A Xenon Flowrate Controller for Hall Current Thruster Applications[1]

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IEPC-01-315

Abstract

As Electric Propulsion (EP) becomes more prevalent within the spacecraft propulsion community, there is an increased need for greater control of the xenon flow. Moog has concluded a Research and Development project that resulted in the Moog Proportional Flow Control Valve (PFCV), which can be used to throttle the flow of xenon over a wide range of inlet pressures and flow rates. Refer to AIAA 2000-3745 [1] for specific information on the PFCV.

Working with both General Dynamics OTS and Lockheed Martin Space Systems Company, Moog leveraged the previous R&D effort into a flow control unit to support a GEO spacecraft application with a propulsion system using Hall Current Thrusters (HCTs) [2]. The Xenon Flowrate Controller (XFC) has the following operational characteristics:

Table 1. Operational characteristics of the XFC, Moog Model 50E947

Parameter	**Value**
Inlet Pressure Range	Maximum Expected Operating Pressure: 2700 psia Normal Operating Pressure: 37 ±3 psia.
Anode Flow Range	Nominal: 8.4 to 14.8 mg/sec xenon Design Goal: 6.5 to 20 mg/sec xenon
Cathode Flow Range	Controlled between 5% and 9% of the anode flow rate
Mass	< 700 grams
Cleanliness	Meets high purity requirements of HCT cathode

This paper will describe the design, development and qualification of the XFC. Qualification test results for both functional testing as well as environmental testing will be presented at the conference.

Introduction

A Hall Current Thruster (HCT) requires controlled xenon flow to the thruster itself and also to a cathode. The XFC provides these flows through a single PFCV, Moog Model 51E245, and two solenoid valves, one to the anode, Moog Model 51E244, and one to the cathode, Moog Model 51E248. The upstream PFCV controls the overall flow rate to both the anode and cathode, while the flow is then split at the downstream solenoid valves. This split is achieved by a difference in the orifice sizes of the solenoid valves, which are otherwise of the same design. . The XFC qualification unit is shown in Figure 1. A functional schematic of the XFC is shown in Figure 2.

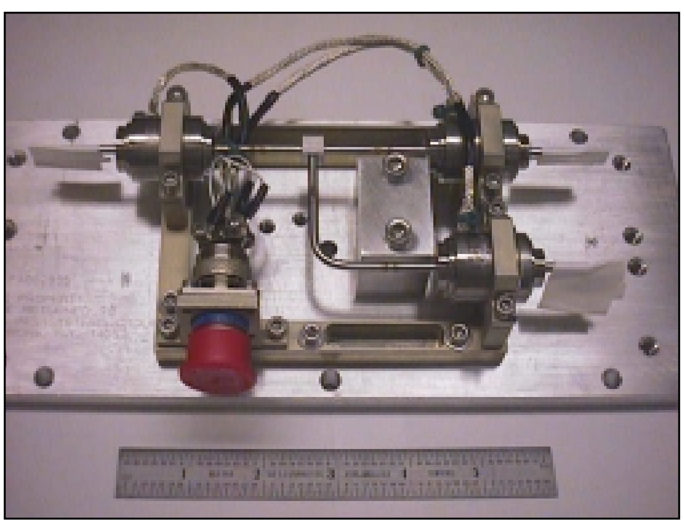

Figure 1. The XFC provides proportional flow control of xenon gas in a small, lightweight package

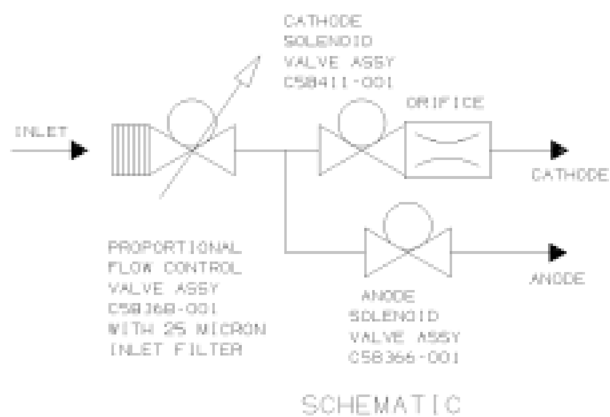

Figure 2. Functional schematic of the XFC.

PFCV Overview

The Moog PFCV is based upon standard space propulsion design concepts and has extensive heritage to solenoid thruster valves that have been used on mono-propellant, bi-propellant and EP systems. This design heritage is important for new EP subsystems because it mitigates a large amount of risk associated with a new xenon feed system. Instead of being concerned about a new valve approach with new materials, the Moog design allows the user to concentrate on the active flow control logic and control.

The PFCV, shown in Figure 3.0, is a suspended armature solenoid design. The key heritage design features are described in Table 2.0:

Table 2. The key design features of the PFCV have extensive flight heritage

Feature	Heritage
Suspended Armature	Same armature configuration as other designs. Examples are Moog models 51-178, 51E190, 51E186, 51E236, 53-235 and numerous others.
Vespel Seal/ Seat Configuration	Same configuration utilized on solenoid and regulator designs. Solenoid examples are Moog models 51E186, 51E190. Regulator examples are Moog models 50-719, 50-823, 50-742, 50-857
S-Spring Design	Extensive use on Moog thruster valves. Examples are Moog models 51-178, 51E190, 51E186, 53-235 and numerous others.
Coil	Same coil design as other standard solenoid valves. Examples are Moog models51-178, 51E190, 51E186, 53-235 and numerous others.
Common Parts	Housings, polepiece, cores, coil forms, armatures, seals.

Minor design features were added and simple changes were made to parts in order to create the proportionality within the valve. Changes in flow rate are initiated by changing the applied current to the coil. The valve remains in the closed position with input currents between 0 and ~85 mA, then starts to modulate flow between 85 mA and a maximum applied current of 125 mA. The 85 mA starting current varies slightly from valve to valve due to build tolerances within the valve. This variation can be accommodated from within the control system.

Figure 3. The Moog PFCV.

Solenoid Valve Overview

Moog Electric Propulsion (EP) solenoid valves have been used on a variety of EP applications. {3, 4, 5} These valves have common heritage to several other monopropellant and bi-propellant engine applications. A summary of the key characteristics of the solenoid valves are listed below:

- Common parts to allow for larger manufacturing and assembly runs. This reduces the overall cost of the valve.
- No sliding fits. Moog utilizes a suspended armature design, which incorporates Moog standard S-Spring technology. This is critical for EP feed systems since contamination control is a driving design requirement.
- A Vespel® seal is used to provide isolation as well as flow metering.
- Common interface for direct integration with standard Moog EP solenoid valves, Moog Models 51E190 and 51E186. This facilitates integration to the top level assembly.
- All welded configuration.
- 0.125 inch inlet and outlet tube configured for orbital tube welding into standard EP systems.

The following table describes the detail performance requirements that have been met by the Moog EP solenoids.

Table 2.0. Moog model 51E190 and 51E186 performance summary.

Parameter	Moog Model 51E190 Pressure Regulation Valve (Pulse Width Modulated)	Moog Model 51E186 Pressure Regulation Valve (Bang – Bang)
Maximum Expected Operating Pressure	1812 psia	2175 psia
Proof Pressure	2730 psia	3265 psig
Burst Pressure	6300 psia minimum	6300 psig
	Structural test unit exceeded 10,000 psig	
Internal Leakage	< 1.0×10^{-4} sccs GHe at 1820 psig	< 3 scc/hr GHe at 3625 psig and 100 psig
	1.0×10^{-7} sccs GHe typical of flight valves.	1.0×10^{-6} sccs GHe typical of flight units
External Leakage	< 1.0×10^{-6} sccs GHe at 1820 psig	< 1.0×10^{-6} sccs GHe at 2180 psig
Coil Resistance	200±10 ohms at ambient temp.	74.5±2 ohms at ambient temp.
Opening Response	< 50 ms at 1820 psig and 28 vdc	< 10 ms at 2200 psig and 15 vdc
Closing Response	< 50 ms at 1820 psig and 28 vdc	< 10 ms at 2200 psig and 15 vdc
Pull-In Voltage	< 28 vdc at 158 ^{o}F	< 14 vdc at 70 ^{o}F
Drop-Out Voltage	< 15 vdc at 158 ^{o}F	< 14 vdc at 70 ^{o}F
Random Vibration	20.75 grms, 2 minutes per axis	17.1 grms, 3 minutes per axis. Pressurized to 2200 psig and monitor internal leakage of valve pair.
Operational Temperature Range	-30^{o}C to +70^{o}C. Verified internal leakage, response, coil resistance, pull-in and drop-out at temperature	+17^{o}C to +60^{o}C Verified internal leakage.
Non-Operational Temperature Range	-40^{o}C to +75^{o}C	-34^{o}C to +71^{o}C
Life Cycle Test	300,000 cycles minimum	900,000 cycles minimum
	Extended qualification testing on Moog 51E186 solenoid demonstrated in excess of 2 million cycles.	
Weight	115 grams	200 grams for the dual valve configuration

Anode to Cathode Flow Split

To achieve the required flow split between the anode and the cathode of the Hall Current Thruster (HCT), Moog implemented a combination of orifices to accomplish this flow split. The requirement is that the cathode flow be between 5% and 9% of the anode flow rate. Since the solenoid valves contains an orifice and seat it was decided that the anode flow rate would be established using the orifice contained within the valve. This orifice was toleranced as necessary to achieve the desired flow rate. Since the required cathode flow rate is so much smaller than the anode flow rate, having the control orifice part of the valve was not feasible due to the small hole size required as well as the tight tolerance required on the nominal hole size. A separate orifice was manufactured and then integrated downstream of the cathode valve seat. This second orifice provided the necessary flow control for the cathode line. To ensure that proper flow rates and flow splits are achieved, both the anode and cathode orifices are flow tested over the full operational ranges prior to installation into the XFC.

Development Test Results

Moog completed development testing on the major components of the XFC This included flow split verification as well as proportional control over the full range of inlet pressure and flow rates. The results of this testing are presented below.

To achieve the required flow split, the orifices of all three valves had to be properly sized such that:

- the maximum flow rate (18.4 mg/sec) through the anode solenoid valve of the XFC can be achieved at the minimum XFC inlet pressure (34 psia).
- the minimum flow rate (8.4 mg/sec) through the anode solenoid valve of the XFC can be achieved at the maximum XFC inlet pressure (40 psia).
- the flow rate through the cathode solenoid valve is 5% to 9% of the flow rate of the anode solenoid valve

Using existing data regarding the flow characteristics of similar valves and additional development testing, an analysis of orifices in series was performed to determine the nominal size and allowable tolerances

In order to verify that the valve orifices were properly sized, Moog fabricated development valves and created a ground-test XFC shown in Figure 4.0.

Flow split verification was performed by opening the PFCV at full stroke, opening each solenoid valve and measuring the flow rate through each solenoid valve. Figure 5.0 graphically illustrates a flow split of 6.4% to 6.5% over an XFC inlet pressure range of 34 psia to 40 psia.

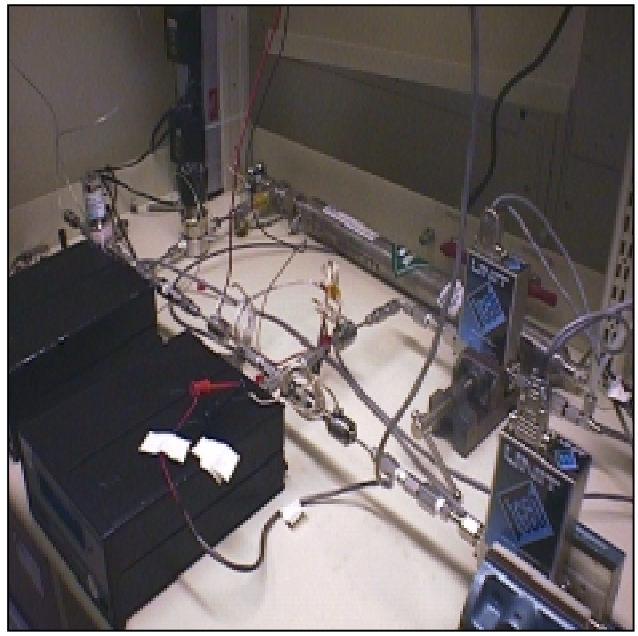

Figure 4.0. XFC Ground Test Set-Up

After establishing that the flow split met the design requirements, flow testing was performed to demonstrate that the PFCV could regulate the xenon flow to meet the range of flow requirements. Using a PID controller, the input current to the PFCV was generated via closed loop control on the flow rate through the anode solenoid valve. The flow rate was set to 4 discrete rates (6.5 mg/sec, 8.4 mg/sec, 14.8 mg/sec and 20 mg/sec xenon). Input current to the PFCV and inlet pressure to the XFC was monitored throughout the test. Figure 6.0 illustrates the ability of the PFCV to meet the flow rate requirements over a pressure range of approximately 34 psia to 40 psia. The PFCV was successful in consistently regulating the xenon to the desired flow rates over the required pressure range.

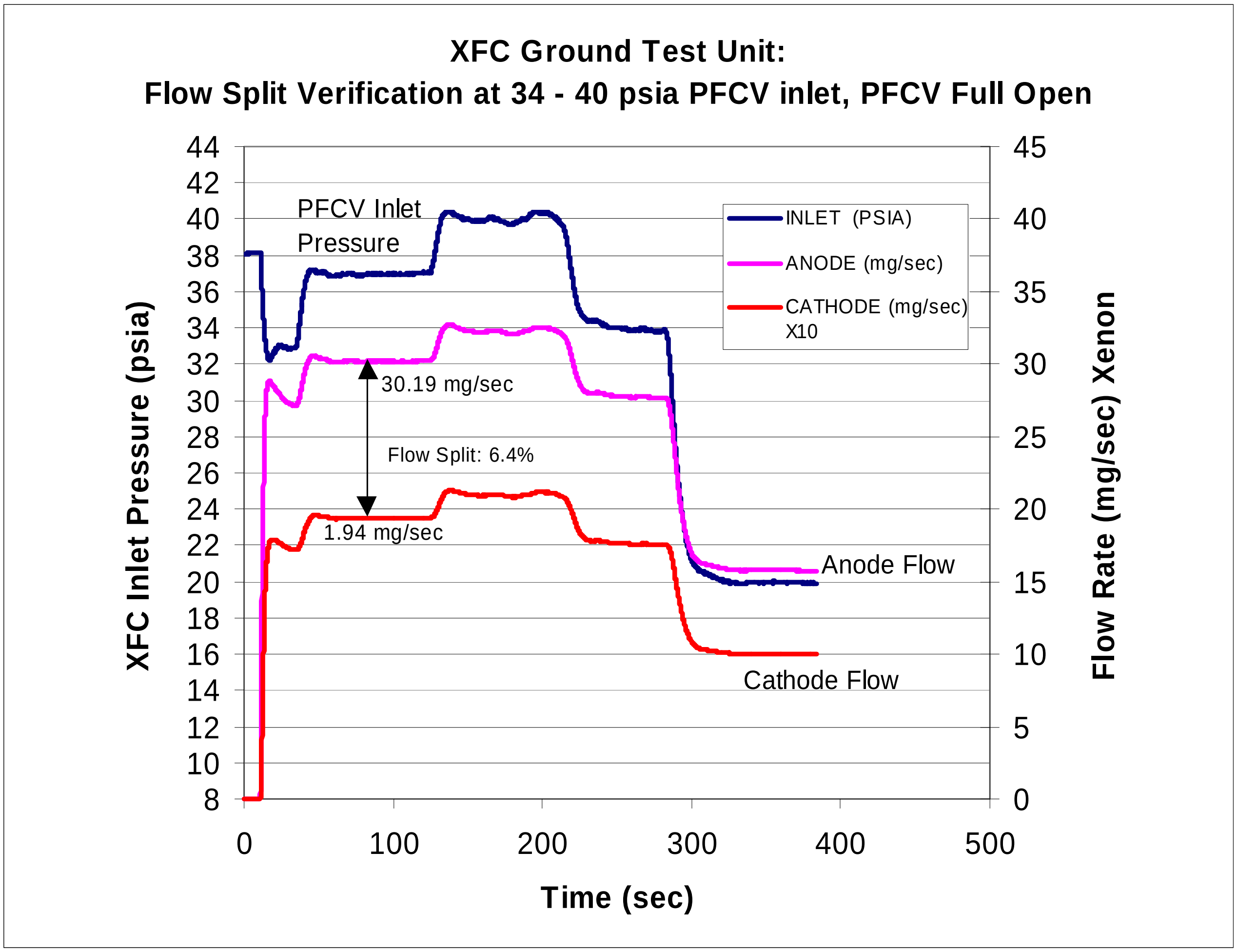

Figure 5. A flow split of 6.4% to 6.5% was achieved with the ground test XFC over an XFC inlet pressure range of 34 to 40 psia. Note that the flow rate of the cathode valve is shown ten times the actual flow rate.

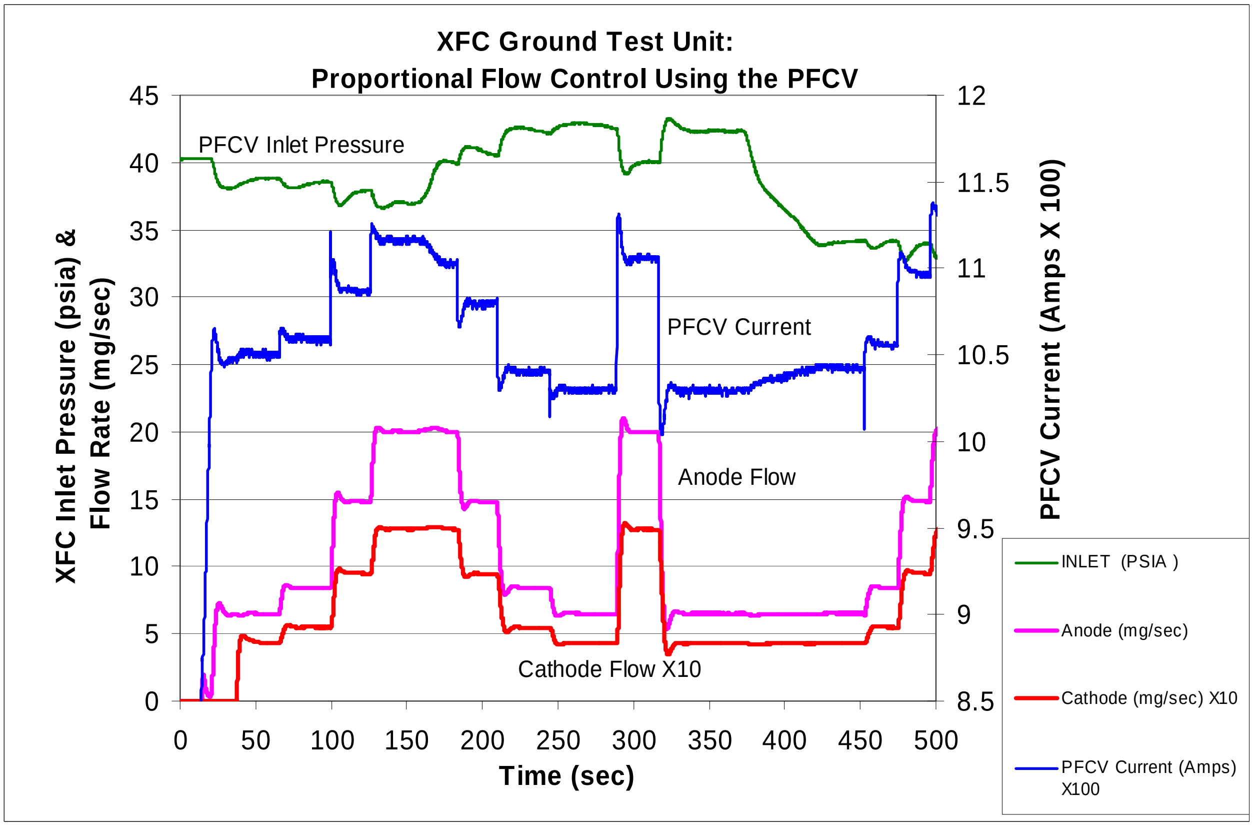

Figure 6. Proportional control of the xenon flow using closed loop feedback to control the input current to the PFCV based on the flow rate through the anode solenoid valve. Note that the flow rate through the cathode valve is shown ten times the actual flow rate.

Qualification Test Plan

After Moog completes the assembly of the XFC, it will be subjected to a complete qualification test sequence. This qualification testing will be broken down into two parts. The first part consists of environmental exposure and performance verification, which will be conducted at Moog Inc. The second part will be a series of engine tests to be completed at General Dynamics. This final set of engine tests will take place when the XFC is fully integrated with the power processing unit and HCT, and will provide the full proportional flow control required for all mission phases.

A brief outline of the environmental qualification tests to be completed at Moog is as follows:

- XFC Inspection
- Proof Pressure
- External Leakage
- Functional Tests
  - Coil Tests
  - Response of each solenoid valve
  - Current versus Flow Rate for the PFCV Valve
  - Pull In and Drop Out for Each Solenoid Valve
  - Internal Leakage for Each Valve
- Anode to Cathode Flow Split Testing
- Sine Vibration Test
- Random Vibration Test (Overall level is 18.6 grms)
- Post Vibration Functional Test
- External Leakage

- Shock Test (Peak G 6000 g's)
- Post Shock Functional Test
- External Leakage
- Thermal Vacuum Testing
  - Functional tests at +71 Deg C, -8 Deg C and –34 Deg C
  - 10 cycles total
- Post Thermal Vacuum Functional Test
- External Leakage
- Preparation for Delivery to General Dynamics for Additional Engine testing.

Qualification testing is scheduled to be completed at Moog in early October 2001 with continued testing at General Dynamics taking place over the balance of the calendar year.

Conclusions

Moog has successfully completed the development of the Moog PFCV. This developed product has now been implemented and will be qualified as part of an Electric Propulsion Satellite system for General Dynamics and Lockheed Martin Space Systems Company. Successful development testing has paved the way for a successful qualification test program.

References

1. Bushway III, Edward D., Richard Perini, "Proportional Flow Control Valve (PFCV) for Electric Propulsion Systems", AIAA 2000-3745, July 2000.

2. Fisher, Jack, Alfred Wilson, David King, Steve Meyer, Carl Engelbrecht, Kristi deGrys, Lance Werthman, "The Development and Qualification of a 4.5 kW Hall Thruster Propulsion System for GEO Satellite Applications", IEPC-01-010, October, 2001.

3. Chojnacki, Kent T., Edward D. Bushway III, "Xenon Feed System (XFS) for the Module M Flight Experiment", AIAA 98-3494, July 1998.

4. Bushway III, Edward D., W.P. Rogers, "Miniature Lightweight Propellant Management Assembly for Stationary Plasma Thrusters", AIAA 97-2788, July 1997.

5. Bushway III, Edward D., Carl S. Engelbrecht, Dr. Gani B. Ganipathi, "NSTAR Ion Engine Xenon Feed System: Introduction to System Design and Development", IEPC-97-044, August 1997.