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Evaluation of Proportional Flow Control Valves for Potential Use in Electric Propulsion Feed Systems

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Abstract

Flow control of propellant to an electric thruster is an important parameter in the design of reliable, versatile and cost effective electric propulsion subsystems for spacecraft. With the great success of the Deep Space 1 mission in proving the reliable operation of electric propulsion for deep space missions, the limitations of the system often go overlooked. One of the most involved aspects of the system was the accurate flow control of xenon to the engine and cathodes. An orifice system utilizing porous plugs was used to control the flowrate which required careful calibration of flow versus pressure and temperature and multiple iterations to converge on the appropriate units for flight use. In additon, once these were installed on the system, special ground handling requirements had to be maintained and system testing was dictated by the time required for upstream pressures to drop to new levels through these fixed orifices. Flowrate through these was highly dependent on accurate upstream pressure control. Utilizing a bang-bang solenid approach, in order to damp out the resulting "sawtooth" generated from each cycle of the solenoids, large plenum volumes were required.

An alternative approach is to utilize a proportionally controlled valve to provide accurate flow to the system. This allows very large flowrates when necessary for quick changes in operating conditions and a reduced sensitivity to ground handling. These types of valves run in a closed loop mode with the PID control responding to a downstream feedback signal. In fact, for Hall type thrusters, this feedback signal can be the operating discharge current itself allowing for precise power consumption at all times and the ability to change power levels almost instantaneously. Two solenoid valves were tested with these considerations. One was provided by Moog Space Products Division and the other from Marrotta Scientific Controls. The results of these evaluations are presented here.

Introduction

Precise flow control of gaseous propellants is a critical factor in the overall performance of a flight electric propulsion susbsystem. Flowrates must be maintained with precisions of <3% at flowrate ranges from 2 to over 100 sccm to properly operate any type of electric propulsion thruster. This poses significant challenges to the feed system employed for this purpose. Controlling flowrates in the range of <10 sccm are for all practical purposes leak rates and are hard to actively control in most cases. Typical applications use flow restrictors of some form which are either input pressure dependent or input pressure and temperature dependent to control these flows. In both cases, in order to maintain the <3% accuracy in the flowrate during operation, the corresponding upstream pressures must be maintained very tightly.

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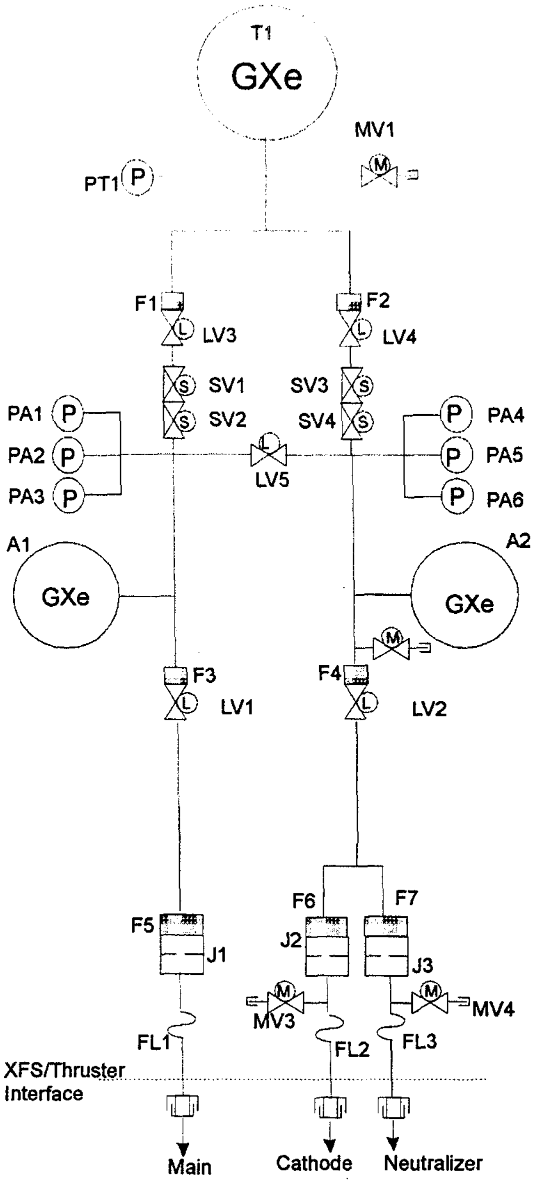

Figure 1. DS1 Xenon Feed System

Background

Deep Space 1 utilized a bang-bang regulation system and relatively large plenum volumes to maintain the pressure deviations during control below the threshold where they would cause flow to exceed the maximum allowable values (see Figure 1). This pressure controlled input to specially tested sintered filters from the Mott Metalurgic company provided the proper flowrate ranges to the cathodes and primary discharge of the 30 cm ion engine employed. Both cathodes were fed from a single plenum branch thus the two Flow Control Devices (FCD's) feeding the two cathodes (discharge and neutralizer) had to match in performance very closely. Many iterations and extensive calibrations were required to achieved a matched pair that provided the desired pressure versus flowrate performance. Similar testing and iterations were required for the primary flow FCD, though it was not necessary to match this to another closely as in the case of the cathodes.

Although this approach was state of the art at the time, there are several drawbacks to flow control in this manner. First, this form of flow control is pseudo passive, as the only way to change the flowrate through these devices is to change their inlet pressures. They are not actively changed in any way, as may be the case with a thermal throttle for instance. This has the resulting implication that changes in operating setpoints can take many hours to achieve, especially for changes in cathode operating points whose flowrates are so low. Low flowrates and large upstream plenum volumes result in long periods for pressure reduction to occur to make a change in the cathode flowrates. For a spacecraft, this results in lost propellant since flowrates would run at a higher than necessary level while the upstream pressure bleeds down (although a small quantity) These long times result in an overall reduction in system performance.

Secondly, these types of flow control devices proved to be highly sensitive to contamination. Very large upstream filters were required to protect each of the separate FCD's on DS1 so that the calibration curves generated for each FCD remained accurate during the ground phase of the mission and throughout the spacecrafts mission operation. Effective orifice sizes through the sintered filter were on the order of 0.02 microns. Ground handling and calibration of the devices were difficult and time consuming and required lengthy measures to keep potential contamination to an absolute minimum.

Thirdly, once the devices are successfully integrated into the feed system, the feed system must be purified and samples of the loaded propellant must be taken to assure the necessary propellant purity requirements as dictated by the cathodes. Purification of the system is done through vacuum bakeouts of the system, as well as multiple vacuum and purge cycles. Obtaining adequate vacuum levels on the feedsystem with these devices in place increases operating times significantly. In taking point of use purity samples of the loaded propellant, 100 liters of Xenon must be flowed through the system and into cryogenically pumped sample cylinders. As one might imagine, it takes approximately 5 days of continous operation in this manner to obtain the required sample volume through the cathodes. Not only is this very labor intensive and time consuming, but any minute leak on the downstream side of the system from the FCDs has 5 days to accumulate contaminants in the sample providing false readings with regard to system purity, which in turn results in extensive re-cleaning and filling operations or potential waivers based upon analytical efforts to disprove the negative results.

Fourthly, careful control of the upstream pressures necessary to achieve the desired flow rate accuracies were driven by intersolenoid volumes. To damp out sawtooth resulting from this operation plenum tanks were necessary. Flow into the ullage upstream of the FCD's was available in quanta only, the size of that quanta a function of inlet pressure. Also, flow restriction can be performed by devices with larger operating bands and in a more linear fashion reducing overall flow errors. In addition, because of the substantial heating incurred during operation (valves were opened with >10W each), the valves were operated at a limited duty cycle. This duty cycle was 33% for DS1 and resulted in substantially increased pressurization times.

The investigation into alternative methods of flow control in order to alleviate these issues precipitated the testing which will comprise the remainder of this paper. The ability to control flowrate actively through the use of a proportionally controlled solenoid valve is a large step in these alternative methods. These devices can control flowrates as low as 1 sccm accurately and yet have the ability to open substantially to provide flowrates in excess of 100 sccm when necessary. For vacuum purposes, instead of orifice sizes on the order of 0.02 microns for Mott FCD's, orifices greater than 4 thousandths of an inch can be achieved with other forms of flow restriction. For reductions in operating points, the valves merely close further resulting in a lower flowrate with -no- loss of propellant. Due to large orifice diameters, these devices are not nearly as sensitive to ground handling problems or contamination issues. Two prospective Flight quality valves that might serve this purpose were tested in an attempt to fully characterize their performance and behavior, as well as limitations and requirements (Ref 1., Ref 2).

Valve Descriptions

Marrotta MFV

The MFV is a proportionally controlled solenoid type valve making use of magnetostrictive technology(Ref 3,4,5,6,7). It has a seprarate actuator and poppet design allowing for garaunteed positive sealing upon closure. The valve as tested at JPL has the following characteristics. It utilizes a 45 Ohm, 200 milli-henry coil consuming from 0.3 up to 10 Watts of power over the full range of inlet pressures and flowrates. The valve measures approximately 1.65" diameter by 2.5" long and weighs approximately 400 grams. The valve is a result of an SBIR/BMDO phase 2 program at Marrotta and is currently under evaluation at numerous locations. These characteristics are largely driven by the coil design which will be changed for future applications, so data presented here is applicable only to the valve as tested.

Moog PFCV

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. The (normally closed) valve includes a spring supported "floating" armature, which eliminates sliding fits and subsequent potential for contaminant generation. This configuration also reduces friction and hysteresis effects normally associated with sliding fit designs. These effects, if present, are known to be a source of "hunting" error when a valve is operated with a PID controller.

A plastic seal operates against a stainless steel nozzle to insure exceptional sealing characteristics. In operation, the armature is attracted to a fixed polepiece on application of control current. As the control current is increased, the attractive force on the armature acts against the spring pre-load, and any pressure forces, and opens the valve.

The valve as tested utilized a 75 Ohm, 200 millihenry coil consuming approximately 1 to 1.5 watts over the full range of inlet pressures and flowrates. It measured approximately 1 inch in diameter by 1.35 inches long and weighed approximately 135 grams.

The magnetic circuit has been designed to provide force in a more linear, proportional mode than is normally associated with solenoids of this type. This results in a somewhat less efficient circuit, with greater heating potential. This trade off of efficiency and linearity is well known to the industry. For example, the efficiency could be reduced further, resulting in a lower flow gain (flow/current) at the expense of higher operating temperatures, or a larger package. Nevertheless, the gain selected is well within the capability of modern controllers, both digital and analog.

The Moog PFCV is based on field qualified valve designs used in numerous applications. Indeed, this heritage allows a valve to be easily designed and configured to meet other operating fluids, pressures, and flow conditions.

Test Setup

A specially created feed system was designed and built as a testbed for potential valve candidates as well as special electric propulsion system testing. This feed system was comprised of two parallel control lines for two separate propellants to feed a hall type thruster (see Figure 2) . For each line, a separate branch for the cathode and one for the main flow extended from each gas source. In this manner, independent gas flowrates can be controlled simultaneously from each of two source gases into an engine. Valves to be tested can be placed in any of the six locations provided for this purpose. Each of these locations can be used with a multitude of feedback signals. For instance, operation of a valve in position 1 (as identified on the feed system schematic) allows for either low pressure regulated input or high pressure input directly from the gas source, with feedback coming directly from either the downstream flowmeters or pressure transducers to control its operation.

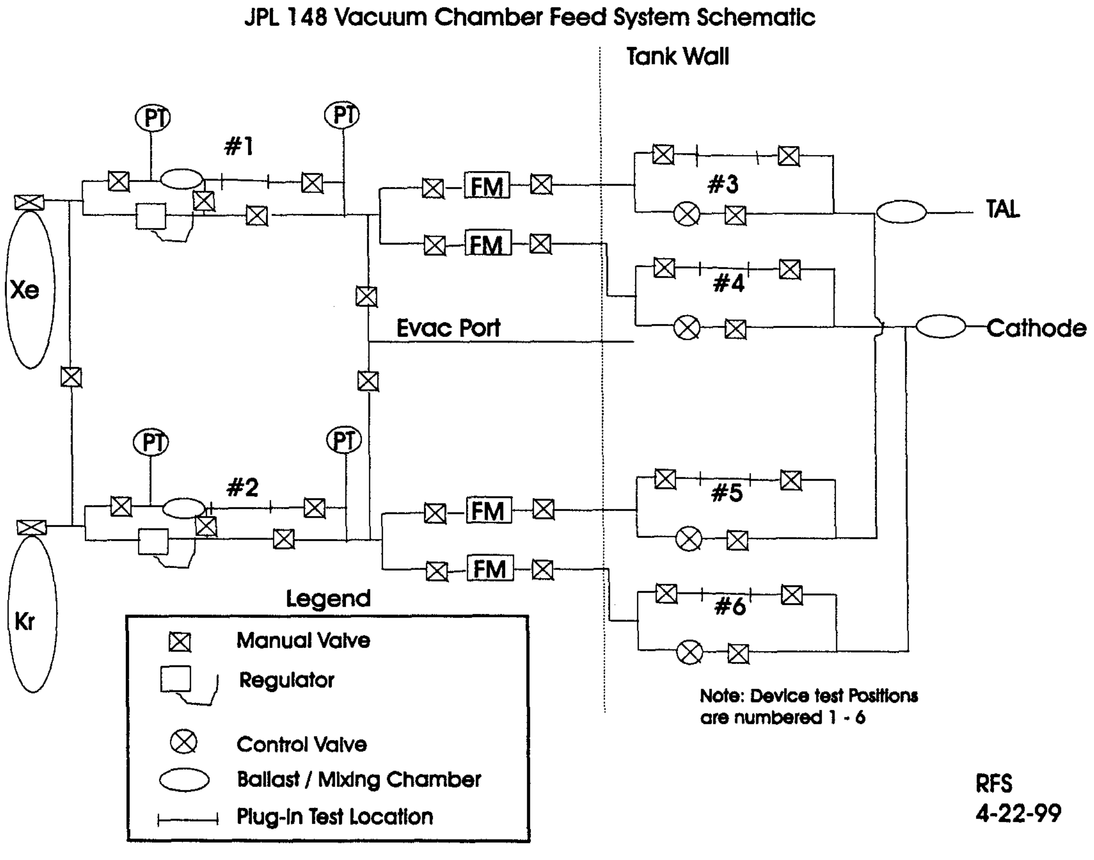

Figure 2. Specially Designed Feed System for System and Component Evaluation

In order to get worst case thermal responses for these valves, no clamping devices of any kind were used to mount the valves to the feed system base plates. the only conductive path available for the valves were the tubing connections. At the 4 locations within the chamber, a separate small feed system panel was installed an enclosed in a sheet metal enclosure which was then blanketed with MLI (see Figure 2). In this manner, in addition to the abscence of convective cooling for the valves, the thermal environment is carefully controlled and monitored. Three thermocouples were added to each valve tested. One was placed on the inlet tube, one on the valve body directly, and one placed on the valve outlet port. A separate signal selector / amplifier box was created at JPL to accept the input signals of all potential feedback sources (pressure transducers, flowmeters and discharge anode current shunt) and map them into a 0-10V range for input to the PID valve controller in use (see Figure 3). The pressure transducers and current shunt signals are 0-30mV signals and required a great deal of amplification. Additionally, the discharge of a thruster is characteristically noisy and to prevent this natural noise from artifically affecting a PID control system, a low pass filter was employed on the discharge current shunt signal path. This filter had selectable cutoff frequencies of 1khz, 100 hz and 20 hz.

Data acquisition during testing was performed using Opto22 A/D systems controlled via Labview. Control setpoints were set through Labview to provide 0-10V output signals to the PID controller. Valve applied voltage and current was monitored during testing through the A/D system, as well as valve temperatures, the amplified feedback signal that was input to the PID, as well as the setpoint voltage applied to the PID. All flowmeters and pressure transducers were monitored as well. Data was collected at a rate of 1/2 hz on all 64 channels.

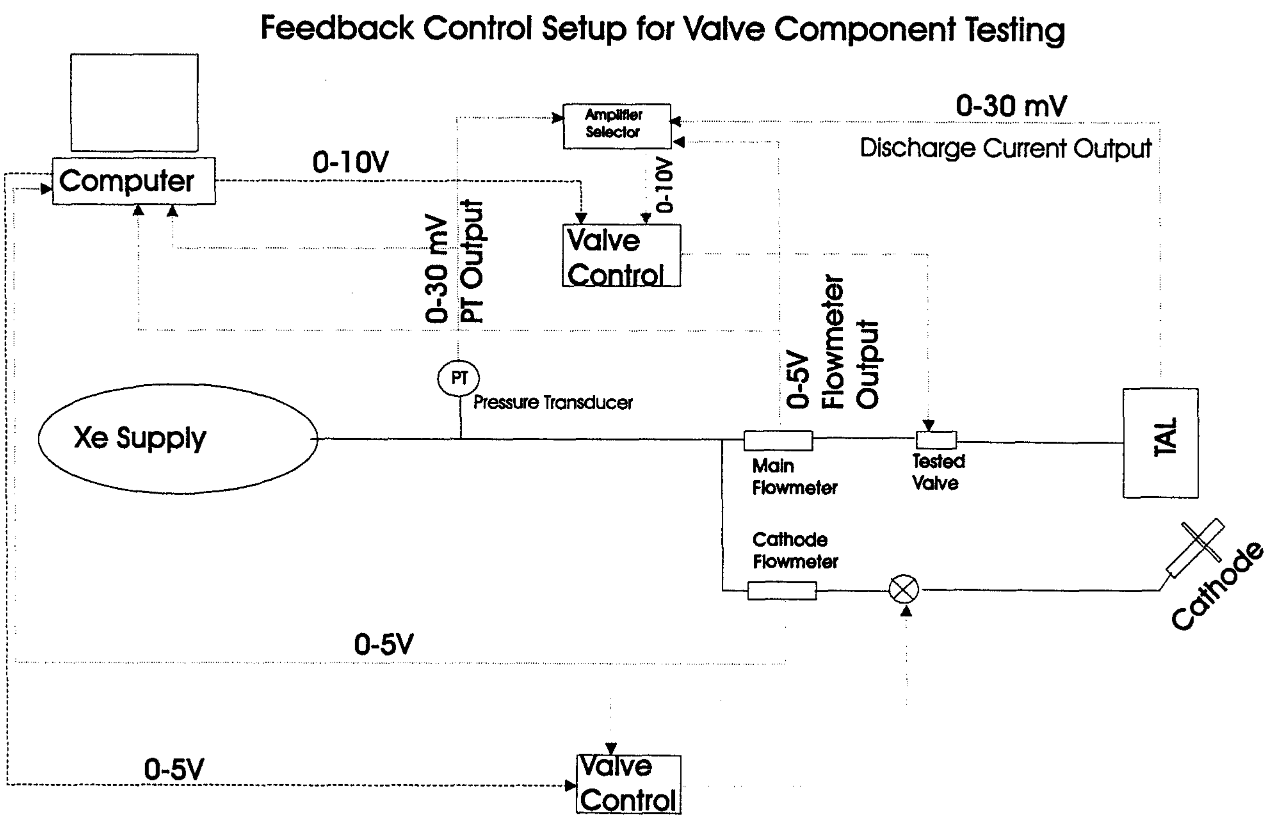

Figure 3. Feedback Signal Paths for Component Evaluation

Test Matrices

Overall, the general test approach for both valves followed the brief description given here. Due to a limited testing budget, the test sequence was intended to maximize the xenon throughput most effectively as the cost for high purity xenon can be prohibitive. Tests were performed at high inlet pressures first, followed by low inlet pressure testing and subsequently by open loop operation. This testing covered the ranges of 20 to 900 psia Xe and 20 to 1400 psia Kr, with flowrates from 1 sccm up to 300 sccm. Several different forms of feedback were tested.

Initially, testing was performed with high inlet pressure Xe. The appropriate gains were determined and system response to step changes was made. Once adequate control was established and demonstrated at high inlet pressures, switching to pressure feedback was performed to demonstrate operation as a regulator, one of the most likely methods of application in the immediate future.

The two valves were tested in sequential order. Following this regulator mode, testing was performed to identify what low inlet pressure limits might exist for the valves and to identify the End Of Life conditions were. Open loop testing was then performed in order to map out a valves general response to fixed current applications. This allowed appropriate starting points to be found for the thruster anode feedback testing to follow.

Thruster feedback testing was performed initally using flowmeter feedback to establish thruster operation. The amplifier output was matched between the flowmeter output signal and the amplified discharge current shunt signal in order to switch between feedback sources. This was performed and allowed for characterization of the system in this mode. Once this characterization was done and the appropriate gain settings were found for the PID control, the thruster was turned off and restarted in open loop mode several times to verify this form of operation.

The Moog PFCV was tested first and was subject

Table 1. Moog PFCV Test Matrix

Control Mode	Controller	Gas	Inlet-P range (psia)	Outlet-P range (psia)	Flowrate Range (sccm)	Valve Environment	Valve Location
Closed Loop-FM	MKS	Xe	900	-atm-	.75- 250	Atmosphere	#1
Closed Loop-Pr	MKS	Xe	880	26-28	12- 23	Atmosphere	#1
Closed Loop-FM	MKS	Xe	876-15	-atm-	112.8	Atmosphere	#1
Closed Loop-FM	MKS	Xe	25-15	-atm-	113	Atmosphere	#1
Closed Loop-FM	MKS	Xe	25	-atm-	70	Atmosphere	#1
Closed Loop-FM	MKS	Xe	22.5	-atm-	105	Atmosphere	#1
Closed Loop-FM	MKS	Xe	35.5	-atm-	26-110	Atmosphere	#3
Closed Loop-FM	MKS	Xe	35.5	<200 mT	1- 134	<200 mT	#3
Open Loop	MKS	Xe	35.5	<200 mT	19- 95	<200 mT	#3
Closed Loop-FM	MKS	Xe	15- 59	<200 mT	23- 163	<200 mT	#3
Closed Loop-An	MKS	Xe	58	thruster	68-80	$<5X10^{-5}$ Torr	#3
OpenLoop>Anode	MKS	Xe	58	thruster	68-80	$<5X10^{-5}$ Torr	#3
Closed Loop-An	Moog	Xe	58	thruster	68-80	$<5X10^{-5}$ Torr	#3
Open Loop	Moog	Xe	25.5- 75	<200 mT	1.5- 170	$<5X10^{-5}$ Torr	#3
Closed Loop-An	Moog	Xe	58	thruster	54-95	$<5X10^{-5}$ Torr	#3
Closed Loop-FM	MKS	Kr	1385	-atm-	13- 300	Atmosphere	#2
Closed Loop-FM	MKS	Kr	40	-atm-	26- 160	Atmosphere	#5
Closed Loop-FM	MKS	Kr	25- 75	<200 mT	6- 305	<200 mT	#5
Closed Loop-FM	MKS	Kr	20- 55	<200 mT	27- 213	<200 mT	#5

Note: FM = Flowmeter Feedback, An = Anode Current Feedback, Pr = Pressure Transducer Feedback, -atm- = atmosphere, mT =

to the test matrix presented in Table 1. Tests were performed approximately in the order they appear in the matrix. Initial tests on the PFCV verified that the valve could be controlled adequately with both flowmeter and pressure transducer feedback. All initial tests were performed with the valve in ambient conditions with natural convective cooling. Control was through the MKS Type 250-D valve controller normally used for lab flowrate control solenoid valves. This testing was funded by Rocketdyne in conjunction with their Hall thruster subsystem development testing. It was supported by members of Moog's Space Products Division who loaned Rocketdyne and JPL the valve and a specially made breadboard PID controller they produced for PID valve testing.

The Marrotta MFV was tested a few weeks after the end of the PFCV tests were completed. Testing was performed per the test matrix listed in Table 2. This testing was funded by the DS4/CNSR mission in partnership with Rocketdyne for purposes of valve evaluation. The valve was provided by Rocketdyne. Data from tests on both valves were then shared by both organizations. Test support from Marrotta included members of the MFV development program who participated on-site for initial tests with the valve.

High Pressure Testing

Both valves were initially subject to high inlet pressure Xe while the bottle pressures were still relatively high. Both valves were tested with inlet pressures greater than 900 psia and were vented to atmosphere while flowing. In this manner, they were tested from 2 sccm up to 300 sccm. Both valves were able to nicely control the flowrates within this regime once the proper PID gain settings were determined. An example of this is presented in Figure 4 above showing the flowrate response to step changes in the setpoint at 900

Table 2. Marrotta MFV Test Matrix

Control Mode	Controller	Gas	Inlet-P range (psia)	Outlet-P range (psia)	Flowrate range (sccm)	Valve Environment	Valve Location
Closed Loop-FM	Marotta	Xe	970	atm	2 - 300	ambient	#1
Closed Loop-FM	MKS	Xe	965	atm	40 - 110	ambient	#1
Open Loop	MKS	Xe	965	atm	60 - 200	ambient	#1
Closed Loop-FM	MKS	Xe	950	atm	40 - 115	ambient	#1
Closed Loop-FM	Marotta	Xe	18 - 47	vacuum	10 - 150	vacuum	#3
Closed Loop-FM	MKS	Xe	20 - 70	vacuum	40 - 200	vacuum	#3
Open Loop	MKS	Xe	56	vacuum	2 - 125	vacuum	#3
Closed Loop-An	Marotta	Xe	56	thruster	60 - 90	vacuum	#3
Closed Loop-An	Marotta	Xe	20-22	thruster	60 - 90	vacuum	#3
Closed Loop-FM	Marotta	Xe	25 - 48	vacuum	40 - 270	vacuum	#3
Closed Loop-FM	Marotta	Kr	1250	atm	2 - 300	ambient	#2
Closed Loop-FM	Marotta	Kr	1250-0	atm	116	ambient	#2
Closed Loop-FM	Marotta	Kr	20 - 35	atm	55 - 173	ambient	#5
Closed Loop-FM	Marotta	Kr	21	atm	20 - 180	ambient	#5
Open Loop	Marotta	Kr	21	atm	2 - 131	ambient	#5
Open Loop	Marotta	Kr	21	vacuum	53 - 164	vacuum	#5
Open Loop	Marotta	Kr	21 -60	vacuum	2 - 365	vacuum	#5
Closed Loop-An	Marotta	Kr	60	thruster	6 - 150	vacuum	#5

Note: FM = Flowmeter Feedback, An = Anode Current Feedback, Pr = Pressure Transducer Feedback, -atm- = atmosphere, mT = milliTorr

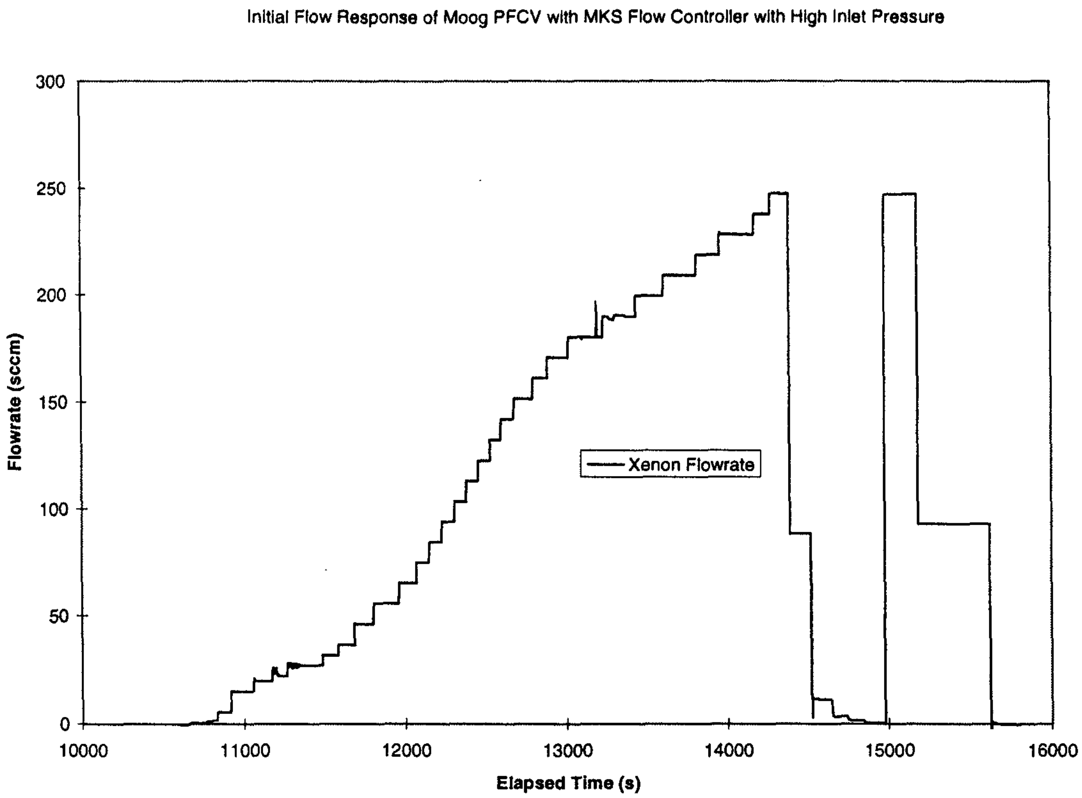

Figure 4. Flowrate Response Achieved with Step Changes in Setpoint at 900 PSIA Inlet Pressure

psia inlet pressure. An expanded view is presented in Figure 5 providing more detail in the overshoot and settling times achieved. Later tests were repeated on both valves with high pressure Krypton. Flow with Krypton was performed at pressures in excess of 1400 psia. Flowrates were controllable from 1 sccm to 300 sccm similar to the performance obtained with Xe. The higher the inlet pressure to the valves however, the more sensitive their performance becomes to extremely minute changes in gain settings. It was noted that higher currents were required to initiate flow with higher inlet pressures. It was also identified that volumetric flowrate of Kr was higher than for Xe (30 to 100% more) at the same applied currents. Additionally, Kr appears to provide a somewhat better convective cooling media than Xe helping to reduce valve temperatures slightly at comparable power levels. Kr has a specific heat 50% higher than that of Xe.

Two different MFV valves were tested with high inlet pressures as a diagnostic test for a noise problem encountered. It was identified that the initiation current level was different enough between the two identical valves that flow could not be established with high inlet pressures with the MKS controller on the second valve. The MKS controller has a current limit at 0.151A. The MFV is designed with a separation between the actuator and the poppet to ensure good sealing properties. Variations in the gap distance result in slight variations in current required for flow onset and current required for a given flowrate, as evidenced by this finding.

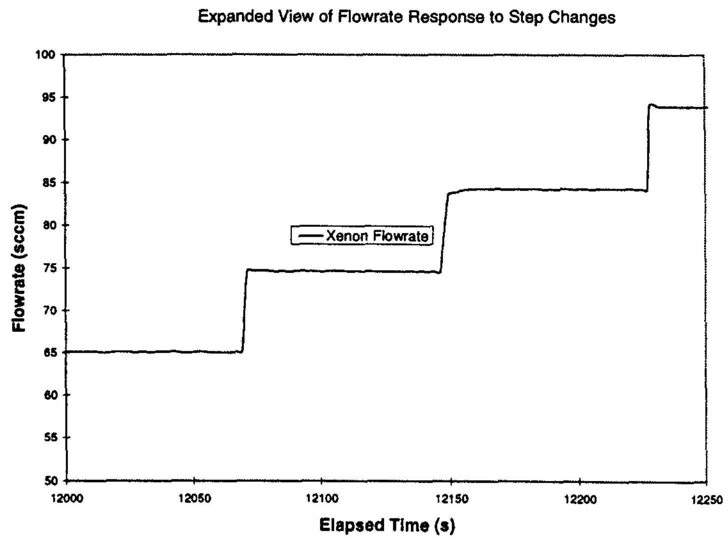

Figure 5. Expanded View of High Pressure Step Changes in Flow

Low Pressure Testing

Low pressure testing of the valves showed extremely fine controllability of flowrate. This is a result of an effctive gain decrease (sccm / A) allowing finer control of the flowrate over the current range useable by the valves. The primary item of interest in low inlet pressure testing is the behavior of the valves under End Of Life (EOL) conditions. Toward the end of the mission when inlet pressures to the valves are low (tank depleted) what are the limiting conditions for nominal operation with the valve? As it happens, temperature limitations are the driving factor in determining the EOL conditions for the valves. In order to provide the necessary flowrate with lower inlet pressures, the valves must open progressively farther to accomodate the lower density gas. This requires increased power applied to the valve in order to open the poppet until it is almost completely open.

EOL conditions for this series of tests were defined as 110 sccm of Xe flow which is the maximum flowrate necessary for a Hall thruster operating at 3.2 kW. Maximum allowable temperatures on the valves was set at 100 deg C. In order to identify what the minimum inlet pressure was that was required to obtain this flowrate, valve inlet pressures were progressively dropped until steady state temperatures no longer remained below 100 deg C.

For the Moog valve operating in a partial vacuum environment (100 to 200 mTorr), the valve required 36 psia in order to control the flowrate at 110 sccm at a steady state temperature of about 100 deg C. The Marrotta valve under the same conditions required 21.5 psia.

At 100 to 200 mTorr, some amount of convective cooling is still present under operating conditions. This cooling could provide temperatures up to 30% lower than the equivalent temperatures operating at hard vacuum. This became evident during later testing of the valves at high vacuum with and without thruster operation. In order to operate the engine at 3.2kW, inlet pressure to the PFCV had to be increased to 58 psia in order to maintain temperatures under the desired limit. During an extended set of low pressure testing performed in June of this year, it was found that the PFCV runs at almost all conditions at about 98 degC. When the valve is operating in a steady state mode, current is constantly applied to the valve to maintain a flowrate. The PFCV starts flowing at approximately 0.121A at higher inlet pressures and 0.117A at lower inlet pressures. With high pressure applied to the valve, 0-300 sccm flowrates are achieved with a delta of only 1 mA! At lower inlet pressures, from zero to maximum flow is attained with a maximum delta of 15 mA. In either case, very little change in applied power (less than 0.1W) over the entire range of operating conditions occurs. As a result, very little change in operating temperatures is evident as well. The MFV on the other hand has a wider current delta over its operating regime and thus is somewhat more sensitive to operating conditions for its steady state temperature. At EOL conditions, the MFV dissipates approximately 2.0 watts compared to the 1.5 watts consumed by the PFCV. However, it demonstrated steady state operation with the thruster at 3.2kW at 22 psia. Increasing this pressure a few psia results in almost 1/2 watt less operating power and a measurable drop in operating temperature.

Open Loop Testing

For a Hall thruster system running with discharge current feedback for flow control, no feedback is available when the engine is off. Since there is no feedback signal during startup, some alternate method must be employed to establish discharge within the engine before anode feedback is possible. Previous tests with the MFV in a current feedback mode of operation were initiated by pulsing the valve to let some amount of Xe into the engine. Engine power was applied to the thruster at some time later and if the discharge could be established for a long enough period, the controller would pick up and start regulating the flow. This method has several problems, including both timing issues and discharge current overshoot upon startup. High current pulsations in the thruster during startup poses potential hazards to the hardware and could even pull down spacecraft bus voltages temporarily if startup power levels are high enough.

A method investigated at JPL to alleviate this problem involves open loop operation of the valve for startup. As opposed to closed loop

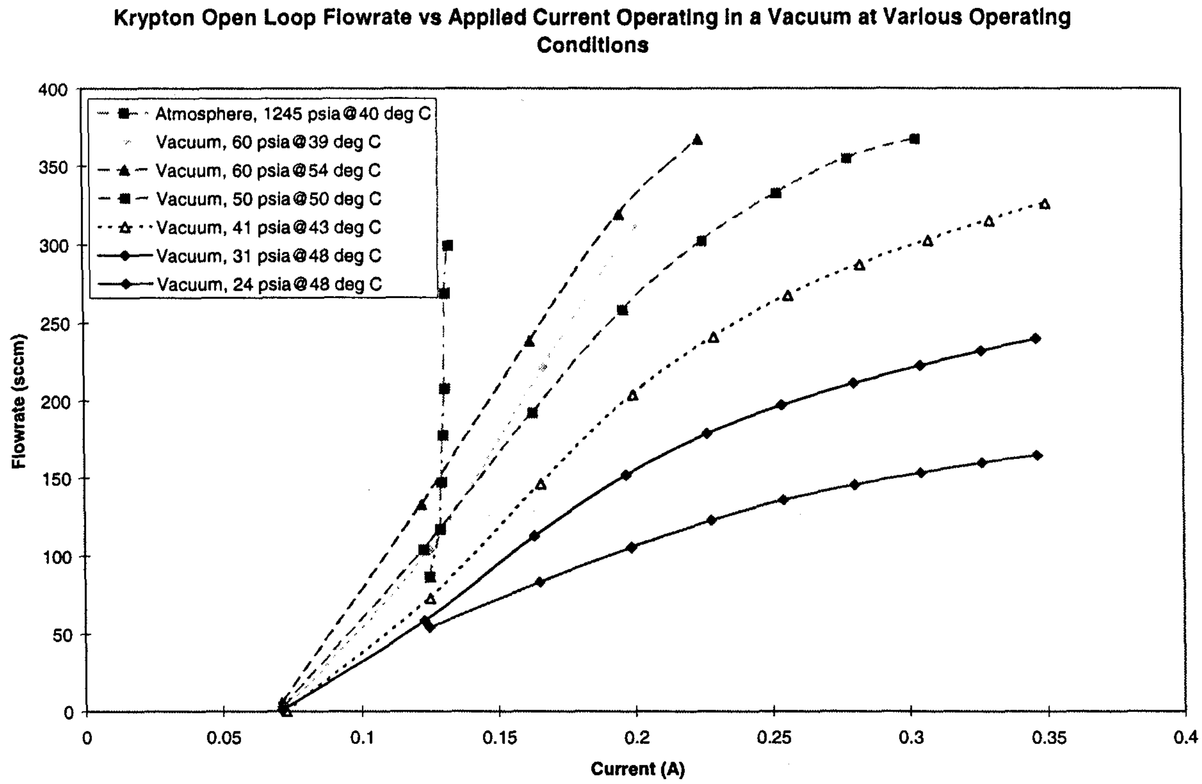

Figure 6. Flowrate Profiles Obtained in Open Loop Operation at Various Conditions

operation where a controller automatically adjusts the output current to the valve to maintain a fixed response level, open loop operation is independent of feedback and is essentially a constant current mode of operation. If the integration and derivation constants can be turned off temporarily, the proportional aspect of a PID controller will essentially act as a constant current output proportional to the setpoint voltage.

By applying some amount of current to the valve, a steady flowrate of some amount can be obtained. This flowrate is a function of valve operating temperature, gas temperature and inlet pressure. The benefit is that a smooth, steady flowrate can be established in the thruster discharge without pulsation or overshoot problems and provides a benign starting method. Once discharge is established, the integration and derivation constants can be turned back on and PID control will resume. Starting at a power level lower than the desired operating point (ie at a slightly lower flowrate) allows the PID to then integrate smoothly up to the desired power level after discharge has been initiated.

Both valves were tested in this manner with both Xe and Kr in order to map out their performance versus current at various inlet pressures and operating temperatures. As anticipated, temperature plays a big role in the resulting flowrate at a given current level. Also, increased inlet pressures require higher current levels before the onset of flow occurs. Profiles such as the one presented here as Figure 6 were obtianed in this manner. These valve mappings were used to identify the proper starting current levels to apply to each valve prior to testing them in open loop mode with the thruster. Due to variations from valve to valve in all valves, open loop operations on spacecraft would require that each valve be similarly pretested prior to integration into a flight system.

One item that was discovered while performing the open loop tests was a small amount of hysterisis apparent in the MFV (Figure 7). While temperature does play a role in the flow

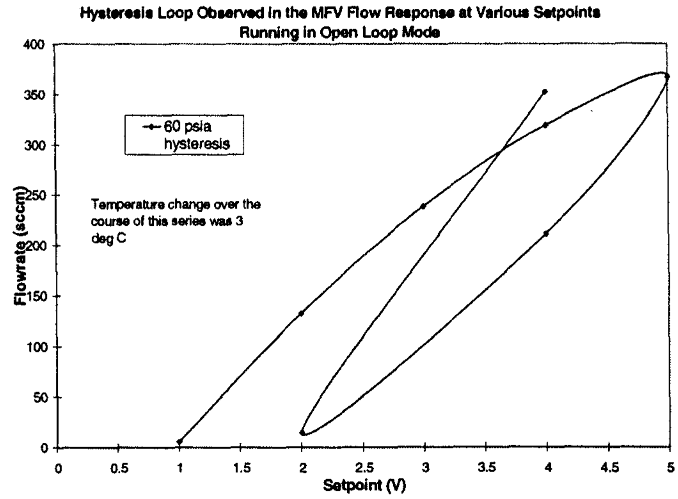

Figure 7. Hysterisis Loop Obtained During Open Loop Testing

performance of the valves, it was not enough to account for the apparent change in flowrate versus current that was obtained for the MFV. This curve (Figure 7) was obtained during this testing. This effect may have also been present in the PFCV, but testing in open loop mode early in the test program was not as thorough as that performed later on the MFV where it became apparent. This hysteresis will need to be thoroughly evaluated if open loop performance is desired in order to establish what the true deviations might be. At no time during spacecraft operation would open loop operation ever require an initially higher current followed by a lower one resulting in some of the hysteresis shown. Flow would always be established from a closed position. The variation in this operation would need to be fully enveloped.

Anode Feedback Testing

By using the discharge current of the thruster as a feedback signal, the PID controller can adjust the flowrate as necessary to maintian a fixed power level during operation. As a thruster heats up, the overall performance changes and flowrate must go up to maintain the same operating power level. Running in anode feedback mode allows this thermal heat up to be performed opitimally without wasted propellant or reduction in performance. Additionally, a change of thruster power level can be easily made simply by setting a new desired operating power and letting the PID controller integrate to the new point, smoothly changing the flowrate and hence curent level. This mode of operation is not as clear cut with an Ion engine and different methods of feedback must be used to control the flow.

Initial tests of anode feedback operation used standard flowmeter feedback to start the thruster and bring it up to thermal equilibrium. The gain of the anode feedback signal was then adjusted until the resulting output was identical to that of the flowmeter. At that time, a switch was flipped putting the PID controller into anode feedback mode. This was done in this manner initially to determine the proper operating gains necessary for this mode of operation without introducing thermal problems, startup problems or other potential problems into the equation.

Once operation in this manner was tested for a length of time, setpoint changes were made, operating condition changes were made and overall operation in this manner was sufficiently characterized, open loop starting was tested. The thruster would be turned off, controller adjustments made and then flow established with a fixed constant current. Discharge was re-established and PID control was allowed to take over flow control operation (see Figure 8). While the proper currents necessary for thruster starting differed between valves, both valves and several controllers were tested in this manner and proved to be very successful. Thruster startups were very benign and switch over to feedback control did not adversely disturb operation. Multiple restarts we made in this manner and the technique was considered very reliable by all those involved.

An interesting benefit that was exploited by operating in anode feedback mode was the ability to mix propellants in an engine at a fixed power level. By setting the discharge to operate at a fixed power setting, the PID controller would adjust as necessary the Xenon flowrate (or Krypton) required to maintain the power level. If some amount of Krypton were to be introduced into the engine in addition to the Xe, the PID controller would reduce the Xe flowrate as necessary to maintian the same power level (see Figure 9). This technique was used to map out performance levels with mixtures of Kr and Xe from 0 to 100% at power levels from 1.6 to 3.2 kW.

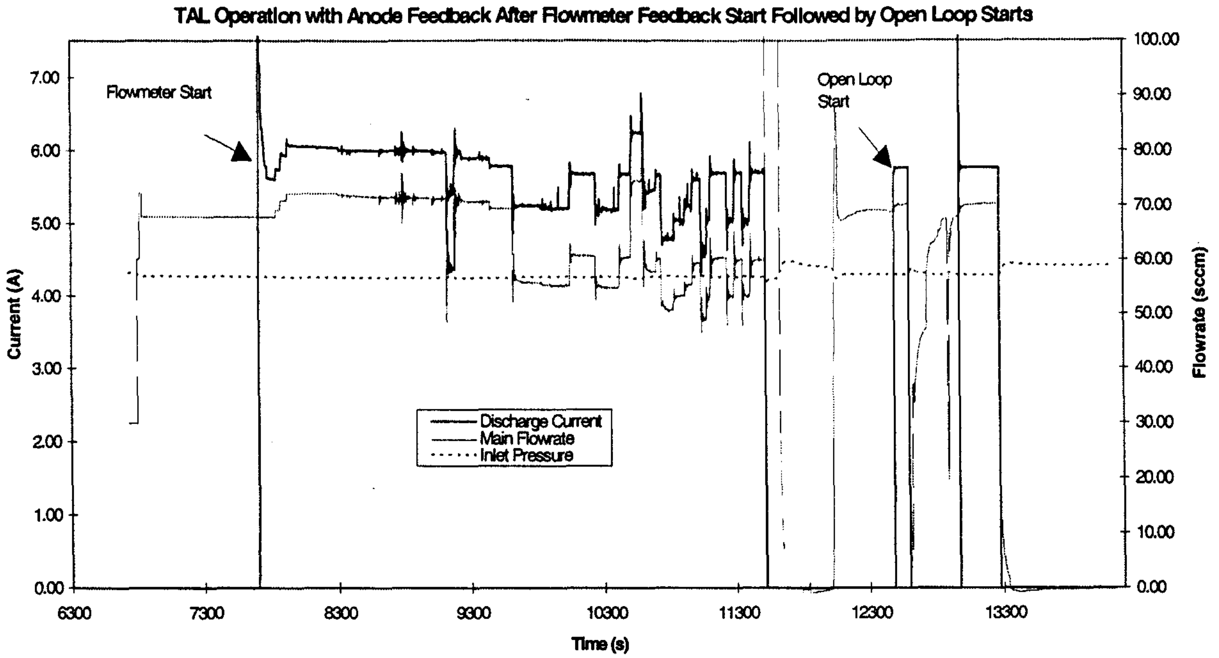

Figure 8. Thruster Operation in Anode Feedback Mode and Open Loop Start

To determine the long term stability of anode feedback operation, the thruster was operated for 400 hours in this manner. A 500 hour test was performed on the Rocketdyne hall thruster subsystem utilizing one of the proportional flow control valves, a newly developed cathode and the Boeing Module M PPU in conjunction with the TAL-110. The first 100 hours of the test were performed in regular flowmeter feedback mode

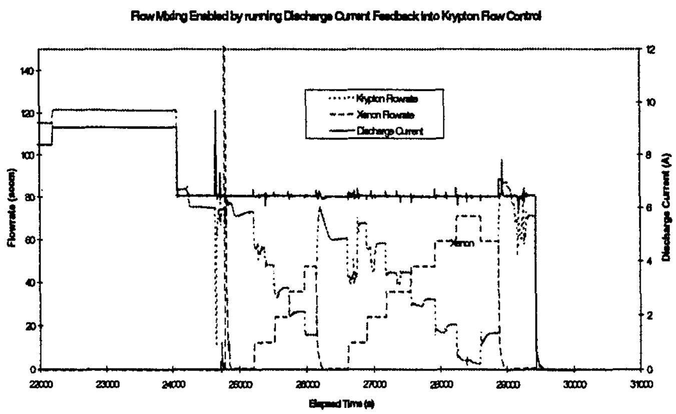

Figure 9. Gaseous Propellant Mixing Using Discharge Feedback

to work out all of the bugs in the continous testing mode. After smooth operation was established without any facility or hardware concerns, feedback to the PID was switched to the anode. A zero offset was introduced in the flowmeter and PID controller in order to provide a non-zero feedback to the PID so that in the event that thruster operation went out at any time, the valve would not go wide open. Additionally, the gain of the anode feedback signal was reduced. The result during a thruster outage would be a slightly positive value. During the shutdown, Labview will provide a zero setpoint to the PID. Since the feedback, a positive value, will exceed the zero setpoint, the PID will remove power from the valve in order to achieve the desired setpoint, hence stop flowing.

Over 400 hours were logged on the subsystem in this manner. During this time, pressure input to the valve was regulated at about 60 psia. Operation was maintianed at a constant 1.6kW. No problems were observed with prolonged operation this manner.

Results

Testing with both valves demonstrated good performance from 1 to greater than 200 sccm at inlet pressures from 20 to over 1200 psia. A good deal of effort was required to identify the appropriate gain settings for each valve in each of the varied operating modes. Marrotta used a transfer function approach and using a model of their valve and models of the system being tested were able to generally predict the gain values that were somewhat close to the necessary values for stable operation. Unfortunately, their electronics were hard wired so that every change of gains in the controller required disassembly of the controller and the removal and installation of new capacitor and resistors. The Moog approach was to build a special breadboard PID controller with variable pots on each of the 3 aspects of the PID broken out to the front control panel. By observing the behaviour of the system, changing the appropriate gain value can be made qualitatively.

Due to the fact that it was desirable to test the valves in numerous operating conditions, in numerous locations with different feedback signals, it was intially very troublesome to use the Marrotta electronics as they were designed. Fortunately, the designer of their electronics was present and able to similarly break out the resistors and capacitors necessary to change the system gains and fed them into a pair of R-C decade boxes making performance changes on the fly a possibility.

Valve testing was not intended to highlight aspects of the PID controller so it was desirable to perform tests on the valves with the same controller in order to identify just valve characteristic behavior. It was relatively obvious that the valves could operate with any form of constant current power supply driven in a PID fashion. To achieve this, much of the testing on the two valves was performed with an MKS lab controller.

One of the primary items of note was that both valves tended to run very hot. Steady state temperatures of about 100 deg C were commonplace. As this temperature is a skin temperature, it is likely that temperatures within the coil and near the poppet and seat are significantly higher. A good thermal model of these valves should probably be attempted if it is anticipated that operation in these conditions is a possibility. Long term operation at such elevated temperatures may have deterimental effects on some parts of the valves such as seat materials, coil insulation, potting, etc.

Moog has suggested that operating temperatures up to 150 degC may be acceptable for the PFCV. In addition, both vendors have identified that operating temperature concerns can be alleviated with changes in coil designs. These changes are often accompanied by larger volumes, masses, etc. however and trade-offs must be made for a given mission to identify which aspect these characteristics is more important.

Both valves sealed very well at shutoff and no leakage was observed at any time at inlet pressures up to 1400 psia. Manufacturing data shows similar performance for both valves in excess of 3000 psia. End of Life (EOL) conditions were tested with both valves as well. One item of interest is what the useable inlets pressures are that will provide sufficient flow at EOL. Since this testing was largely driven by Hall thruster applications, maximum flowrate requirements of 110 sccm were used. Inlet pressure to the valves were reduced until they could no longer safely maintain 110 sccm. Both valves could easily provide 110 sccm with very low inlet pressures, however valve heating became substantial and would have easily exceeded the 100 deg C limit imposed on the valves. Hence, the true determining factor for EOL safe operation was dictated by steady state operation at 100 deg C at 110 sccm. It was found that the PFCV required 36 psia Xe to achieve this condition. The MFV required 22 psia.

Summary

The primary difference between the valves was in the applied current values and full stroke movement. It was found that the PFCV would operate between 0.115 to about 0.145 A for zero to full stroke. This implies that at low inlet pressures, the effective gain of the valve was 300sccm/0.03A $\approx$ 10,000 sccm/A. For the MFV at low pressures the equivalent gain was about 1000 sccm/A. This results in finer controllability for the MFV and a slight reduction in noise sensitivity. For high inlet pressures, the effective gain can be as high as 300,000 sccm/A for the PFCV and 20,000 for the MFV. This puts large demands on the PID controller to not only be able to carefully control current levels at the micro to nano-ampere range, but to also be able to change PID gains throughout the course of the mission in order to maintain reasonable performance characteristics of the overall PID loop. This may be accomplished through a digital approach to PID logic controlling a current limiting power supply. If the entire function of the PID control were performed via software and not through analog circuitry as is normally done, it would provide substantial flexibility in the control of these valves over the course of a mission. This type of approach is currently being investigated by JPL in conjunction with Spectrum Astro for potential application on the CNSR mission.

Both of the valves investigated here have proven to be adequate for flow control over a wide range of operating conditions. Both valves have also been subjected to some preliminary qualification testing, or in the case of the PFCV, due to its close similarity to the solenoid valves flown on DS1, qual by similarity may be sufficient. Either valve could readily be incorporated into a flight feed system. Each valve has a few pros and cons associated with its design that might make them more appropriate for a given mission profile than the other. In most respects however, both valves are very similar in their reliability and tight sealing capabilities.

Reference

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