Qualification of an Advanced Xenon Flow Control Module

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Abstract: VACCO has built and qualified a Xenon Flow Control Module (XFCM) using ChEMS™ under a NASA In-Space Propulsion advanced development contract. The resulting XFCM is a two-channel electronic flow controller capable of precise control of xenon from 0 to 80 sccm at any inlet pressure from 10 to 3,000 psia. This single assembly contains a 10 micron System Filter, a High Pressure / Temperature Transducer, two High Pressure Latch Valves, two Proportional Flow Control Valves, two Low Pressure / Temperature Transducers and two Flow Resistors. The entire assembly has a mass less than 1.3 kg and occupies a footprint less than 21 square inches. This paper will summarize the capabilities of this technology as verified through extensive qualification testing. Application to both single-string and distributed feed system architectures will be presented. Lessons learned will be reviewed and the status of future work will be delineated.

Nomenclature

ChEMS™	= *Chemically Etched Micro Systems*
GHe	= *Gaseous Helium*
G_{rms}	= *Root Mean Square Acceleration*
GUI	= *Graphic User Interface*
HiVHAC	= *High Voltage Hall Accelerator*
Kg	= *Kilograms*
MiLV	= *Micro Latch Valve*
MIPS	= *Mechanically Induced Pyrotechnic Shock*
NASA	= *National Aeronautics and Space Administration*
PCV	= *Proportional Control Valve*
PFCV	= *Proportional Flow Control Valve*
PID	= *Proportional, Integral, Differential constants*
PPU	= *Power Processing Unit*
psia	= *Pressure per Square Inch*
scch	= *Standard cubic centimeters per hour*
sccm	= *Standard cubic centimeters per minute*
sccs	= *Standard cubic centimeters per second*
SFCM	= *Smart Flow Control Module*
SN	= *Serial Number*
TRL	= *Technology Readiness Level*
XFCM	= *Xenon Flow Control Module*

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I. Introduction

VACCO is an industry leader in propulsion fluid controls for satellites, launch vehicles and interplanetary spacecraft. For the past several years we have been developing highly integrated, modular feed systems for electric propulsion based on our Chemically Etched Micro Systems (ChEMS™) technology. On 20 May 2010 the In-Space Propulsion Technology Project competitively selected VACCO under advanced development contract to application-engineer our existing ChEMS™ technology to produce and qualify a Xenon Flow Control Module that includes all the functional components of a xenon feed system suitable for electric propulsion. The resulting XFCM met all of specified requirements while remaining substantially less massive, less costly and more compact than conventional distributed feed systems based on discrete components that require far more power to operate. The fully qualified XFCN SN 001 was delivered to NASA Glenn Research Center on 7 June 2012 where it is currently undergoing hot-fire testing with the HiVHAC thruster. Based on the Qualification Matrix shown in Table 1 , the technology readiness of the XFCM is TRL-6.

Specification	Metric	Compliance	Verification Method
Mass	≤ 1.3 kg	Yes	By Inspection
Flow rate	3 sccm to 80 sccm	Yes	Qualified by Test
Flow Control Accuracy	≤ 3% End-of-life uncertainty of flow	Yes	Qualified by Test
Footprint	≤ 120 cm^2	Yes	By Inspection
Power Consumption	< 1 watt Steady state	Yes	Qualified by Test
Vibration Environment	Frequency (Hz) — G^2/Hz 20 — 0.096 50 — 0.6 500 — 0.6 2,000 — 0.04 1 minute/axis for Acceptance 3 minutes/axis for Qualification	Yes	Qualified by Test
Shock Environment	Frequency (Hz) — G's 100 — 100 1,000 — 2,000 10,000 — 2,000	Yes	Qualified by Test
Thermal Environment	+12ºC to +70ºC Operational +2ºC to +80ºC Qualification	Yes	Qualified by Test
Operational Cycle Life	13,000 Cycles >10,000 Cycles at 3000 psia	Yes	Qualified by Test
Maximum Inlet Pressure	3,000 psia (4,500 psia Proof, 7,500 psia Burst)	Yes	Qualified by Test
Minimum Inlet Pressure	≤ 10 psia	Yes	Qualified by Test
Radiation Environment	100,000 Rad Total Dose	Yes	To be verified by Customer
Electronics Parts Class	S Level	Yes	By Inspection

Table 1. XFCM Qualification Status Matrix

The ChEMS™ technology is extremely flexible and can be optimized for a variety of propulsion system architectures and electric thruster types. Over the past several years a variety of functional components have developed for use in these modules including filters, pressure transducers, temperature sensors, normally-closed valves, latching valves and proportional valves.

The XFCM is a highly integrated feed system that accepts unregulated xenon directly from storage tanks and outputs precision, throttleable flow through two independent channels. Adding a third output channel is a straightforward incremental extrapolation of the qualified design. An all-welded manifold provides the structural backbone of the module while eliminating the need for tubing connections. All the functional components are EB welded to the inside face of the manifold while the interface tubes are welded to outer face. A cover acts as a protective environmental enclosure for the electrical components. Mounting flanges machined into the cover can be customized without altering the manifold or its functional components. Interface with the spacecraft avionics and power systems is facilitated by a single high-density electrical connector.

Figure 1. XFCM SN 001

The XFCM design is optimized for a single string propulsion system architecture where each Hall Effect Thruster has an independent feed system that draws propellant from common storage tanks. In this context the XFCM is the entire feed system for each thruster providing tank isolation, propellant gauging, and precision, throttleable xenon flow to the anode and cathode independently. If the thruster only requires a single flow channel, the XFCM can control two thrusters independently. If desired, the flow resistors can be removed through the outlet tubes converting the XFCM into a dual channel electronic pressure regulator.

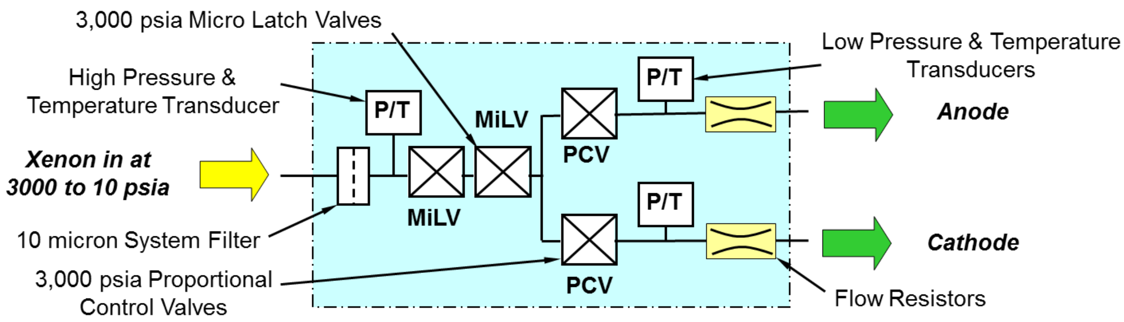

Figure 2. XFCM Functional Schematic

To protect against contamination, unregulated xenon enters the XFCM through a 10 micron (absolute) etched disk filter. The incoming xenon then flows past a 3,000 psia Pressure & Temperature Transducer before entering two 3,000 psia Micro Latch Valve arranged in series. The flow then splits into two flow control channels. Each channel has a Proportional Control Valve, 100 psia Pressure & Temperature Transducer and Flow Resistor in series. When closed, the internal leakage performance of the PCVs seal against internal leakage as well as the MiLVs. For this reason the XFCM provides three independent interrupts against overboard leakage of xenon from the storage tanks.

II. XFCM Qualification

After passing a full set of acceptance tests the XFCM was subjected to a series of qualification tests summarized in Table 2 below.

Test No.	Test Description	Test Result
1	Examination of Product	Pass
2	Proof Pressure Test	Pass
3	Pre-Qualification Transducer Calibration Check	Pass
4	Vibration Test	Pass
5	Shock Test	Pass
6	Post Vibration and Shock Functional Test	Pass
7	Life Cycle Test	Pass
8	Post Life Cycle Functional Test	Pass
9	Thermal Vacuum/Thermal Cycle Test	Pass
10	Post Thermal Vacuum/Thermal Cycle Functional Test	Pass
11	External Leakage	Pass

Table 2. XFCM Qualification Test Program Outline

Except as noted, all testing was conducted in sequence at VACCO's facility in South El Monte under the surveillance of our Quality Engineering department.

A. Examination of Product

The XFCM was examined to verify compliance with all assembly requirements and interface drawing dimensional requirements. The XFCM was found to be compliant with all assembly and dimensional requirements. The actual mass was 1.234 kg, substantially less than the 1.3 kg requirement.

B. Proof Pressure Test

The XFCM was subjected to a proof pressure test to verify structural integrity of the assembly. The proof pressure test was divided into two parts.

The first test was conducted on XFCM cavities that are exposed to high pressure. These cavities include the inlet port with the inlet filter assembly, MiLVs and all manifold passages leading up to the inlets of PCVs. High pressure proof test was conducted with MiLVs open and PCVs closed. Outlet ports were not capped to prevent the possibility of damage to the low pressure transducers in the event of PCV leakage. 4,500 psig GHe was applied to the inlet port and maintained for six minutes. After a total of three high pressure cycles there was no evidence of deformation or functional defects.

The second test was conducted on all XFCM cavities including those normally exposed only to 50 psig. The low pressure proof test was conducted with all valves open and outlet ports capped. A pressure of 75 psig was applied to the inlet port and maintained for six minutes. After a total of three low pressure cycles there was no evidence of deformation or functional defects.

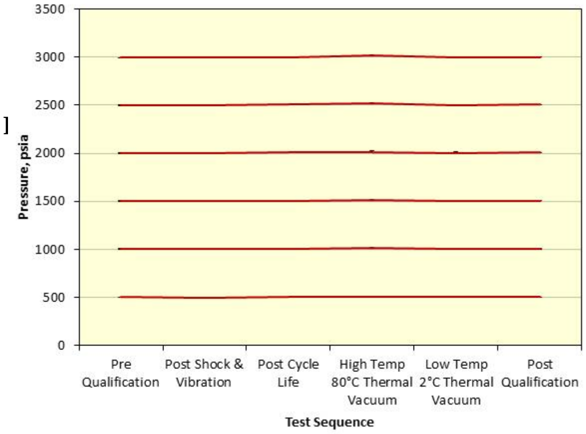

Figure 4. High Pressure Transducer

C. Pre-Qualification Transducer Calibration Check

Accuracy of the high and low pressure transducers was checked by applying a known pressure to the inlet port and measuring their voltage output and converting the output to pressure using a linear equation. High pressure transducer accuracy was verified against a calibration transducer in incremental steps of 500 psi increasing from 0 to 3,000 psia then descending from 3,000 to 0 psia. Low pressure transducer accuracy was similarly verified in incremental steps of 10 psi increasing from 0 to 50 psia then descending from 50 to 0 psia. At each step the output of the transducer was measured and recorded.

The transducer calibration check was repeated at various milestones throughout qualification testing to verify continued accuracy. A small nonlinearity in the low pressure transducer output was observed at elevated temperatures. The consistency and repeatability of output allows for effective non-linear compensation. The results of the calibration checks for the high pressure and low pressure transducers conducted throughout qualification testing were recorded and plotted. The resulting plots are shown in Figures 3, 4 and 5.

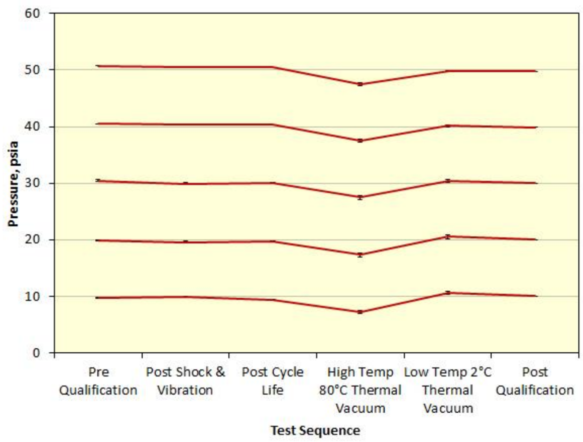

Figure 4. Low Pressure Transducer #1

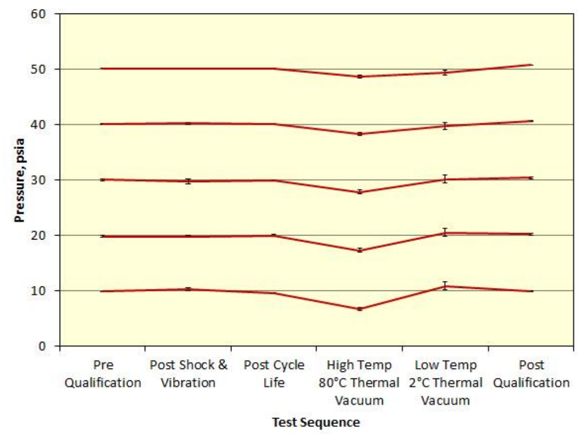

Figure 5. Low Pressure Transducer #2

D. Vibration Test

The XFCM was subjected to a vibration testing conducted at a Wyle Laboratories facility located in El Segundo, CA.

Random vibration testing levels shown in Table 3 were performed on each of 3 mutually orthogonal axes as defined in Figure 6. Random vibration exposure was maintained for 3 minutes for each axis. Overall G_{rms} for each axis was 22.59 G_{rms}. Prior to random vibration exposure a 0.5 g, 10 to 2000 Hz resonant frequency search was conducted in each axis. Following random vibration exposure the resonant frequency search was repeated in order to check for any evidence of damage or loosening of parts within the module. The XFCM completed each axis of vibration exposure with no evidence of damage as demonstrated by the post vibration resonant frequency searches.

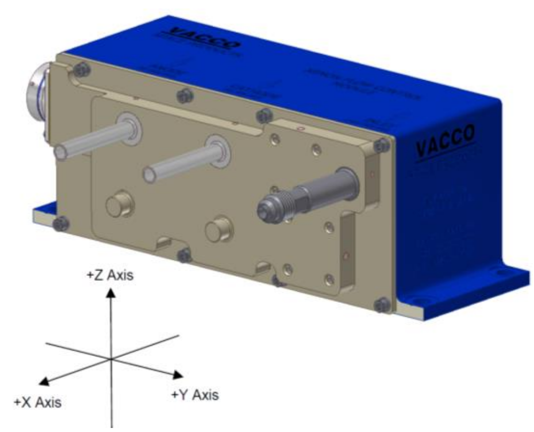

Figure 6. Orthogonal Axes

Frequency	PSD Level (G^2/Hz)
20	.096
50	.6
500	.6
2000	.04
Overall GRMS	22.59 Grms

Table 3. Random Vibration Levels

E. Shock Test

Following vibration testing the XFCM was subjected to shock testing conducted at the Wyle Laboratories facility in El Segundo, CA.

The test method used to conduct shock testing was Wyle's Mechanically Induced Pyrotechnic Shock (MIPS) method. The MIPS test method uses pneumatic cannon to fire a projectile at a suspended shelf to which the unit under test is mounted. As with typical pyrotechnic shock test methods the MIPS method applies shock in all three axes simultaneously with each strike of the projectile. The MIPS test method allows for adjustment of the applied shock response spectrum by adjusting cannon location, pneumatic pressure setting, projectile size and shelf characteristics.

Prior to shock testing of the XFCM a mass simulator was mounted to the MIPS fixture and several shocks were applied in order to adjust parameters to meet the required shock response spectrum. The shock response spectrum requirements for the XFCM are shown in Table 4.

Once an adequate result was achieved with the mass simulator the settings were recorded and the mass simulator was replaced with the XFCM qualification unit. The XFCM was subjected to one shock application and the recorded results were evaluated to ensure test levels met or exceeded test requirements. The test levels did exceed the test requirements and there was no evidence of damage to the XFCM.

Hz	G's
100	100
1000	2000
10000	2000

Q=10

Table 4. Shock Profile

F. Functional Tests

Functional tests were conducted at various milestones throughout the acceptance and qualification test program to detect any degradation in XFCM performance. The functional tests conducted are delineated in Table 5.

Functional Test No.	Test description
1	Transducer Calibration Check
2	High Pressure Internal Leakage PV1 and PV2
3	High Pressure Internal Leakage LV1
4	High Pressure Internal Leakage LV2
5	Low Pressure Internal Leakage PV1 and PV2
6	Low Pressure Internal Leakage LV1
7	Low Pressure Internal Leakage LV2
8	High Pressure Latch Valve Pull-In LV1
9	High Pressure Latch Valve Pull-In LV2
10	Low Pressure Anode Flow
11	Low Pressure Cathode Flow
12	High Pressure Anode Flow
13	High Pressure Cathode Flow

Table 5. Functional Tests

For ease of comparison, data for all functional tests is summarized for acceptance testing, post shock & vibration, post cycle life, during high temperature thermal vacuum at +80°C, low temperature thermal vacuum at +2°C and post qualification.

G. Functional Transducer Calibration Check

Functional test number 1 repeated the pre-qualification calibration check that was conducted after proof pressure testing. The results for all of the transducer calibration checks conducted during qualification were recorded and can be seen in Figure 4, Figure and Figure .

H. Functional Leakage Tests

Functional test number 2 measured the internal leakage of both PCVs with 3,000 psig GHe applied to the inlet port. Functional test number 3 measured the internal leakage of the upstream MiLV with 3,000 psig GHe applied. Test number 4 measured the internal leakage of the downstream MiLV with 3,000 psig GHe applied to the inlet port. Maximum allowable high pressure internal leakage was 3.0 scch of GHe for all valves.

Functional test number 5 measured the internal leakage of both PCVs with 10 psig GHe applied to the inlet port. Functional test number 6 and 7 measured the internal leakage of both MiLVs respectively 10 psig GHe applied. Maximum allowable low pressure internal leakage was 3.0 scch of GHe for all valves.

The XFCM passed all internal leakage tests conducted throughout both acceptance and qualification testing. Internal leakage test data is summarized in Figure . Internal leakage was typically below the sensitivity of the test method (<0.1 scch). Worst case internal leakage rates of 0.3 scch (10% of allowable leakage) occurring under low temperature conditions.

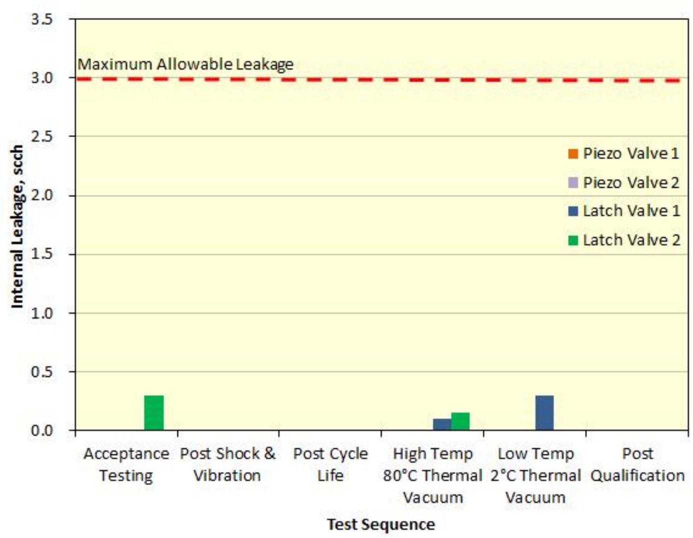

Figure 7. Internal Leakage Test Results

I. High Pressure Latch Valve Pull-In Tests

Functional tests 8 and 9 respectively verified that both MiLVs operated with a 100 millisecond, 23Vdc pulse applied with 3,000 psi pressure differential applied across them in the direction of flow. The XFCM passed all high pressure latch valve pull-in tests conducted during both acceptance and qualification testing.

J. Functional Flow Tests

Functional tests 10 and 11 measured the closed-loop low pressure flow capability of the anode and cathode channels respectively. A laboratory electronic controller provided closed-loop PID flow control using the XFCM low pressure transducers as feedback and the PCVs as pressure control actuators. A set point flow command of 55 sccm was applied using a GUI running on a laboratory laptop with 10 +0/-1 psia xenon applied to the inlet and vacuum to the outlet ports. After flow stabilized at 55 sccm the set point flow command was increased to 85 sccm. In all instances both channels successfully controlled both 55 and 85 sccm flow rates with minimal pressure applied to the inlet. This is significant in that a minimum inlet pressure of 10 psia reduces the mass of unusable residual propellant left in the storage tanks at the end of a mission.

Functional test 12 and 13 measured the closed-loop high pressure flow capability of the anode and cathode channels respectively. A laboratory electronic controller provided closed-loop PID flow control using the XFCM low pressure transducers as feedback and the PCVs as pressure control actuators. A set point flow command of 55 sccm was applied using a GUI running on a laboratory laptop with 3,000 +50/-0 psia xenon applied to the inlet and vacuum to the outlet ports. After flow stabilized at 55 sccm the set point flow command was increased to 85 sccm. In all instances both channels successfully controlled both 55 and 85 sccm flow rates with maximum pressure applied to the inlet. This is significant in that an inlet pressure of 3,000 psia allows the maximum propellant storage density to be achieved. A plot showing typical results of the functional flow tests is shown in Figure .

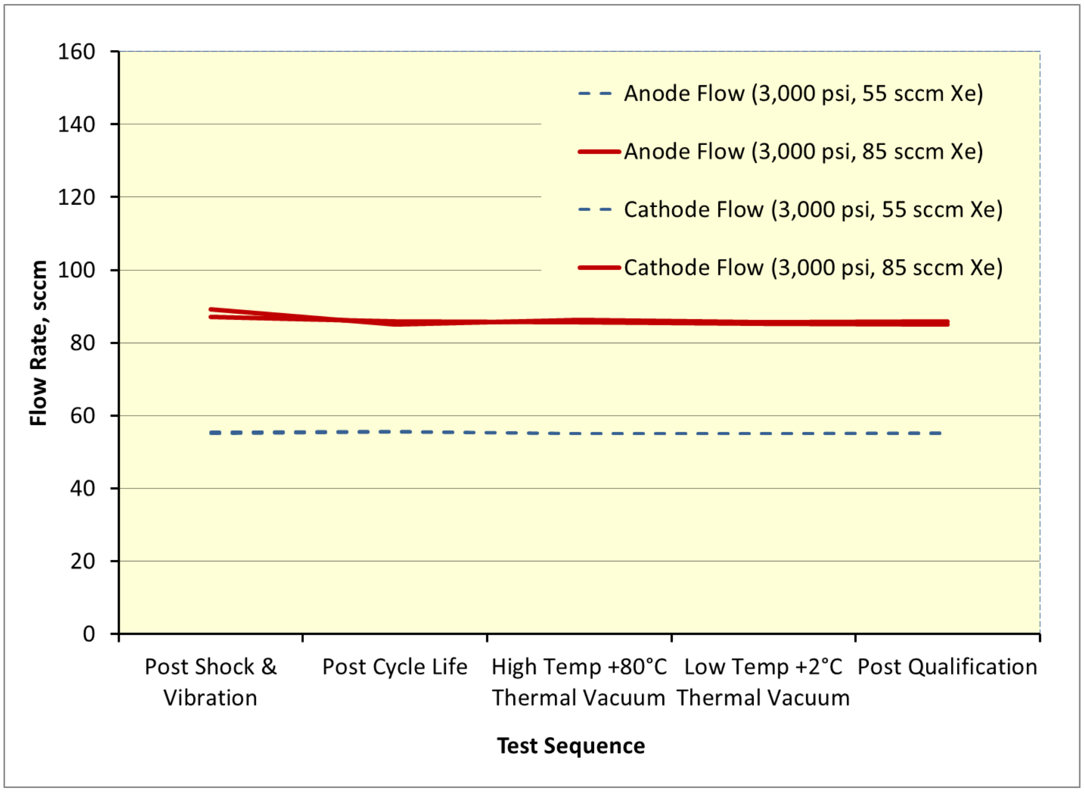

Figure 8. Worst-Case Xenon Flow Control Test Data

The XFCM passed all of functional flow tests conducted during both acceptance and qualification testing.

K. Life Cycle Test

The XFCM was subjected to 35,000 life cycles. During each cycle test both MiLVs and PCVs valves were operated. To simulate reduction is supply pressure over mission life the inlet pressure was varied during the life cycle test. For the first 13,000 cycles the inlet pressure was set at 3,000 psia. For cycles 13,001 through 23,000 the inlet pressure was set at 1,500 psia. For cycles 23,001 through 35,000 the inlet pressure was set at 1,000 psia.

The XFCM operation was monitored electronically throughout the life cycle test to verify sustained functionality. The XFCM completed the life cycle test with no malfunctions recorded. Post cycle life functional testing indicated no degradation in performance.

L. Thermal Vacuum/Thermal Cycle Test

The XFCM was subjected to 27 cycles of thermal vacuum/thermal cycle testing. The first 8 cycles were thermal vacuum cycles with chamber pressure at or below 1 x10^{-4} torr. The remaining 19 cycles were conducted in a thermal chamber under laboratory ambient pressure. The thermal vacuum/thermal cycle test profile is shown graphically in Figure . For each temperature extreme shown in the profile the XFCM was required to dwell at that temperature for a minimum of one hour after stabilization.

During the first thermal vacuum cycle the XFCM was subjected to the high operating temperature of +80 deg C and the non-operating survival low temperature of -12 deg C. Over the next 7 thermal vacuum cycles the XFCM was subjected to the maximum operating temperature of +80 deg C and the low operating temperature of +2 deg C. The functional tests of Table 5 were conducted during the 2nd and 8th cycles at both the high and low temperature conditions.

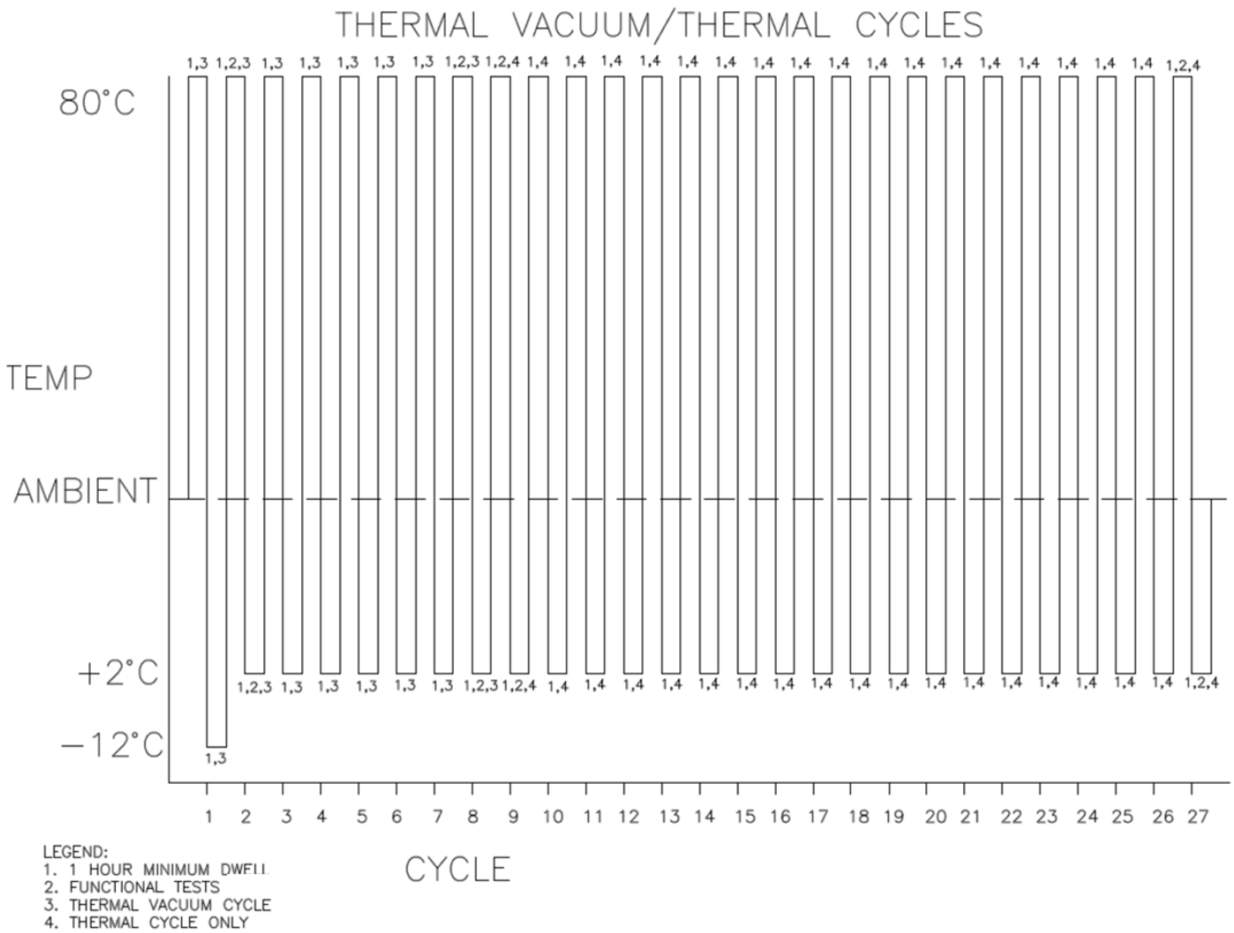

Figure 9. Thermal Vacuum/Thermal Cycle Profile

The remaining 19 thermal cycles were identical to cycles 2 through 8 except that the test chamber was at laboratory ambient pressure. The functional tests of Table 5 were conducted during the 9th and 27th cycles at both the high and low temperature conditions.

The XFCM completed the thermal vacuum/thermal cycle test with no evidence of damage. The XFCM passed all of the functional tests that were conducted during the thermal cycling. Post thermal cycle functional testing also indicated no degradation in performance.

M. External Leakage

After subjecting the XFCM to all the potentially destructive tests, high pressure external leakage test was measured with 3,000 psia GHe applied to the inlet port over a period of 6 minutes. Worst-case external leakage was 1.4×10^{-8} sccs of GHe or 2% of the maximum allowable high pressure leakage rate of 1.0×10^{-6} sccs of GHe.

The XFCM was then subjected to a low pressure external leakage test. External leakage was measured with 50 psia GHe applied to the inlet port over a period of 6 minutes. Worst-case external leakage was 2.0 x 10^{-8} sccs of GHe or 2% of the maximum allowable high pressure leakage rate of 1 x 10^{-6} sccs of GHe. .

N. Steady-State Power Consumption

Extremely low steady-state power is a key capability that enables future deep space solar electric missions. For this reason the maximum allowable steady-state power consumption was 1.0 watt. After completing acceptance and qualification testing the steady-state power consumption was measured at 0.402 watts, well below the specified requirement.

III. Future Plans

VACCO Industries is currently under contract with NASA GRC to build two additional modules called Smart Flow Control Modules (SFCM). SFCM SN 001 will be fully qualified by September 2014. SFCM SN 002 will be acceptance tested and made available by NASA GRC for a potential flight opportunity.

The SFCM shown in Figure 11 is a derivative of the XFCM designed to increase flow capacity to 202 sccm and be compatible with existing, flight proven PPUs. A key aspect of this is the capability to emulate the Moog PFCV. To minimize technical risk, the SFCM leverages the XFCM by retaining proven elements of the qualified design. The resulting SFCM design has less mass, lower profile and is less costly than the XFCM. These differences are a reflection of the XFCM capability to control two flow channels independently while the SFCM controls the total flow rate which is passively spilt into a fixed ratio of 93% anode and 7% cathode.

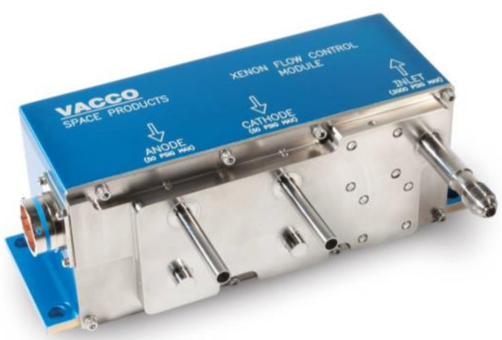

Figure 5. VACCO XFCM

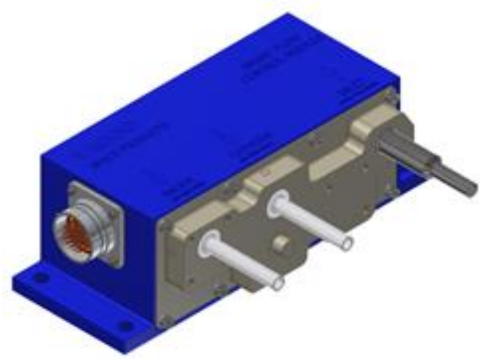

Figure 6. VACCO SFCM

A. SFCM Design and Capabilities

As shown in Figure 12, the SFCM is a two channel electronic flow controller with integral S-class electronics. The inlet port is equipped with 10 micron (absolute) filter with 100 mg dirt capacity. The SFCM has an optional high pressure and temperature sensor that can be replaced with a plug. Normally-closed solenoid valves (NCVs) provide flow isolation and the PCV provides precision flow proportional to applied voltage. A pressure switch protects the module against over-pressure when operating open-loop during start-up. The anode channel is equipped with a normally-closed valve to isolate the anode during cathode start-up. The SFCM PCV can be either directly controlled (0-130Vdc) or controlled through the PFCV emulator interface.

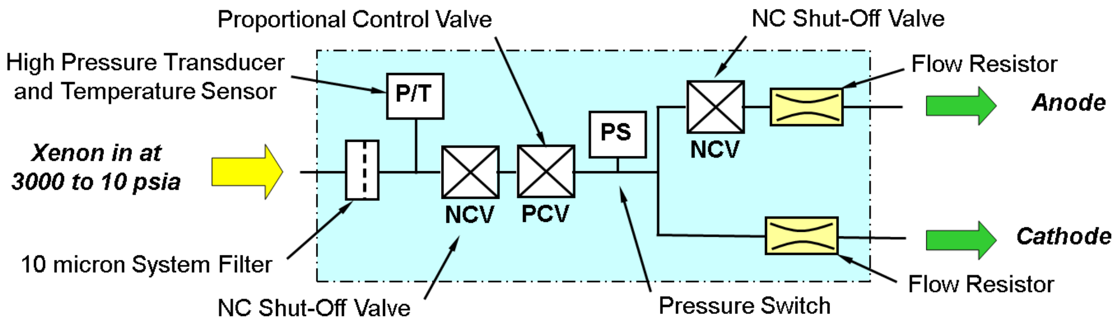

Figure 7. SFCM Functional Schematic

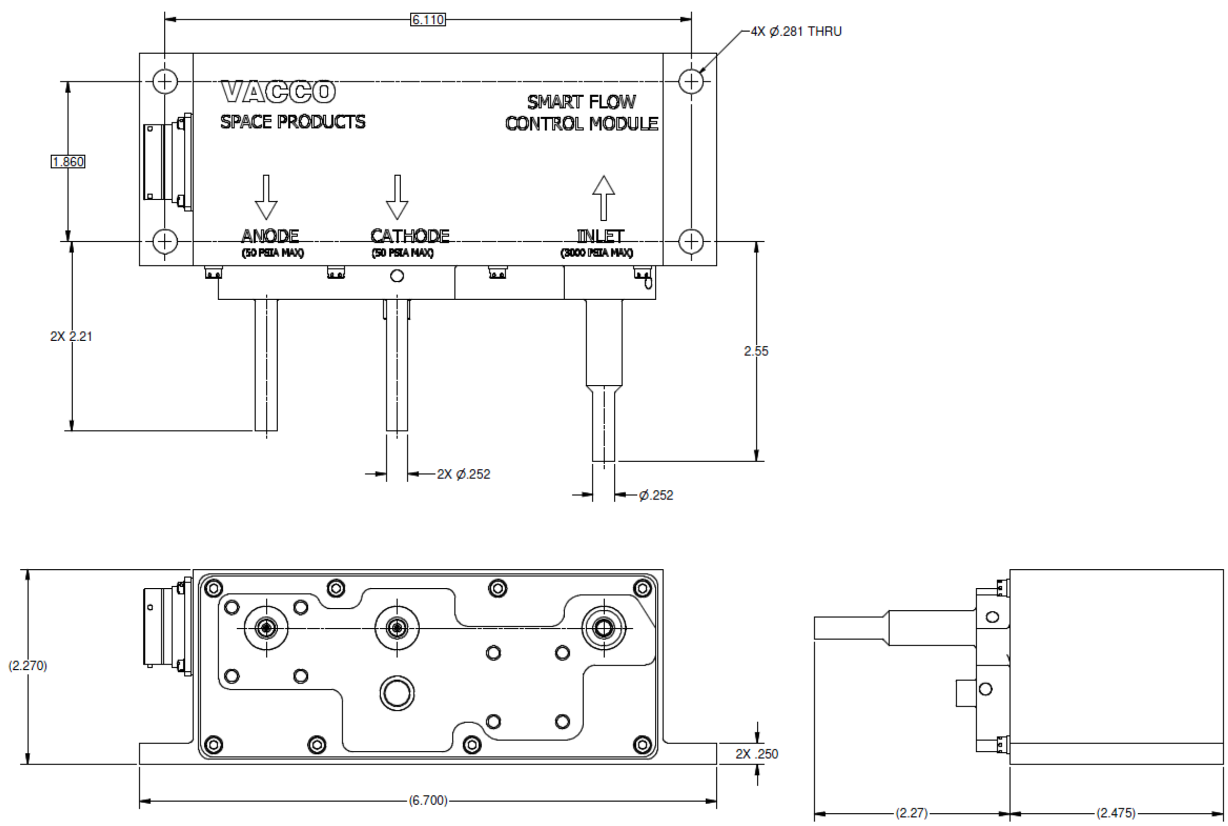

Figure 8. SFCM Envelope

B. SFCM Test Plan

VACCO will complete the acceptance and qualification testing of SFCM SN 001 before delivery to NASA GRC.

Acceptance testing will incorporate the following:

- Pressure Transducer Calibration Check
- Proof Pressure
- External Leakage
- Internal Leakage (All Valves Tested Independently)
- Pull-In Voltage
- Flow Capacity And Power Consumption
- Flow Control Accuracy
- Thermal Tests

Qualification testing will incorporate the following:

- Pressure Transducer Calibration Check
- Proof Pressure
- Vibration Test
- Shock Test
- Life Cycle Test
- Thermal Vacuum/Thermal Cycle Test
- External Leakage Test

IV. Conclusions

The XFCM demonstrated reliable operation over a wide range of environmental conditions and high cycle life exposure without any detectable degradation in performance. The XFCM was capable of meeting all of the specified qualification requirements. The XFCM is fully qualified at TRL-6 and ready for flight.

The SFCM complements the XFCM with more flow capacity at lower cost in a smaller, lighter configuration. Once qualified, SFCM compatibility with existing PPUs eliminates the need for costly, special purpose control electronics.

Acknowledgments

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References

Dankanich, J.W., Cardin, J.M., Dien, A., Kamhawi, H., Netwall, C.J., Osborn, M., "Advanced Xenon Feed System (AXFS) Development and Hot-fire Testing," *AIAA Joint Propulsion Conference*, AIAA 2009-4910, Denver, CO., August 2009.

J.M. Cardin, "A Standard Architecture Feed System Using VACCO ChEMS™ Technology", 2008 Advanced Space Propulsion Research Workshop, Pasadena, CA, 2008.

J.M. Cardin, "An Advanced Xenon Flow Controller", presented at the Electric Propulsion TAG Meeting, Denver, CO, May 2007.