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Oxygen Compatibility and Challenge Testing of the PLSS Variable Oxygen Regulator (VOR) for the Advanced EMU

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The Variable Oxygen Regulator (VOR), a stepper actuated two-stage mechanical regulator, is being developed for the purpose of serving as the Primary Oxygen Regulator (POR) and Secondary Oxygen Regulator (SOR) within the Advanced EMU PLSS, now referred to as the xEMU and xPLSS. Three prototype designs have been fabricated and tested as part of this development. Building upon the lessons learned from the 35 years of Shuttle/ISS EMU Program operation including the fleet-wide EMU Secondary Oxygen Pack (SOP) contamination failure that occurred in 2000, the VOR is being analyzed, designed, and tested for oxygen compatibility with controlled Non-Volatile Residue (NVR) and a representative worst-case hydro-carbon system contamination event (>100mg/ft^2 dodecane). This paper discusses the steps taken in testing of VOR 2.0 with for oxygen compatibility and then discusses follow-on design changes implemented in the VOR 3.0 (3rd prototype) as a result.

Nomenclature

VOR	Variable Oxygen Regulator
SOR	Secondary Oxygen Regulator
POR	Primary Oxygen Regulator
EMU	Extravehicular Mobility Unit
PLSS	Portable Life Support System
NVR	Non-Volatile Residue
STP	Science and Technology Program
	Standard Temperature and Pressure
PVR	Primary Variable Regulator
DCM	Display and Control Module
DCS	Decompression Sickness
PPRV	Positive Pressure Relief Valve
OCA	Oxygen Compatibility Assessment
AIT	Autogenous Ignition Temperature
SOP	Secondary Oxygen Pack
PDA	Pre Delivery Acceptance
WSTF	White Sands Test Facility
ABO	Aviator's Breathing Oxygen
LEO	Low Earth Orbit
MEOP	Maximum Expected Operating Pressure
PT	Pressure Transducer
CHDS	Conair Heat Delivery System
EVA	Extra Vehicular Activity
TMG	Thermal-Micrometeroid Garment
SEM	Scanning Electron Microscope

I. Introduction

The Primary Oxygen Regulator (POR) also referred to as the Variable Oxygen Regulator (VOR) by the Science and Technology Program (STP) has been under development since its initial conception in 2008. For the purposes of this paper, POR will be used as the primary method for reference of the regulator. The first bench-top prototype unit referred to as the Primary Variable Regulator (PVR) (1), demonstrated the following improvements over the regulators used for the Apollo EMUs and Shuttle/ISS EMUs:

- Multiple set-point capability of ~4000 steps over a pressure range of 0-8.4 psid
    - The Apollo EMU was a single set-point at 3.75 psid and the Shuttle/ISS EMU utilized a dual set-point regulator that offered ~.9 and 4.3 psid set-points.
- Common regulator design between the primary and secondary oxygen loops with a lower operating pressure (3000 psi nominally) than typical secondary regulators and higher than typical primary regulators.
    - This enables the recharge of the primary/secondary supplies on-orbit without the need to treat the secondary gas as a consumable that cannot be recharged.
- In-suit decompression sickness treatment via the 8.4 psid operating pressure which can be set by switch position on the Display and Control Module (DCM)
    - The Shuttle/ISS EMU offers DCS treatment but only with the addition of an external kit that covers the on-board Positive Pressure Relief Valve (PPRV) and then requires the cycling of the primary regulator from IV to OFF to dump gas into the suit ~.5 psid per cycle. This has to then be maintained by the crew manually.

The second iteration of the regulator design has been referred to as the POR 2.0. This particular design focused on materials selection, oxygen compatibility, packaging of the body/assembly into a tighter volume, and performance improvements to ensure proper performance under a failed open first stage regulator.

For the POR 2.0 design, specific attention was paid to the materials selections, tolerance, and component design such that the regulator should be compatible with oxygen. An assessment of the regulator design with respect to materials selections and ignition mechanisms was performed by the White Sands Test Facility personnel and documented in their Oxygen Compatibility Assessment (OCA) (2). In that assessment, the regulator was found to be well designed with respect to oxygen compatibility. One regulator failure mode, however, presented a case worth further investigation, especially with respect to the goal levied on the regulator from the onset of the design:

"The POR shall not ignite or indicate signs of combustion when operated with up to 100 mg/ft^2 of medium weight hydrocarbon oil coating the wetted parts/passages."

That regulator failure involved the failure of the first stage regulator to full-open, which would then pressurize the interstage volume from ~200 psia to supply pressure in the tanks. Due to the small volume of the interstage region, the pressurization is near adiabatic resulting in very high gas temperatures ~600F which are well above the AIT for potential contaminants. Given this, one may ask why this is being considered as it is normally defined that for a given regulator to remain safe, it must have an Non-Volatile Residue (NVR) that remains below 2 mg/ft^2 such that the assumptions made in the OCA with respect to the kindling chain ignition mechanism remain applicable. However, declaring that a system will be maintained clean does not guarantee it to be so as this would be a procedural control to a hazard and the best option for control of such a hazard is a hardware design solution that can tolerate it. The Shuttle/ISS EMU Program utilized procedural controls to ensure that the primary and secondary oxygen loops remained clean, however in the year 2000, contamination was detected during a regulator refurbishment that yielded an evidence of fleet wide contamination. At that time, the failure analysis (3) concluded that there were at least three different mechanisms that contributed to the contamination of the Secondary Oxygen Pack (SOP) regulators despite the apparent procedural controls:

1. Direct contamination of the SOP Test Stand at the field testing organization due to improper connection of a non O2 compatible dead-weight tester. The original dead-weight testers used for this function which utilized O2 compatible fluorinated oils such as Fomblin were replaced by the calibrating organization with one that included Sebacate. On one occasion, there was a report of a contamination event of the rig by observation of the pouring of the redish fluid from flexhoses used to connect the tester to the rig. Sebacate was later found in multiple regulators when analyzed as they were being refurbished.
2. Direct contamination of the Test Rig feeding the SOP during Pre Delivery Acceptance (PDA) testing the OEM due to rupture of diaphragms on the Aminco high-pressure compressors. These compressors utilize Fomblin oil as a hydraulic fluid that is compressed by either a pneumatic piston or electric drive which then

acts across a metal diaphragm to compress the isolated gas which was either GN2 or O2. These compressors had been around for 30years at that time and were known to have issues with contamination of the working fluid via breach of the metallic diaphragm. WSTF had made a number of design improvements to these units such as the addition of triple diaphragms, cycle counters to monitor the pressure cycles on the diaphragms and mandate replacement, and in some cases the addition of an oil detector in the outlet. These updates had not been incorporated in the setup used at the OEM at the time of the failure and the single diaphragm was found to have ruptured. From that point, the contamination was still just Fomblin which is a fluorinated oil considered oxygen compatible. However, the rest of the system between the pressure intensifier and the SOP was cleaned, most likely with Freon 113 leaving a back-ground contamination permissible per the associated cleanliness specification. For example, for JPR 5322.1 (4), a cleanliness level of 100A is permitted to have up to 1 mg/ft^2 of NVR when tested at the end of the cleaning cycle. It was then theorized that as the Fomblin oil moved along through the system, it picked up back-ground hydrocarbon contamination such that when it reach the SOP regulator, hydrocarbon contaminants were transported into the regulator.

3. Direct contamination of the regulator seat via Joule-Thompson cooling of the gas that is expanded across the 1st stage regulator seat. In that scenario, the 1st stage regulator drops the inlet gas pressure from ~6000 psia down to ~200 psia. During this expansion, the gas is cooled to temperatures below -50F which would allow very small amounts of contaminants in the gas phase within the supply gas to condense on or near the regulator seat. These gas phase contaminants are permitted by the military specification for Aviators Breathing Oxygen (ABO) (5), which is then called out and adjusted by various other specifications such as Shuttle Fluids Procurement Specification (6) then leading to accepted contamination levels of 55 ppm total hydrocarbons reported as methane. In this mechanism, the acceptable NVR limit of <2 mg/ft2 is exceeded by the flowing a lot of gas (hundreds of pounds at PDA) and condensing a small amount of contaminant on the very small regulator seat area.

By the end of the investigation, the SOP regulator still had the low acceptable limit but the procedural controls were further strengthened by the implementation of cryogenic cold-traps positioned in front of the SOP regulator whether it was being tested at the OEM or field processing organization. These cold-traps would then protect the test article (SOP) from contamination from all of the above mechanisms but only to the established filtering efficiency for the cold-traps which was empirically determined to be ~50%. As a result, the program tracks logistical spreadsheets that total the mass of gas flowed through each regulator as a limited life item. Once this life is exceeded, the regulator would then be cleaned and refurbished.

In the end, the procedural controls that were employed were defeated in three different ways over time without the knowledge of the operators or OEM until the contamination was fleet wide. As the agency moves toward exploration beyond LEO, the ability to access or refurbish hardware that may become contaminated is reduced and impacts to an intolerant system are increased. The goal for the Primary Oxygen Regulator (POR) was to take advantage of reliable, demonstrated features of the existing Shuttle/ISS EMU SOP regulator while adding functional capabilities and robustness required for an exploration system. The goal is to get to a position where the contamination tolerance of the regulator is demonstrated by analysis and then test.

II. Ignition Analysis

With reference to an earlier discussion, the main failure mode being evaluated is the failure of the first-stage regulator in which the interstage volume is pressurized from its nominal pressure ~200 psia to the maximum supply pressure ~3750 psia nearly instantaneously. For this test, an initial first order adiabatic compression analysis was performed that predicted a gas temperature of ~900F. Given that this temperature is above the AIT for all elastomers included in the regulator, it necessitated a more detailed analysis that examined contamination along the walls, associated wall vs gas temperatures, and energies released to determine if conditions could result in combustion of the contaminant and subsequent kindling to the regulator softgoods. Hence, a high fidelity Primary Oxygen Regulator Thermal Kindling Chain Analysis (7) (8) was performed using Thermal Desktop with the imported regulator detail geometry. Three distinct analytical approaches with the detailed model were executed to assess the potential for kindling within the POR interstage. The first was a straightforward transient simulation of the POR failure mode in which the first stage fails open and 3750 psia oxygen flows into the POR interstage. The second approach calculated additional energy required to raise the temperature of the dodecane film on the POR interstage walls to their AIT of 401F during the transient simulation of the first approach. The third analytical approach assumed combustion of all available dodecane. Figure 1 depicts the regulator body geometry imported into Thermal Desktop.

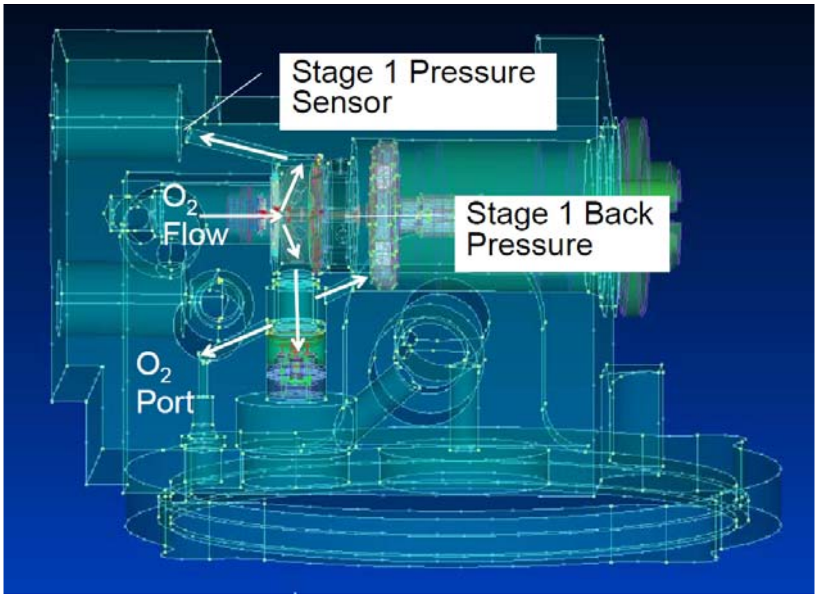

Figure 1 - Regulator Body Geometry

In the first approach, the O2 flows through the 1st stage regulator inlet and then through a fixed orifice which represents the failed open regulator seat, then into a diffuser, through the legs of the diffuser and the annular flow paths that lead to either a dead end at the supply pressure sensor or to the filter assembly and 2nd stage regulator seat assembly. Convection between the O2 and the regulator body was computed by Thermal Desktop; a factor was then used to multiply the result up to 3 times to provide conservatism. A sensitivity study was performed and determined that the maximum contaminant or oil temperature was not affected by the thickness of the oil film below 100mg/ft^2, so the 100mg/ft^2 was used. Additional assumptions and key findings include:

- Oxygen supply boundary conditions of 3750 psia and 275 F
- Initial regulator temperature = 70-150F
- Maximum gas temperature = 580-674F depending on convection factor
- Maximum film oil temperature = 170-200F depending on convection factor

While the predicted dodecane film temperatures remained relatively low, the results of this transient simulation suggest dodecane combustion is possible given the listed dodecane AIT is 399-401F, 180 to 270 less than predicted maximum insterstage gas temperatures. Reported dodecane AITs were determined by ambient combustion testing, a method in which the liquid chemical is heated in one atmospheric air until its vapor spontaneously ignites. A partial test at WSTF at 1500 psia and 100% O2 (9) seems to indicate an AIT around 400F as well but the test fixture was damaged during the testing and additional testing will be required to confirm this result. Finally, these analysis predictions should viewed with respect to the dodecane 160F flashpoint, the temperature the material forms a combustible vapor. It is possible the additional vapor released due to film temperatures of 160F could potentially be ignited by energy released from contaminant already in vapor phase prior.

The second analytical approach determined the amount of dodecane needed to burn in order to raise the dodecane film on the regulator interstage surfaces to the 401F auto ignition temperature. This was accomplished by using the detailed model to calculate additional energy required to raise dodecane film temperatures during the transient first stage failure simulation. The additional energy was then divided by the heat of combustion to yield mass of dodecane. Two methods of applying additional energy were used with results listed below:

1. Add energy directly to the oxygen at the center of the diffuser (hottest point) until the oil reaches 401F
    - Mass of oil required was found to be 2.4 mg
    - Mass of oil available at 100 mg/ft^2 is 14.9mg
2. Increase the inlet oxygen temperature until the oil on the diffuser reaches 401F

- Mass of oil required was found to be .54 mg
- Mass of oil available at $100 mg/ft^2$ is 14.9 mg

Results from this analytical approach do not indicate that combustion is expected but rather that combustion of only a small percentage of the available mass would yield enough energy to combust the remainder of the mass.

A final analysis was run to determine if the combustion of the available dodecane could be expected to kindle to the available softgoods in the regulator. In the end, it determined that if all available dodecane burned and the energy was injected at the diffuser (hottest area with least coupling to the regulator body walls) temperatures on the diffuser approach AIT for silicone and Vespel making the kindling to the softgoods possible.

III. Contaminant Selection

During the contamination investigation that was conducted by the Shuttle/ISS EMU Program, the lower pressure primary oxygen regulator was tested at WSTF to demonstrate its contamination tolerance in the event of another future contamination event. For that test series, Mobil DTE24 was selected as a good medium weight oil to use. However, as the regulators were disassembled, sampled, cleaned, and refurbished as part of the contamination recovery effort, spectra were generated that indicated a wide range of carbon chains spanning from C10-C34. Figure 2 was excerpted from (3) and is a chromatogram showing the hydrocarbon constituents found in SOP regulator S/N 102.

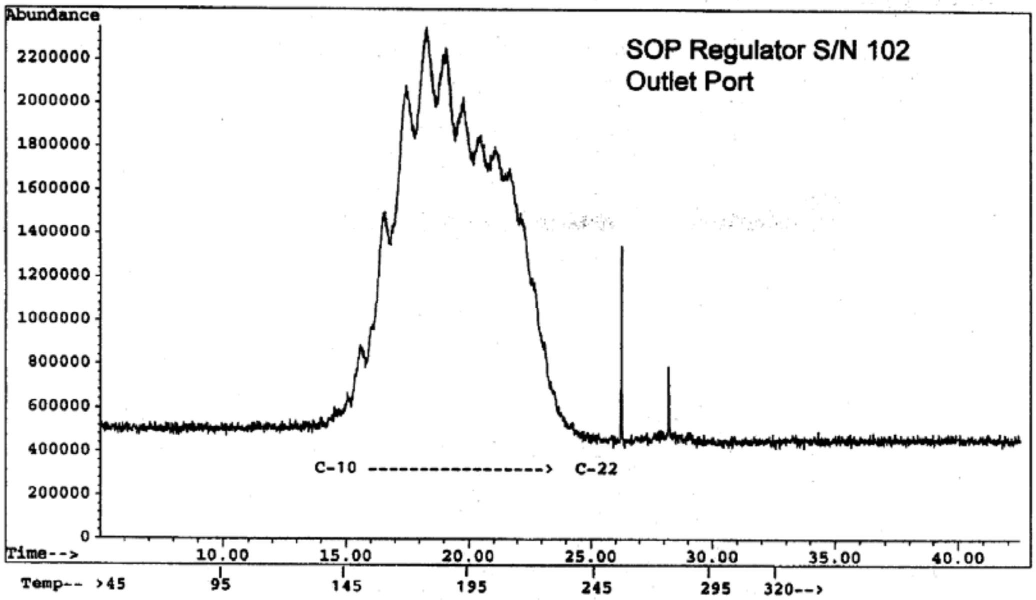

Figure 2 - Chromatogram – SOP Regulator S/N 102

Given that the longer chain, heavier hydrocarbons would have lower vapor pressures, WSTF recommended testing a hydrocarbon that fell on the low end of the observed ranges while not gaseous under ambient conditions. At that point, WD-40™ was initially chosen which included dodecane but the full formulation could not be ascertained. As a result, pure dodecane was used instead so that the materials properties would be known and the composition could be repeatable and known.

IV. Test Objectives

This test series sought to achieve the following objectives:

1. Oxygen wetting of the POR via dry gas adiabatic impacts of the regulator interstage at Maximum Expected Operating Pressure (MEOP)

    a. This seeks to demonstrate oxygen compatibility with clean oxygen per ABO (5)

2. Dodecane kindling chain adiabatic compression testing of the interstage volume at MEOP and associated temperature

This sought to expand the demonstration of oxygen compatibility performed as part of the OCA to include the conditions where kindling chain conditions could exist due to the presence of a hydrocarbon contaminant.

V. Test Configuration

The test was performed at the White Sands Test Facility (WSTF) in Test Cell 107 located in the 800 area of the center. The regulator tested was the Primary Oxygen Regulator (POR) 2.0, s/n 003 (Figure 3) produced by Cobham Mission Systems.

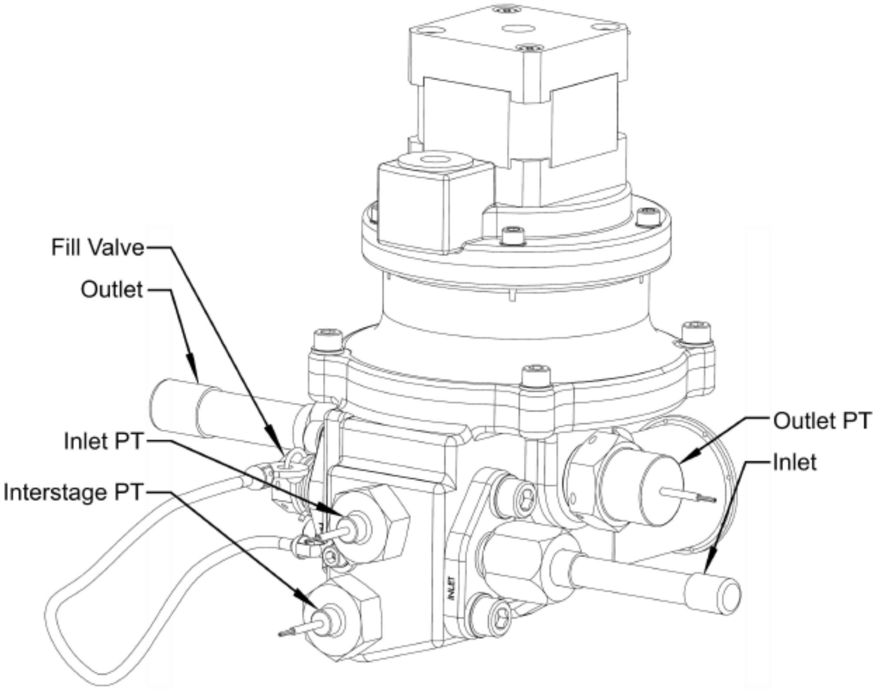

Figure 3 - POR 2.0 Rendering

The focus of this test is the green colored area noted in Figure 4 and Figure 5 referred to as the "interstage" area which is located downstream of the 1st stage regulator and upstream of the 2nd stage regulator. The nominal operating pressure for this region is ~200 psia but for the case where the 1st stage regulator fails open at the MEOP for the tankage, the interstage region will be pressurized from the ~200 psia nominal operating pressure to the 3750 psia supply pressure on the order of 150 msec.

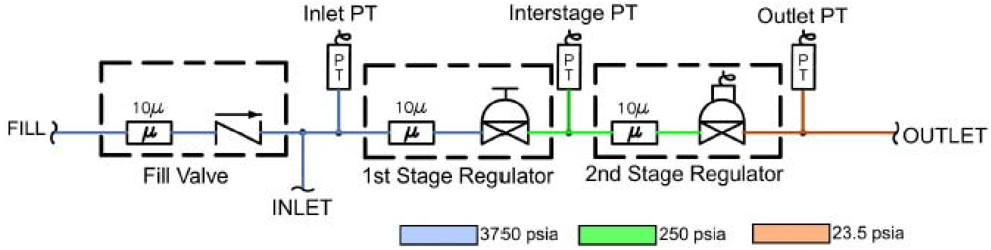

Figure 4 - Pneumatic Schematic for POR 2.0

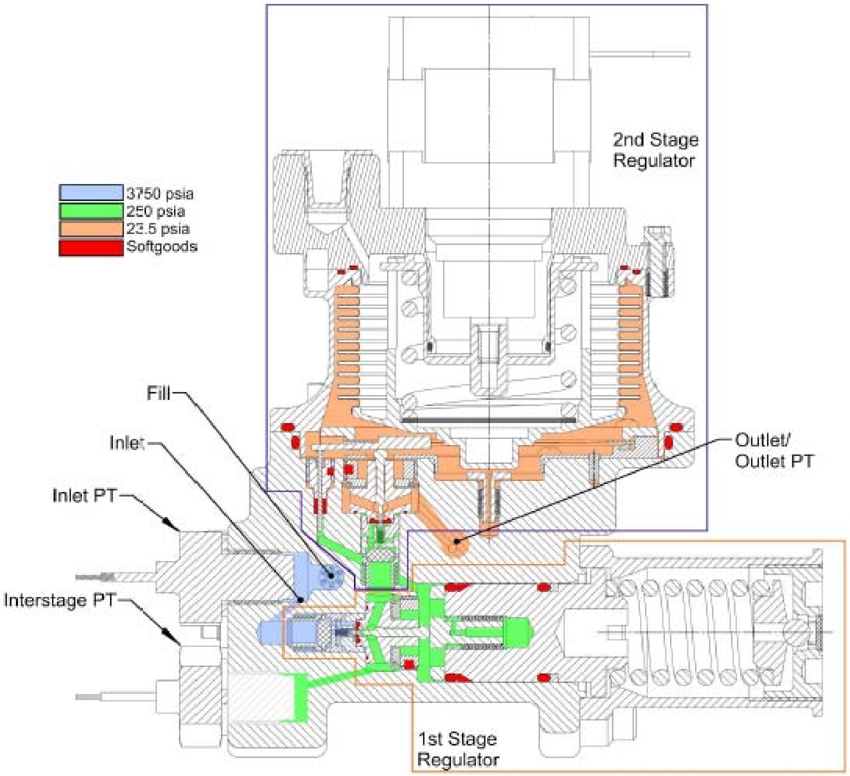

Figure 5 - Cross-Section of POR 2.0

For this test, the Interstage Pressure Transducer (PT) was removed to gain access to the interstage region (Figure 6). A special fitting was made to connect to this port and enable connection to the WSTF Test Cell 107 impact valve for the purposes of performing rapid pressurization events. In order to enable a pressurization from the nominal interstage pressure up to the MEOP of 3750 psia, a 3750 psia supply was connected to the inlet such that the 1st stage regulator would operate to maintain the nominal interstage pressure. Then, using a "Little Richard Valve" in Test Cell 107 with the prescribed muscle pressure[1], pneumatic impacts were performed on the interstage pressure transducer port. This configuration efficiently allowed for the planned rapid compression testing and pre/post-test nominal POR operations functional testing in which proper 1st and 2nd stage pressure regulation is maintained while a small demand up to ~ 1pph is placed on the regulator. Were a significant combustion event to occur, the outlet or interstage regulation

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[1] "muscle pressure" is the pneumatic drive pressure used to control the piston stroking the valve

pressures and total demand would be affected due to malformation of the seats, damage to non-metallic seals on the balance stem, or other static seals causing external leakage.

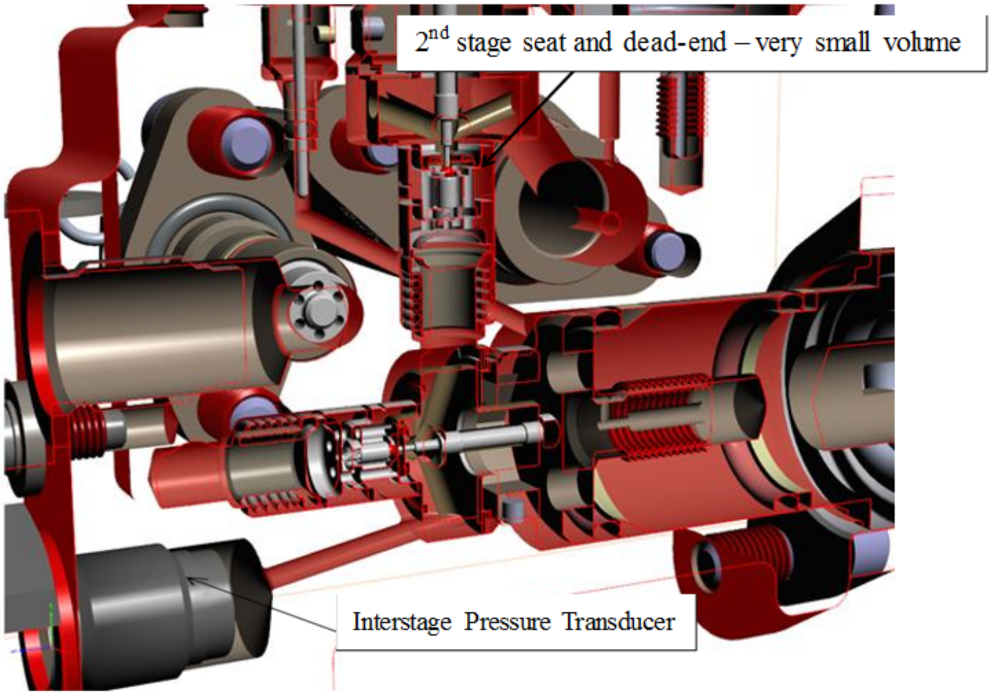

Figure 6 - Cut-away of POR 2.0

The original fitting stack-up was used for the dry-impacts, then for the impacts with the dodecane contamination, the orifice and back-to-back that limited pressurization rate were removed to enable faster pressurization from the "Little Richard Valve" feed in the test cell. Several Type-T thermocouples were placed on key locations on POR 2.0: next to outlet, bellows housing, next to inlet port, bottom face, and on the interstage port fitting. For the dodecane runs, 20uL was injected at the insterstage port using a syringe with the regulator manipulated to work the contaminant onto the surfaces seeking to achieve ~100 mg/ft^2 film coating. The as-built test setup photo is shown in Figure 7 with annotations.

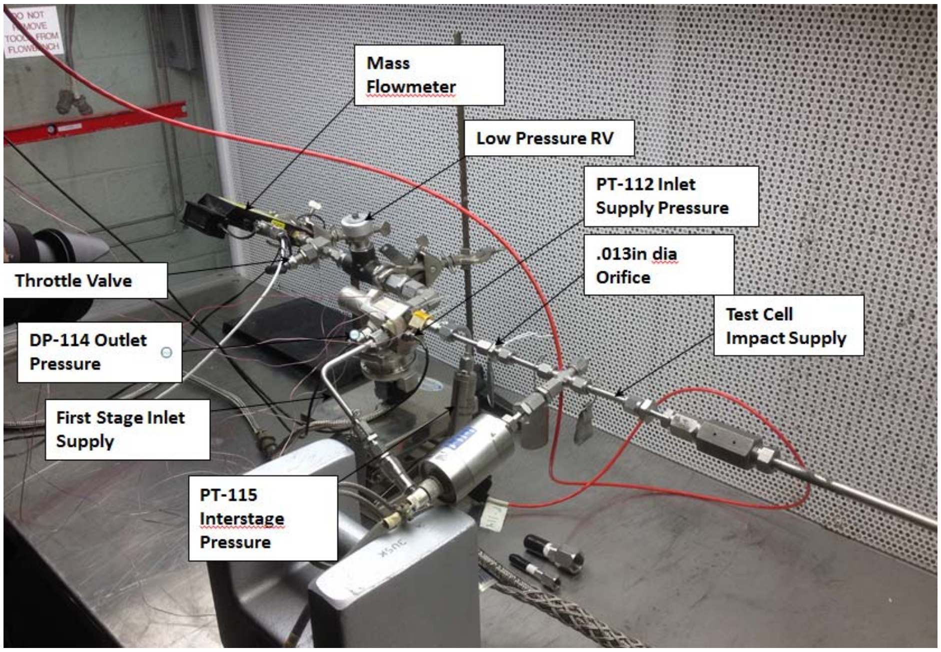

Figure 7 - POR 2.0 Impact Test Setup

VI. POR 2.0 Testing

The initial testing prior to moving onto contaminated challenge testing was to perform 60 dry pneumatic impact tests. Prior to initiation of impact sequence, the POR was setup with a GN_2 supply to enable nominal expected operation within the test system (Figure 8). After functional checks were completed, personnel were evacuated from the test cell and the cell was switched over to oxygen operation. Sixty test runs were executed with typical impact times during this test sequence of ~360 msec (Figure 9). Through leakage from the impact valve resulted in the gradual asymptotic rise of the interstage pressure to as high as ~700 psia prior to initiation of a given impact dependent on the dwell time between impacts. The impacts were performed manually rather than with the automated system to enable more control for the limited set of impacts. The actual impacts which are the linear portion of the curves remained consistent through-out.

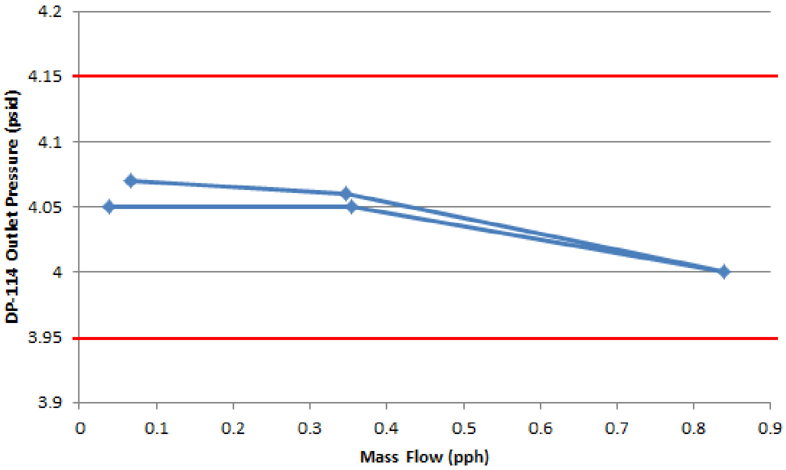

Figure 8 - POR 2.0 Pre-Impact Functional Test with GN2

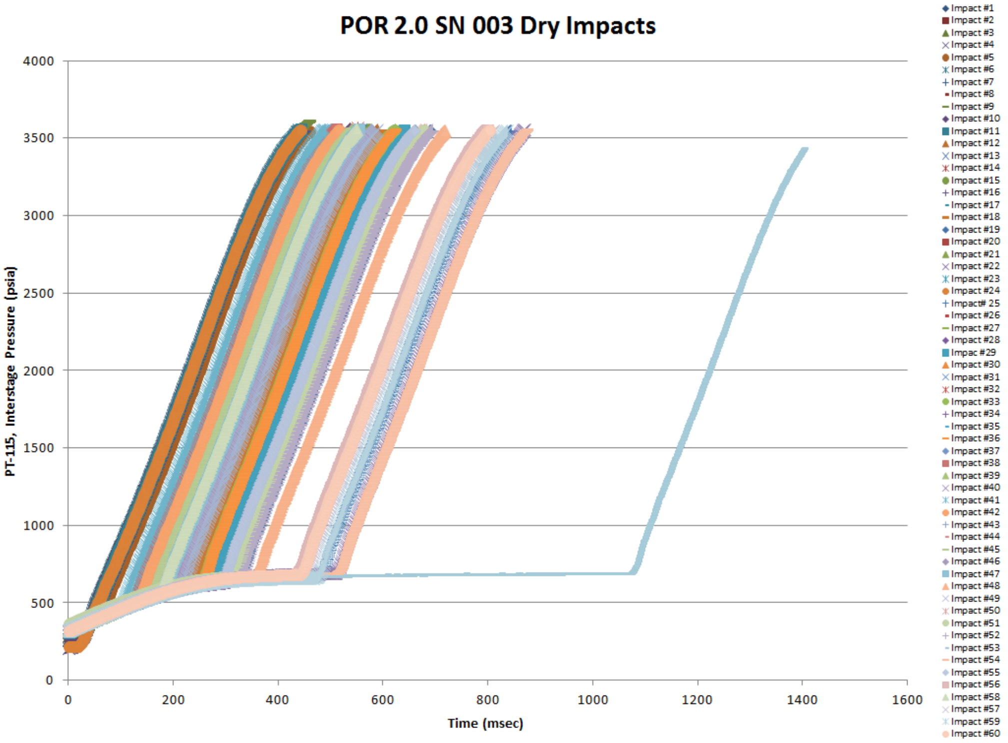

Figure 9 - POR Interstage Pressure Measurements During the Sixty O2 Wetting Dry Impact Tests to 3750 psia

Nitrogen functional testing performed after the dry impact testing showed nominal POR performance (Figure 10), thus indicating no damage to the POR internal components. This functional test validated real-time testing observations of the POR, which maintained its 4.05 psid setpoint with approximately 1 pph demand. The POR quickly re-established the downstream setpoint conditions after each dry impact test.

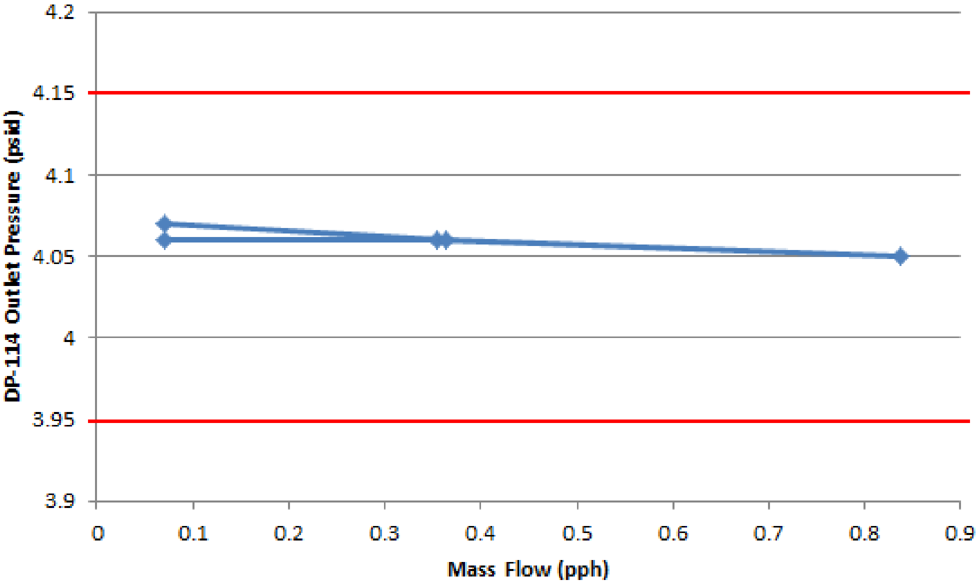

Figure 10 - Post Dry-Impact Functional Check

The test system was then re-configured for the wet impact testing by removing the 0.013in dia orifice and configuring the "Little Richard" impact valve muscle pressure to reduce the impact times. Impact times of 80-93 msec were measured after adjustments and prior to re-connecting the POR test article to the test system. In addition, the "Conair

Heat Delivery System" (CHDS) was set up to elevate POR body temperatures for the test series. The dodecane was injected into the POR interstage, the POR was manipulated, and then reinstalled in an inverted position so that gravity could assist the flow of dodecane towards the 2nd stage.

Five impacts were then executed with the dodecane load in the POR interstage port. The impact times ranged from 137-148 msec (Figure 11). After the second impact, a leak was noted with the interstage/supply fitting connections which use the same interface used on the Measurement Specialties, Inc EPXO series pressure transducer used for both the supply and interstage pressure transducers. This particular connection uses a fluoro-silicone seal captured between two stainless compression limiting/backup rings. The elevated temperatures of ~185F during the first two test runs appeared to have softened the seal resulting in a leak. The leak was not significant enough to affect the test results so the impacts continued to completion. As shown in Figure 12, the CHDS was adjusted to reduce POR body temperatures for the remaining three test runs.

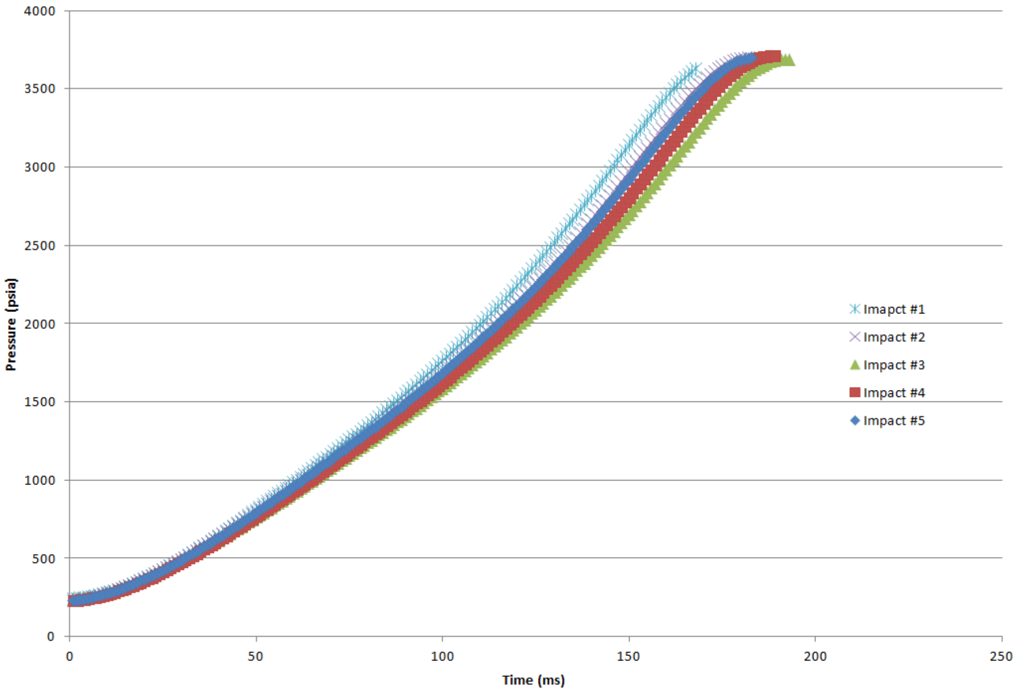

Figure 11 - POR Interstage Pressures During the First Dodecane Wetted POR Interstage Impact Test Series (~140 msec Average Impact Time)

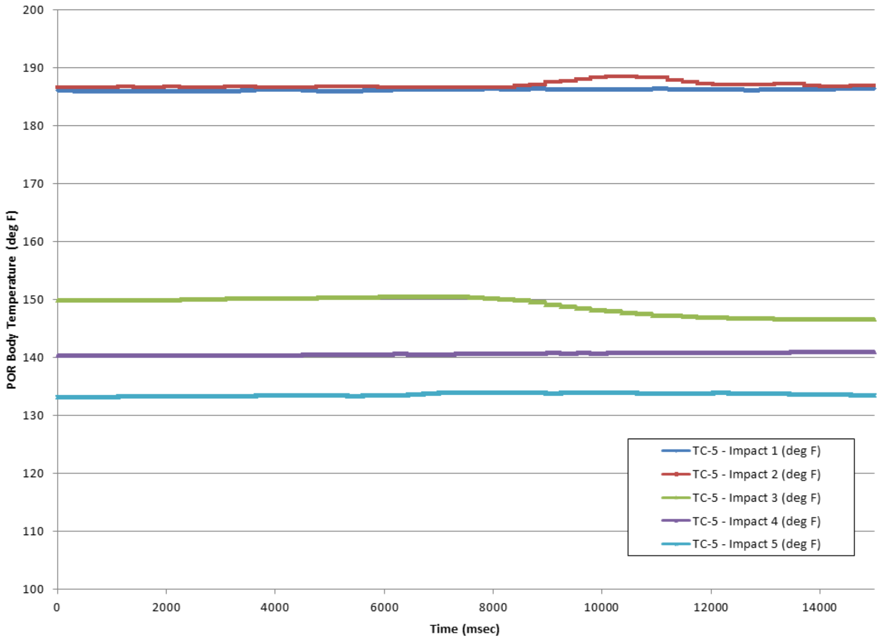

Figure 12 - POR Body Temperature (TC-5)

Functional testing performed after the initial wet impact testing demonstrated nominal POR operation (Figure 13), and again indicated no damage was detected by functional degradation. It is important to note that this was anticipated as the regulator was operating at ~.4 slm demand during the interstage impacts and continued to operate during and after each impact.

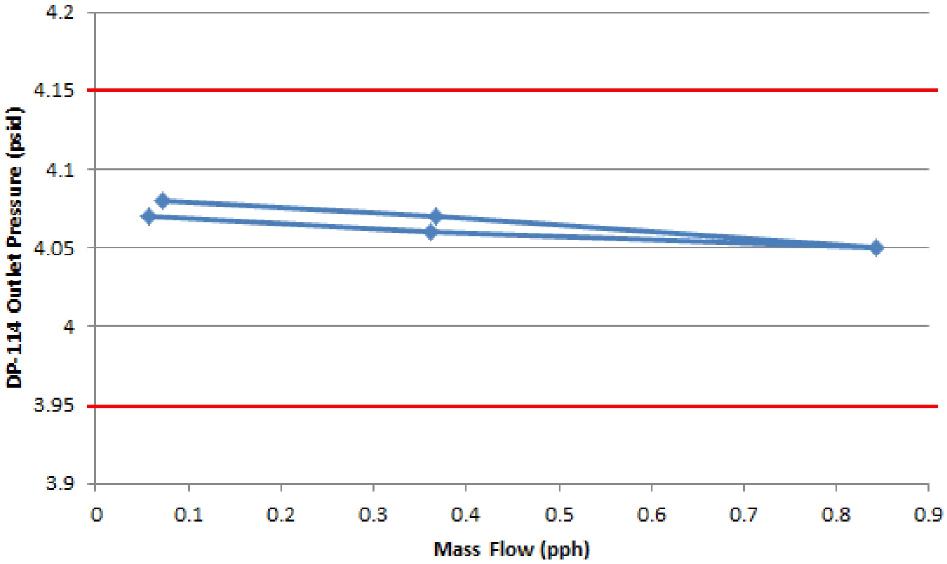

Figure 13 - Post Dodecane Impact Test Series #1 Functional Regulator Check

A final series of 5 wet impacts was executed after the test cell was adjusted to further reduce impact times and another 20 µL of dodecane was injected via syringe into the interstage pressure transducer port. Results from this second wet impact series are presented in Figure 14, which shows impact times ranging from 46-49 msec. POR body temperatures in this series were generally lower than in the first wet impact series as shown in Figure 15 but still >20°F warmer than the current PLSS 2.5 Thermal Desktop Model indicates the POR will see during a full EVA in a Lunar Crater

Hot Case with a contaminated Thermal-Micrometeroid Garment (TMG) assuming an ε* = 0.1 (10). While not shown, the POR maintained the ~4.05 psid set-point at the ~1 pph demand throughout testing.

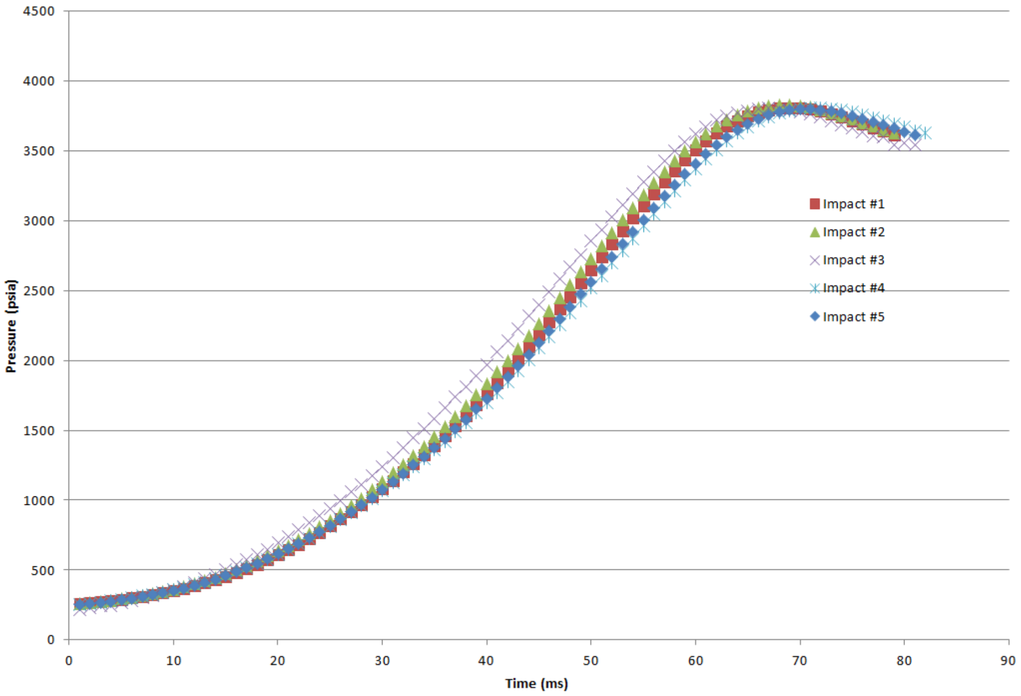

Figure 14 - POR Interstage Pressures During the second Dodecane Wetted POR Interstage Impact Test Series at ~50 msec Pressurization Time

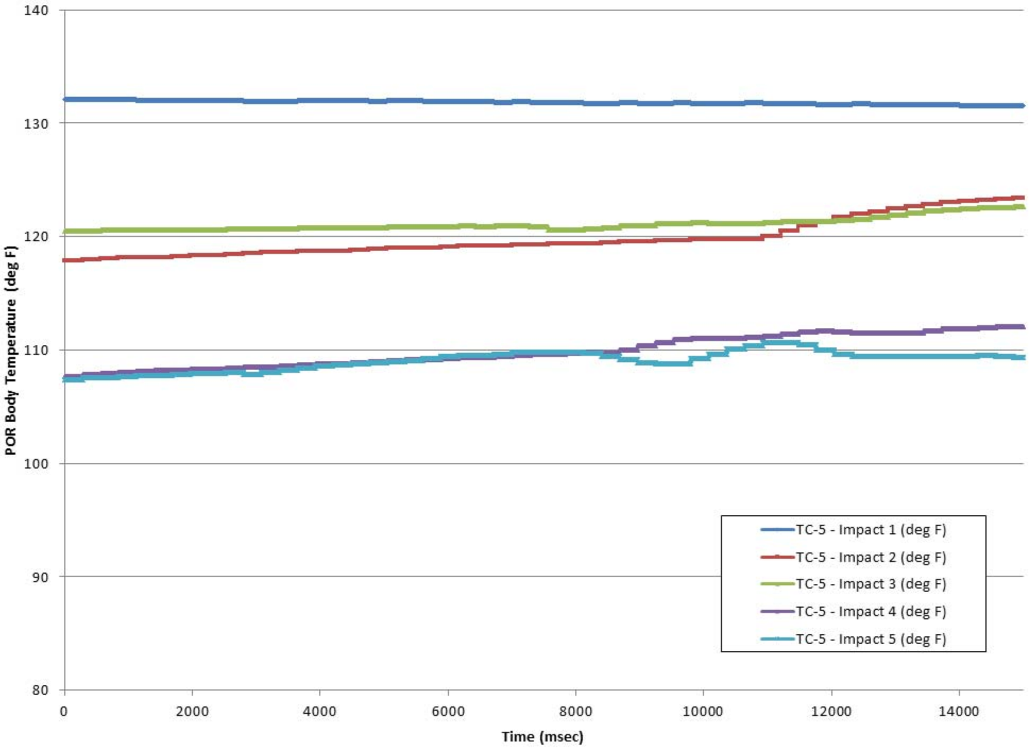

Figure 15 - POR Body Temperature (TC-5)

The test cell was then switched over to GN_2 supply and the POR had two final performance sweeps performed at ~4 psid and then ~1 psid to confirm operation. No issues were noted as the regulator still met specifications (see Figures 25 and 26) with no evidence of poor lock-up, excessive droop, or regulation loss.

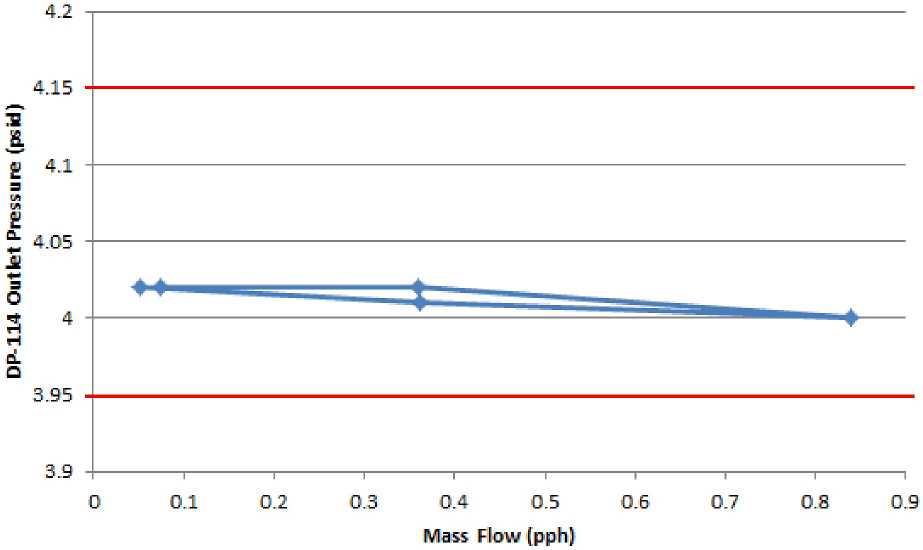

Figure 16 - Post Dodecane Impact Functional Test at ~4psid set

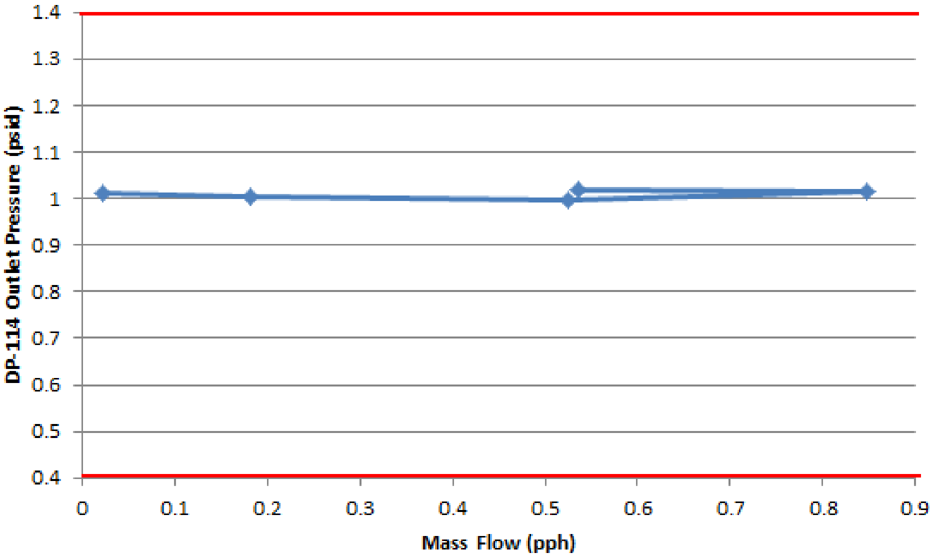

Figure 17 - Post Dodecane Impact Functional Test at ~1psid set

At the end of POR testing, the POR was disconnected and then a demonstration was setup. The .013in dia orifice was injected with 20uL of dodecane and then installed on the end of the impact fitting. The system was then pressurized and impacted using the same settings used for the last set of wetted impact tests with the POR. The lights were dimmed in the test cell. Upon impact, a small, brief flame was generated from the impact demonstrating that the adiabatic compression conditions were adequate to ignite the dodecane contaminant.

VII. POR 2.0 Post Test Disassembly and Inspection

At the completion of the POR testing at WSTF, the unit was shipped back to Cobham Mission Systems for a more detailed functional check followed by careful disassembly looking for damage and evidence of combustion of the dodecane.

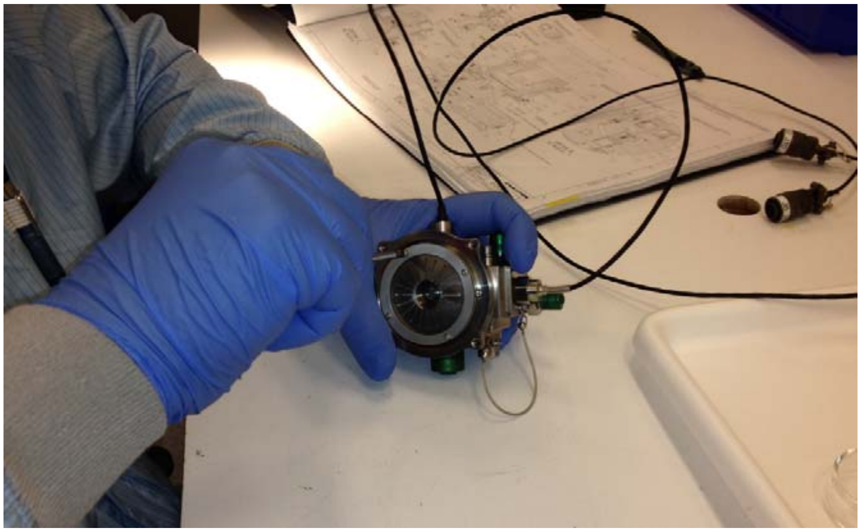

Figure 18 - Disassembly of the POR at Cobham

During disassembly, the regulator was visibly clean (normal light, no magnification) through each step from the removal of the actuator, bellows housing, Belleville spring assembly, and even the second stage seat, stem, and ball. The initial pass through of the disassembly did not yield noticeable contamination but under magnification with the Keyence Video Microscope system, a few notable areas were found as evidence of combustion. Figure 19 depicts the sapphire ball from the 1st stage regulator which was found to have what appears to be a carbon witness mark from the 1st stage seat. SEM analysis could not verify this as the quantity was too small. The ball in the figure is 1mm diameter.

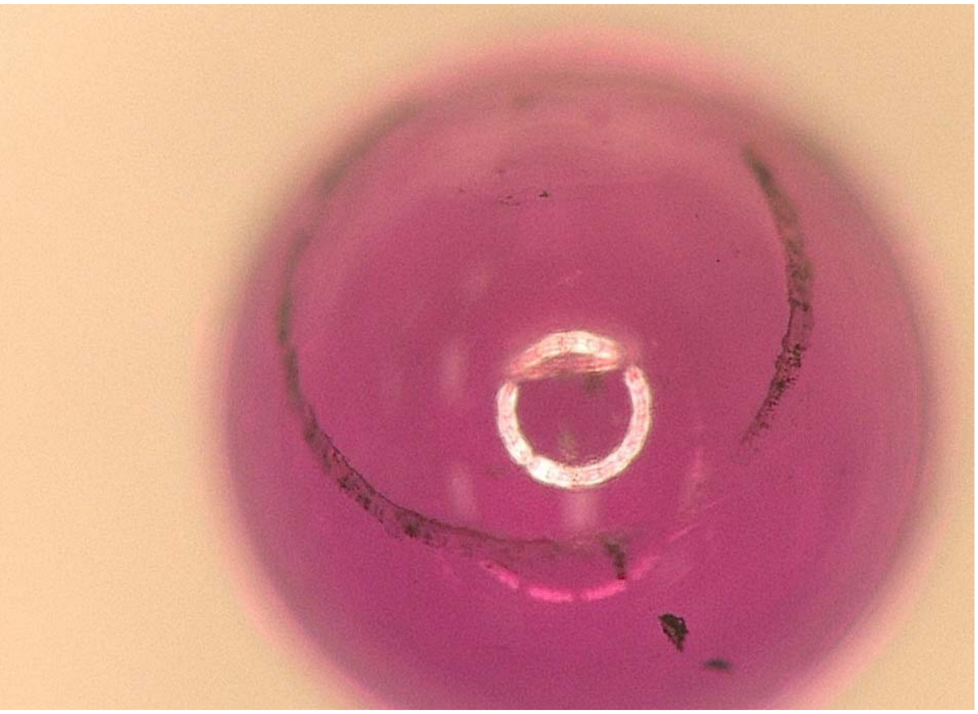

Figure 19 - Sapphire Ball from 1st Stage Regulator

The filter located in front of the 2nd stage regulator had no visible carbon contamination to the naked eye or with the Keyence System, however, SEM of the filter found carbon as shown in Figure 20.

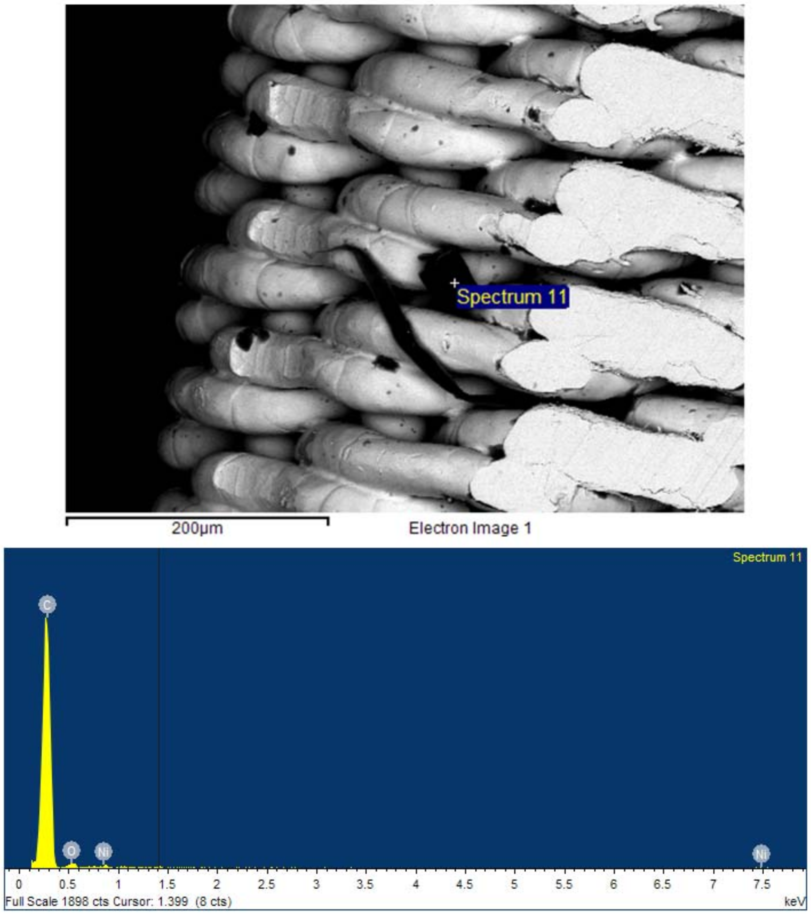

Figure 20 - SEM of filter in front of 2nd stage regulator

The presence of the contaminant on the filter in front of the 2nd stage and the 1st stage ball makes sense given the setup and conditions used during the test. Under those conditions, a supply pressure of ~3750 psia was supplied to the inlet of the 1st stage and a demand of ~.4 slm was setup on the outlet of the 2nd stage regulator which was set to ~4 psid. Under these conditions, the interstage would be pressurized to ~200 psia and the 1st stage and 2nd stage seats would be open and flowing (not in lock-up). Reference Figure 21 for the following description of events. The impact was then fed into the interstage pressure transducer port raising the interstage pressure rapidly from ~200 psia to ~3750 psia and simulating the failure of the 1st regulator seat. At that point, the rapid pressurization both from the impact and then the subsequent ignition of the dodecane pushed combustion products to both ends of the volume. At one end, the open 1st stage seat which would then close from pressure loading as the interstage exceeded the set-pressure of the regulator but not before some combustion products were pushed through the seat opening leaving a witness mark on the ball from the contaminants. On the other end, the 2nd stage regulator was open and flowing with the 20 micron filter in front. As the ignition expanded, there was an increase in the regulator outlet pressure momentarily until the balance stem/Belleville spring could compensate and reduce the stroke on the ball to reduce the outlet pressure given the higher interstage pressure. This can be seen in Figure 22.

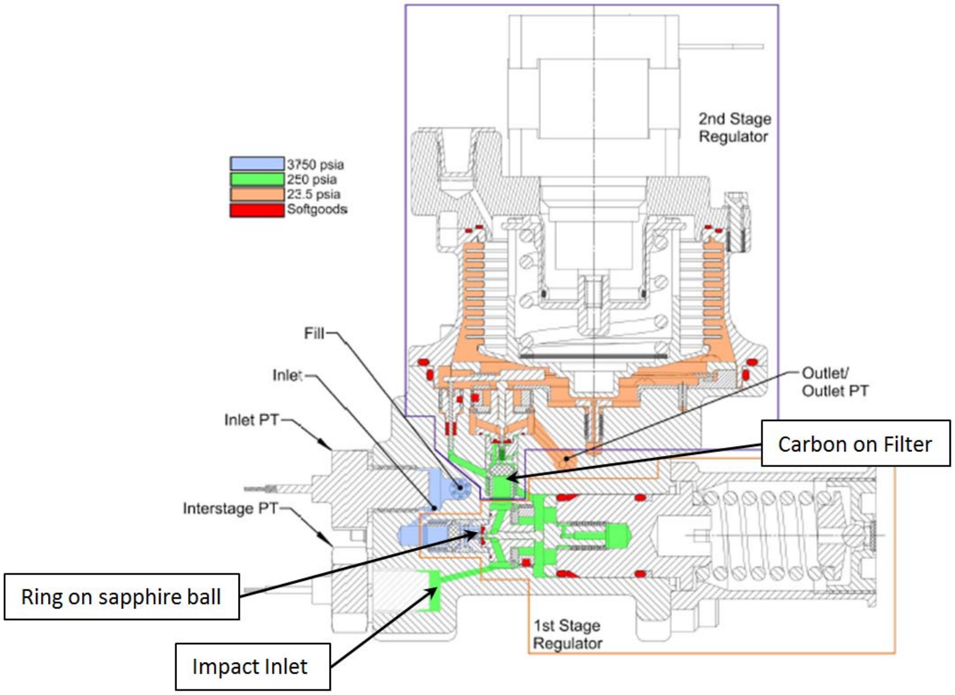

Figure 21 - POR 2.0 Cross-section with Interstage Pressurization Annotation

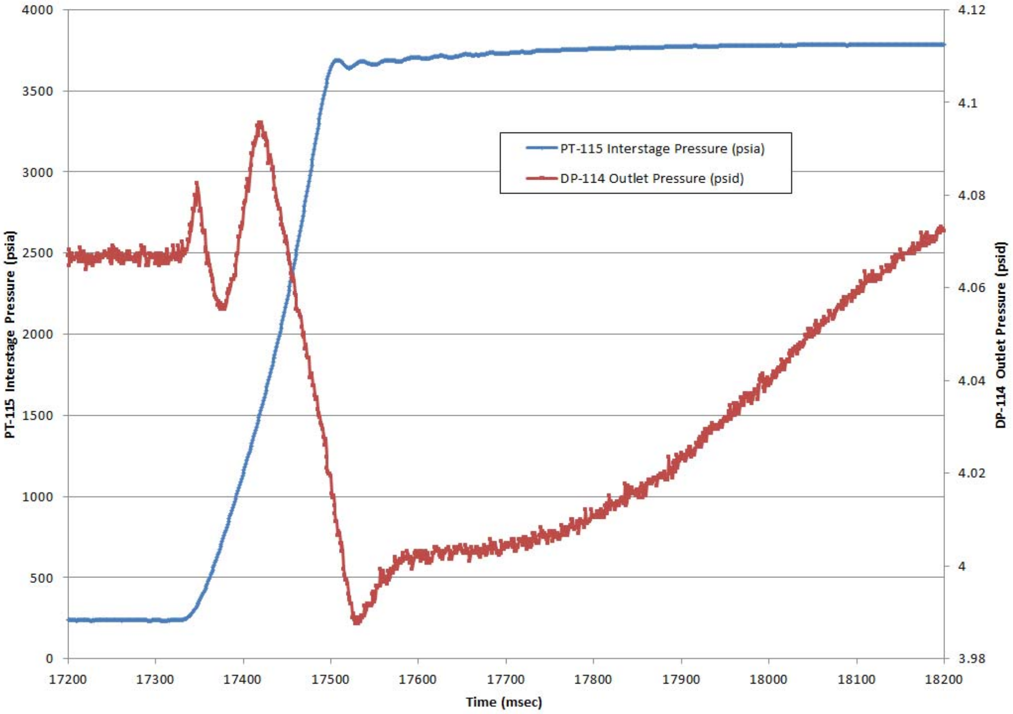

Figure 22 - Outlet vs Interstage pressure on Impact#1 for Wet Test Series#1

VIII. Post-test Thermal Desktop Model Updates and Correlation

After completion of the test series at WSTF, the Thermal Desktop model of the POR was updated based on the test setup and the inlet pressure readings at the interstage were used as a forcing function. One of the initial concerns was that the short drill passage from the Interstage Pressure Transducer port to the diffuser area within the body of the regulator would present enough of an obstruction as to create a lag in the pressurization in the actual interstage area thereby slowing the pneumatic impact pressurization rate. The model confirmed that for both the 150 msec and 60 msec pressurization cases tested, the lag was negligible as shown in Figure 23 and Figure 24 where all of the predicted pressures from the inlet to interstage were so close with respect to the plot scale that they appear on the same line.

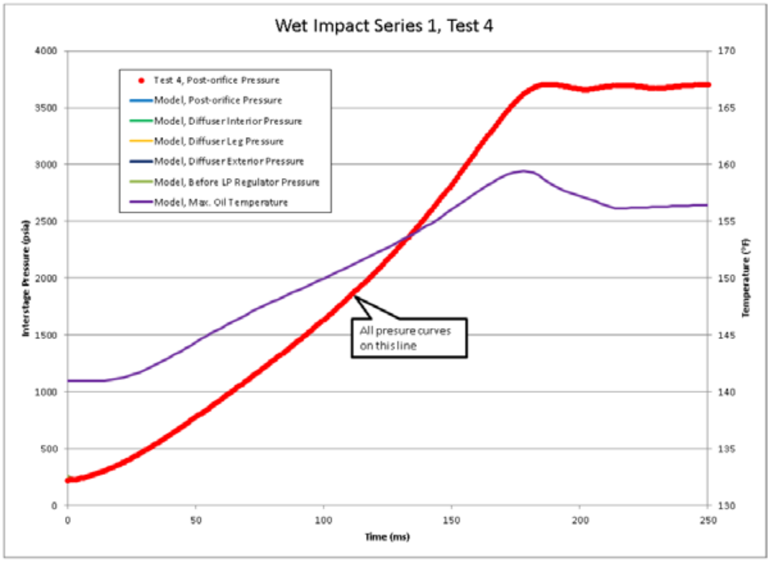

Figure 23 - POR Thermal Desktop Model 150 msec Pressurization Test

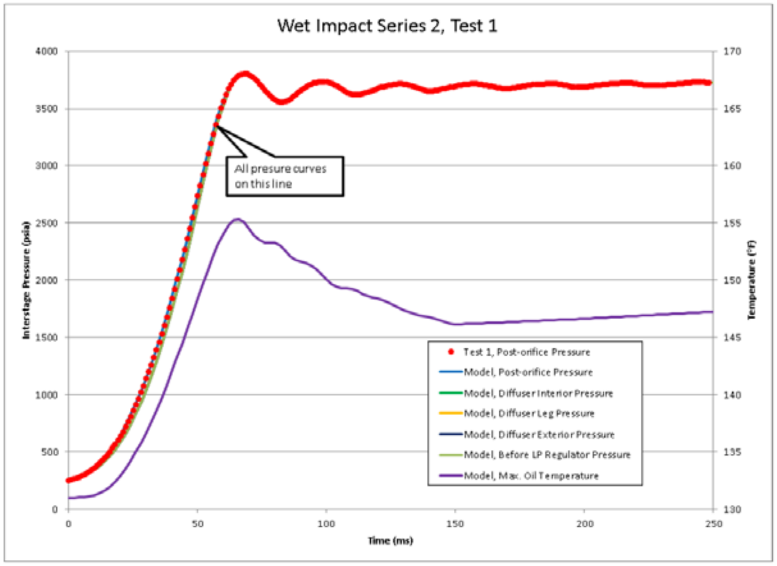

Figure 24 - POR Thermal Desktop Model 60 msec Pressurization Test

IX. Conclusion

The objectives for this test were fully satisfied by the data collected. The POR design was "wetted" with 60 impacts of dry oxygen, followed by two sets of 5 impacts of oxygen with a lightweight hydrocarbon contaminant, dodecane at levels > 100 mg/ft^2. The impacts with the kindling chain contaminant were performed at the MEOP for the regulator, with elevated regulator body temperatures, and at pressurization rates up to 3 times faster than could be achieved from the failure of the 1st stage regulator under these unlikely conditions. The contaminant levels used (>100 mg/ft^2) were far in excess of the required cleanliness level of < 1 mg/ft^2 specified and maintained in Level 100A per JPR 5322.1 and the < 2 mg/ft^2 typically assumed for Oxygen Compatibility Assessments (OCA). The regulator performed nominally prior to, during, and after the entire impact series. In the end, evidence of dodecane combustion was found in the regulator but did not result in any functional degradation. Should a systemic or specific contamination event such as that discussed regarding the EMU SOP Regulator recur with with this regulator/system during an exploration mission 200,000+ miles away from the cleanrooms/labs on earth, the demonstrated POR performance indicates that if the event is known about at all, it will not be expected to be as a result of a regulator malfunction.

Acknowledgments

This test and the data collected from it would not have been possible without the assistance from the wonderful folks at the White Sands Test Facility (WSTF). We would like to specially thank Steve Peralta, Kyle Sparks, Jonathan Tylka, and Tim Gallus who invested time, helped us to pull this test off, and who were great hosts for the entire experience.

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