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A Flexible Approach for Electric Propulsion Pressure Regulation

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Pressure regulation for electric propulsion (EP) systems on spacecraft have historically utilized solutions with fixed pressure set points. In the case of mechanical regulators, changes to the design may be needed in support of different pressures for different applications. In the case of bang-bang regulation, a high cycle count may be required to keep within a desired pressure range. Additional components to the regulator are also typically needed for heritage solutions, such as isolation valves for mechanical regulators, or plenums in the case of bang-bang systems. Fixed pressure set points may also limit the capability of a downstream flow controllers typically used in EP systems. Alternatively, a solution that uses electronic pressure regulation can support a wide range of pressure set points for different applications and without the need for additional supporting components. Designed by Moog, Inc., the Pressure Regulation Assembly (PRA) utilizes the same proportional flow control valve (PFCV) design used for anode and cathode flow control to the engine, except for pressure regulation. An overview of the PRA design, performance, challenges, and comparisons to other regulated systems will be reviewed in this paper.

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I. Introduction

This paper will provide an overview of the PRA design and performance, and comparisons to traditional electric propulsion regulation and or feed system solutions[1,2]. Information presented herein will also attempt to show that a common PRA design is able to support most all electrical propulsion regulation applications, resulting in the potential for a common design across multiple missions and electric propulsion architectures.

II. Pressure Regulation Assembly (PRA) Design and Operational Overview

A. PRA Design Configuration Overview

The PRA consists of an all welded stainless steel tubing and component construction that includes two Proportional Flow Control Valves (PFCVs) in parallel flow, one upstream high pressure transducer, two downstream low pressure transducers, an aluminum flight plate, and all associated brackets and hardware. The inlet tube interface connects to the propellant source and the downstream tube interface connects to a low pressure flow control feed system, or control orifices. The assembly has redundancy for the PFCV and low pressure transducer with only one each of these components needed for operation. The PFCVs are normally closed current driven devices that typically operate in the 80 – 150 mA range. The transducers are typical strain gauge designs that have linear voltage to pressure ratios. The transducers are not amplified in the case of the current PRA design, mitigating the risks associated with EEE parts use in a radiation environment. The overall PRA is a compact design with an approximate envelope of 180 x 240 x 50 mm and a mass less than 1.8 kg.

A PRA functional schematic and final assembly photograph are provided in Figures 1 and 2, respectively.

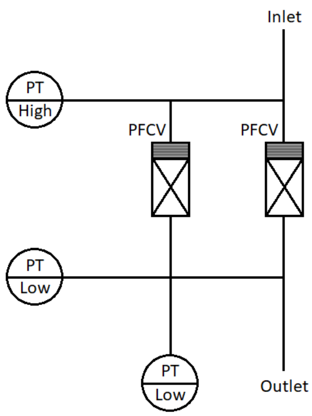

Figure 1. PRA Functional Schematic

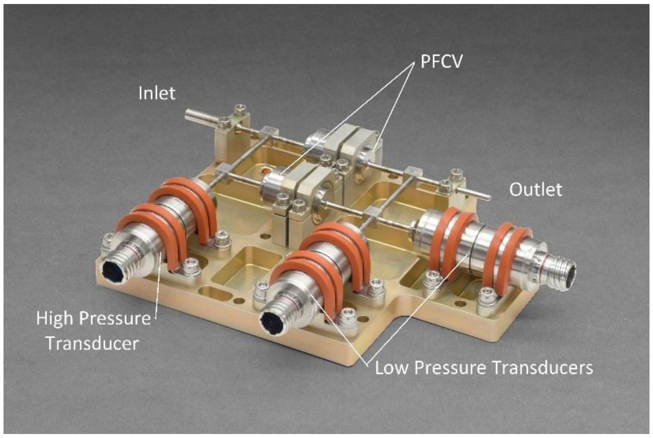

Figure 2. PRA Final Assembly Photograph

B. PFCV Design Overview

The Moog Proportional Flow Control Valve (PFCV)[3] shown in Figure 3 is an all welded stainless steel, normally closed solenoid-type valve that can provide controlled gas flow or regulated pressure in proportion to input current when used in a feedback control circuit. It can also be operated directly in an open loop circuit configuration. The PFCV incorporates a 25 micron absolute filter at the inlet to mitigate contamination risk, and provides a leak tight seal when in the normally closed position.

Figure 3. Proportional Flow Control Valve

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C. PRA Operational Overview

Operation of the PRA is via a closed loop feedback control with the low pressure transducer telemetry and an electronic controller card that can be integrated into the system PPU, or as standalone box. Only one PFCV and one low pressure transducer are required to support regulation, with the additional PFCV and low pressure transducer incorporated for redundancy. The low pressure transducers have a range that matches closely with and envelopes the full pressure range desired for operational regulation. The controller is a proportional integral device that has the ability to receive an input voltage command and to output a current over a range that envelopes the PFCV operation. The input voltage command corresponds with the low pressure transducer voltage at the corresponding pressure desired. A proper controller design will smoothly iterate the current output until the pressure output matches the command signal and thus obtaining the desired regulated pressure. The maximum power to operate the PFCV over its operational range is less than 1 W.

III. PRA and PFCV Performance Results Overview

A. High Inlet Pressure Performance Results

High pressure PFCV performance development testing has been performed on several occasions on different units and with various testing parameters. One of the first uses of the PFCV as a regulator was demonstrated on an advanced concept mission in 2006[4]. This simple system shown in Figure 4 regulated xenon from a maximum operating pressure of 2200 psia to a regulated pressure of 5.25 +/- 0.25 psia. Some development and design delta efforts were successfully applied to tune the baseline controller for pneumatic and electrical response. The risk of water or other foreign constituents is related to the Joule-Thomson effect at the PFCV outlet and the potential of freezing these substances, resulting in restricted or blocked flow. Appropriate precautions were therefore applied throughout the process of the system to mitigate the risk of internal contaminates and the potential of freezing potential foreign substances. Not unique to the components used, the thermal effects and related freezing risks are applicable to any typical regulated xenon system.

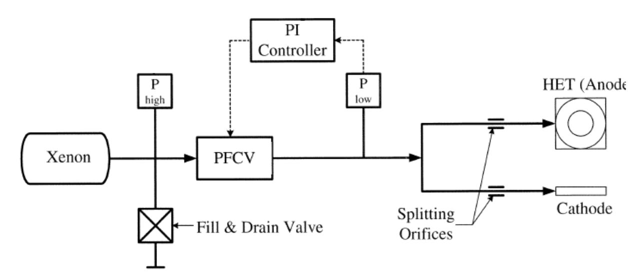

Figure 4. Feed System with PFCV Regulation

Subsequent to the noted demonstration program, additional research into the use of the PFCV as an electronic regulator have been pursued to determine operational and thermal limits, and to explore a simplified controller design that could support a wide range of operating conditions. Several development tests were performed on a setup the same as or similar to the one shown in Figure 5. Similarities between this test setup and the flight configuration previously noted can be made. Test conditions varied for each investigation depending on parameters investigated, and both argon and xenon were used with the argon flow rates adjusted to equivalent xenon flow rates. Flow rates were manually adjusted using the downstream valve in conjunction with the inline vacuum pump. The Moog PFCV used for this testing was verified with various inlet pressures between 100 psia and the maximum expected operating pressure (MEOP) of 2700 psia, however the maximum inlet pressure is the most difficult test condition due to the high flow gain. In all PFCV test cases the controller was set to maintain a regulated nominal pressure of 37 psia. Different flow rates were applied ranging from

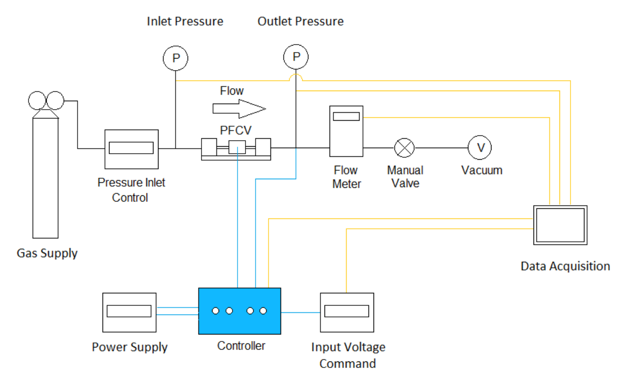

Figure 5. PFCV Test Setup for Regulation

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5 mg/s to 200 mg/s xenon, depending on the test. The sample rate for the data acquisition system was 10Hz in these test cases.

Performance summary at maximum pressure, under ambient conditions, using argon, and a simplified controller designed by Moog, are shown in Figure 6. Results indicate a 37 psia nominal regulated pressure is maintained within 1 psia across all flow ranges (5 mg/s to 200 mg/s).

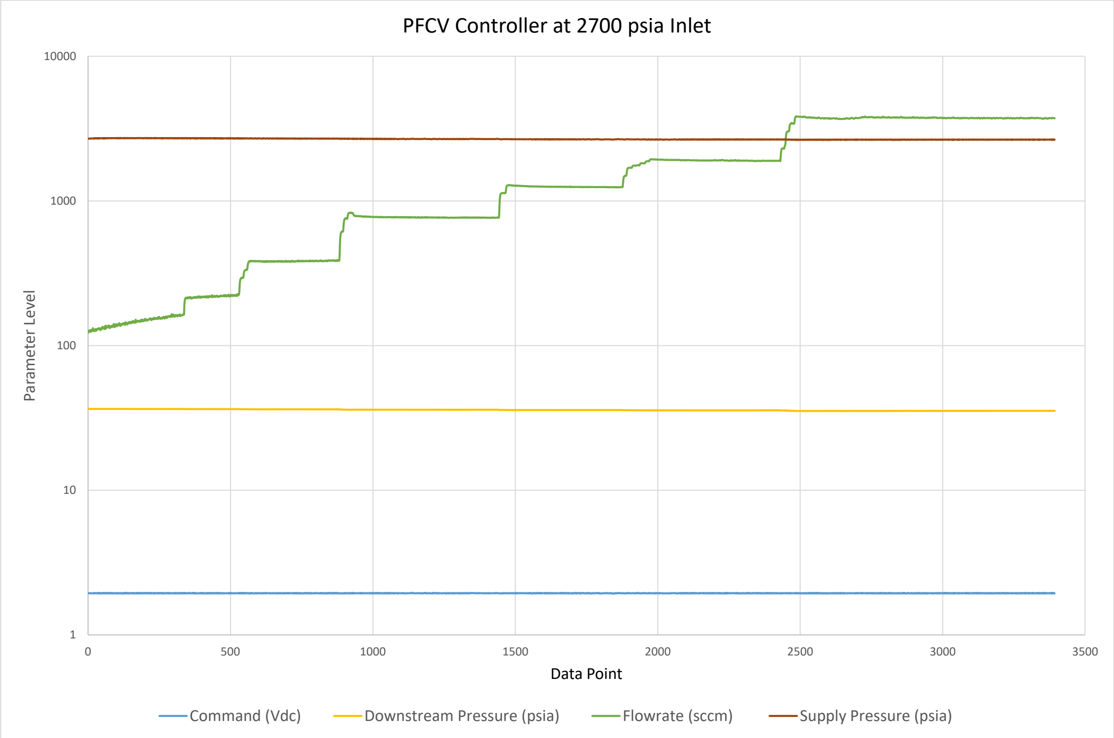

Figure 6. PFCV Maximum Inlet Pressure Regulation Test with Various Flow Rates (Argon)

Xenon results at maximum pressure, under ambient temperature and vacuum pressure, are shown in Figure 7 at flow rates of 9.8 mg/s and 155 mg/s. Results indicate a 37 psia nominal regulated pressure is maintained within 1 psia for both flow rates. Additionally, for this test setup thermocouples were added to measure temperature at various test locations with specific media temperature results indicating a temperature drop at the location downstream of the PFCV from approximately 70°F to just under 0°F in less than 4 minutes.

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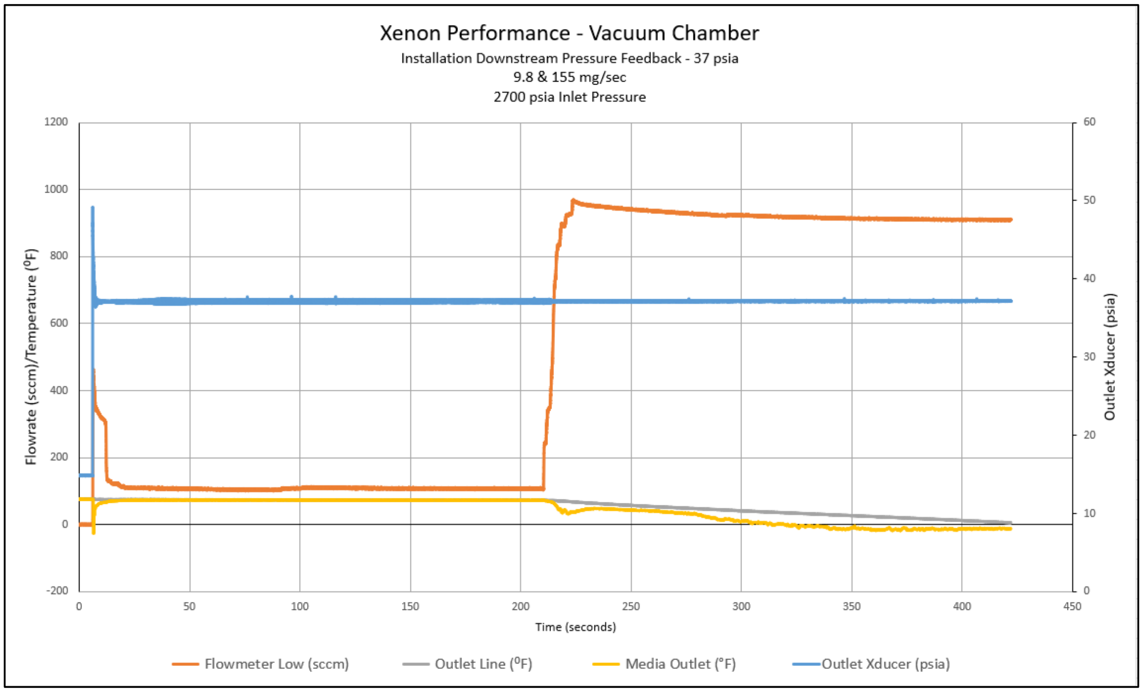

Figure 7. PFCV Maximum Inlet Pressure Regulation Test – Vacuum Pressure (Xenon)

B. Long Duration Thermal Results

Long duration xenon flow testing was also performed to determine the impact of the Joule-Thomson effect and what the media delta temperature would be in a flight like flow configuration. Specifically, the test was performed in a vacuum chamber with the same general setup as shown in Figure 5, except with the unit thermally isolated, and with addition of thermal couples at various locations. The media temperature was obtained by teeing in a thermocouple directing in the media flow path. A worst case condition to an existing specification was applied by operating at 2700 psia inlet, 60 mg/s flow rate, with a regulated pressure of 37 psia, and no heaters. Flow and pressure results are provided in Figure 8, with the corresponding temperature results are provided in Figure 9.

In summary, there were some issues with the test setup that resulted in variations for inlet pressure, flow, and temperature. At the test start there is a spike in flow and regulated pressure due to the manual application of the parameters. Beginning around the 1000 sec mark there was a loss of inlet pressure that was identified and corrected without stopping the test. The inlet pressure also was depleted just after the 5000 sec mark. There may also have been an influx of pressurant gas due to intensifier leakage just before the initial pressure drop as evidenced by the flow and temperature changes. Despite the noted inlet pressure variations, the regulated pressure held to the nominal setting of 37 psia. Beginning just after the 2000 sec mark, 3-4 psia pressure spikes were observed over an approximate duration of 1000 sec. The cause of the pressure spikes is attributed to small amounts of water or other contamination constituents migrating from the intensifier, freezing at the PFCV orifice exit and then quickly breaking free. This same phenomenon has been observed on mechanical regulators that were intentionally injected with small amounts of water and then operated, and a similar visual observation was made during xenon cold gas thruster testing[5]. A similar spiked occurrence is also noted just prior to the 5000 sec mark, however in this case argon was noted to be leaking into the xenon side of the intensifier resulting in corresponding flow and temperature deltas, as shown. Again, the nominal regulation was maintained within a relatively tight tolerance of approximately +/-1 psia during the end of test conditions noted.

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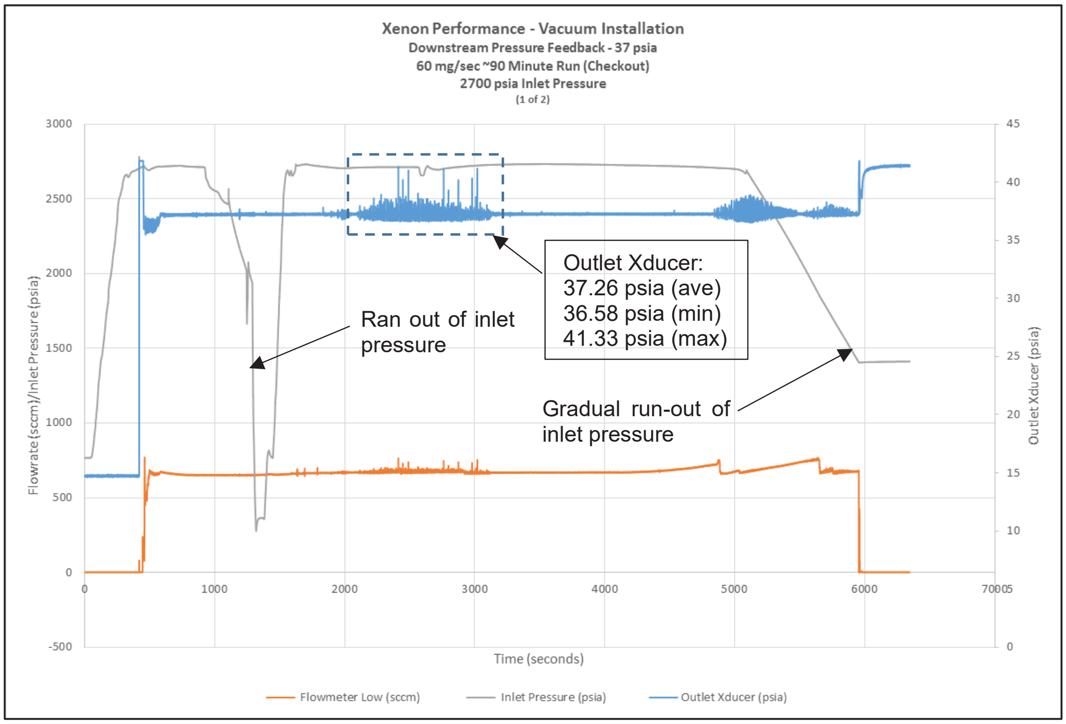

Figure 8. Long Duration Pressure and Flow Results - Xenon

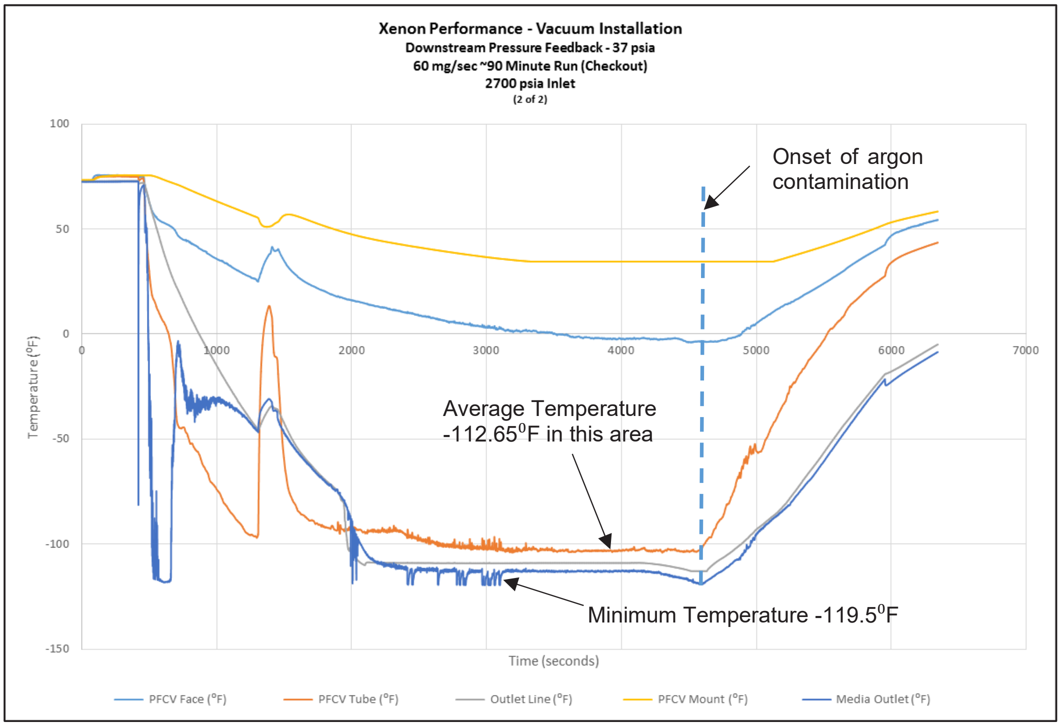

Figure 9. Long Duration Thermal Results – Xenon

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Besides regulation verification, one of the main takeaways from the longer duration xenon test is the minimum temperature observed in the downstream media and the PFCV downstream tube, both achieving less than -100°F (-73°C). The temperature at the PFCV orifice outlet is expected to be even lower than the downstream thermocouple readings but cannot be easily measured. For other applications the same design has been used with liquids and temperatures below -180°C. While this thermal condition does not affect the PFCV function, it is very important that the system be free of non-propellant media, even to the low PPM levels.

C. High Pressure Testing Results

The PFCV has also been verified for regulation at a simulated 4000 psia maximum expected operating pressure (MEOP) in support of potential EP systems that use krypton as the propellant. Krypton EP systems typically have a higher MEOP as compared with xenon systems to accommodate propellant loads approaching xenon systems within a similar propellant volume. The closed loop test results shown in Figure 10 maintained inlet pressure around 4000 psia and manually varied the flow rate from a low of 18 sccm GN_2 (~11 sccm GKr) to a maximum of approximately 3100 sccm GN_2 (~1922 sccm GKr). The PFCV closed loop nominal pressure set point was 48.5 psia, and the resulting variance from this set point varied by less than +/-0.4 psia over the entire test duration. Some minor structural reinforcement of the PFCV is anticipated to meet typical stress safety margins at operating pressures higher than the qualified level of 2700 psia. However, the PFCV has survived burst testing to 20,000 psia, suggesting potential operating pressures in excess of 4000 psia are feasible.

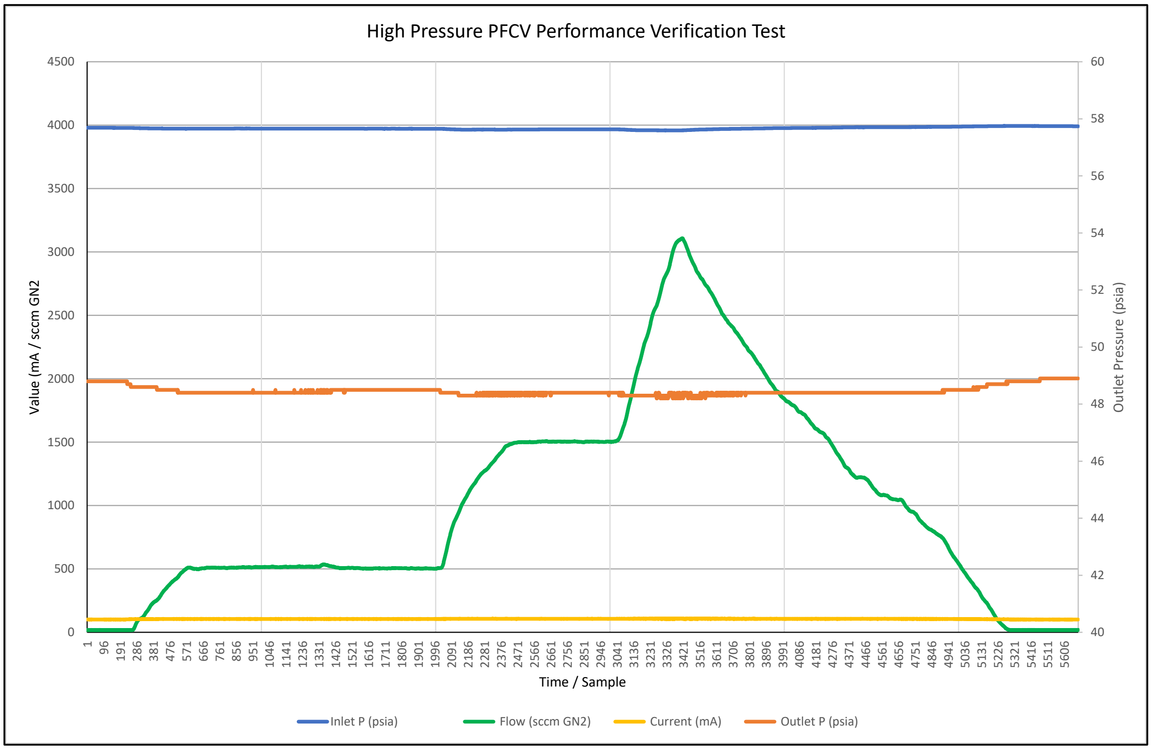

Figure 10. High Pressure PFCV Verification Testing

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D. PRA Testing Results

Acceptance level flow and regulation performance tests were performed on the first flight PRA before random vibration testing, during thermal cycle testing at hot and cold plateaus, and after thermal cycle testing. All regulation tests were performed on the primary and redundant PFCV of the PRA. Examples of the final PRA test results for maximum flow rate and gain, and for closed loop regulation are summarized in this section.

The maximum flow rate and gain test results shown in Figure 11 were performed using argon at 50 psia inlet and ambient downstream pressure. Results are typical for the PFCV design with expected hysteresis on the decreasing current due to effects of residual magnetism, which has no impact to regulation performance when operating in a closed loop feedback control system.

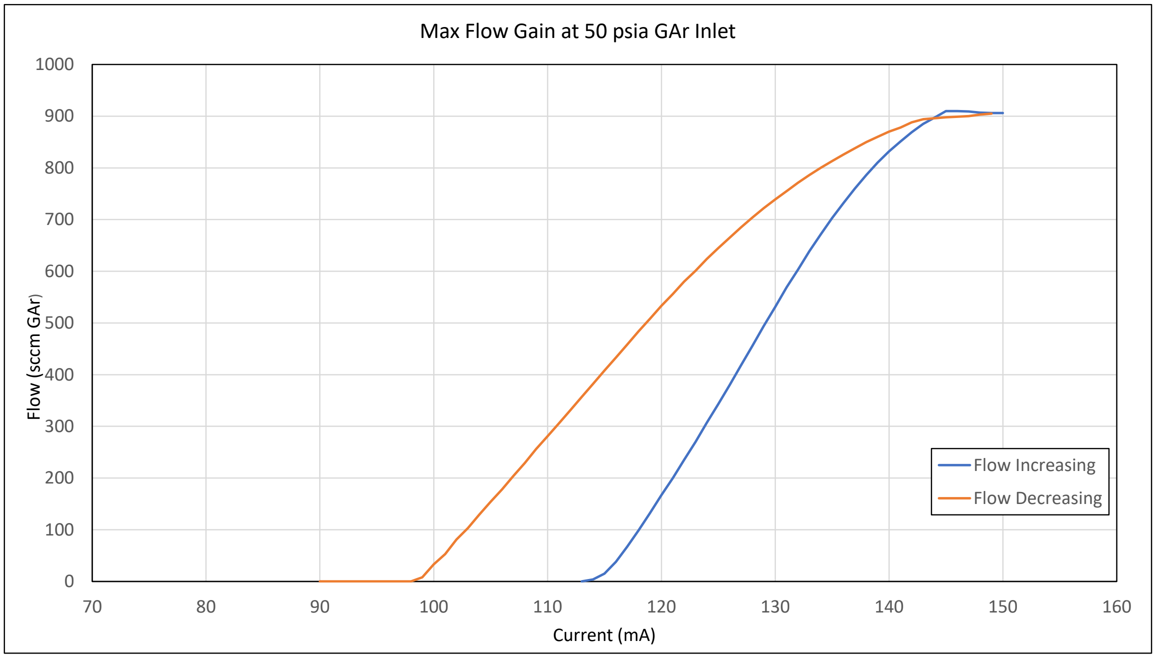

Figure 11. PRA Maximum Flow and Gain Test

Closed loop regulation testing results shown in Figure 12 were performed at low, medium, and high inlet pressures and at low and high flow rates at each pressure location, with a constant regulation pressure set point of 20 psia for all cases. Graphical results are presented for inlet pressure, flow rate, PFCV control current, and outlet regulation pressure. Deviations in the flow rate results are indicative of the manual operation used to control this parameter, while still meeting the steady state flow rate tolerance requirements. Steady state regulation pressure was maintained within +/-0.2% from nominal throughout all test locations. The pressure spikes from nominal at the test transition locations shown in the outlet pressure graph are a result of a low response setting of the controller. These spikes would not be present with a high response controller setting, as was the case in the previous examples shown in Figures 6 and 7.

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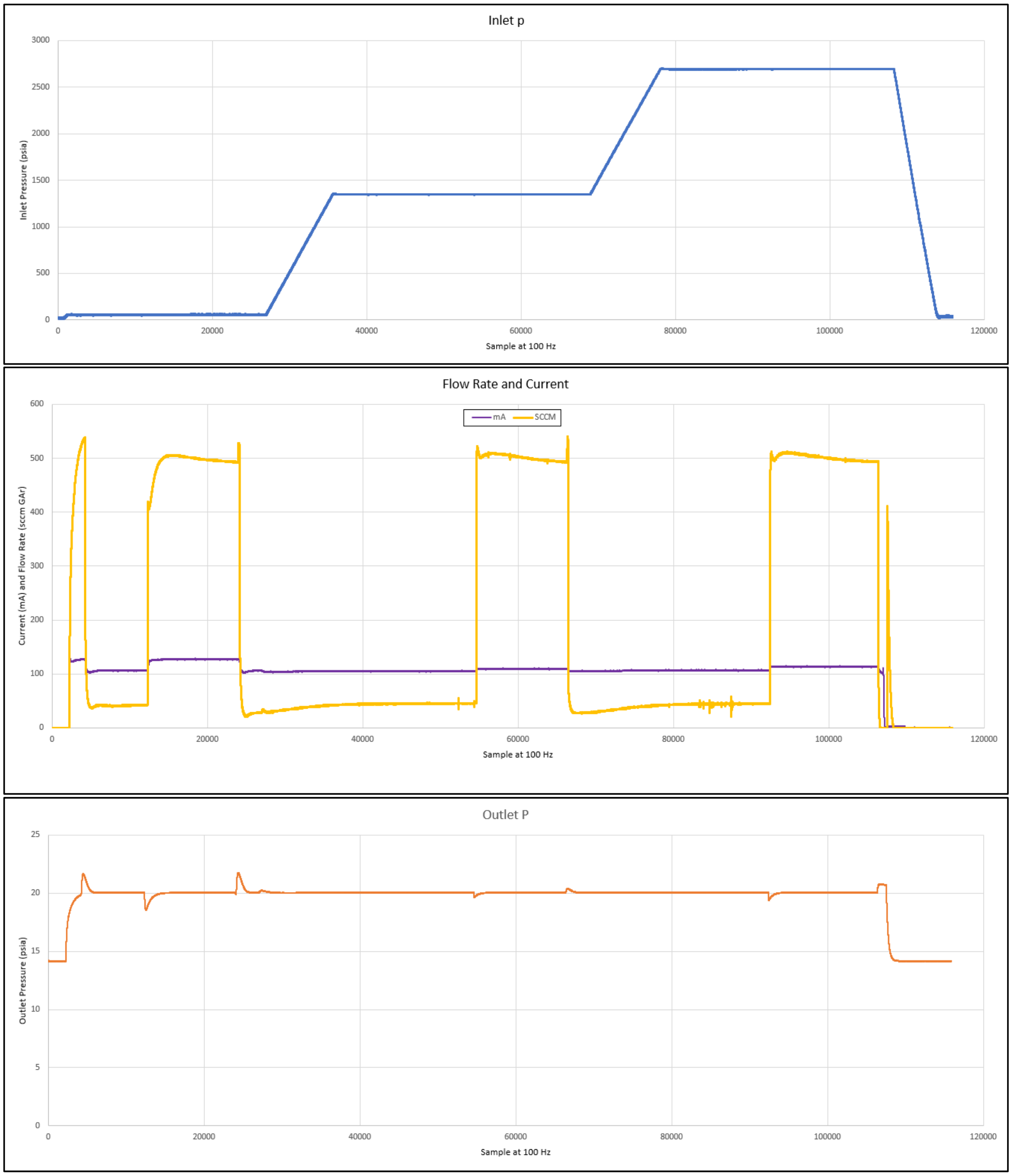

Figure 12. Closed Loop PRA Regulation Testing Results

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IV. Regulation Comparison Discussion

A. Mechanical Regulation

Mechanical regulators[6] are typically single set point devices that are not adjustable once the regulator assembly is complete. Set points can be altered within design limitations prior to final assembly, and this approach has been proposed in support of using two parallel mechanical regulators at different set point pressures for an application using a downstream thermal throttle that is limited in flow range at just one inlet pressure setting. Each regulator in the two pressure set point solution also has separate isolation valves to allow selection of the desired pressure. Two isolation valves per regulation line (four total) are utilized to achieve two high pressure inhibits for the normally open regulator design. In comparison, the PRA has the flexibility to support the same application, and with the same number of inhibits with the additional of one isolation valve and a controller. The PRA can also support future missions with different set points with no additional changes, as compared to the mechanical regulator solution that would require a different assembly set up, and possibly new parts, to meet different set point pressures.

B. Bang-Bang Regulation

Bang-bang regulation[1,2,8] is typically performed by solenoid valves in series and work in a closed loop feedback control system using downstream pressure transducer telemetry, similar to the PRA closed loop feedback. During operation a solenoid valve repeatably actuates to allow a buildup of downstream propellant pressure to a set level. Once the upper pressure limit is reached the solenoid will be commanded closed to isolate the propellant source until the downstream lower pressure limit is reached, resulting in a repeat of solenoid actuation to get the pressure back to the upper limit. This sequence is repeated as required to maintain a nominal set point pressure in support of a downstream feed system or directly supplying an engine. Different approaches can be applied in terms of isolation, cycling, and control algorithms for one, two, or sometimes three solenoid valves in series, in order to achieve the desired outlet pressure. A downstream plenum is also often incorporated to provide pneumatic capacitance, increasing the time period between pressure recharge cycles.

An example of a bang-bang feed system flow rate and corresponding pressure cycle profile in support of a proposed system solution are shown in Figure 13. In this case the feed system design has an orifice and a plenum downstream of the control solenoid to help control the pressure rise rate. A cycle rate of approximately 1 Hz is required to maintain steady state operation at 12.7 mg/s nitrogen or ~23 mg/s krypton, and a corresponding pressure level in the downstream plenum between approximately 47 and 60 psia, or +/- 6.5 psia from nominal. This specific application results in an estimated total cycle count of >10 million cycles with a propellant load of 420 kg of krypton. The PRA in comparison is capable of steady state flow with less than 1 psia delta pressure from nominal and with no valve cycles applied during steady state operation.

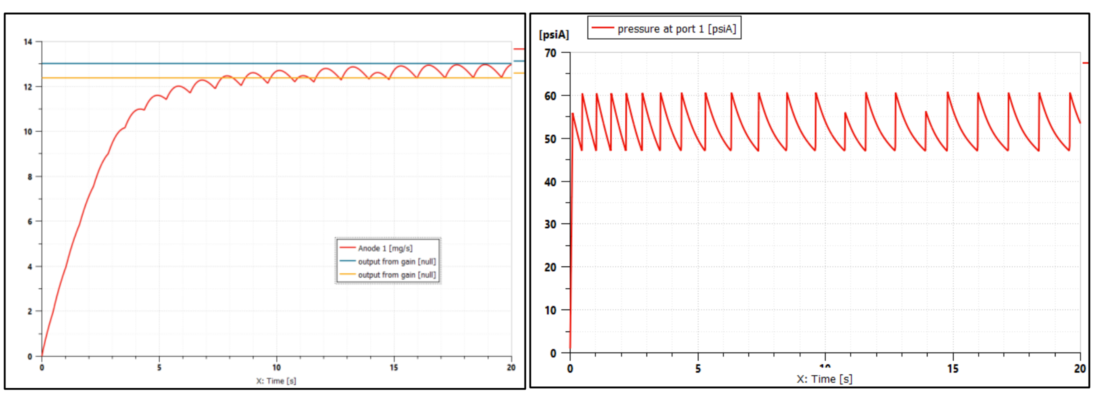

Figure 13. Estimated Flow and Pressure Cycle Rate for a Bang-Bang Feed System

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V.Conclusion

The PRA is the culmination of proven flight heritage and extensive development testing performed on the PFCV over several years. The performance results summarized in this paper support the PRA as a viable, flexible pressure regulation option for EP architectures supporting precise pressure control set points over a wide inlet pressure range and flow demand, with little to no thermal input, and controllable with a simple proportional integral driver. The limited number of full operational cycles further mitigates contamination, leakage, and life risks associated with high cycle count devices.

References

[1] John Steven Snyder, Thomas M. Randolph, Richard R. Hofer, and Dan M. Goebel," Simplified Ion Thruster Xenon Feed System for NASA Science Missions", IEPC-2009-064, 31st International Electric Propulsion Conference, University of Michigan, Ann Arbor, Michigan, USA, September 20 – 24, 2009

[2] I. Johnson, et.al., " New Avenues for Research and Development of Electric Propulsion Thrusters at SSL," IEPC 2017-400, 35th International Electric Propulsion Conference, Atlanta, GA, Oct. 8-12, 2017.

[3] Pehrson, D.M. and David, M. "Continuing Development of the Proportional Flow Control Valve (PFCV) for Electric Propulsion Systems". 30th International Electric Propulsion Conference, IEPC-2007-346, Florence, Italy 2007 Sep 17.

[4] Joseph K. Barbarits and Paul T. King, "Xenon Feed System Progress", AIAA 2006-4846, 42nd, AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 9-12 July 2006, Sacramento, California, USA

[5] Ian Johnson, Dustin Warner, Kevin Neff, Sean McCormick, "Xenon Cold Gas Thruster (XCGT)", IEPC-2019-941, 36th International Electric Propulsion Conference, University of Vienna, Vienna, Austria, September 15-20, 2019

[6] Jameson-Silva, K., J.J. Delgado, R. Liang, P.W. Lord, L. Rotlisburger, M. Torres, B. Tomescu, S.P. Malone, E. Werner, and J. Waranauskas, "Adaptability of the SSL Electric Propulsion-140 Subsystem for use on a NASA Discovery Class Missions: Psyche," IEPC 2017-181, 35th International Electric Propulsion Conference, Atlanta, GA, Oct. 8-12, 2017.

[7] Snyder, J.S., D.M. Goebel, V. Chaplin, F. Aghazadeh, I. Johnson, T. Kerl, and G. Lenguito, "Electric Propulsion for the Psyche Mission," IEPC-2019-244, to be presented at the 36th International Electric Propulsion Conference, Vienna, Austria, Sept. 15-20, 2019.

[8] Louis Dandaleix, Pablo Lopez, Sabine Lebeau, Dr. Hans-Peter Harmann, Dr. Heiko Dartsch, Marcel Berger, Guillaume Cautru, Marco Sabia, Dan Kroboth, "Pioneering EP Fluidic Feed Systems from Constellation Success Stories", IEPC-2022-584, 37th International Electric Propulsion Conference, Massachusetts Institute of Technology, Cambridge, MA USA, June 19-23, 2022

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