities allow a user settable regulator that can be electronically and safely controlled to provide more outlet pressure setpoints for improved prebreathe and DCS treatment. Prebreathe protocol has drastically evolved over the evolution of the spaceflight program and can vary depending on vehicle atmosphere makeup. A user settable regulator allows for the flexibility to adjust setpoints based on mission requirements and helps reduce prebreathe time. A linear actuator drives the regulator setpoints and enables a fly-by-wire system that eliminates the need for mechanical linkages currently used on the EMU which have been the source of multiple failures(3). The implementation of the linear actuator approach to vary the compression on a traditional mechanical regulator load spring enables the variability of the set-pressure while also enabling the continued regulation even with loss of power or controller function. Other technologies such as Pulse Width Modulated (PWM) proportional solenoid valves and solenoid valvepiloted regulators were evaluated prior to selecting this approach, however both had limited ability to meet regulation function during loss of power.

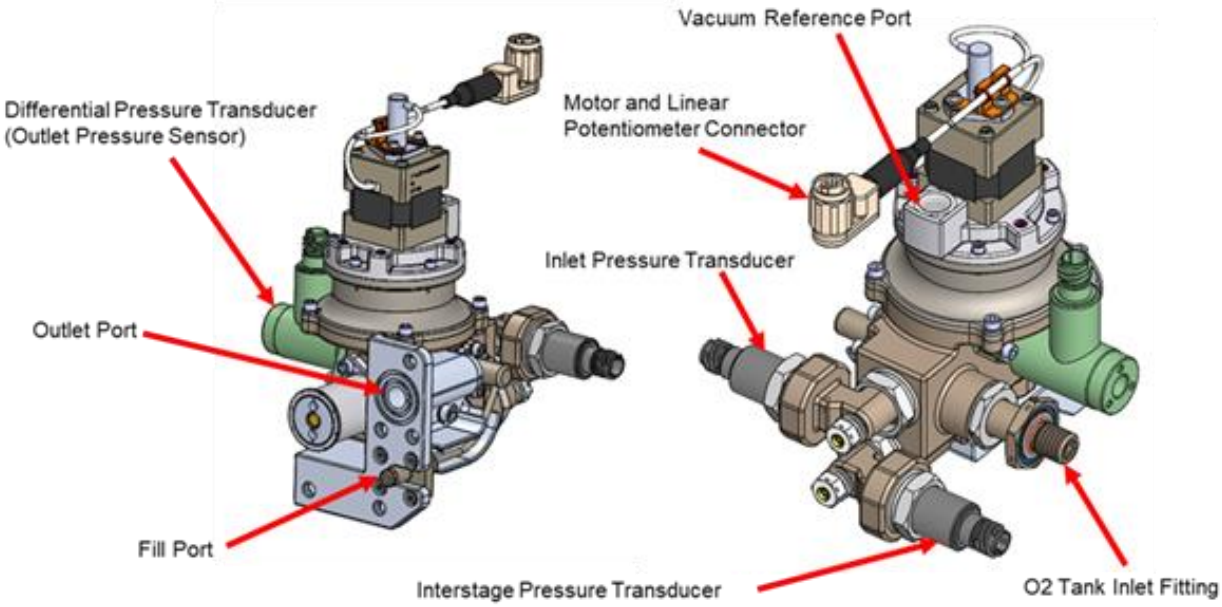


Figure 2. Regulator External Diagram

The Pressure Regulating Valve (PRV) design for both the POR & SOR is based primarily on the EMU SOP regulator system. Figure 1 shows a pneumatic diagram of the xEMU regulator design while Figure 2 shows the external model of the regulator with key areas indicated. Several design elements were inherited from the SOP regulator and customized based on the new xEMU suit requirements and lessons learned from review of the failure history for the Shuttle EMU Program[(3)]. Some critical design features include:

1) Maximum Expected Operating Pressure (MEOP): The xEMU regulator is designed to handle 3,750 psia MEOP despite being charged to only 3,000 psia nominally. This MEOP was selected for several reasons:
   a. As oxygen pressure is increased, more ignition mechanisms become active and/or more vigorous such as flow friction heating which has been found to ignite non-metallics via leakage across the seal.
   b. There were multiple 3,000 psia charging system possibilities available in vehicle planning cascading down from either a 4,000-5,000 psia tank or from separation and compression via a multistage low speed compressor.
   c. The adiabatic compression heat during in-situ recharge and Joule-Thomson cooling of the gas during discharge could be tolerated within the design packaging and fluid requirements for moisture and hydrocarbon content.

   A driving objective for the xEMU was to limit logistical impacts historically imposed by previous suit designs that included non-rechargeable high-pressure secondary gas supply (~6,000 psia). The MEOP chosen represnets a compromise between packaging into a selected PLSS volume/mass while limiting the impact on the required vehicle interfaces to enable that in-situ recharge. Hence, the xEMU POR and SOR allow tanks to be recharged on orbit; a shift from the EMU design which requires the SOP to be charged on Earth and transported to orbit and then tracked and managed as a logistics item. This approach works for short duration missions with available up-mass/volume or for ISS with a number of cargo resupply vehicles feeding the system, but one that does not trade well for long term exploration missions or ones with a greater number of EVAs.
2) Flowrate: During any purge event, the regulator can reliably provide a flowrate of up to 5.6 pph while maintaining constant regulation pressure within tolerance. The flowrate is limited to no more than 7.49 pph in a failed open second stage regulator condition such that it does not exceed the suit relief valve flowrate.
3) Fill Port & Check Valve: Inlet pressure can be supplied from the fill port (when refilling the O_2 tank) or directly from the tank inlet fitting. The check valve on the fill port allows for charging and serves as a control

for external leakage through that port. For the xEMU a secondary control is the recharge poppet in the Display and Control Unit (DCU) Service and Cooling Connector (SCC).

4) Pressure Monitoring: Pressure transducers are located on the inlet, interstage and outlet (differential pressure transducer) to monitor these areas for regulator function. The inlet and interstage transducers are 6,000 psia rated, while a 15 psid differential sensor is located on the outlet which connects to the xEMU ventilation loop.
5) Two Stage Regulator Design: The regulator is designed with two stages to prevent over pressurization as in the EMU SOP. The first stage acts as a knock-down style regulator which reduces the inlet pressure from 3,750 to 250 psia down to interstage pressure of 200 +/- 40 psia. The second stage regulates further down to 0-8.2 psid. This two-stage design allows the second stage regulator to maintain a very tight regulation band by utilizing a large sensing area with low hysteresis.
6) First Stage Failure Tolerant: The second stage can regulate to a slightly deteriorated regulation band while still meeting the system level requirements for maintaining life-sustaining pressure and flow requirements if the first stage regulator fails open.
7) Balance Bar Feature: The balance bar acts as a force multiplier in the case of a first stage failure to reduce the effects of inlet pressure acting on the second stage regulator seat assembly and helps keep the regulation band tight for all inlet pressures. It essentially reduces the proportional stroke of the seat to compensate for the increased gas density in the interstage during this operating condition.
8) Second Stage Failure Tolerant: If the second stage fails open, the suit RV is designed to keep the pressure to a maximum pressure of 10.1 psid at maximum flowrate of 7.49 pph. The maximum flowrate is limited to the orifice size in the failed open regulator seat assembly at the maximum possible 240 psia interstage pressure. The flowrate for the RV is set to 7.49 pph at 10.1 psid. The suit design uses a 10.6 psid MDP to provide margin over this condition. If either stage fails closed, the SOR is designed to take over and crew returns to airlock.
9) Linear Actuator & Potentiometer: The linear actuator works to control the spring mechanism in the second stage of the regulator to accurately vary the setpoint desired from 0 to 8.2 psid. A linear potentiometer acts to provide position feedback and failure detection.
10) Stroke Limiter: The use of stroke limiter contained within the second stage spring assembly provides two key design features. The first is to prevent overtravel past a lower RV cracking pressure of 8.6 psid. The second is to prevent damage to the second stage pressure sensing elements due to an overtravel condition caused by either proof pressure testing or back pressuring the second stage sensing area through the outlet.
11) On / Off Shutoff Feature – The regulator does not contain an upstream shutoff valve or isolation valve. It remains pressurized the entire time upstream pressure is applied to the inlet. When there is a lack of downstream demand, shut off is achieved by holding the second stage in lock-up. Seat leakages are low enough that an EMU SOP charged on Earth is expected to remain above the minimum pre-EVA charge pressure for a minimum of 2 years. This consistenly demonstrated feature of the EMU SOP regulator design was well-suited to enable several potential mission operation plans for cis-lunar and mars missions while incorporating the lessons learned from the EMU fire, by avoidance of an upstream shutoff valve potentially adding an adiabatic compression heating failure mode at the regulator first stage.
12) Oxygen Compatible Material Selection – Oxygen compatibility has been maximized in the selection of materials when possible. Components chosen were selected to be non-flammable under operating conditions. This included the use of materials such as Monel body and features, Ni-Cu filters, SS springs, etc. For certain components comprising of materials such as Vespel, Silicon, and PTFE, there were no equivalent non-flammable materials available that could perform the itended function, so the focus then became identification and control of the active ignition mechanisms in the design.
13) Filtration: There are numerous 25-micron absolute filters which can be found in critical areas of the regulator. These protect against contamination which could lead to catastrophic functional failure or O_2 hazards.

B. xEMU Controls & Setpoints [6]

Since the regulator setpoints are controlled by a stepper-based linear actuator, a motor controller is required. This provides flexibility to control the exact setpoints and rate of change of pressure. Furthermore, it allows for the programming of safety lock outs so the crewmember cannot inadvertently set the regulator to unsafe conditions.

Table 2. Regulator Setpoints

Setpoint (psid)	Purpose
0.9	POR - Purge/prebreathe (IVA)
3.6	SOR – nested backup pressure (EVA)
4.3	POR - Nominal EVA pressure (EVA)
5.0	POR - Reduced prebreathe (EVA)
6.2	POR - Reduced prebreathe (EVA)
8.2	POR – Reduced prebreathe and DCS treatment (EVA/IVA)

The controller setpoints showed in Table 2 are programmed in the controller as predetermined step counts and are paired with each serial number regulator for maximum accuracy. At present the long-term plan is to have regulators and controllers that are interchangeable without the need to lower crew over-head for ORU change-outs. The setpoints are shown in the table with their purpose. Many of the setpoints are used for prebreathe and allow adaptability depending on the type of mission. While the ISS is maintained at nominal 14.7 psia with 21% O_2, the lander for the lunar Artemis mission could use a lower 8.2 psia at 34% O_2. The lower pressure and higher oxygen content could significantly decrease the prebreathe time. Should the need to adjust these be required in the future, the controller mapping can be updated without physical changes. A notional EVA prebreathe logic using this regulator would be as follows(21):

1) Set the POR to 0.9 +/- 0.2 psid to initiate suit pressurization.
2) Set the SOR to ON to further increase the suit pressure to 3.6 +/- 0.1 psid.
   NOTE: The SOR pressure is set to 3.6 +/- 0.1 psid such that it sits in stand-by if the POR fails or the tank is empty the SOR will take over at a lower pressure.
3) Set the POR to 4.3 psid to pressurize the suit to nominal EVA pressure ahead of the leakage check.
4) Set the SOR to OFF
5) Set the POR to 0.9 psid to start the pressure decay leakage check
6) Set the POR back to 4.3 psid (it will have dropped only a few tenths of a psi if it passes the leakage check) to support purge
7) Open the suit purge valve for 10-12 minutes to transition cabin mixed gas to >95% O2
8) Set the POR to 0.9 psid
9) Close the suit purge valve as the suit pressure drops to regulation band
10) Prebreathe at ~ 0.9 psid
11) Start airlock depress with a stop at 5.0 psia
12) Open the secondary suit purge valve to drop suit pressure to 4-5 psid and check the secondary purge valve operation, then perform a second suit leakage check
13) Upon completion of suit leakage check, Set SOR to ON
14) Set the POR to 4.3 psid
15) Depress down to <0.5 psia with EV hatch opening and then vacuum
16) The suit pressure will decay down to the regulation set point
17) Perform the EVA
18) Return to airlock and repressurize to nominal vehicle pressure

Depending on the vehicle pressure schedule of 14.7 psia, 10.2 psia or 8.2 psia and associated transition timing for crew, the prebreathe protocol will vary. To enable the start of EVA earlier within the scope of a given prebreathe protocol, the suit pressure can be set to 5.0 psid, 6.2 psid, and 8.2 psid at EVA start, ramping down during the EVA to the nominal EVA pressure. If at any point, indication of DCS is observed or felt by the crewmember, the regulator can increase to 8.2 psid to start treatment.

C. Internal Operation

Both the first and second stage regulator seat assemblies are pressure closing designs which utilize ball and seat poppet geometry shown in Figure 3. The first stage regulator design can be traced back to the POR 2.0 phase. This is a standard spherical poppet design and utilizes a piston style sensing area. The second stage regulator utilizes the same spherical poppet design but makes use of a bellows pressure sensing area to reduce the frictional effects that influence the regulator tolerance bands. The regulator outlet setpoint is controlled by using a linear actuator to change the main helical spring height which in turn changes the outlet pressure. The force of the spring load balances the load placed on the regulator sensing area by the pressure acting within the sensing cavity. The variability in spring compression provided by the linear actuator can increase or decrease the force output from the spring on the pressure sensing area which changes the outlet set point pressure accordingly. A Belleville spring is placed in series with the main helical spring to create a net zero effective spring rate over the poppet stroke required to achieve full flow. This design also utilizes the balance bar feature found on the SOP EMU regulator which helps maintain the tight regulation bandwidth across all inlet pressures.

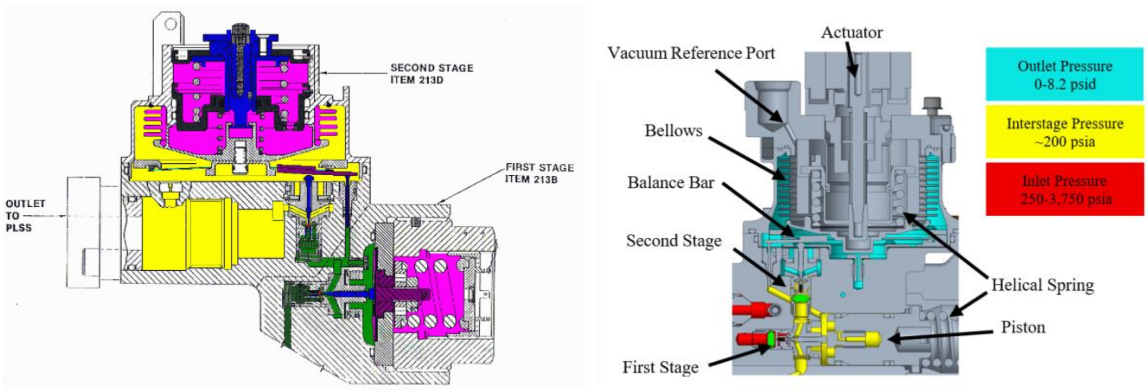


Figure 3. Internal Cross Section: EMU SOP regulator (Left) to PRV 4.0 Regulator (Right) Comparison

The balance bar used in the second stage is a beam soldered between two fingers of the Belleville spring. It rests on top of the second stage poppet stem and head of a small balance pin. The balance pin is subject to the same interstage pressure which acts on the balance bar. As interstage pressure increases, the force required to push the ball off the seat increases and the force exerted onto the balance bar from the balance pin also increases. This balance pin force is multiplied through the balance bar fulcrum and acts upon the poppet stem. The balance bar thus acts as a lever arm to multiply the force acting to open the poppet stem which reduces the interstage pressure closing effects seen at the second stage.

D. Oxygen Compatibility Analysis [9]

For high-pressure O_2 systems such as this regulator assembly, an Oxygen Compatibility Assessment (OCA) is conducted to analyze all the ignition mechanisms associated with the pressurization, material choices, and geometry of the regulator. The assessment concluded that the possibility of ignition remained remotely possible. The concerns that could cause ignition are leaking, chatter in the valve due to vibrations, and rapid pressurization during testing when there is no O_2 tank. Additionally, it was noted that Non-Volatile Residue (NVR) was found in the previous EMU SOP regulator upon inspection. Since the inception of the development of this regulator design, there has been a requirement levied on the design for "contamination tolerance" based on the EMU SOP fleet-wide failure that occurred in 2000(10). The only mechanism for adiabatic compression of the interstage results from a failure of the first stage regulator. This failure was simulated with rapid pressurization of the interstage dry and contaminated with > 100 mg/ft^2 dodecane using POR 2.0.

E. Finite Element Analysis Summary

A Finite Element Analysis (FEA) was performed on the POR and SOR assemblies to evaluate the response of the structure under environmental loads expected to be encountered during normal operation conditions. ANSYS simulation software was utilized for Finite Element Method (FEM) model generation, preprocessing, solving and post processing. A Margin of Safety (MOS) calculation using equation 1 for each component within the assembly was generated using Metallic Materials Properties Development and Standardization (MMPDS) material allowables, applied Temperature Reduction Factors (TRF) and applicable Safety Factors (SF). TRF percentages were found using maximum and minimum temperatures obtained from environmental loads. In equation 1, the yield limit loading is based on the von-Mises yield criterion while the ultimate limit loading is the maximum of the von Mises equivalent stress, or the maximum principal stress calculated from the eigenvalues of the stress tensor.

$$MOS_{Yield\ or\ Ultimate} = \frac{(Yield\ or\ Ultimate\ Tensile\ Stength) * TRF}{Limit\ Loading_{(Yield\ or\ Ultimate)} * SF} - 1 \qquad (1)$$

The static loads applied to the FEM model consisted of operating pressure, ambient pressure – non-operational, decreasing – non-operational, inadvertent contact load during maintenance, and minimum and maximum operating temperatures. After applying a maximum operating pressure of 3,750 psi, proof pressure of 5,630 psi and burst pressure of 9,375 psi to the internal passages and wetted surfaces of the regulator, the POR showed positive MOS for all components. In addition to the operating pressures, an ambient pressure of 18.8 psi was applied to the outside surfaces of the regulator. Finally, an inadvertent contact load of 25 lbs was applied to the most extreme locations accessible to the crew during maintenance, as well as external temperatures ranging from 35°F to 125°F and gas temperatures extremes from charging or purge ranging from -50°F to 250°F. After applying these static loads, all components of the POR assembly showed positive MOS.

The dynamic loads applied encompass a 9.3 g worst case landing acceleration, a 9.47 grms xEMU launch package input random vibration profile – both applied to all 3 axes individually, and a modal analysis to determine the natural frequency and the participation factors of the entire regulator assembly. The results of the modal analysis indicated the POR to have fundamental frequencies above 50 Hz, as well as showing positive MOS for the applied acceleration and random vibration loads. For the random vibration analysis, a conservative transmissibility factor of Q=15, or damping of 3% was used and 3 sigma stresses evaluated to calculate MOS. The results of both the static and dynamic analysis showed positive MOS for all environmental conditions. The PRV has been designed with acceptable stress margins and will be validated with rigorous testing.

F. Sensor Selection

The tank and interstage sensors are rated to 6,000 psia operating pressures enabling them to operate within nominal allowable conditions during processing such as proof pressure testing at 5,625 psia (1.5 x MEOP). Pressures significantly above the MDP of the sensor, even if only at proof pressure could cause the sensor reading to skew and require re-calibration. Additionally, the higher margin allows for potential future increase in MEOP if the stress margins allow for it. While the interstage sensor will only typically read ~200 psia which is significantly lower than the sensor full-scale range, the higher-pressure detection capability is needed so it can detect and still operate in the event of a first stage regulator failure.

G. Stroke Limiter

The stroke limiter utilizes a mechanical hard stop to prevent the maximum set point pressure of the regulator to exceed the suit RV cracking pressure and draining the supply tanks prematurely. Due to the RV cracking at 8.6 to 8.8 psid and the 8.2 psid setpoint having an accuracy of +0.2/ -0.4 the stroke limiter needs to be machined to 8.5 +/- 0.1 psid. This poses a manufacturing challenge since a 0.1 psid change in outlet setpoint pressure corresponds to approximately 0.005" of travel in the stroke limiter position requiring very precise machining. To compound this, the stepper motor resolution lacks the appropriate amount of fidelity to determine the precise value of machining of the stroke limiter. Finally, at 8.5 psid, the regulator pressure sensing components behave in a nonlinear manner due to that setpoint being approximately 0.2 psid higher than the linear region of the spring rate which was designed to 8.2 psid outlet pressure. Some initial machining attempts overshot the target hard stop set point pressure, therefore the 2nd stage spring had to be shimmed 0.005" to increase it by 0.1 psid. An easier methodology that has been formulated but not yet attempted is to predict the outlet pressure at a lower pressure (8.35 or 8.4 psid) and shim the 2nd stage spring to produce the final hard stop target outlet pressure.

H. Filters

Filters reduce the amount of particulates within the O_2 path and help mitigate the risk of failure or fire within the O_2 system. There are a total of four filters inside each of the regulators: One in the fill port check valve, one in the tank inlet fitting, and one filter inside each of the regulator seat assemblies. Each of these provide critical filtration to enable precise function and control particulate size for the particle impact ignition mechanism. The filters are sized for 25-micron absolute and 10-micron nominal.

Figure 4. Pleated Mesh Filter (Left/Middle) Diffusion Bonded Filter (Right)

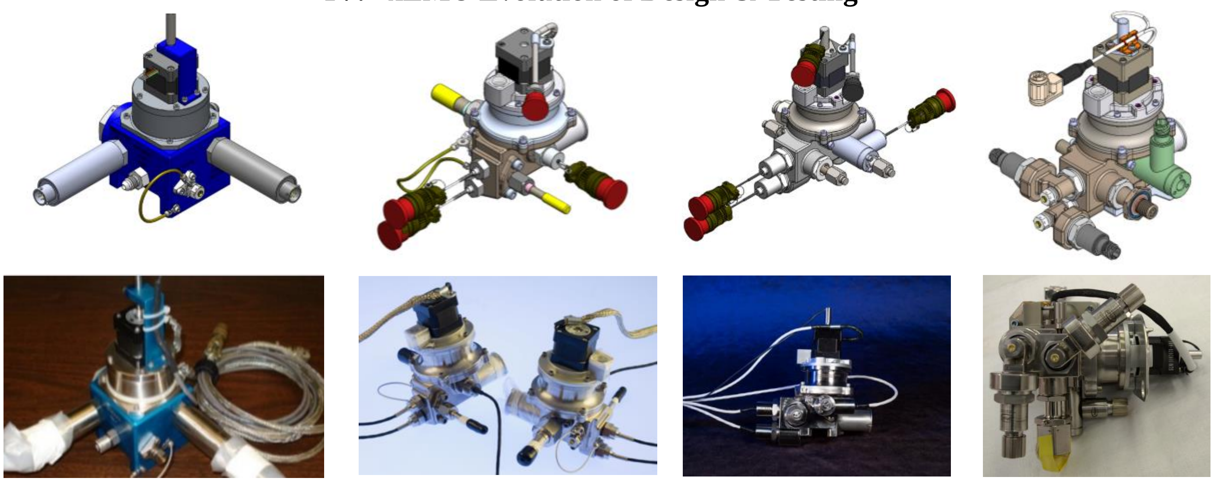
The pleated filters shown in Figure 4 were originally manufactured using a nickel 200 mesh crimped and electron beam welded inside a Monel body. Nickel is chosen as an O_2 compatible material, and the filter is pleated to increase area and decrease pressure drop. Historically, pleated filters have a very low first pass yield with only 2 out of 60 passing the 25-micron requirement bubble point acceptance test criteria. An investigation revealed the pleating process was the likely cause of the filters not meeting this requirement as well as the electron beam and crimping process. These root causes were investigated as potential to create voids in the pleated mesh, however resolutions to the manufacturing challenges revealed only minor improvements.

An alternative supplier was approached that offered diffusion bonded (sintered) nickel 200 filters which have been used in high pressure O_2 breathing applications, space probes, and rovers. These filters do not require additional crimping, pleating, or welding, making them an ideal alternative. Using the same housings, a powder is pressed into the filter and sintered. Testing was performed on different powder particle sizes and it was found that the 5-micron powder was able to meet the 25-micron bubble point acceptance test with a higher first past yield. The new filters also met the same pressure drop requirement.

I. Temperature During Discharge/Purge

An important consideration in the design of the regulator is the significant temperature decrease that occurs in the regulator due to Joule-Thomson expansion cooling during discharge or suit purge operations. During purge, the expansion cooling drops the gas temperature and if allowed long enough conducts to the seals and body. As the expansion cooling begins in the tank, the inlet temperature to the regulator further decreases prior to expansion across the first stage down to ~200 psia. An analysis estimated that the O_2 tank gas temperature could be as low as -42 °F with the regulator expansion dropping the gas temperature further[17]. The cooler operating temperature range affects seal selection with the use of Silicone vs Viton.

IV. xEMU Evolution of Design & Testing



PVR 1.0 (PLSS 1.0) | POR 2.0 (PLSS 2.0) | POR 3.0 (PLSS 2.5) | POR 4.0 (xEMU DVT)

Figure 5. PRV Regulator Design Evolution

A. PVR 1.0 – (2008-2009)

PVR (Primary Variable Regulator) 1.0 shown in Figure 5 was designed primarily on the existing SOP regulator that is currently employed on the US space suits. The first stage of the regulator was replicated from the SOP, with the second stage seat and balance beam/piston based on the SOP second stage but modified with an extended bellows assembly and spring with engagement of a stepper based linear actuator to enable the multi-set point capability. The goal of this first iteration was to allow for a minimum of five outlet pressure setpoints, while being continuously variable across the outlet pressure range of 0.4 to 8.2 psid. For this first prototype, nitrogen was selected as the working fluid enabling the use of a simplified aluminum body, with a COTS actuator and instrumentation to reduce the cost of manufacturing and fabrication time. The Inlet pressure range was between 250 to 3,750 psia.

PVR 1.0 demonstrated that the regulator could provide expected flowrates and pressure setpoints[1]. It successfully demonstrated setpoints from 0.4 to 8.2 psid and maintained pressure tolerances for flowrates up to 5.6 pph with nitrogen pressures up to 3,750 psia. The regulator performance curves for each setpoint typically followed the notional graph in Figure 6 during testing. PVR 1.0 was tested at component level and assembled into PLSS 1.0[20]. After completion of testing for this regulator, the design was then updated (POR 2.0) with lessons learned and further evolved to meet the next higher level of fidelity in requirements including oxygen compatibility, reduced mass/volume, and other requirements towards space flight implementation.

B. POR 2.0 – (2011-2012)

POR 2.0 was the next evolution of the PVR 1.0 design with higher fidelity oxygen compatible materials selections and flight packaging/mass reductions, with lessons learned from PVR 1.0. Several design modifications were made during this iteration. The first stage was updated from the heritage diaphragm sensing style design to a more robust piston style design based on review of the failure history of the SOP Regulator in the Shuttle EMU Program (there were failures of this diaphragm during the early 1990's)[3]. This simplification of the design also offered the benefit of reducing the manufacturing time required to set up the first stage assembly. A POR specific fill valve was developed to meet the evolving requirements of the POR specification. A Monel K500 body was designed and machined for O_2 compatibility as it is non-flammable under operating conditions. The body geometry was optimized for mass reduction. The low-cost COTS (large) pressure transducers were replaced with reduced form factor transducers. A second stage reference/vacuum port was added to support potential implementation of SuitPort for the suit system architecture and also offered easier access for testing. The linear potentiometer and associated supports were removed based on inconsistencies found in testing with PVR 1.0 which had used a spring-loaded potentiometer that would frequently bind and no longer represent actuator position. The intent at this time was to use pressure feedback which is somewhat of a fallacy for a suit system with multiple potential means to change the connected ventilation loop pressure of the regulator (the potentiometer will return on future versions but with better integration).

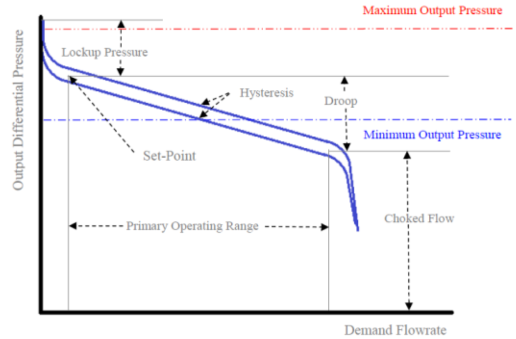


Figure 6. Regulator Performance Curve

In addition to functional and environmental tests[12] such as operating vibration[11], POR 2.0 was assessed for oxygen compatibility via an Oxygen Compatibility Assessment (OCA) per ASTM Manual 36 and then tested at the White Sands Test Facility (WSTF) with 60 dry impacts as well as two sets of five impacts wetted with 100 mg/ft^2 of dodecane[10]. During testing, the regulator operated nominally meeting specification and was subsequently disassembled post-test for inspection. Carbon was identified in the second stage inlet filter and witness residue on the first stage seat noting that the dodecane combusted in the interstage during testing but without propagation. Evidence of combustion was also found on the sapphire ball which had a carbon witness mark and a small amount of carbon on the filter only visible using a Scanning Electron Microscope (SEM). One other finding discovered during disassembly was a partially cut O-ring and extruded back up ring. This demonstrated a lesson learned in previous high pressure system designs with dual seals in which the pressure cycling between proof and depress enable the internal seal to be pressurized in the reverse direction from the intended design, extruding the seal into the regulator. The previous designs used a single seal to address this issue however the xEMU was being held to a dual seal requirement. The seals were then redesigned to use a primary metallic internal seal and secondary elastomeric seal which mitigates the experienced failure mode.

Environmental and vibrational testing was also conducted on the POR 2.0 regulator using nitrogen[11]. The regulator was tested for sensitivity to gravitational field orientations, temperatures, external vacuum, and up to 3.3 G_{RMS} while operating. Additional testing exposed the regulator to variations in temperature and relative humidity. The POR generally performed as expected and met most requirements. It was found however the regulator did not maintain differential pressure at the highest demand flowrates (5.6 pph) for many cases tested. The regulator experienced slightly degraded performance at high environmental temperatures (125°F), especially at the higher flowrate demand. Operation with a lunar rover while moving was required by the SuitPort mission concept but the rover design and mission were not mature enough to provide roving vibration requirements. Hence, the POR 2.0 design was tested to determine the operational limits of the regulator design to tolerate vibration while functioning in a regulation mode (i.e., ball off the seat flowing GN_2 rather than firmly held into the seat off position) to develop the suit side of this possible requirement. Testing revealed that while the POR operates properly at the 2.0 G_{RMS} test case, the 3.3 G_{RMS} test indicated a failed open second stage in some cases. Despite the failures and degraded performance at highest design envelope, the POR returned to normal performance after being subjected to these conditions.

C. POR 3.0 – (2014-2015)

POR 3.0 continued to build on the lessons learned from the previous iterations. New transducers replaced the previous ones used on the 2.0 configuration to match updated requirements. A new linear potentiometer design was added back to the overall assembly as a secondary method of tracking motor position (stroke length verification). The potentiometer was also redesigned to improve the measurement linearity from +/- 1% to +/- .5%, and its housing was modified to directly install on the linear actuator using three bolt mounting pattern. This hole pattern was drilled and tapped directly onto the motor body with the potentiometer directly threading into the aft of the linear actuator drive screw for direct mechanical coupling. This helped reduce the overall height envelope of the new assembly when compared to the PVR 1.0 configuration and resolved the position divergence issues noted. The regulator interface fittings (fill port, inlet port, and outlet port) were changed from a tube stub configuration to a 37° flared style fitting which utilized copper conical flare seals to provide a primary metallic seal with a secondary elastomeric seal (dual seal) applied to this design iteration. With a primary metallic seal, the need for the secondary elastomeric seal has been eliminated for future iterations.

The POR 3.0 was tested before integration with the PLSS 2.5 prototype(12). This was a much less in-depth test than what was executed during the POR 2.0 testing due to the timing of the development program. There was a transition from early development to the start of the xEMU ISS Demonstration which quickly pivoted the PLSS design team towards the DVT design of the regulator. This testing consisted of mapping the regulator then testing leakage which passed requirements of 25 sccm leakage rate. The regulated flow test evaluated the POR at different supply pressures, outlet setpoints, and flowrates to determine a curve for regulation and flow and the maximum flowrates for each. At the highest supply pressure, most cases were able to meet the maximum flow rate of 5.6 pph. The lower supply pressures however had lower than expected maximum flowrates especially for the highest outlet setpoint 8.2 psid case. In some cases, the outlet pressure at the maximum flowrate dropped below the setpoint accuracy required. The 0.4 and 0.9 psid case tested did not achieve the maximum supply rate required at only ~2 pph and ~4 pph respectively. For the final dynamic flow regulation, the suit was tested with varying flowrates for a range of activities, metabolic rates, and suit purges. The 4.3 psid pressure set point showed consistent levels for nominal operation and drooped slightly to about 4.2 psid during a 3.08 pph purge.

D. POR 4.0 – (2019-2023)

POR 4.0 continued to build upon the lessons learned from previous design iterations, while adapting to meet new specification requirements. An effort was undertaken to create commonality between drawings in respective systems. A new outlet manifold was designed which placed the regulator outlet and fill port inlet on the same common plane to facilitate On-orbit Replacement Unit (ORU) interfaces to the PLSS backplate. Monel elbows were designed to move the inlet and interstage pressure transducers to meet new packaging constraints. Provisions were made to allow orientation of the pressure transducers to be independent of the retaining nuts. A more rigorous development test plan was implemented to further validate the POR / SOR designs prior to formal qualification. Testing environmental situations like hot and cold performance, pre and post vibration testing, and O_2 compatibility were included to identify any performance related issues prior to a qualification effort. Strain relief provisions were added to the linear potentiometer and motor cables resulting from cracking issues that occurred during the POR 3.0 builds. A new spring seat and stroke limiter was implemented to prevent the linear actuator from exceeding a maximum distance (resulting in over pressurization) due to motor failure or runaway controller.

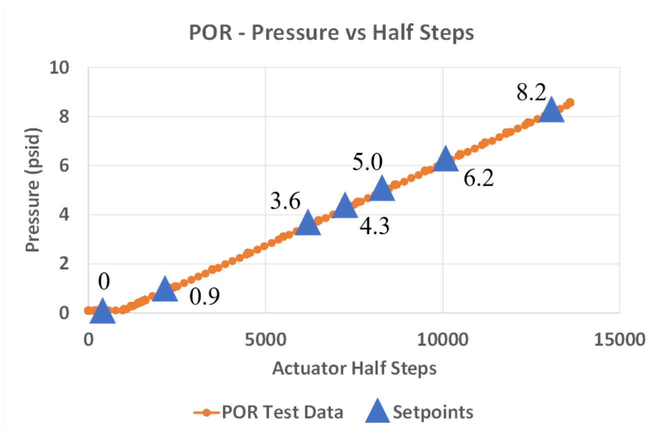


Figure 7. POR 4.0 Pressure vs. Half Steps

Before being delivered to NASA, Pre-Delivery Acceptance (PDA) tests are performed on every regulator including the POR 4.0(13). Preliminary testing of the latest POR 4.0 design (second set of regulators) in PDA is yielding higher droop at the required mass flow rate of >5.6 pph. This behavior was not seen when the unit was initially tested with an inlet pressure of 3,750 psia at the same outlet set point. It appears that the filter changes are having a compounded impact on the integrated performance such that the regulator seat design is being further evaluated for modification to bring the droop back into compliance.

The first set of POR 4.0 regulators were tested on the Suit Regulator GN_2 Test Rig before integrating into the xEMU DVT PLSS design. This evaluated limited operation at ambient lab pressures with pressure output vs actuator commanded position mapping to aid with integration. Figure 7 plots the response curve of the regulator. The flat line zero output pressure response from ~800 steps down to zero (home) highlights the separation between the OFF and regulating positions. Figure 7 superimposes both increasing and decreasing regulation data indicating very little hysteresis. The regulator mapping resulted in ~725 steps/psi.

During the initial testing of this first regulator set, the setpoint on the upper end (8.2 psid) appeared to slip steps noting hysteresis on the setpoint pressure vs step count while returning to lower pressures. This was identified as a risk early in DVT as this COTS actuator does not presently meet NASA-STD-5017 force margins for this application. It is especially sensitive to the commutation scheme for force output. This application requires a force output of ~60 lbf with most of the COTS units offering force outputs in the mid-40 lbf range. The subject actuator was found to be providing ~36 lbf (marginal vs requirement). Forward work remains with improving the force margin and mitigation of jamming with the actuator design given the challenging application that the regulator presents.

After component mapping, the regulators were assembled with the respective Primary Oxygen Vessel (POV) or Secondary Oxygen Vessel (SOV) to create the respective Primary O_2 Assembly (POA) or Secondary O_2 Assembly (SOA). Figure 8 depicts a Primary Oxygen Assembly.

Figure 8. Primary O_2 Assembly (POA)

The POA and SOA are very similar in design with a larger wetted volume for the SOA and additional ambient pressure sensing for the POA. The first regulator set has been installed into the xEMU DVT PLSS assembly where it has completed PLSS level Pre-Installation Acceptance Testing (PIA) and vacuum performance testing and xEMU level ambient functional testing. The full xEMU system functional is shown in Figure 9. Testing as part of the Short xEMU (xEMU without a lower torso) Ambient Functional and Thermal Vacuum (TVAC) performance testing is planned for the remainder of FY23.

During the PLSS PIA and Chamber C integrated testing, the risk of jamming known with this current actuator was realized on multiple occasions resulting in the need to vary motor drive currents and commutation speeds to free the actuator. The actuator was then rebuilt with a different drive lubricant which has been shown to reduce the risk of jamming and has not repeated during subsequent integrated PLSS testing.

Figure 9. xEMU Suit Assembly

One other anomaly that occurred during integrated testing during vacuum was that the SOR failed to come out of lock-up and regulate the suit pressure to 3.6 +/- 0.1 psid as the POR drooped into the SOR range when the supply was depleted. The SOR failed to come out of lock-up until the suit pressure reached 2.4 psid. The first ship set of the regulator design was not tested at vacuum during component functional testing due to meeting integrated testing schedule requirements for the xEMU project. This was noted as a risk as the regulator would not have been tuned or verified for this function. The second shipset of regulators will be tested during component acceptance at the vacuum reference condition to verify function.

V. Future Work

The regulators have made progressive improvement in maturity as the iterations have evolved from the initial prototype to the DVT phase of the design. The DVT design is presently undergoing testing and updates to refine the design to one that fully meets all flight requirements heading into a CDR level maturity for what will become the qualification effort. For xEMU, much of this work ceased with termination of the project and transition to the commercialization approach for EVA. The work that remains includes but is not limited to:

1) The refinement of the flow performance with the new filter design (in-process with second shipset of regulators).
2) Completion of sub ambient performance and tuning of the regulator to meet regulation performance at vacuum reference conditions (in-process with the second shipset of regulators).
3) Design updates to fully address linear actuator jamming under all conditions with force margins compliant to NASA-STD-5017 along with testing to confirm compliance (not currently in-work).
4) Component level launch vibration testing with both full charge and pad pressure to validate there are no issues with leakage in lock-up at the reduced pressures. This is only necessary if a particular program plans to fly the system with pad pressure. The risk for failure with full pressure is low given the leveraging of SOP regulator design, certification, and heritage use, but is still a risk that needs mitigation with xEMU no longer performing this testing.

VI. Conclusion

The variable oxygen regulator has evolved through multiple iterations increasing fidelity and refining the design to flight performance requirements. The regulator began with leveraging the success of the EMU SOP and extending its capability via addition of a motor settable second stage. This extended capability is an enabling technology for both LEO and lunar exploration and beyond usage by providing flexibility to address varied vehicle pressure schedules, varied prebreathe protocols, enable treatment of DCS during EVA and IVA, and resolve the issues both in fabrication and operation with the tightly toleranced mechanical linkage used in the current Shuttle/ISS EMU. This is in addition to improving the safety of the regulator to tolerate loss of cleanliness control (contamination) and preclude faulty/unsafe pressure command inputs during an exploration mission to cis-lunar and beyond. Some of these improvements included a piston sensed first stage, better protection of soft goods within the assembly, lower operating pressure from the SOP and integration of sintered nickel filters to replace the nickel mesh filters. Finally, stroke limitation was implemented to preclude a forced failure or overshoot on setpoint pressure with a controllable interface that can include a setpoint pressure lock-out as currently implemented with xEMU to preclude inadvertent setting of the commanded pressure below habitable pressures and uninhabitable environmental pressures (< 4 psia).

The regulator design has been tested throughout development for operating performance during vibration, thermal, vacuum, oxygen adiabatic compression testing with contamination, and has integrated progressively with the maturing PLSS design. This regulator is expected to satisfy requirements for applications in suits designed for ISS missions, Artemis missions, and other future missions.

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