Continuing Development of the Proportional Flow Control Valve (PFCV) for Electric Propulsion Systems

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Abstract: This paper documents the continuing development at Moog of a family of Proportional Flow Control Valves (PFCV) for use on Electric Propulsion (EP) systems. The PFCV provides the capability to actively control both the system pressure and the propellant flow rate to the engine using a single flow control component. Recent development has resulted in improved valve performance and an increase in the operating flow ranges. Background design information as well as development and qualification test results are presented.

I. Introduction

The Moog Proportional Flow Control Valve (PFCV) is a proportional electro-mechanical device developed to combine pressure regulation capability, flow control capability, and propellant isolation and leak protection for electric propulsion (EP) systems in a single device [1]. The PFCV has successfully flown as a pressure regulator and sole propellant isolation device on the TACSAT-2 mission [2, 3], 12 units have been delivered as part of the AEHF Xenon Flow Control (XFC) assembly [4], and the PFCV has been base lined for the NASA NEXT ion propulsion system architecture.

Moog continues to expand the capabilities of the PFCV family to incorporate lessons learned and to meet evolving EP system requirements. As part of that effort, Moog has an on-going internal development program to develop an improved version of the Model 51-245A PFCV used on the XFC program. The goals of the development program include:

- Increase the Model 51-245A operating pressure capability beyond 2700 psia,
- Improve PFCV operating characteristics such as gain slope while maintaining Model 51-245A electrical operating envelope (e.g., current operating range, minimum opening current) to allow for use of the valve with existing Power Processing Unit controllers (PPUs).

Concurrently, Moog undertook the development of a high flow (> 100 mg/s Xenon) version of the Model 51-245A PFCV in response to a request from an external customer.

II. Performance Requirements

The requirements for the Model 51E339 derivative of the AEHF PFCV and the Model 51X362 high flow PFCV were derived from existing and planned EP applications. These requirements are summarized in Table 1. The performance characteristics of the Model 51-245A PFCV are included in Table 1 for comparison purposes.

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Table 1. Proportional Flow Control Valve Performance Requirements

Performance Characteristic	**AEHF Model 51-245A PFCV**	**Model 51E339 PFCV**	**Model 51X362 High Flow PFCV**
Operating Flow Rate Range	6 to 20 mg/s Xenon	0 to 30 mg/s Xenon	**0 to 100 mg/s Xenon**
Inlet Operating Pressure Range 1. Pressure Regulation 2. Flow Regulation	1. N/A 2. 35 to 40 psia	**1. 0 to 2700 psia min** 2. 35 to 40 psia	3. N/A 4. 35 to 40 psia
Outlet Control Pressure Range 1. Pressure Regulation 2. Flow Regulation	1. N/A 2. 0 to 40 psia	1. 35 +/- 2 psia 2. 0 to 40 psia	3. N/A 4. 0 to 40 psia
Maximum Expected Operating Pressure (MEOP)	900 psia	**> 2700 psia**	900 psia
Proof Pressure	1.5X MEOP	1.5X MEOP	1.5X MEOP
Burst Pressure	2.5X MEOP	2.5X MEOP	2.5X MEOP
Non-Operating (Survival) Temperature Range	-34 ºC to +71 ºC	-40 ºC to +125 ºC	-39 ºC to +76 ºC
Operating Temperature Range	-8 ºC to +71 ºC	-10 ºC to +100 ºC	-8 ºC to +71 ºC
Minimum Opening Current	≥ 75 mA between 10 and 900 psia inlet pressure	≥ 75 mA between 10 and 2700 psia inlet pressure	≥ 75 mA between 10 and 900 psia inlet pressure
Maximum Full Open Current	Full Open Current ≤ 150 mA	Full Open Current ≤ 150 mA	Full Open Current ≤ 150 mA
Open Loop Gain	2 < x < 8 mg/s/mA when measured with Xenon	TBD mg/s/mA	TBD mg/s/mA
External Leakage	< 1 X 10^{-6} scc/s GHe at MEOP	< 1 X 10^{-6} scc/s GHe at MEOP	< 1 X 10^{-6} scc/s GHe at MEOP
Internal Leakage	< 8.3 X 10^{-4} scc/s GHe @ 30 and 900 psia	< 1 X 10^{-4} scc/s GHe @ 30 and 2700 psia	< 1 X 10^{-4} scc/s GHe @ 30 and 900 psia
Cycle Life	6635	> 10,000	> 10,000
Open/Close Response Time	≤ 25 ms	≤ 20 ms	≤ 20 ms
Mass	≤ 115 g	≤ 115 g	≤ 115 g
Materials of Construction	All wetted surfaces shall be compatible with high purity Xenon.	All wetted surfaces shall be compatible with high purity Xenon.	All wetted surfaces shall be compatible with high purity Xenon.
Design & Construction	All welded construction	All welded construction	All welded construction

III. Design Overview

The Moog Proportional Flow Control Valve (Figure 1) was developed to combine the functions of the traditional EP pressure and flow control systems in a single unit. The traditional pressure and flow control architecture typically relies on mechanical or "bang-bang" pressure regulators to provide a constant feed pressure to fixed flow control orifices, providing a constant propellant flow to the EP thrusters. Separate latching or normally closed valves are used to provide flow isolation capability. The only way to change the flow through these systems is to change the system inlet pressures. Alternate architectures employ devices such as thermal throttles to provide an active flow control capability over a limited flow range.

The Moog PFCV replaces the traditional pressure and flow control architecture, providing the ability to actively throttle either the operating pressure or propellant flow rate of the system while also providing the system propellant isolation capability. The PFCV can provide active system throttling for either open loop or closed loop operation. In the open loop mode, the operating current of the PFCV is manually commanded to provide the required flow rates through the system. The closed loop mode uses downstream performance feedback telemetry to control the valve operating current. During closed loop operation, the PFCV will be actively controlled by a proportional integral derivative (PID) controller, which responds to system performance feedback provided by a downstream telemetry device. The system performance feedback can be provided by a telemetry device such as a pressure transducer or a flow meter, or can be measured directly off engine feedback current. Figure 2 provides an example of a typical PID circuit.

Figure 1. Moog Model 51E339 Proportional Flow Control Valve is a compact, multifunctional device with a mass of less than 115 grams. The configuration shown has 0.125" inlet/outlet tubes.

The PFCV is a suspended armature solenoid design with a simple orifice and a Vespel® seal. The PFCV design is based on standard space propulsion design concepts and has extensive heritage to solenoid valves used extensively in mono-propellant, bi-propellant, and electric propulsion subsystems. Because the PFCV traces it heritage to standard solenoid valves, it could easily be modified to support a liquid or cold gas application. Valves of the PFCV family have the following common critical characteristics:

- Common parts to the greatest extent practical to allow for larger manufacturing and assembly runs.

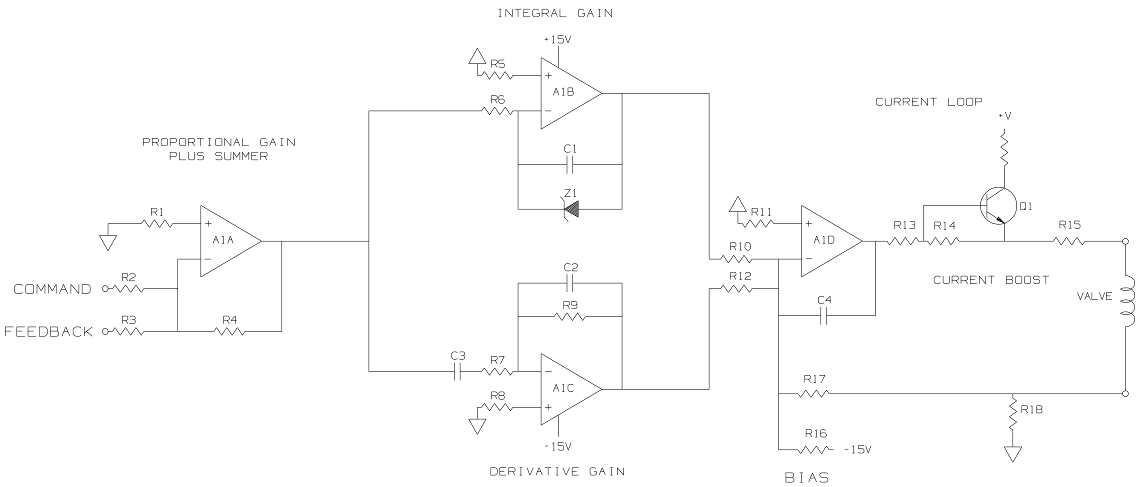

Figure 2. A Typical PID Controller used for closed loop PFCV control

This reduces the overall cost of the valve.

- No sliding fits. The PFCV utilizes a suspended armature design, which incorporates Moog standard S-Spring technology. This is critical for EP systems since contamination control is a driving design requirement.
- Vespel® seal, which is used to provide isolation as well as flow and pressure metering. Vespel® is utilized in EP systems due to its dimensional stability as well as its low outgassing properties.
- All welded configuration.

Maintaining this design heritage was an important design criterion for the 51E339 and 51X362 designs to minimize the risks of using these designs on future xenon feed systems. The key heritage design features are described in Table 2.

Table 2. Key PFCV Design Features

Feature	Model 51-245A Heritage	Model 51E339 / Model 51X362 Configuration
Suspended Armature	Same armature configuration as other Moog designs. Examples include Moog Models 51-178, 51E190, 51E186, 53-235, and numerous others	No change.
Vespel Seal / Seat Configuration	Same configuration utilized on Moog solenoid and regulator designs. Solenoid examples include 51E186 and 51E190. Regulator examples include 50-719, 50-823, 50-742, and 50-857.	No change.
S-Spring Design	Extensive use on Moog thruster valves. Examples include Moog Model 51-178, 51E190, 51E186, 53-235, and numerous others.	S-Spring design unchanged. Minor process changes already incorporated on similar valves to improve manufacturability and yield.
Coil	Same coil design as other standard Moog solenoid valves. Examples include Moog Model 51-178, 51E190, 51E186, 53-235, and numerous others.	No change.
Common Parts	Housing, polepiece, cores, coil forms, armatures, seals common to numerous Moog solenoid valves. Examples include Moog Model 51-178, 51E190, 51E186, 53-235, and numerous others.	No change to common part designs. Assembly sequence modified based on lessons learned to improve valve manufacturability.

IV. Model 51E339 Performance

Model 51E339 development testing included both open and closed loop testing using the test set-up shown in Figure 3. Open loop testing was performed manually to determine the operating current, flow range, and gain-slope characteristics. Closed loop testing was performed using a Moog ground test PID controller to demonstrate control as either a pressure regulator or a flow control device. The pressure regulation tests used the transducer T1 for feedback control. Flow meter FM1 was used as the feedback telemetry for the flow regulation testing. Gaseous Argon (GAr) was used as the test medium for all testing.

The flow gain performance characteristics of the Model 51E339 PFCV over a temperature range of -40°C to +100°C are presented in Figure 4. Figure 5 is a comparison of the flow-gain performance characteristics of the baseline Model 51-245A and the 51E339. The 51E339 provides a greater total flow capacity and has a gain-slope of 1.75 (mg/s xenon)/mA over an operating range of 5 to 30 mg/s, a significant improvement over the typical 2.5 to 3.0 (mg/s xenon)/mA gain-slope of the baseline Model 51-245A. The reduction in gain-slope is desirable as it allows finer control of flow at the system level.

The demonstration of Model 51E339 PFCV pressure regulation capability over a varying flow demand is shown for an inlet pressure of 3600 psia in Figure 6. The outlet pressure is stable at a constant 35 psia as the flow demand is varied over the range of 20 to 600 standard cm^3/sec GAr. This represents a pressure-throttling ratio of 100:1 over a 30:1 flow turn down ratio. Figure 7 demonstrates the ability of the Model 51E339 qualification unit to actively regulate pressure over a wide flow range at a typical system end of life pressure of 100 psia.

Figure 8 compares the measured flow through the PFCV with the flow meter FM1 flow demand. Demonstrated flow was within 5 standard cm^3/sec GAr of demand at all inlet pressure conditions tested. This successfully demonstrates the flow regulation capability of the Model 51E339 PFCV.

The Model 51E339 Proportional Flow Control Valve is currently undergoing qualification testing at Moog. At the time this paper was published the valve had successfully completed random and sine vibration testing. Shock exposure, followed by thermal cycle testing, remains to be completed.

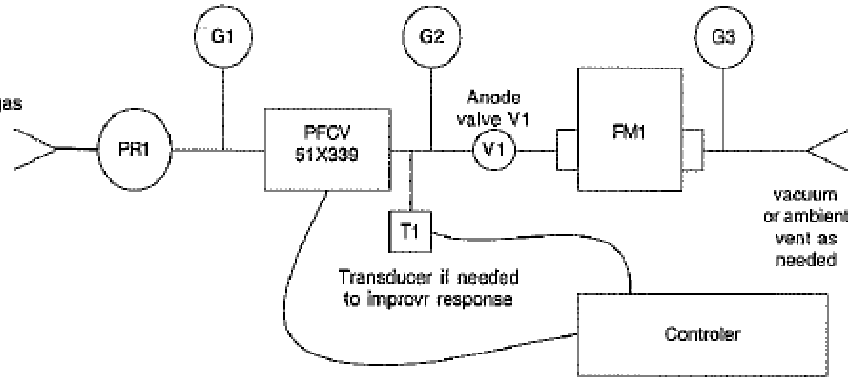

Figure 3. Test System Schematic used to verify PFCV open and closed loop performance

V. Model 51X362 Performance

Development testing of the Model 51X362 has been performed at the unit level and in a simulated XFC assembly (Figure 9). The valve level flow-gain performance characteristics are presented in Figure 10. This test demonstrated a flow capability of 3,500 cm^3/sec GAr, equivalent to 177 mg/s of xenon flow, using a development level bolt-together valve. Testing with a welded PFCV in the simulated XFC assembly demonstrated a flow capability between 90 and 107 mg/s of xenon, depending on the XFC assembly inlet pressure. This data is presented in Figure 11.

Further testing was performed using the simulated XFC to demonstrate the limits of the XFC assembly flow control capability using the 51X362 PFCV. The Model 51X362 demonstrated the ability using the Moog PID controller to control discrete XFC flow changes of less than 1.0 cm^3/sec GAr, equivalent to a control capability of 0.05 mg/s of xenon. This results of this testing is presented in Figure 12.

VI. Conclusion

Moog continues to expand the capabilities of its flight-proven Proportional Flow Control Valves to incorporate lessons learned and to meet evolving EP system requirements. The PFCV combines the pressure regulation, flow control, and propellant isolation capabilities required for electric propulsion systems in a single multifunction valve. A successful internal development effort has yielded two new PFCV models to support future EP systems:

- Model 51E339 PFCV, a successor to the AEHF Model 51-245A with higher flow capability, improved flow-gain slope characteristics yielding better flow control resolution at the system level, and a demonstrated ability to regulate pressures as high as 3600 psia.
- Model 51X362 High Flow PFCV, a high flow derivative of the AEHF Model 51-245A which expands the PFCV flow regulation capability from 0 – 20 mg/s xenon to 0 – 100 mg/s. The Model 51X362 also shares the improved flow-gain slope characteristics of the Model 51E339.

The Model 51E339 Proportional Flow Control Valve is currently undergoing qualification testing at Moog. Qualification testing will be complete late September 2007.

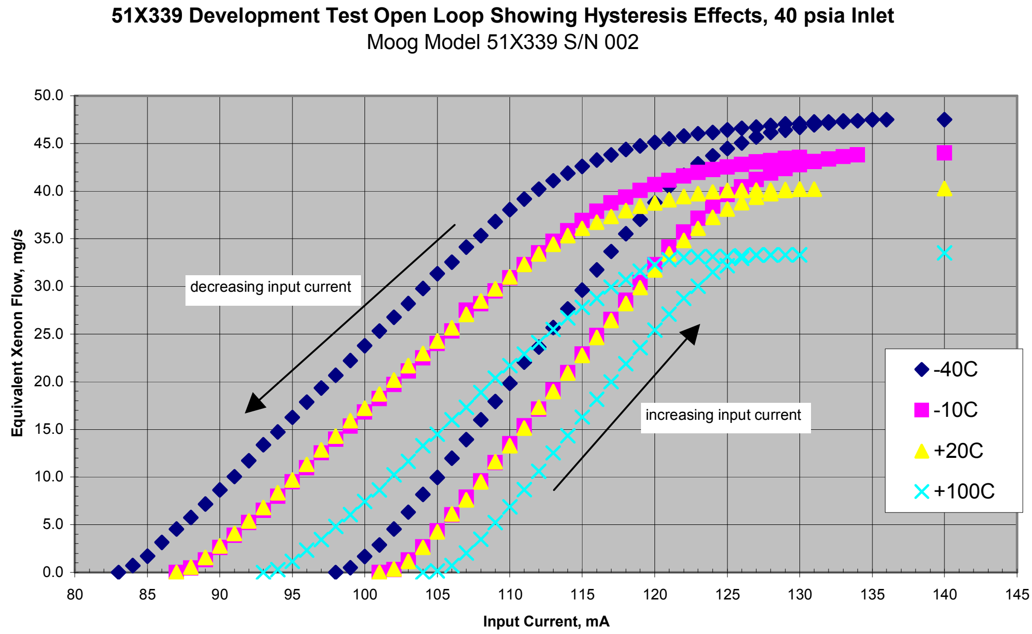

Figure 4. Model 51X339 PFCV Demonstrates Consistent Flow and Gain Slope Performance Over a Wide Operating Temperature Range

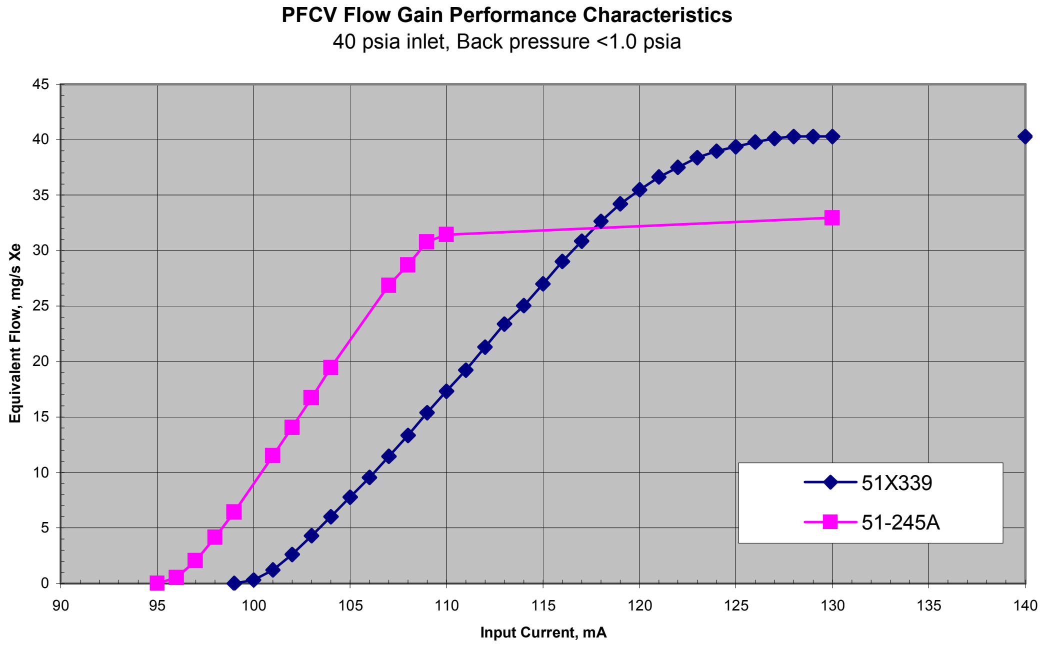

Figure 5. Model 51X339 PFCV Demonstrates Improved Gain Slope Characteristics over Previous Generation

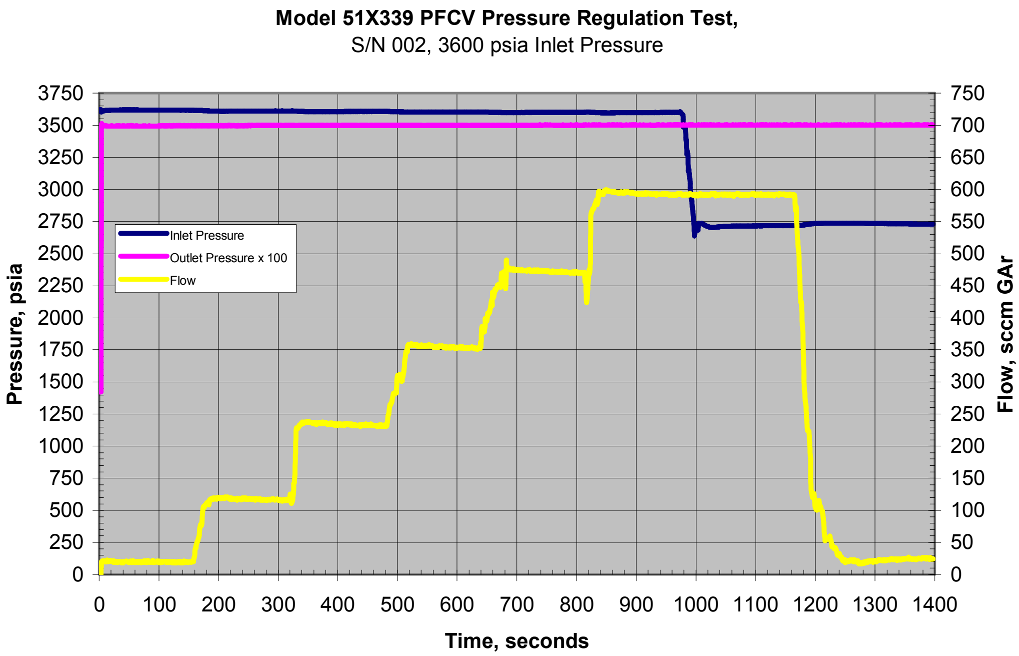

Figure 6. Model 51X339 PFCV Demonstrates Ability to Provide Single Stage 100:1 Pressure Throttling Over Varying Flow Demand

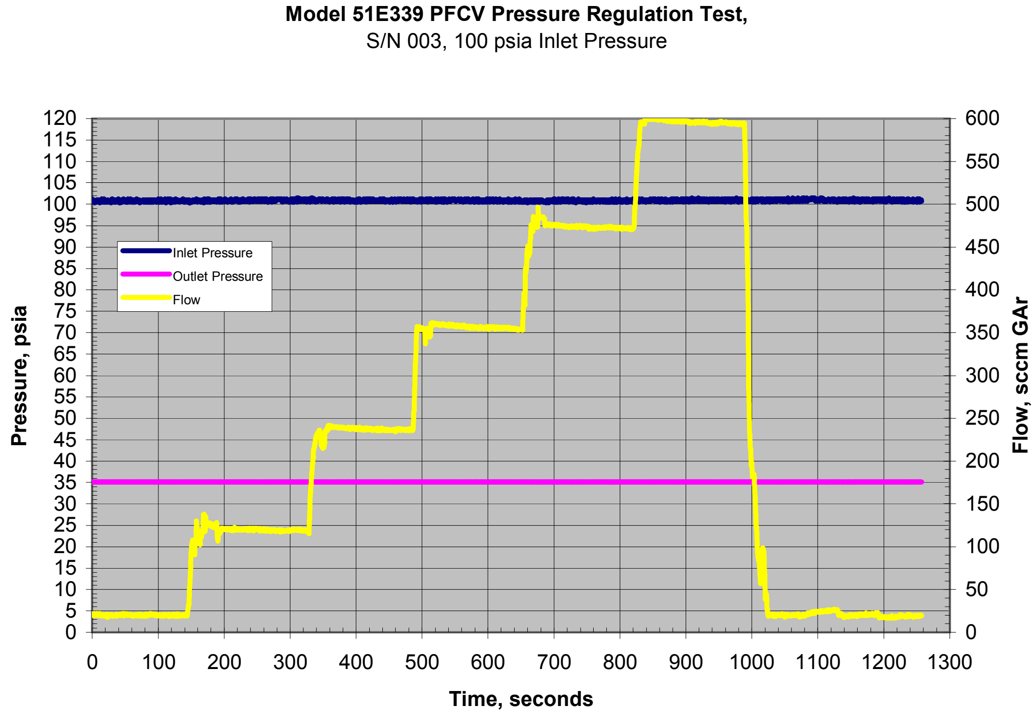

Figure 7. Model 51E339 PFCV Demonstrates Ability to Satisfy Varying Flow with Minimal Pressure Drop Across Valve

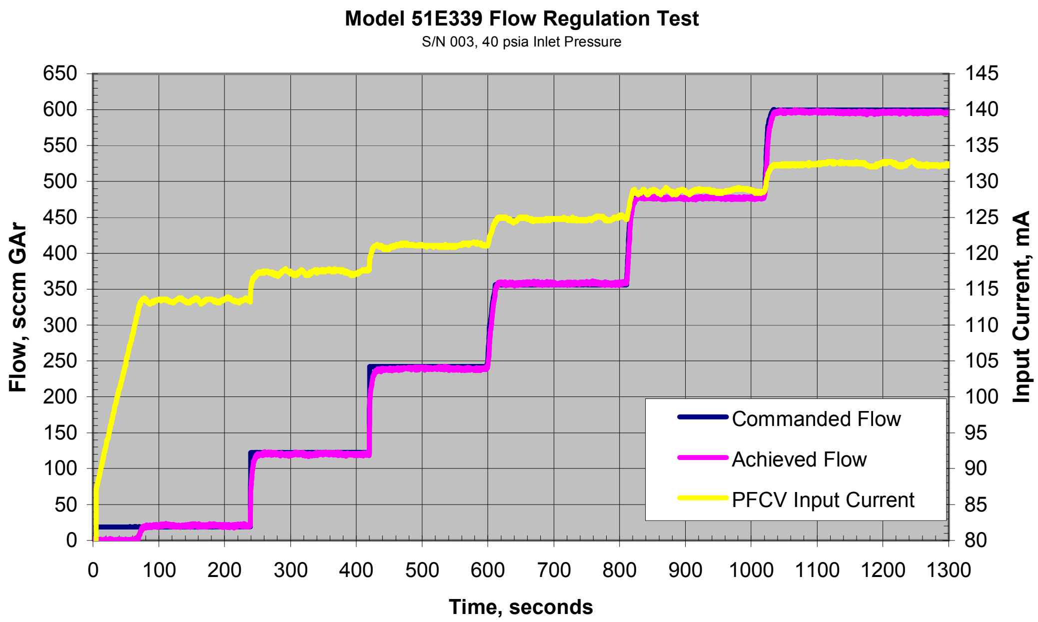

Figure 8. Model 51E339 PFCV Provides Accurate Flow Response in Closed Loop Control to Satisfy Varying Flow Demand

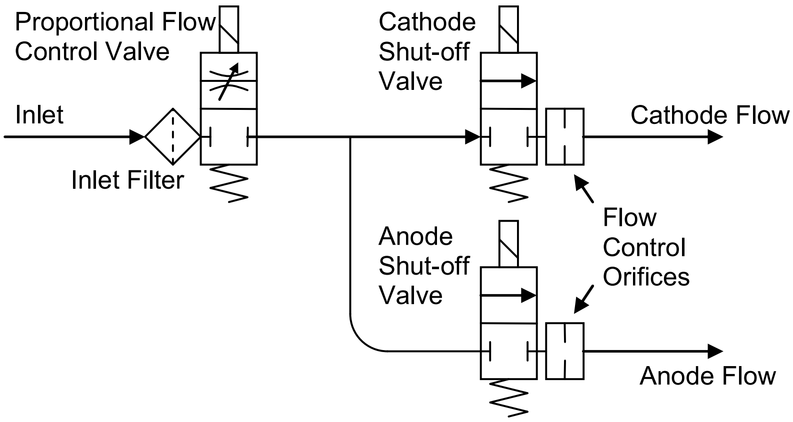

Figure 9. Notional Xenon Flow Controller (XFC) Assembly Schematic

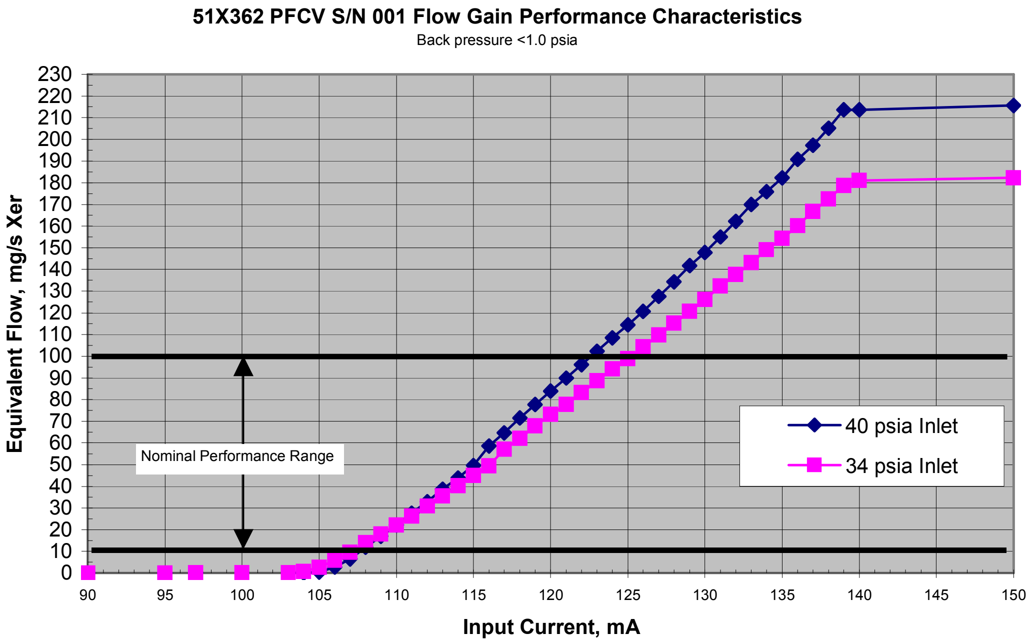

Figure 10. Model 51X362 High Flow PFCV Demonstrates Ability to Meet Flow Requirements Greater Than 150 mg/s of Xenon

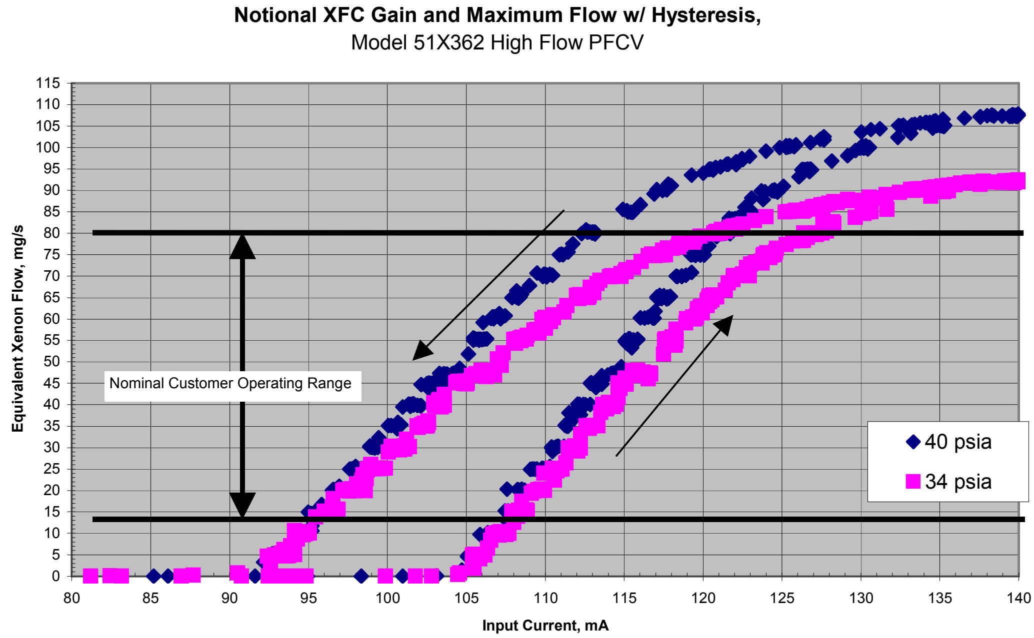

Figure 11. Model 51X362 High Flow PFCV Provides Increased Flow Capability for a Notional XFC Assembly

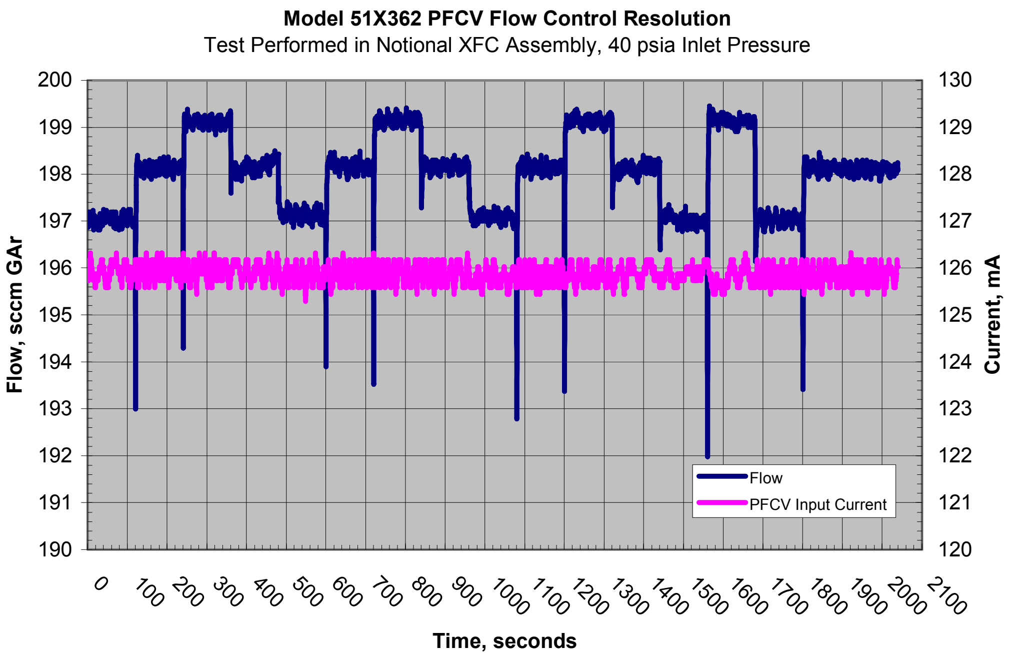

Figure 12. Model 51X362 High Flow PFCV Demonstrates Ability to Accurately Control Changes in Required Flow to Less Than 1.0 sccm GAr (Equivalent to Less Than 0.05 mg/s Xenon)

References

[1]Bushway III, E. D., and Perini, R., "Proportional Flow Control Valve (PFCV) for Electric Propulsion Systems", AIAA 2000-3745, July 2000

[2]Barbarits, J. K., and Bushway III, E. D., "Xenon Feed System Development", AIAA 2003-4879, July 2003

[3]Barbarits, J. K., and King, P. T., "Xenon Feed System Progress", AIAA 2006-4846, July 2006

[4]Bushway III, E. D., King, P. T., Engelbrecht, C., and Werthman, L., "A Xenon Flowrate Controller for Hall Current Thruster Applications", IEPC-01-315