The Use of Modular Valve Assemblies in Flexible Propulsion Feed System Design and Assembly

IEPC-2017-256

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

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Abstract: The volume available for propulsion feed systems is becoming limited as satellite size decreases and/or the size and capability of the payload increases. There is also a continual effort to integrate various satellite features in order to accomplish a more elegant and efficient satellite system design. Both of these factors drive the need to look closely at how propulsion feed systems are currently designed and manufactured, and how improvements to decades old technology can be accomplished. This paper reveals a highly modular feed system assembly that eliminates the need for welding and provides high external leakage performance. Significant volume, mass and cost efficiencies are demonstrated, as well as preliminary test results in the bang-bang regulation system presented.

Nomenclature

$\dot{U}_t, \dot{U}_r, \dot{U}_1,, \dot{U}_2$ = change in internal energy of control volumes with respect to time
$\dot{m}_t, \dot{m}_r, \dot{m}_1,, \dot{m}_2$ = mass flow rate out of control volumes (tank, regulator, plenum 1, plenum 2)
$\dot{m}_a, \dot{m}_c$ = mass flow rate out of anode and cathode
$\Delta\dot{m}_t, \Delta\dot{m}_r, \Delta\dot{m}_1,,\Delta\,\dot{m}_2$ = net mass rate of change of each control volume
Vt , V_r ,V_1,V_2 = flow velocity out of tank, regulator, plenum 1, plenum 2
$\dot{Q}_t, \dot{Q}_r$ = heating power to tank and regulator volumes
$\dot{u}_t, \dot{u}_r, \dot{u}_1,, \dot{u}_2$ = change in internal energy pre unit mass
h_t ,h_r ,h_1 ,h_2 = enthalpy
ρ_t,ρ_r,ρ_1,ρ_2 = density of fluid in control volumes
A_r, A_1, A_2,A_a,A_c = area of restrictions (solenoids, orifice, anode, cathode)
slpm = standard liters per minute
W = Watt

I. Introduction

CONVENTIONAL satellite propulsion feed system designs typically contain multiple strings of fluidic components that contain inlet and outlet weld tube stubs. Interconnecting metal tubing is used to join one component's outlet to another's inlet, and then welded in place to achieve a leak tight seal. Often times the tubes are shaped into complicated geometries in order to allow the needed connections. The tube stubs themselves require a

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minimum distance between the valves and minimum tube height requirements from the mounting structure in order to provide enough room for the welding equipment. These techniques increase the required feed system volume, mass, and cost, and the welding operation itself introduces system manufacturing cost, risk, and the need for system level leak testing and overall verification.

The new market paradigm of reduced lead time, cost, envelope and increased competition puts pressure on traditional methods of manufacture that make aggressive goals difficult to achieve. Additionally, many satellite integrators have the need for extreme system flexibility as satellite busses are often used for widely varying mission and payload requirements, on top of varying launch vehicle provider requirements.

Figure 1. Rendering of bang-bang solenoid modular valve feed system assembly.

This paper discusses a novel approach that promotes a product family of modular valves that minimized mass and envelope, the cost intensive welded tube stub system approach while maintaining performance, and provides the flexibility in quickly modifying system design. We provide the results of system modeling to eventually compare against actual system performance tests for the bang-bang type regulation control. Results of the breadboard testing to date are presented to substantiate the sealing methodology to be employed.

II. Modular Feed System Assembly Design

The modular feed system assembly described herein is a ‘bang-bang’ regulation system utilizing a normally closed solenoid valve. The system consists of a Cobham pressurization tank filled to 2700 psi, a fill/drain valve, a high pressure solenoid valve to serve as a tank isolation valve, a solenoid valve as the bang-bang regulator with two plenums separated by orifices to help dampen the downstream pressure feed to the thrusters when regulating solenoid opens, a low pressure solenoid valve, and a cathode/anode outlet. The feed system configuration as assembled is shown in Fig. 1. There are four distinct modules that make up the feed system. Each module is interconnected with flange unions and attached together with four screws. No welding is performed and any external leak path is sealed off with crush seals. Since outgassing of elastomers contaminating electric feed propellant is a concern, the use of elastomers in the modular assembly is also eliminated through extensive use of engineering plastics such as Teflon and Vespel as crush seals.

Figure 2. Rendering of the isolation valve module.

The first module is shown in Fig. 2 and contains a simple AN style tank fitting that facilitated the testing of this initial configuration. Also in this module is a fill/drain valve that is based on a proven, miniature valve that Cobham has offered to the industry for many years, and is used to fill the pressurization tank. The module also contains a cartridge style heater to preheat the Xenon gas in order to minimize the potential of two phase flow through the regulating solenoid downstream. The high pressure solenoid is based on a recently developed Cobham coaxial valve that was changed to be compatible with the manifold packaging configuration. The solenoid valve actuates (pull-in) at 28V and can be held open at a lower voltage (12V). This solenoid is a common design to the three other solenoids in the system and was intentionally done to promote cost savings via an increased economy of scale.

Figure 3. Rendering of the regulation solenoid module.

The second module is shown in Fig. 3 and contains the regulating solenoid valve, the pressure switch/transducer used for control feedback, a flow restricting orifice, and a fitting for the first plenum. A cartridge heater is also added downstream of the regulating solenoid to help minimize the potential of two phase flow due to Joule-Thomson effects that are especially prevalent at high inlet pressures which introduce the largest pressure drop. Effort was made in the design of this module to place the flow restrictor as close as possible to the regulating valve. Minimizing the volume between the two system features compensates for slow solenoid total response time (time to fully open and then fully close) and inherent system feedback delays. It also allows a reduction in plenum size because it reduces the amount of mass flow at high inlet pressures, which in turn reduces potential downstream pressure overshoot issues. The negative tradeoff is increased regulating solenoid cycles, which we treated as a design requirement and show compliance through thorough testing at the breadboard stage. A port for a thermocouple is placed near the regulating solenoid in order to monitor the fluid temperature for test information.

Figure 4. Rendering of the low pressure thruster isolation solenoid module.

The third module is shown in Fig. 4 and is composed of another restrictor close to the same size of the first restriction, a port for the second plenum, and a low pressure 15 psia solenoid valve used to conserve gas at the end of thruster firing. As mentioned above, this is the same solenoid as is present in the other two modules. Two thermocouple ports are included in order to monitor fluid temperatures between the plenums and after the low pressure solenoid.

Figure 5. Rendering of the cathode and anode module that supports a single thruster.

The final module is shown in Fig. 5 and contains the cathode (a fixed orifice restriction) and the anode, which consists of a thermo throttle device. The thermo throttle offers fine mass flow adjustment capabilities by heating the xenon gas, changing the density, and changing mass flow. As the gas is heated, the density decreases and the mass flow also decreases. This device was recently internally developed by Cobham and a similar standalone product was developed. Both the anode and cathode outlet ports feature AN fittings that facilitate easy adaptation for testing.

III. Performance Goals

The control of the Xenon gas flow is based on the demand of four separate thruster feed lines consisting of an anode and a cathode. The desired total flow to each branch is 2.5 mg/sec, with the anode being 90% of the flow (2.25 mg/sec nominally) and the cathode making up the balance (0.25 mg/sec). The tolerance goal for both the anode and cathode is +/- 10% of nominal including any possible overshoot. Each of the feed lines consists of a low pressure, normally closed solenoid valve to isolate the outlet. The mass flow rates and tank pressures are based on multiple recent inquiries as well as references[2,4].

The modular assemblies feeding the four branches of thrusters must be able to flow at least four times the individual thruster lines, so for this system they must flow minimally 10 mg/sec at the minimum tank pressure of 50 psia. The low pressure requirement sets the minimum orifice sizes needed to meet the flow of four thrusters active simultaneously, but still meet the tolerance goal of each thruster if only one is active.

The nominal downstream feed pressure is chosen to be 15 psia to set the anode/cathode branch orifices to provide the nominal flow at the nominal feed pressure. The anode itself consists of a Cobham thermo throttle that provides fine tuning capability of the outlet flow.

The regulating solenoid will be tested using two control methodologies. Initial testing will include a pressure switch that provides feedback to the solenoid to open or close based on the pressure sensed between plenums 1 and 2. The modeling results are used to set the initial limits with the expectation some adjustments will need to be made. The pressure switch will eventually be replaced by a pressure transducer that utilizes laboratory (Labview) based control to achieve the nominal 15 psia downstream pressure measured at the same location as the previously used pressure switch.

IV. System Model

A mathematical representation of the system was developed in MATLAB[5] to optimize the orifice and plenum sizes based on the desired feed system flow requirements. The energy based state equations shown below were derived for four control volumes that are representative of the tank, the volume between the regulating seat and the first orifice, plenum 1 as bounded by the two orifices, and plenum 2 schematically depicted in Fig. 6.

Energy Conservation:

$$\dot{U}_t = \dot{Q}_t - \dot{m}_r\left(h_t + {V_r^2}/{2}\right)$$

$$\dot{U}_r = \dot{Q}_r + \dot{m}_r\left(h_t + {V_r^2}/{2}\right) - \dot{m}_1\left(h_1 + {V_1^2}/{2}\right)$$
$$\dot{U}_1 = \dot{m}_1\left(h_1 + {V_1^2}/{2}\right) - \dot{m}_2\left(h_2 + {V_2^2}/{2}\right)$$
$$\dot{U}_2 = \dot{m}_2\left(h_2 + {V_2^2}/{2}\right) - (\dot{m}_a + \dot{m}_c) * \left(h_{out} + {V_{out}^2}/{2}\right)$$

Continuity:

$$\Delta\dot{m}_t = \dot{m}_r = \dot{m}_r(u_t, \rho_t, A_r, u_r, \rho_r)$$
$$\Delta\dot{m}_r = \dot{m}_r - \dot{m}_1 = \dot{m}_r - \dot{m}_1(u_r, \rho_r, A_1, u_1, \rho_1)$$
$$\Delta\dot{m}_1 = \dot{m}_1 - \dot{m}_2 = \dot{m}_1 - \dot{m}_2(u_1, \rho_1, A_2, u_2, \rho_2)$$
$$\Delta\dot{m}_2 = \dot{m}_2 - (\dot{m}_a + \dot{m}_c) = -\dot{m}_a(u_2, \rho_2, A_a, u_{vac}, \rho_{vac}) - \dot{m}_c(u_2, \rho_2, A_c, u_{vac}, \rho_{vac})$$

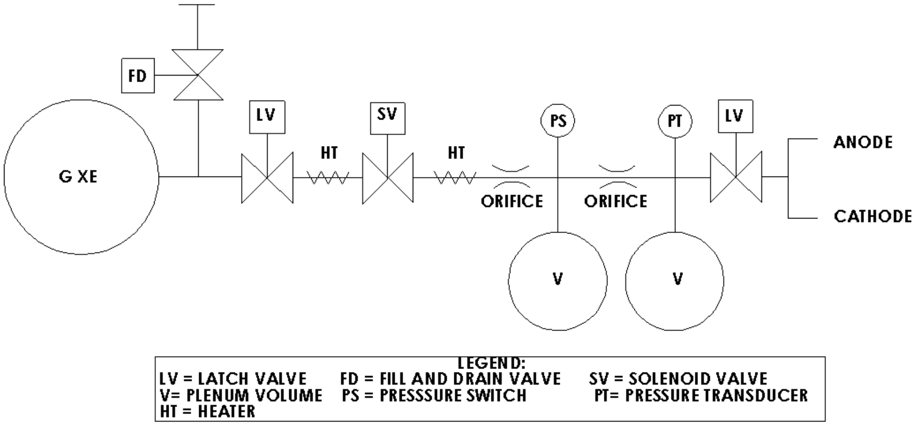

Figure 6 System Schematic

The state equations determine the internal energy and density information from mass flow (continuity) that is then used to make function calls to REFPROP[3], a gas property program developed by NIST. The function calls return pressure, temperature, entropy, enthalpy values to be used in the state equations.

A 15 psia nominal downstream pressure was selected to feed the anode and cathode outlets. This is slightly above atmospheric pressure, and reduces testing complexity and reduces the Joule-Thomson effects through the regulating solenoid. The larger the pressure drop across the orifice, the more unstable the real gas model is because of its proximity to the triple point of Xenon. The physical drawback however is that the higher downstream pressure results in a smaller anode and cathode orifice sizes. The low pressure solenoid valve is added to the system to prevent the residual 15 psia gas in the lines downstream of the regulating solenoid from being wasted. With a low pressure solenoid present in the system, a downstream pressure of 15 psia should result in near zero leakage especially considering the molecular size of Xenon.

A pressure switch was envisioned and modeled as the main control device for the regulating solenoid valve. The pressure switch is located between the two fixed flow restrictors so that it senses the pressure in plenum 1 with set points around 15 psia to keep the pressure in plenum 2 and further downstream close to the 15 psia nominal pressure. When the pressure reaches the maximum set value the switch removes power from the regulating solenoid and it closes. When the pressure drops below the minimum set pressure the switch allows the power to be reapplied to the solenoid and it opens.

Determining the mass flow of the system caused the most model instability. This is because of the sonic pressure drop across the regulating solenoid orifice caused by the large differential pressure between the 2700 psia tank and the 15 psia desired nominal downstream pressure. Xenon has a rather high critical point relative to room temperature at tank pressures above 847 psia[1] that created issues with the analysis in the early stages.

An optimization algorithm was developed to determine the critical pressure ratio. Xenon is a real gas and its critical pressure varies with respect to the inlet pressure as shown in Fig. 7. Specifically, we tried to determine if the critical pressure sonic flow was occurring assuming the fluid to be completely gaseous in order to determine the mass flow rate. Care was taken during the critical pressure ratio search to ensure that the related temperatures did not drop below the triple point value (161 K) or exceed the temperature limits in REFPROP. This required a heater upstream of the regulating orifice. The algorithm assumed constant entropy across the orifice, and from that information the determination of enthalpy and velocity upstream and downstream of the orifice. Once the algorithm was established, sonic mass flow could be determined and the state equations based in the internal energy and fluid mass of each control volume could be solved iteratively.

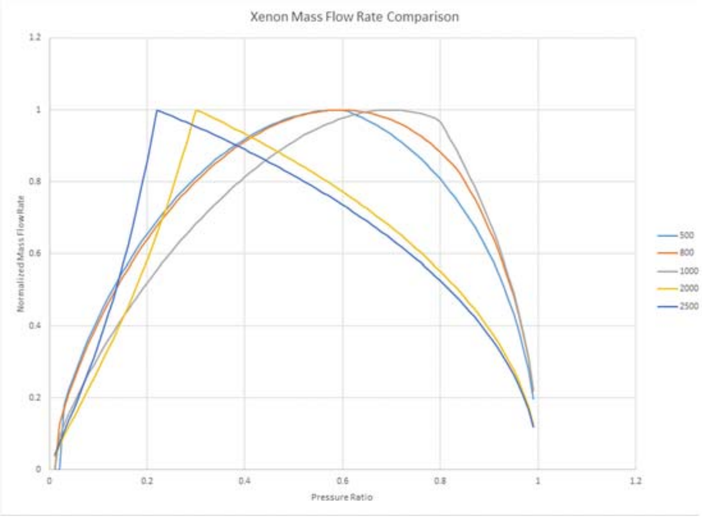

Figure 7. Critical Pressure Ratio vs Inlet Pressure

Due to the highly non-linear nature of the model, a true optimization routine could not be used. Instead, one variable at a time was altered based on starting values of calculated orifice sizes. These variables included the set points of the pressure switch, the two plenum volumes, the diameters of the orifice between the regulating solenoid and plenum 1, the orifice between plenum 1 and 2, and the orifice diameters of the anode and cathode. The orifice of the regulating solenoid valve, and the high and low pressure solenoid were assumed the same since they are the same design in the assembly. The output goal was to keep both the mass flow rate of the anode and the cathode within +/-10% of the nominal desired mass flow rate values. If this could not be achieved, the anode thermothrottle was trusted to provide the capability to adjust the out of tolerance value back into the allowable range.

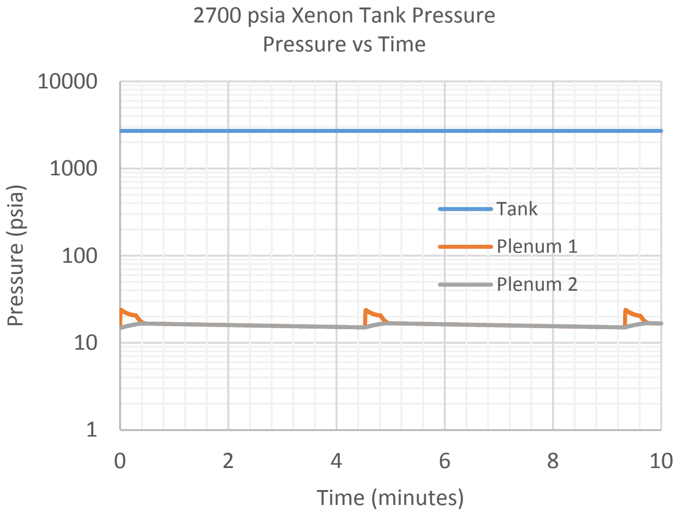

Figure 8. System Performance with Tank Pressure of 2700 psia

A main concern at the start of the analysis was the response time required of the solenoid valve, specifically at the starting tank pressure (2700 psia). The duration needed for the solenoid to open and close determines how much gas flows into the volume between it and the first orifice. If the actuation time is long, it could lead to an overshoot condition further downstream at the anode and cathode. This can be somewhat offset by minimizing the volume between the regulating solenoid and orifice 1 because as the volume becomes smaller, the less gas mass that can get through before the pressure equalization occurs. This can also be helped by reducing the size of the first orifice, but it must be large enough to allow the flow to all four thrusters working simultaneously at the lowest desired tank pressure. A third alternative is to increase the plenum sizes to compensate. This especially pertains to plenum 2, which controls the overshoot more so than plenum 1 after it reaches a certain volume. However, it is our goal to minimize required plenum size to save overall system envelope. Results of the expected system performance at 50 and 2700 psia with Xenon as the propellant are provided in Fig. 8 and 9.

The results of the modeling established the initial sizing for the development hardware. Our initial testing consisted of the first three modules that are designed to feed four thrusters, and a single fourth module that represent the feed system to only one thruster.

With the solid model established for the design, further analysis using ANSYS CFD[6] was performed to determine how the heat from the idealized heaters will transfer to the fluid to help prevent two phase flow from occurring downstream of the regulating solenoid orifice. The analysis determined that while two phase flow cannot be completely eliminated, it can be minimized to being a very small portion of the resulting mass flow such that its vaporization does not result in radical pressure spikes downstream.

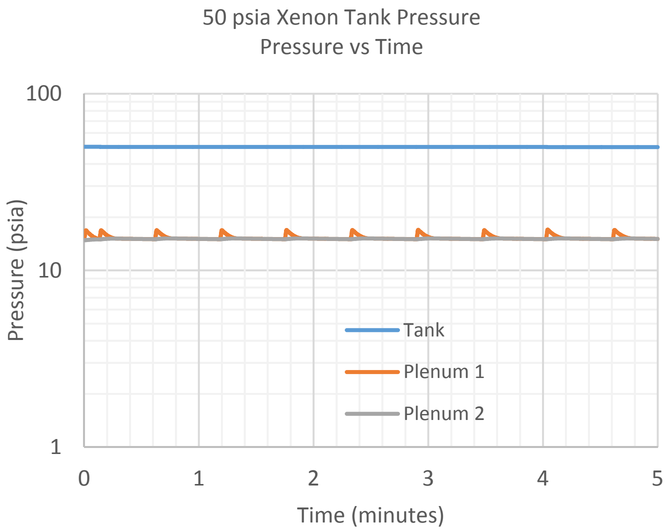

Figure 9. System Performance with Tank Pressure of 50 psia

V. Breadboard Testing

The sealing techniques employed in this modular design are unique and not commonly considered in satellite feed systems. This fact caused us to test our sealing concepts ahead of the full modular assembly to prove feasibility and reduce risk. Welding is currently assumed necessary to achieve low external leakage levels, but comes with a large cost, mass and envelope burden. The satellite integrator that eliminates this from their propulsion system will find a significant competitive advantage by creating more room more payload, improving satellite bus integration process and reducing costs, reducing verification (post weld) testing, and associated rework costs. Crush seal technology would enable standard end fittings for common items like pressure transducers, switches, or other sensors. It would provide for simple system assembly, rapid rework if necessary and enables a single supplier to provide an entire system to an integrator fully assembled and tested.

A crush seal configuration was designed for AN fittings and was tested using replicate AN mating features. Testing including proof, pressure cycles, and thermal cycles with leakage tests at the extremes. Measured leakage performance was in the low 1x10^{-7} sccs GHe to 1x10^{-8} sccs GHe, and equivalent to welded configuration expectations. These values were achieved across all the testing performed.

Figure 10. Breadboard crush seal test unit

Crush seals for valve components were also evaluated on the regulating solenoid valve breadboard hardware. After a minor design issue with the concept was overcome, the results achieved were again in the lower 1x10^{-7} sccs GHe range. These early tests were enough to provide confidence that the crush seal methodology was at least equivalent to welding and could be employed across the modular concept, including the main module interconnecting seals between the modules.

A breadboard of the solenoid valve was designed to confirm the modification from a coaxial standalone type design to a modular design in which the parts are incorporated into a common housing. The crush seal technology was employed and tested on this unit and the solenoid itself was cycled 120,000 times without any signs of degradation. Although in the modular assembly design concept, the dominant pressure is always from one direction, response times and leakages were successfully tested in both directions at different points in the cycling at 2700 psig. The breadboard solenoid valve was also subject to thermal cycles, and performance was measured at both the hot and cold extremes. Results indicated very little change in leakage over temperature.

To determine margin, the solenoid was evaluated using MagSoft to predict the forces from the coil based on the lift required to meet the flow and pressure drop requirements. This was compared against pressure loads at the poppet and the subsequent forces needed to provide adequate sealing when the solenoid is unpowered and closed. Results showed proper margins with respect to the net forces in the most unfavorable conditions. This was confirmed when running pull in and drop out tests by slowly increasing the voltage until the solenoid opened. We continued up to 28V, which is the nominal design voltage, and then decreased the voltage until the solenoid valve closed. There was no deterioration seen in either the response time or leakage rates at the end of the cycle life.

Figure 11. Breadboard solenoid regulation valve

The thermo throttle used as the anode restrictor is a Cobham design that was developed on internal funding. Two different design approaches were pursued, one using a cartridge style heater that is easily adaptable to a modular valve design approach, while a flat heater style lends itself better to an "in-line", standalone component. This standalone component is now offered to customers. The thermo throttle has the ability to fine tune the mass flow by changing the viscosity of the fluid through heating, and has shown the ability in testing to alter volumetric flow 2.7 slpm/W.

VI. Module Testing

As of this paper release, development testing is taking place on each module to verify performance prior to integrating as a full assembly. Three orifices (one, two, and the cathode) are fixed orifices that cannot be removed easily. Once assembled, system level adjustments could be made by altering the pressure switch setting or changing the plenum volumes by adding or subtracting volume.

Module 1 includes the high pressure solenoid valve, the fill/drain valve, and the upstream heater. Baseline testing was performed using Nitrogen as the test media and Helium for leakage testing. The testing verified leakage, flow, and response times of the solenoid as well as the temperature vs power of the heater based on thermocouple measurements. The module must be capable of isolating the 2700 psig, so the sub-assembly was proof pressure tested to 4050 psig prior to performing any of the performance characterization testing.

Module 2 testing is more complex than module 1. The inlet pressure is 2700 psig but components beyond the first orifice should not see more than 30 psig due to expected overshoot at this point in the system. Initial testing will start at lower pressure pressures, and step up in pressure to ensure the pressure switch/solenoid interface is responsive enough to control the downstream pressure within expected bounds. A test relief valve will be plumbed in line with plenum 1 set to 35 psig to prevent an overpressure situation from occurring as a safety feature early in test. Since orifice one is contained within this module, flow tests will be important in order to characterize the orifice. Also solenoid response time and leakage will be important as well.

Module 3 is a low pressure module (30 psig) containing the plumbing to plenum 2, orifice 2, and a low pressure solenoid valve. A low pressure transducer is also installed to capture downstream pressure data to help with model validation runs. Ports for thermocouples also exist for fluid temperature monitoring. Due to the presence of orifice 2, flow characterization will also be needed to verify the module before integration along with leakage tests.

Module 4 consists of the fixed orifice cathode and the variable orifice anode composed of a thermo throttle. Tests consist of low pressure flow tests for characterization and thermo throttle verification.

After characterization of the modules, the full feed system will be assembled and tested. Module performance at the system level will be compared against the subassy module performance results in an effort to understand and possibly adjust variable parameters like the set pressure of the pressure switch and/or the plenum volumes.

VII. Future Work

A. Testing

The tested modules will be coupled together through their mating flange interfaces and use of crush seals. Initial testing at the full assembly system level will be performed using a regulated nitrogen pressure line feeding the AN inlet port. This approach allows constant inlet pressure, and makes system performance verification much simpler because easy adjustment of the inlet pressure from pressures ranging from 50 to 2700 psig can be made. Nitrogen will be used as an initial surrogate gas to minimize Xenon gas cost.

Bottle "blow down" tests that run the system from full pressure to minimum pressure unabated will then be performed. Nitrogen will be used to fill a 10 in^3 volume to 2700 psig, and the system will be tested in its ability to control downstream pressure until the small tank is fully depleted. This approach allows a full characterization of the system performance over the entire pressure range prior to introducing Xenon.

After completion of the nitrogen tests, the volume will then be filled with Xenon. A full blow down test will be performed and selected inlet pressures were chosen to compare results to. The results will be compared against the analytical modeling.

B. Design

The use of a plastic crush seal is planned for the interface between separate modules given the success seen in the breadboard testing and the individual module level. Additionally, accelerated long term testing is planned that will subject the seals to simulated mission durations. Their use will allow more use of Aluminum which will help reduce overall feed system weight when compared to stainless steel, and cost when compared to the typical Titanium construction. Crush seals are also implemented in standard AN fittings that provide flexibility when ordering standard pressure transducers and pressure switches, as well as interfacing with pressure lines and flow sensors.

Additional further work will be performed incorporating fully active control using a pressure transducer to minimize the error term composed of the difference of the sensed pressure and the desired nominal downstream pressure. Also, the incorporation of a pressure transducer upstream of the regulating solenoid may be added to provide the upstream tank pressure into the control methodology for a feed forward control element in hopes of improving the regulation at high bottle pressures by tuning the voltage pulse to the regulating solenoid.

Additionally, because of the flexible nature of the modular system approach presented, Cobham plans to offer much of its existing satellite product portfolio in the modular format. This will allow customers to select versions of isolation valves (pyro, latching, solenoid), regulators (mechanical, bang-bang, PFCV), thruster valves (PFCV, solenoid), and various ‘splitter’ options to suit system preference. Inhibit modules can also be added depending on the number required for the application. This combined approach allows customers to select the system that meets the requirement for their spacecraft and realize the competitive advantage of eliminating welding and all its associated costs.

VIII. Conclusion

The Cobham Modular Valve Feed System Assembly concept is designed to provide the satellite integrator with the ability to rid their system of welded interfaces while maintaining current performance expectations. The modular nature of the system allows significant flexibility to modify system architecture both during system design and system integration. The envelope and mass savings enables the manufacturer to minimize propulsion and maximize payload, thus making the customer more competitive.

The current bang-bang regulation approach is designed and proven that external seals are capable of matching welded external leak path performance. The system analysis shows that the regulation approach will meet performance parameters and achieve xenon supply tolerance as desired.

Future papers will document the results of the development testing and evolution of the flexible nature of the system.

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