Elimination of Feed System Envelope by Integration of Feed System Components inside a Composite Overwrapped Propellant Tank

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Abstract: A continual effort within the satellite industry exists to integrate various satellite features together in order to accomplish a more elegant and efficient satellite system design. The volume available for satellite propulsion feed systems is becoming limited as satellites become smaller and/or the size and capability of the payload increases. Cobham developed a highly efficient Xenon feed system that saves envelope, mass, and integration effort by placing a majority of the feed system components inside a composite pressure vessel. This innovative design eliminates welding and external leakage concerns that are common burdens in the satellite industry. This paper presents the proportional valve based design approach as well as development testing plans and future design goals.

I. Nomenclature

$\dot{m}$ = Mass flow rate
P_1 = Inlet pressure
P_2 = Outlet pressure
A = Orifice cross sectional area
Cd = Orifice discharge coefficient
γ = Specific heat ratio
R = Individual gas constant
T = Gas temperature

II. Introduction

Traditional satellite electrical propulsion based feed systems may employ valves, regulators, heating elements, filters, plenums, and transducers to adequately control pressure and flowrates of Xenon gas from a high pressure storage tank to ion thruster assemblies. The feed system hardware is often constructed from separate components connected together with welded tubing. This architecture drives cost, envelope, mass, and integration difficulties. A new industry shift of reduced satellite cost, lead time, and size bring about pressure on traditional methods of propulsion system design and manufacturing to meet the needs of an evolving satellite market.

Several different optimized approaches for electrical propulsion feed system architectures are actively being pursued by Cobham (Ref. 4, 5). This paper focuses on one of the approaches under development, which is integrating much of the feed system fluid control components within the pressure vessel itself. The Valve in Tank Assembly (ViTA) conserves significant envelope and mass that can be used for increased payload capability.

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III. Design Approach

A. Requirements Definition

Based on a thorough review of various customer specifications and data from NASA (Ref. 1, 2) a set of requirements was established for the ViTA feed system.

- Operational temp: -15 to 60°C (5 to 140°F)
- Inlet pressure range: 186-3 bar (2700-43 PSIA)
- Flow range: 0-2.5 mg/sec (0-27.4 scc/m) per line
- Heater Power: <45 Watts
- External Leakage: <1 x 10-6 sccs GHe
- Internal Leakage: <1 x 10-5 sccs GHe
- Filtration: 10 Micron absolute

B. Initial Design Considerations

Valve component miniaturization needed to occur in order to place feed system components into standard composite wrapped pressure vessels. A review of existing regulating architectures, i.e. mechanical regulation, bang-bang solenoids, and PFCV (proportional flow control valve), revealed that a PFCV approach is preferred because it would likely yield the most envelope optimization by reducing the need for plenums. Accordingly, the configuration shown in Fig. 1 was developed for the VITA development assembly. It consists of a fill and drain valve for direct interfacing with the high pressure bottle as well as a high pressure transducer port to sense the bottle pressure. A closed loop pressure controller is used for three parallel path PFCVs utilizing a pressure transducer along with a downstream fixed orifice to control flowrates. Closed loop regulated pressure shall be controlled from 0-12 psia which will yield flowrate from 0-2.67 mg/sec (0-29.2 scc/m) of gaseous xenon to the main, cathode, and neutralizer ports based on a calculated orifice size.

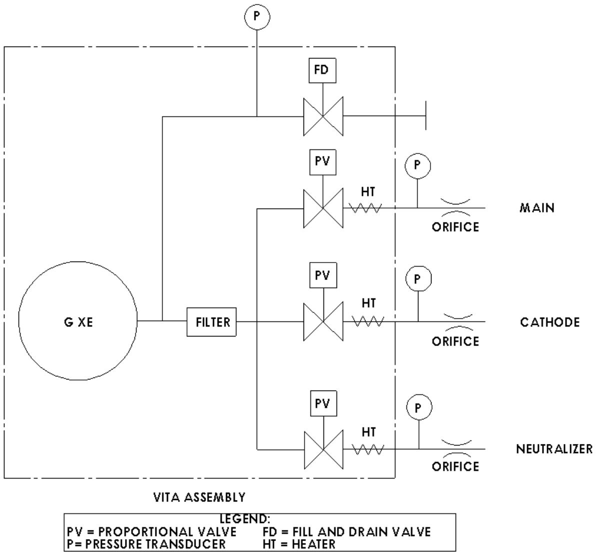

Figure 1. Valve in Tank Assembly Configuration

C. Design

Excluding the bottle, the ViTA assembly is approximately 2.89 lb with envelope dimensions of 2.5 in. hex by 6 in. long. Much of the ViTA assembly envelope resided within the high pressure bottle, and the primary material of construction is corrosion resistant steel (CRES). A 10 pin micro connector is used as an electrical interface for the Piezo actuators and the heaters. 1/8 in. OD weld tube stubs are used as interfaces for the main, cathode, and neutralizer ports. Although these interfaces were chosen for this ViTA development unit, they can be modified as necessary to meet individual customer needs. All electronic components are isolated from the Xenon gas and reference ambient pressure outside the bottle. The electrical interface schematic and pin out are shown in Fig. 2. The ViTA assembly design is shown in Fig. 3, 4, and 5 interfaced with a carbon fiber wrapped composite pressure vessel.

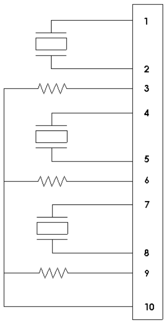

Figure 2. ViTA Electrical Interface Schematic

Figure 3. ViTA Integrated in a Carbon Fiber Wrapped Pressure Vessel

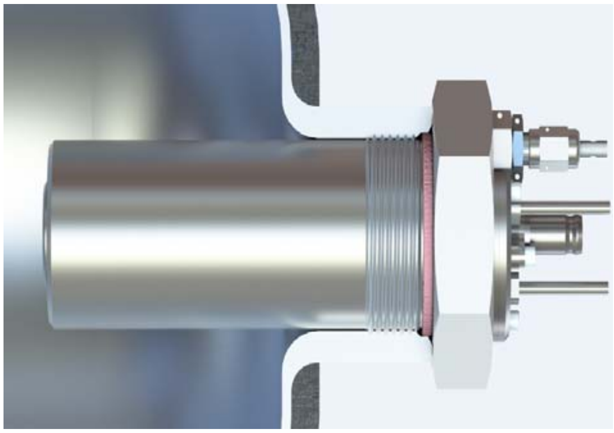

Figure 4. Cross Sectional View of ViTA Integrated in a Carbon Fiber Wrapped Pressure Vessel

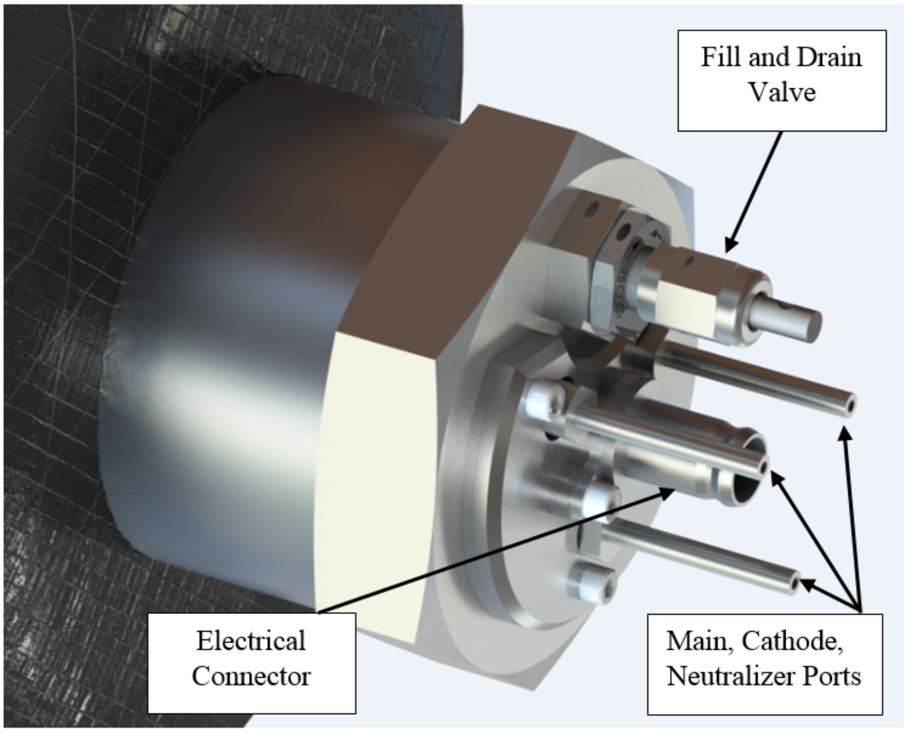

Figure 5. ViTA Interfaces

D. Xenon Tank

The high pressure tank is an aluminum lined composite wrapped tank (fiberglass or carbon fiber) sized to meet any specific customers needs for mission duration. The interface between the tank and ViTA assembly is an AN5202-24 Port. An additional o-ring face seal is used for a redundant external leakage seal with the o-ring gland machined into the ViTA housing. The tank shown in the illustrations is approximately 500 in^3 volume, but can be sized as needed to meet mission duration.

E. Fill and Drain Valve

The fill and drain valve used is an existing Cobham production part number that was slightly modified to interface with the ViTA assembly. It consists of a -2 male AN port to interface with bottle fill and draining operations. When not in use the primary internal seals are redundant metal seals consisting of a conical poppet and the AN cap. Redundant external seals consist of an o-ring and welded flange seal. Although the fill and drain valve was face mounted on the ViTA assembly, it could be easily relocated to a service panel for access if the ViTA location is not convenient for integration for a given customer.

F. Proportional Flow Control Valve

The proportional flow control valve is a normally closed linear Piezo actuated valve. The valve portion consists of a spherical ball on a Vespel seat. A nickel deposited bellows assembly with welded end plates is used as a dynamic seal to isolate pressure between the valve and the Piezo. A mechanical lever mechanism is used to amplify Piezo stroke to push the ball off of the seat. The Piezo grows in length proportionally to an applied 0-100 Volts to open the valve.

G. Filtration

The filter consists of a pleated filter disc with a 2 micron nominal, 10 micron absolute rating. The shape of the ViTA assembly also acts a dip tube to prevent any potential bottle contamination from entering the ViTA assembly regardless of bottle orientation.

H. Heaters

Three 15W electric resistance heaters are incorporated into the ViTA design. It is possible that the heaters may not be needed due to the closed loop feedback system of the PFCV's. Both heated and non-heated Xenon test runs are part of the development test plan to see if heating the gas at the point of regulation has a discernable effect on downstream pressure accuracy. When in use, the heaters will be activated for each branch for a period of 90 seconds prior to flow and maintained through the thruster commands. The use of heat at only at the point of regulation minimizes power consumption as opposed to heating the entire bottle.

I. Transducers

Pressure transducers are used to monitor bottle pressure and as closed loop feedback for the PFCV's. Due to transducer size, it is not practical to mount the transducers within the ViTA assembly. Temperature transducers are not being used for development testing, but can be incorporated in the ViTA schematic as necessary per a given customer's needs.

IV. Analysis

A. Orifice Calculations

Equations 1 and 2 (Ref. 3) are used to calculate compressible flow through an orifice:

Sonic Flow:

$$\dot{m} = P_1 \times A \times C_d \sqrt{\left[\left(\frac{\gamma}{RT}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right]} \tag{1}$$

Subsonic Flow:

$$\dot{m} = P_1 \times A \times C_d \sqrt{\left[\left(\frac{\gamma}{RT}\right)\left(\frac{2}{\gamma - 1}\right)\left\{\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right\}\right]} \tag{2}$$

Downstream orifice were sized to achieve desired flowrates for the main, cathode, and neutralizer ports. Figure 5 shows the regulated pressure vs. calculated flowrate based on vacuum pressure on the outlet side of the orifice.

B. Thermal Analysis

A preliminary transient FEA thermal analysis was performed on the ViTA assembly to determine the rate of heat transfer and stabilization from a single heater. Figure 6 shows the transient results of applied heat to the gas port within the PFCV at the point of pressure regulation.

C. Stress Analysis

A preliminary FEA stress analysis was performed on all preloaded and pressure boundary components at an assembly level. Calculations were also performed on all pre-loaded threaded joints. The stress analysis showed positive margins of safety for all worst case load conditions including proof (1.5x) and burst (2.5x) pressures.

D. Force Margins

A force margin analysis was performed to verify the Piezo could open the valve under worst case conditions. There is a force margin factor of 26 times under normal operating conditions. Furthermore, an analysis was performed under a failed condition of getting bottle pressure downstream of the Piezo valve. Under this condition there is a force margin of 7.3 times. Based on the analysis, there is no pressure condition in which the valve will fail to open or close when commanded.

E. Piezo Properties

Travel range for 0-100 V: 45 µm ±20 %
[‡]Resolution: 0.45 nm
[§]Static large signal stiffness: 19 N/µm ±20 %

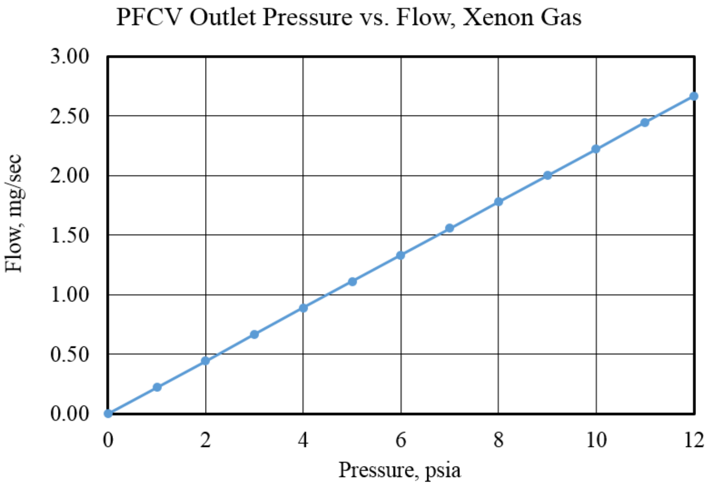

Figure 5. Outlet Pressure vs. Flow

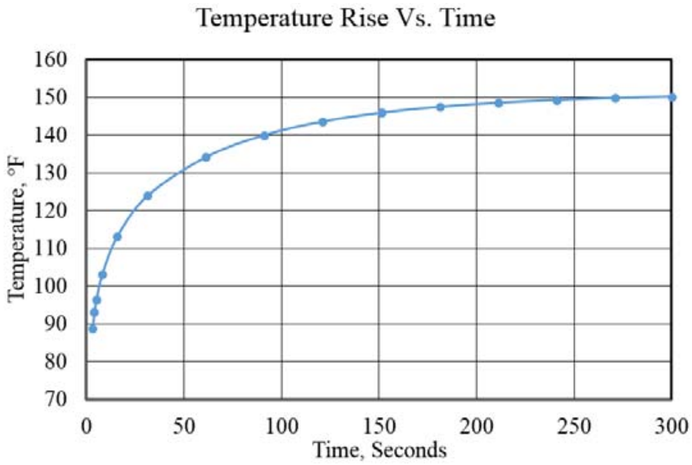

Figure 6. Temperature vs. Time

[‡] The resolution of Piezo actuators is not limited by stiction or friction. Value given is noise equivalent motion.
[§] Dynamic small- signal stiffness is approximately 30% higher. Operating temperature range: -20 to 80 °C. Case / end pieces: Nonmagnetic steel / stainless steel

Push/pull force capacity: 1000/5 N
Electrical capacitance: 4.5µF ±20 %
Dynamic operating current coefficient: 12.5 µA / (Hz × µm)
Resonant frequency (unloaded): 8.5 kHz ±20 %

F. Heater Electrical Properties

Rated Heater Power: 15W @ 24V ±20% (3.8W @ 12V and 0.90W @ 6V)
Diameter: 0.122” nominal ±0.002” (3.1mm)
Length: 0.5” nominal ±0.015” (12.7mm)
Heater Resistance: 38.4Ω ±10%
Lead Length: 2.5” Typ. (63.5mm)
Maximum Block Temperature**:** 315°C (600°F) (when installed in a 0.125” diameter bore in a metal block)

V. Development Test Plans

A. Development Testing

Development testing of the ViTA assembly is scheduled to begin October 2017 and scheduled to be completed by December 2017. A custom pressure vessel was designed and manufactured to closely envelope the ViTA assembly and to minimize test volume to about 1 in^3. This ensured only a minimum amount of xenon gas would be consumed during testing and helps to keep project cost low. Furthermore, full bottle blow downs can be performed in a timely manner to see how the ViTA performs under the full spectrum of inlet pressures.

All flow testing will be performed under no-heat and heated conditions. When in use, the heaters will be activated for each branch for a period of 90 seconds prior to thrust and maintained through the thruster commands.

B. Piezo Adjustment/Proof Testing

The ViTA assembly has internal adjustability designed into the PFCVs due to the small displacements of the Piezo actuators. In testing, the three Piezo actuators will be adjusted to the proper locations and once set, permanently locked into that position. When the setup is complete, the inlet will be proof tested to 4050 psig (2700 x 1.5) and held for 5 minutes. Since the outlet operates in a vacuum condition (0-15 psia) relative to the test lab, no proof will be performed on the outlet side. An outlet relief valve set for 1 PSIG (approximately 15.7 psia) will be used for all testing.

C. Closed Loop Controller Testing using GN2

A development Piezo controller was also developed that allows a set pressure to be specified and maintained based on feedback from the downstream pressure transducer. The controller will also allow for incremental voltages to be applied to the Piezo actuators in which pressure, flow, and hysteresis will be measured.

D. Internal and External Leakage Tests

Internal and external leakage tests will be performed at high and low bottle pressures using GHe and a helium mass spectrometer.

E. Bottle Blow down (GN2) (Flow Testing, Regulation Performance)

The 1 in^3 test bottle will be pressurized to 2700 psig GN2. Numerous bottle blow downs will occur where the bottle depletes to ambient pressure and the Piezo actuator performance will be recorded on a data acquisition system. Inlet pressure, outlet pressure, flow, and applied Piezo voltage will be recorded.

F. Xenon Bottle Blow downs Ambient, Hot, and Cold

Similar to the nitrogen bottle blow downs, Xenon bottle blow downs will be performed with the same measured parameters. They will include conditioning the assembly to hot and cold temperatures in a thermal chamber over an operational test temperature range of 15-60°C (59-140°F).

VI. Future Design work

The existing ViTA assembly is configured and tested for a single ion thruster. Future work may involve having the ViTA assembly feed three or more ion thrusters. The PFCV’s, as designed, are capable for flowing considerably more xenon (>200 mg/sec) such that each of the three branches could feed one or more ion thrusters individually, or even a cold gas system. Additional PFCV's, manifold assemblies, or thermo throttles (all under development at Cobham) can be used to adjust flows outside of the ViTA assembly to the additional thrusters as necessary.

We are also planning to investigate how to add additional inhibits to the design scheme because of the many current demands on satellite propulsion system design. Cobham is working on miniaturizing latching and non-latching solenoid valves because we plan to add a bang-bang regulation approach in this packaging format.

VII. Conclusion

The Valve in Tank Assembly approach is a new and innovative concept for solving the challenges associated with an evolving Satellite market where satellite integrators look to minimize propulsion and maximize payload. The combination of valves within a composite tank provides significant advantages over traditional systems that include envelope and mass intensive welding requirements and external leakage concerns. The ViTA assembly provides maximum system operation flexibility and performance by featuring closed loop proportional flow control valves. The development testing plans presented in this paper are sound and will be accomplished in the very near future. Results are planned for presentation in future papers.

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