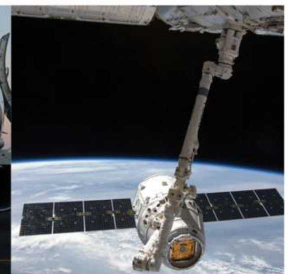

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Development of an Electronic Pressure Regulation System with Proportional Control Valve for Xenon-fed Electric Propulsion Systems

Technical Paper

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ABSTRACT

New propulsion capabilities necessary for all-electric satellites require advanced pressure feedback control systems with higher flow rates, particularly for electric orbit raising up to the geostationary ring. Electronic pressure regulation offers advantages in accuracy, remote adjustability, robustness, and lifetime stability when compared with equivalent mechanical regulators. Regulating xenon gas for propellant feed systems has particular challenges in this specific application due to Joule-Thompson cooling and the resulting 2-phase flow. This paper presents the development of a single-stage, cold-redundant, standalone, electronic pressure regulation system which throttles xenon propellant flow using a normally-closed magnetostrictively-actuated proportional control valve operated with a dedicated electronic control unit. This system design results in high-accuracy, adjustable pressure control performance without the steady-state droop of a mechanical pressure regulator, and without the accumulation volume associated with a bang-bang design. This paper will also emphasize design drivers and system architecture with a focus on pressure control and thermal control aspects. The design, analysis, and extensive verification testing will be described, and system models will be introduced to provide a correlation with test results and to support the product validation.

1 INTRODUCTION

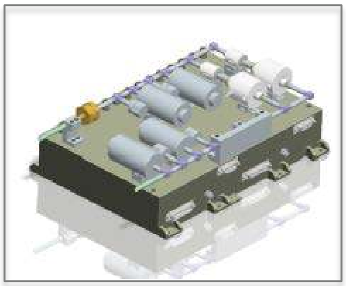

Figure 1 – Xenon Pressure Regulation Assembly XPRA

The propulsion demands for the next generation of all-electric satellites offer unique challenges for propellant delivery systems. Electric orbit-raising satellites require accurate and flexible pressure control systems which can be used for EP thruster systems with varied flow demands. The Spacebus Neo next-generation space bus is one such satellite system which will perform orbit-raising, station-keeping, and de-orbit maneuvers with electric propulsion. Marotta Controls' Xenon Pressure Regulation Assembly (XPRA) is a single- stage electronic pressure regulation system contracted by Thales Alenia Space UK, and designed to meet the propellant pressure management demands of a modern all-electric satellite.

The XPRA has redundant fluid control branches, two isolation barriers, and redundant electronic control units integrated with the assembly. High- and low-pressure telemetry, and downstream fluid temperature telemetry are supplied to the vehicle during operation.

The XPRA accomplishes pressure control through the use of Marotta's magnetostrictively-actuated, proportional Multi-Function Valve (MFV) in an electronically-controlled feedback pressure control system. This offers high-accuracy, adjustable pressure control performance without the steady-state droop of a mechanical pressure regulator, and without the accumulation volume associated with a bang-bang design.

2 SYSTEM ARCHITECTURE

The XPRA is composed of a Fluid Assembly mounted atop an Electronic Control Unit (ECU). The Fluid Assembly contains two parallel fluid branches, each with a latching isolation valve (MV602L), a proportional control valve (MFV), and a heater.

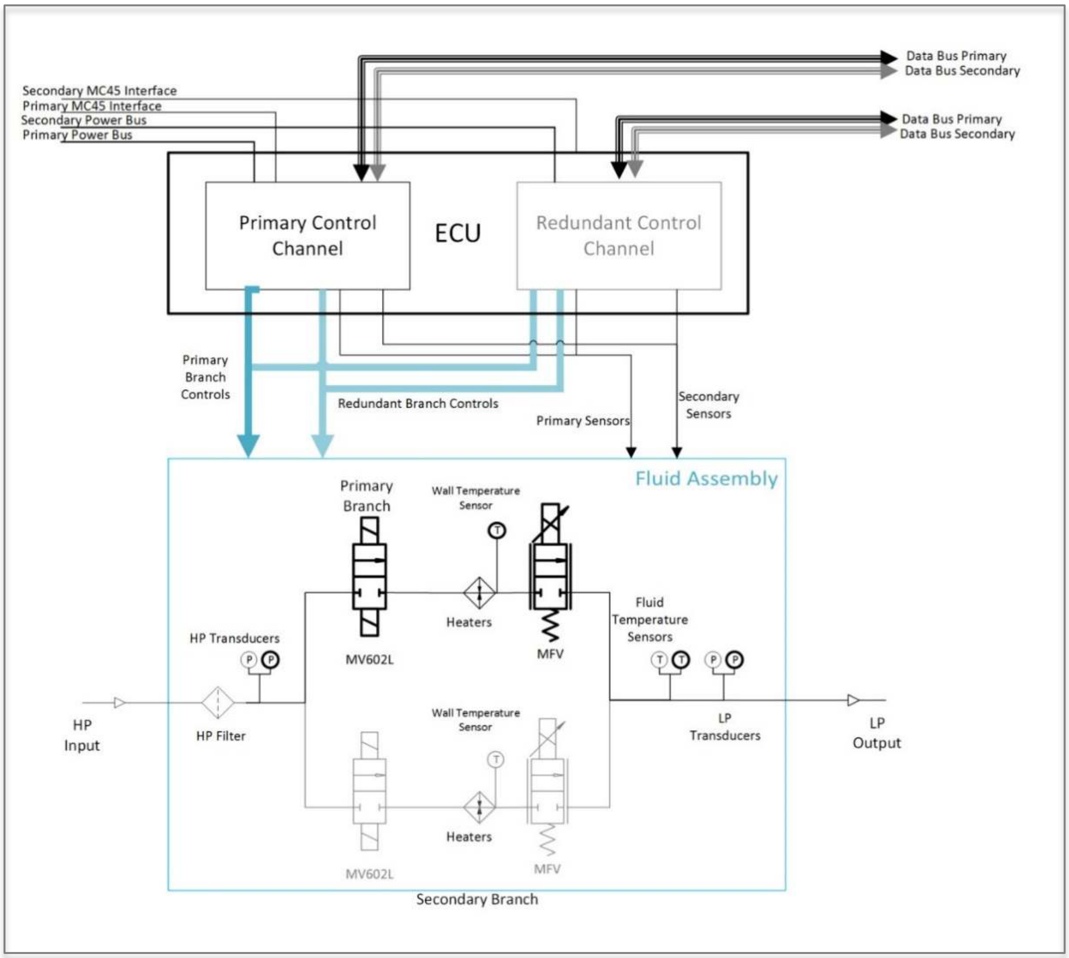

Figure 2 – XPRA System Layout

2.1 MULTI-FUNCTION VALVE

Figure 3 – Multi-Function Valve

The Multi-Function Valve (MFV) is the enabling technology of the XPRA. It is a TRL-9 component of the XPRA with flight heritage as a flow control valve on the GOCE mission.

The MFV is actuated by an axial expansion element made of Terfenol-D, which is a magnetostrictive material that expands axially in the presence of a similarly-oriented magnetic field. This magnetic field is supplied by a coil in the valve, providing fine control of EP propellant flow with extremely tight, normally-closed internal seal. The expansion element is wetted and enclosed within the fully-welded valve, so there are no dynamic seals or pass-throughs in the design, eliminating external leak paths. Instead, the magnetic field operates through the pressure boundary.

3 DESIGN DRIVERS

3.1 SET-POINT ADJUSTABILITY

Electronic pressure regulation offers the benefit of remote set-point adjustability, allowing multiple operating points at thruster level, and flexibility in propellant management. This allows thruster operating points to be changed from the ground as new issues impact a mission.

3.2 PROPORTIONAL FLOW CONTROL OF XENON

Regulating xenon pressure with a proportional valve has particular challenges due to Joule-Thompson cooling of the fluid through the pressure drop. At high inlet pressures, the cooling can result in a saturated liquid/vapor mixture (2-phase flow). Without an accumulation volume downstream of the regulator, this phenomenon calls for careful thermal control of the gas flow to ensure stable regulation.

At inlet pressures above 20 to 30 bar, the states of xenon in the XPRA flow frequently encounter the saturation curve of the gas, with some flows occurring near the critical point. This non-ideal behavior requires a more general treatment of the orifice flow equations in the design, simulation, and control of the XPRA.

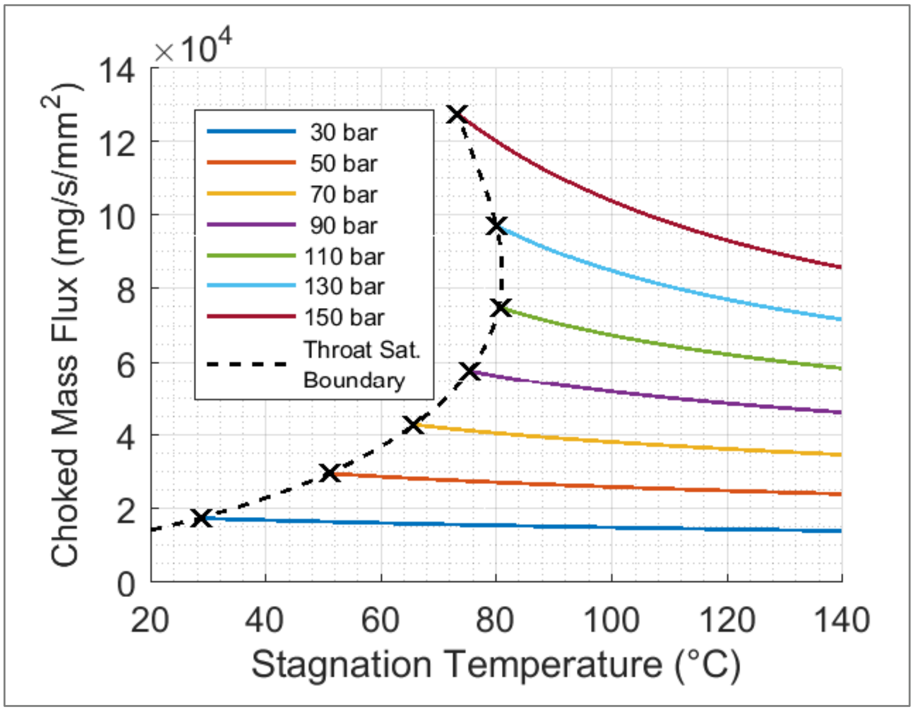

Figure 4 – *Xenon Choked Mass Flux Vs. Stagnation Temperature At Various Stagnation Pressures.*

For an isentropic choked flow starting from a stagnation enthalpy and entropy, $hstag$ and $sstag$, the conditions at the throat satisfy Eqs. 1 & 2:

$$h_{stag} - h_{crit}\left(P_{crit}, s_{stag}\right) = \frac{1}{2} v_{crit}^2$$

Equation 1

$$v_{crit} = \sqrt{\left(\frac{\partial P}{\partial \rho}\right)_s}\Bigg|_{(P_{crit}, s_{stag})}$$

Equation 2

where h_{crit} is the local enthalpy at the throat, and v_{crit} is the local fluid velocity at the throat, equal to the local speed of sound. Analytical solutions exist for ideal gases, but in this case, Eqs. 1 & 2 are solved numerically for the critical pressure (or density), and the choked mass flow through the throat is then given by:

$$\dot{m} = \rho_{crit} v_{crit} C_D A$$

Equation 3

where ρ_{crit} and v_{crit} are the critical density and fluid velocity, A is the geometric cross sectional area of the flow, and C_D is the coefficient of discharge.

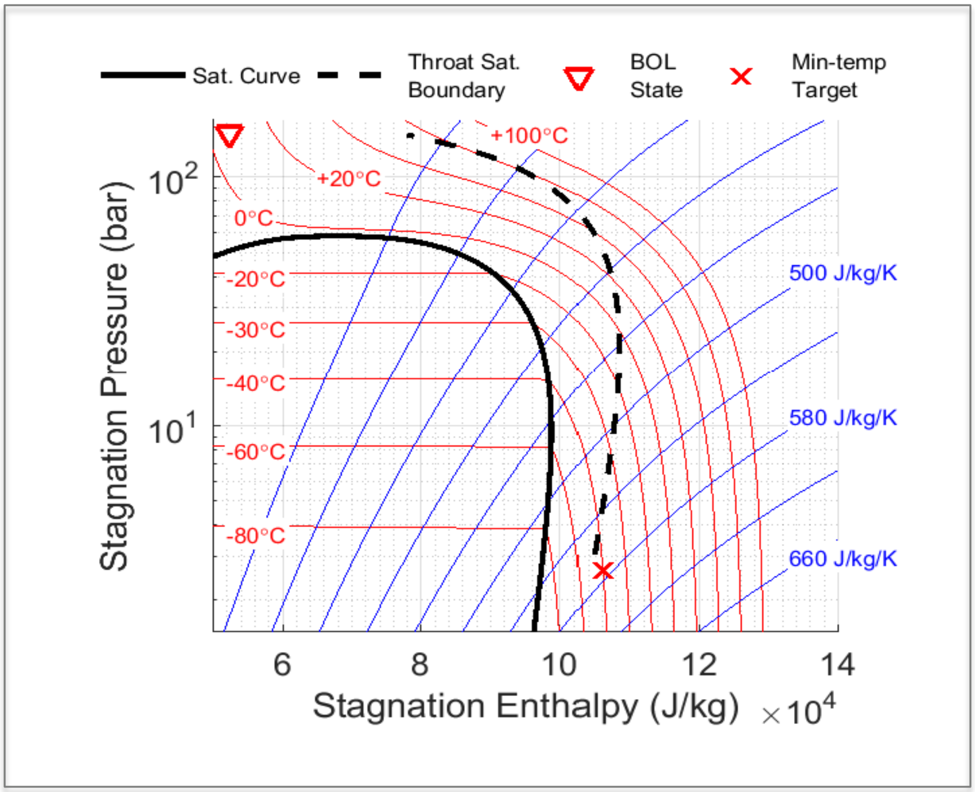

Figure 5 – Xenon P-h diagram with Saturation Curve. Isotherms are shown in red and spaced every 20° C between -40 °C and +100° C. Isentropes are shown in blue.

For a given flow area, $C_D A$, the maximum (i.e., choked) mass flow rate through it is a function of the stagnation state – taken as the upstream pressure and temperature – *provided the flow remain single-phase up to the throat*. Thus, the throat mass flow per unit area, or mass flux, φ_m (P_{stag}, T_{stag}), is an intrinsic property of the gas at a given stagnation condition. Fig. 4 shows a contour plot of φ_m (P_{stag}, T_{stag}).

Lacking a mass-flow model for 2-phase flow in the valve throat, the design philosophy of the XPRA is to use thermal control to avoid 2-phase flow in the throat. The dashed line in Fig. 4 represents the stagnation conditions which result in saturated xenon vapor in the MFV throat after undergoing an isentropic expansion. All upstream conditions that fall to the left of this curve in Fig. 4 will result in a 2-phase mixture of xenon at the throat. This line is referred to in the figures as the "throat saturation boundary".

3.3 THERMAL CONTROL

Fig. 5 shows a P-h contour plot of xenon gas with the saturation like and the throat saturation boundary superimposed. Also highlighted are: 1.) the worst-case beginning-of-life (BOL) flow conditions with respect to thermal control (minimum XPRA inlet temperature and maximum inlet pressure), and 2.), the minimum allowable temperature of the outlet gas at the nominal target pressure. This plot shows the specific enthalpy that must be added to the xenon flow – particularly at high inlet pressures – in order to ensure delivery of single-phase gas. The added enthalpy relates to the required xenon heating through Eq. 4.

$$Q_{heat} = \dot{m}(h_{out} - h_{in})$$

Equation 4

In the case of Fig. 5, it is approximately .050 J/mg, which corresponds to 4.5 W of heat addition at 90 mg/s of mass flow.

4 SIMULATION

The XPRA system dynamics are simulated in Matlab/Simulink, with blocks for the valve characteristics, real-gas thermodynamics, thermal models, and a discrete PID controller to represent the ECU. The thermal characteristics are split into upstream and downstream models. The simulations lack a theoretical flow model for 2-phase choked flow, so both the XPRA design and its simulations will avoid this condition until an empirical model can be developed.

The MFV has a hysteresis band, which is one source of error in the current system models.

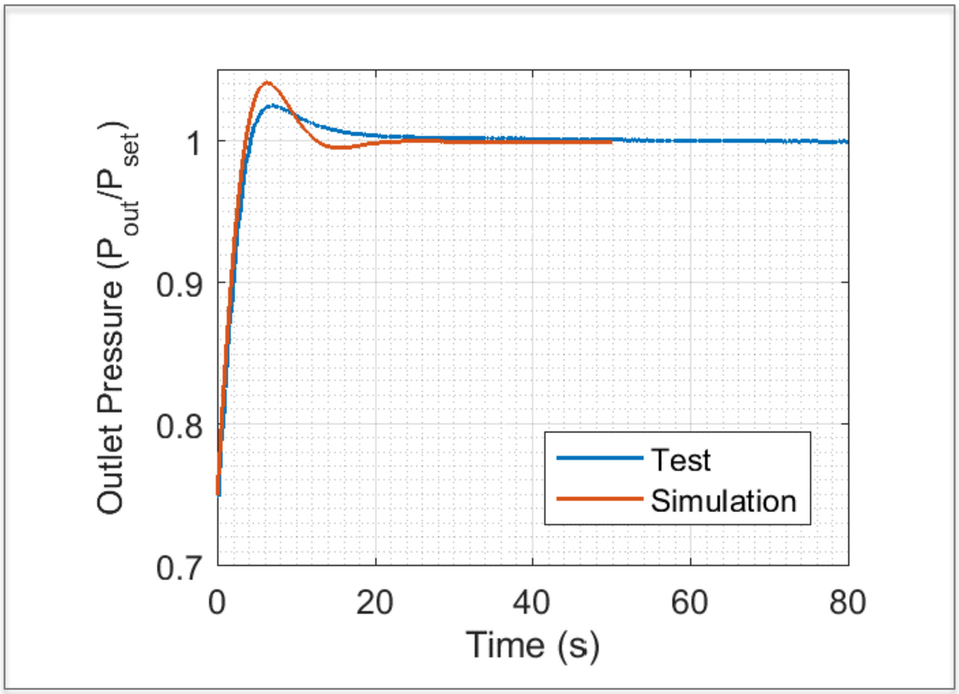

Figure 6 – Set point step responses at 40 bar inlet pressure.

5 DEVELOPMENT TESTING

Development testing and verification are currently underway. Testing with xenon is being performed on a simplified subsystem consisting of a single branch of the XPRA, shown in Fig. 8. The development subsystem is controlled by a computer equipped with LabView software.

As seen in Fig. 7, the system response is dramatically different at differing inlet pressures. The two tests shown were performed with the same gains. The stability of the high-pressure test is contingent on the thermal control of the fluid; it does not stabilize without the thermal control. Conclusions

While the XPRA continues its path through the development and qualification cycle the key elements of the assembly have been proven in flight applications. The system has shown capability to operate with flexible set pressures over a range of xenon inlet pressures. Accuracy requirements have been met in bench development tests with TRL-9 hardware. Active thermal control has been demonstrated to sufficient degree to ensure stable, single-stage pressure regulation with xenon gas at inlet pressures up to 150 bar while managing 2-phase flow.

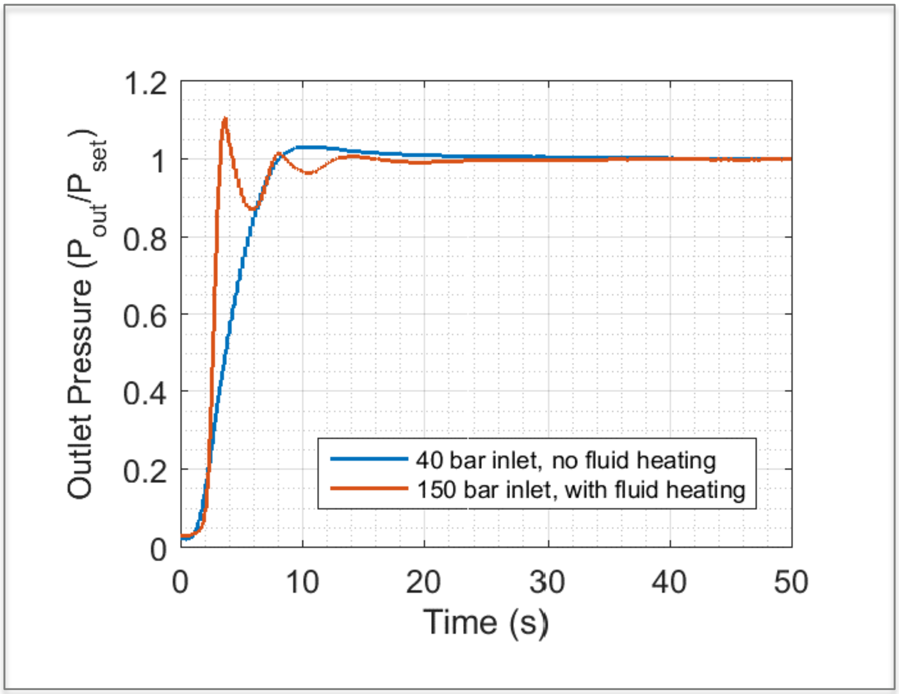

Figure 7 - Set point step responses in development at different inlet pressures. The high-pressure test was performed with fluid heating. Both tests were performed with identical controller gains.

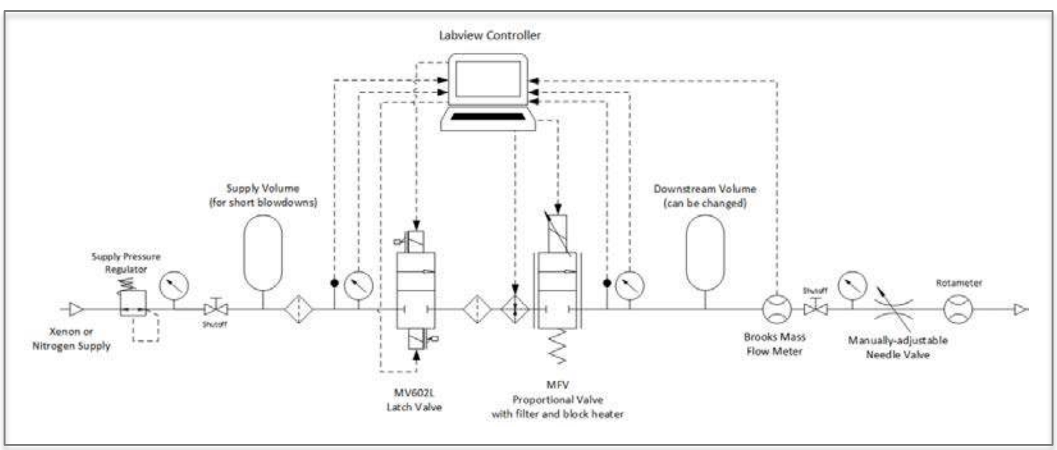

Figure 8 – Development Subsystem Diagram

5.1 ONGOING WORK

Development testing is ongoing, aiming to verify performance and further refine simulation models. Goals of the remaining product development are to verify system performance over the range of expected operating and environmental conditions. Performance verification will accompany a move to flight-similar assembly configurations for confidence testing of final design leading up to qualification and delivery.

Simulation model verification is proceeding in parallel to ensure accurate prediction of performance in simulation. Further simulation goals include developing an empirical 2-phase mass-flow model to explore optimization of power efficiency.

ABOUT THE AUTHOR:

Patrick Boyle, Engineer
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Patrick has many years' experience with the engineering design and development of controls for space applications, including the design and test of high-performance check valves and solenoid valves for launch vehicles and satellites. He has developed custom dynamic simulation tools for the analysis of pneumatic and thermodynamic systems that have been used successfully to support the analysis and design of a high-speed active pressure regulator, and satellite subsystems such as the XPRA.

Patrick holds a BS/MS in Mechanical Engineering from Lehigh University with a focus on control systems, and a BS in Mathematics.

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