Advanced Flow Control System for In-Space Electric Propulsion

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ABSTRACT

The Cycle Automated Mass Flow (CAMFlow) system is a compact flow control unit with precise flow regulation and reliable, life tested valves. CAMFlow uses a control scheme that enables a stable control and operation using fixed frequency valve openings with variable duration, even at the low flow rates necessary for sub-kilowatt Hall effect thrusters. This methodology alleviates system complexity, places the onus of reliability on valve cycle life, and combined with fixed operational frequency, allows for a direct correlation between system life and valve cycle life. Through the use of space-rated control electronics and careful-COTS power electronics, CAMFlow can provide a flow control system for budget minded sub-kilowatt Hall / ion thruster missions. The CAMFlow control scheme was successfully implemented in a TRL 6 integrated XFC + PMA system called CAMFlow-3 (**Figure 1**). Reported herein is the design, manufacturing, subsystem life testing, and flow testing in open and closed loop control schemes. Valve life testing of the XFC valves exceeded 114 million cycles, and PMA valves exceeded 56,000 cycles, which equates to 300 kg Xenon throughput (or 200% margin on 100 kg). With readily customizable flow balancing orifices, CAMFlow-3 can provide any anode / cathode ratio of flow, from a total flow of 0-15 mg/s Xenon.

INTRODUCTION

There are a number of sub-kilowatt Hall effect thrusters that have been or are currently under development [Levchenko, 2018; Lemmer, 2017]. Domestic, higher TRL concepts include Busek's BHT-200 and BHT-600 systems [Hruby, 2019], NASA Glenn Research Center's Sub-Kilowatt Electric Propulsion (SKEP) thruster [Schmidt, 2018; Kamhawi, 2019], and NASA Jet Propulsion Laboratory's Magnetically Shielded Miniature (MaSMi) thruster [Conversano, 2017a; Conversano, 2019]. These thrusters typically employ xenon as a propellant with discharge voltages ranging from 200-400 V and currents from 0 – 5 A. Given the Hall thruster rule of thumb that 1 A of discharge current corresponds to 1 mg/s flow of xenon propellant through the anode, these voltage and power requirements translate to the flow range identified in the NASA solicitation i.e. 0-5 mg/s. An additional 7-10% of this anode flow must be supplied to the electron source for the device, the cathode. In terms of total propellant throughput, i.e. lifetime, mission studies for small-scale, class-D missions have shown that 500 kg class missions could require as much as 100 kg of propellant over lifetimes exceeding 20 khrs [Conversano, 2017b]. Similarly, the number of cycles on the system (for start-up and shut-down) can be >10,000.

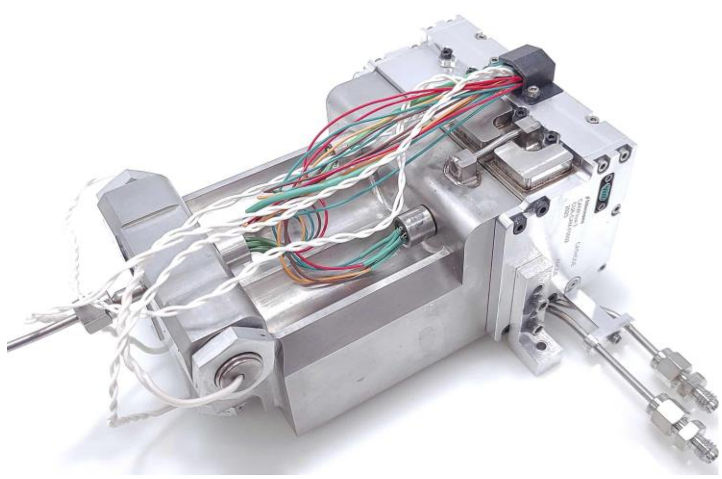

Figure 1. Assembled CAMFlow-3 system.

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These flow and lifetime requirements must be coupled with other system considerations. Examples include the limits on inlet and outlet pressure, the flow control accuracy, mass and power requirements, and fault tolerance. While the early effort was for an XFC only, the project evolved to also include PMA capabilities [Woodruff, 2022], regulating all the way down from bottle pressure to the hall thruster. While the units could be offered separately, the system as designed integrates both together, with a shared control board. **Table 1** presents goals for the CAMFlow-3 XFC unit alongside what was achieved from hardware shown in **Figure 1**, and **Table 2** presents the same for the PMA.

Table 1. XFC Requirements

	XFC Goals	CAMFlow-3 XFC
Flow Rate	0 – 8 mg/s for BHT-600	0 – 15 mg/s
Flow Split to Cathode	15 – 16% for BHT-600	15 – 16% for BHT-600 w/ quick change option for different % split
Flow Pressure Variation at Outlet	< 3%	< 2%
Single Point Failure	Permissible if demonstrated through testing and use of high reliability parts	Single fault tolerance through entire system and dual fault tolerant for valves in series
On/Off Cycles	> 2000	> 100 million
Inlet Pressure	40 – 100 psia	30 – 100 psia
Outlet Pressure	< 2 psia	< 6 psia
Total Throughput	100 kg	300 kg
Working Gas	Xenon	Xenon, Argon
Gas Cleanliness	10-micron inline filter	10-micron inline filter
Mass	< 0.7 kg	0.66 kg
Volume	< 0.4 liters	0.4 liters (w/ PCBs)
Internal Leakage	$1x10^{-4}$ scc/s of helium	< $1x10^{-4}$ scc/s of helium
External Leakage	$1x10^{-6}$ scc/s of helium	< $1x10^{-6}$ scc/s of helium

Table 2. PMA Requirements

	PMA Goals	CAMFlow-3 PMA
Flow Rate	0 – 8 mg/s	0 – 15 mg/s
Flow Pressure Variation at Outlet	100 +20/-80 psia	100 +20/-80 psia
Single Point Failure	Permissible if demonstrated through testing and use of high reliability parts	Single fault tolerance through entire system and dual fault tolerant for valves in series
On/Off Cycles	> 2000	> 55,000
Inlet Pressure	100 – 2500 psia	100 – 3500 psia
Outlet Pressure	40 – 100 psia	30 – 100 psia
Total Throughput	100 kg	300 kg
Working Gas	Xenon	Xenon, Argon
Gas Cleanliness	10-micron inline filter	10-micron inline filter
Mass	< 2.0 kg	2.1 kg (can reduce mass by switching from stainless to titanium)
Volume	< 0.6 liters	1.1 liters
Internal Leakage	$1x10^{-4}$ scc/s of helium	< $1x10^{-4}$ scc/s of helium
External Leakage	$1x10^{-6}$ scc/s of helium	< $1x10^{-6}$ scc/s of helium

DESIGN AND INTERFACE

SYSTEM DESIGN AND MANUFACTURING

Figure 2 shows the flow path diagram for the combined XFC-PMA system. The design generally follows that of the previously reported CAMFlow-2 system [Woodruff, 2022].

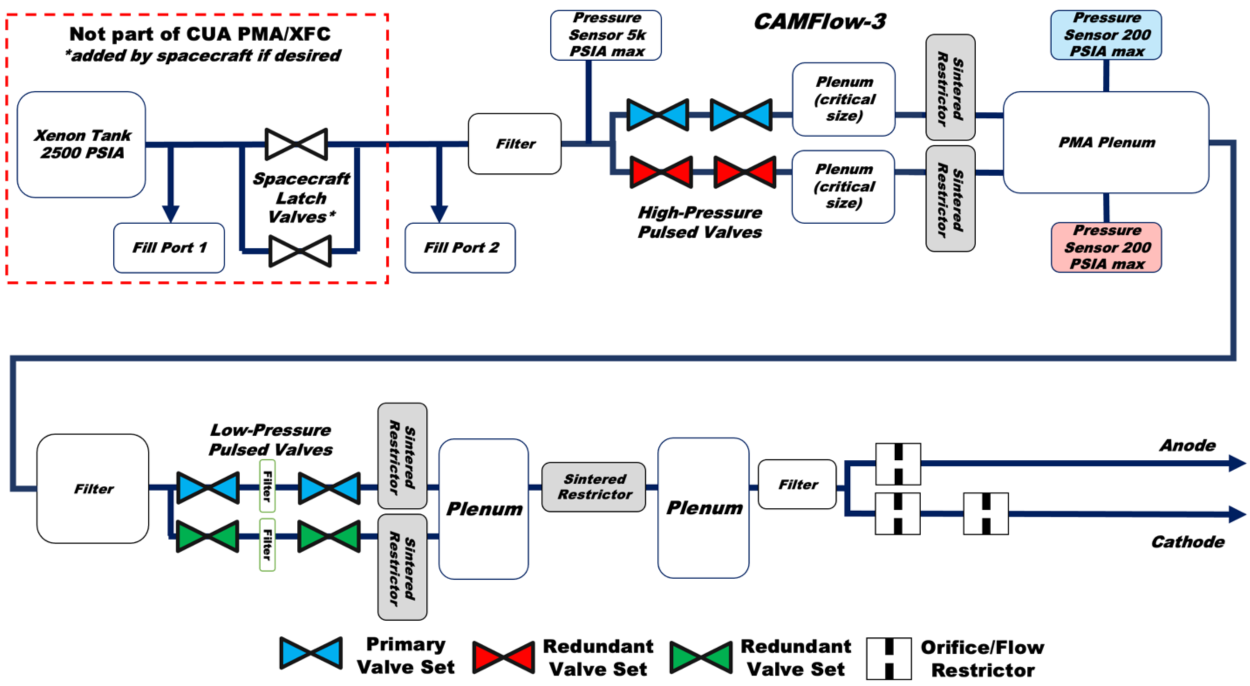

Figure 2. Flow path diagram for CAMFlow-3

The top portion of **Figure 2** comprises the PMA and the bottom portion of **Figure 2** the XFC. Starting from the PMA, there are series-parallel redundant valve sets and dual low-pressure sensors. The pressure in the PMA plenum is loosely regulated by filling to ~ 100 PSIA and allowing blowdown to ~30 PSIA. This operation requires a single cycle on the active set of PMA valves. By narrowing the pressure band, finer ultimate flow control is possible, but at the cost of system life. In the event an active valve is stuck closed, the secondary valve set can be used. A stuck open valve is more difficult to detect, but should not affect operation. Similarly, the pressure sensors are tied to their respective PMA valve chains, so if readings become anomalous, they can be swapped. Depending on the control electronics (2 versions) there exist some cases where there is only single fault tolerance, but most situations allow for dual fault tolerance.

The bottom section represents the XFC. This takes the low-pressure output from the PMA and regulates flow rate. By design, the XFC operates in a closed loop mode targeting hall thruster current. Open loop operation is possible, but the accuracy and consistency of this mode depends on external factors.

Note that CAMFlow supports a second XFC for a cathode cold start operation (e.g. for the MaSMi thruster [Conversano, 2017a; Conversano, 2019]), but it was not included in this build as the test unit did not require the feature. This would attach to the same place as the existing XFC portion.

Figures 3 and 4 show the external components of CAMFlow-3. Note the pressure sensors are small in relation to their cutouts. This is because flight heritage sensors are supported in addition to smaller, less expensive devices.

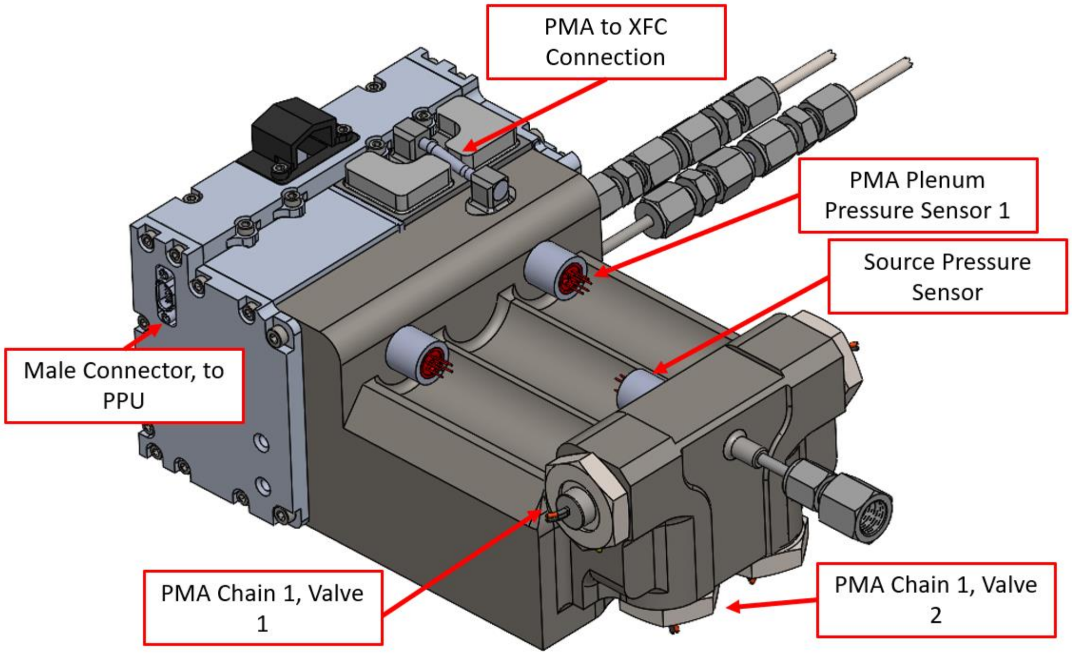

Figure 3. CAMFlow-3 features shown from the PPU connector side.

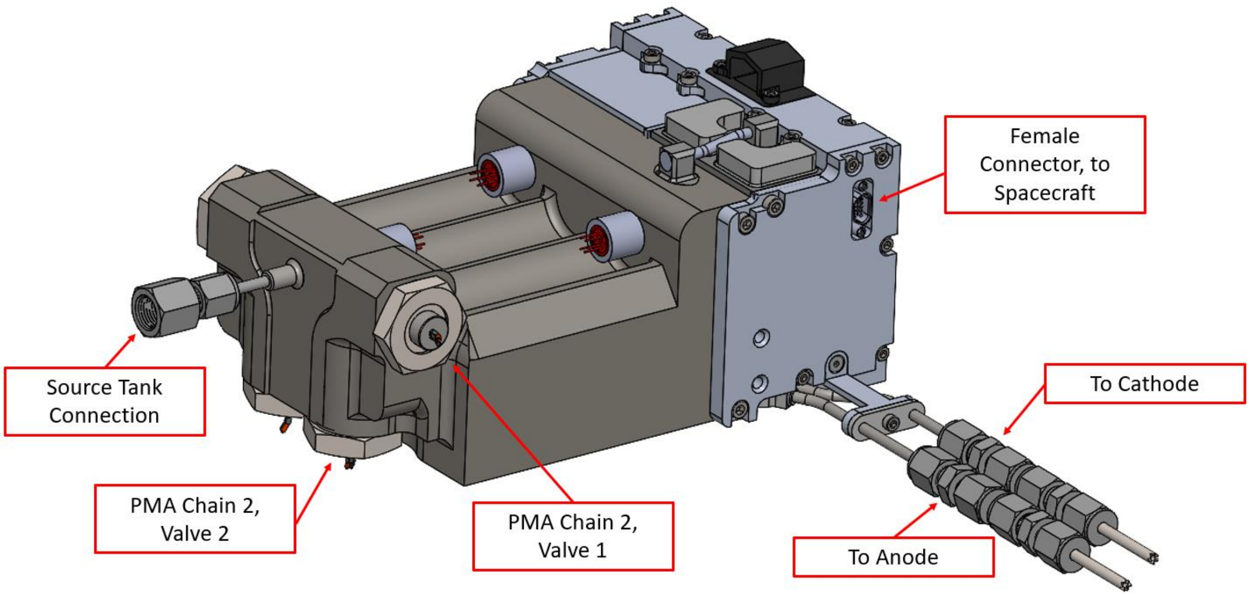

Figure 4. CAMFlow-3 features shown from the spacecraft connector side.

The CAD renders here show Swagelok fittings on the exits, although tube welding is preferred for a flight system. Further, the final flow balancing orifices for anode and cathode are externally attached in this version, allowing for systems to customizable long after the internal features are welded shut. **Figure 5** shows the exterior dimensions of CAMFlow-3 in inches. A photograph of the fabricated CAMFlow-3 hardware is shown in **Figure 1**.

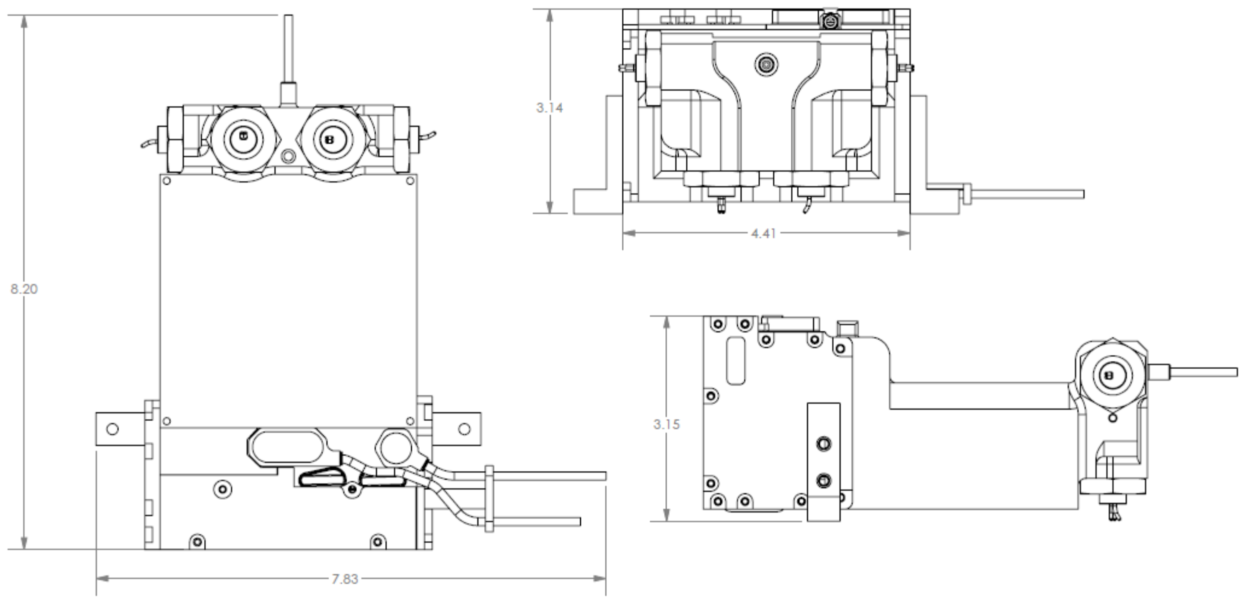

Figure 5. CAMFlow-3 Exterior Dimensions (inches)

Two versions of control electronics were developed for CAMFlow-3. The first system uses discrete timing and control logic without an onboard microcontroller. Analog voltages go into and out of the system, as well as GPIO pins for control. The timing and control parts are all available as space rated options, however size constraints mean that most switching components are careful-COTS. A male and female micro-Dsub connector are used for each connection to the unit. **Table 3 and 4** describe each connection.

Table 3. Spacecraft Connections

Pin #	Color	Signal	To Spacecraft (DCCM9SCBRPN, Female) Description
1	Black	Source Tank Pressure	Output. Pressure of propellant source tank.
2	Brown	PMA Chain 2 Indicator	Output. 5V indicates that pressure in plenum is such that PMA Leg 2 will activate if enabled.
3	Red	RTD Out	Output. Temperature of RTD.
4	Orange	Plenum Pressure 2	Output. Pressure of PMA plenum as read by sensor #2.
5	Yellow	GND	Input. Spacecraft signal ground.
6	Green	PMA Chain 1 Enable	Input. Controls PMA Leg 1. Enable = 3.3V.
7	Blue	PMA Chain 2 Enable	Input. Controls PMA Leg 2. Enable = 3.3V.
8	Purple	Plenum Pressure 1	Output. Pressure of PMA plenum as read by sensor #1.
9	Gray	Bus Voltage	Input. 22-36V unregulated bus voltage. Only used for PMA valve hit.

Table 4. PPU Connections

Pin #	Color	Signal	To PPU (DCCM9PCBRPN Male) Description
1	Black	Regulated 5V	Input.
2	Brown	GND	PPU signal ground.
3	Red	12V	Input. Requires up to 1 A supply current.
4	Orange	GND	PPU signal ground.
5	Yellow	Cold Cathode Start	Input. Enables cathode valve chain. Cathode valve open time is automatically controlled by the XFC. Not present in STTR unit
6	Green	Regulated 3.3V	Input. Requires up to 1.5 A supply current.
7	Blue	XFC Control Voltage	Input.
8	Purple	12V	Input. Requires up to 1 A supply current.
9	Gray	XFC Chain Switch	Input. Controls XFC chains 1 and 0 - 2. 0V = Chain1, 5V = Chain2.

These connections allow for the spacecraft to monitor and enable the PMA, while providing the hall thruster PPU the ability to regulate the XFC and maintain closed loop control. A microcontroller version was developed but not produced in this effort. It still requires power rails from the XFC to operate, but allows a single RS422 interface to control the entire system. **Figure 6** shows a LabView interface compatible with the analog version of CAMFlow-3. This was used in all testing of the device.

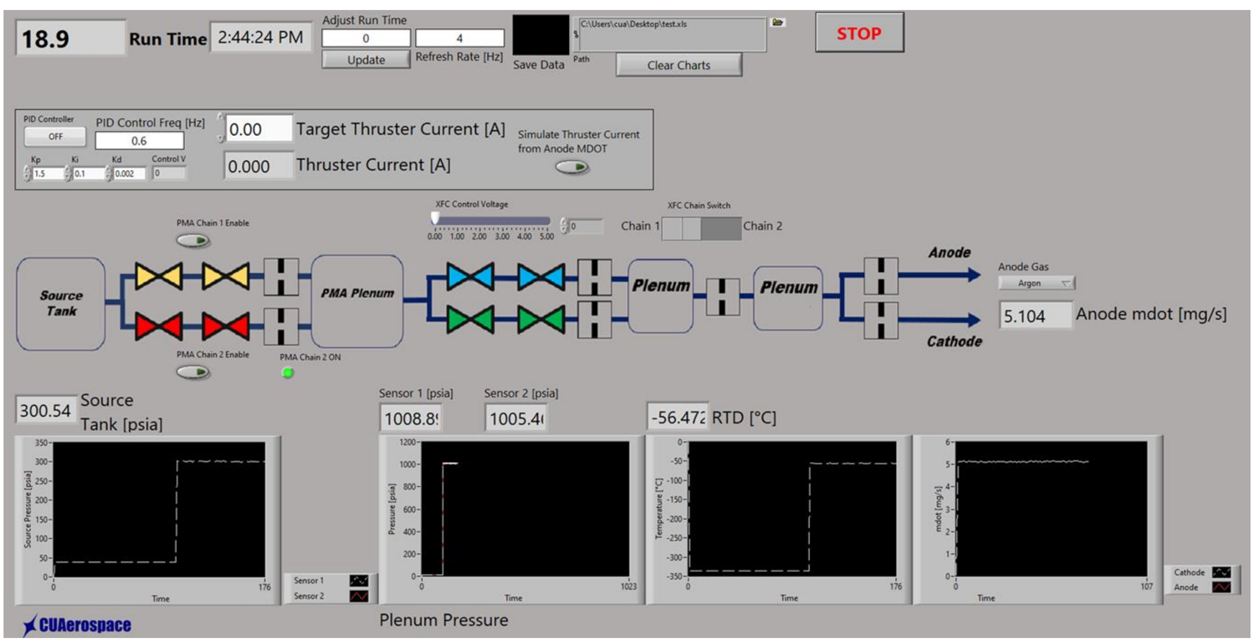

Figure 6. LabView Control Interface

RESULTS AND DISCUSSION

VALVE LIFE TESTING

Since CAMFlow uses discrete valve states rather than proportional valves, accelerated life testing is a reasonable estimate of system life. For the XFC valves, nominal operation of the valves involves on times less than 20 milliseconds. This means that total valve open time can be matched to the real system. Accelerated testing for these valves was performed at 60 Hz operation vs. the system's standard 1 Hz rate by modifying the timing circuit on a prototype control board. The setup consisted of two valves in series, such that any contamination from one valve would affect the downstream valve. 90 PSIA compressed air and a flow restrictor enabled similar internal pressures and flow rates. Periodic leak checks were performed at a maximum expected operating pressure (MEOP) of ~100 PSI with helium using a bubble rate method [Marr, 1968]. This is more than sufficient for the rated leak rates of the valves. **Figure 7** shows the test progression of the XFC valve life test. The ~120 million actuations represent roughly 300 kg Xenon throughput. **Figure 8** shows the leak rate results of the testing.

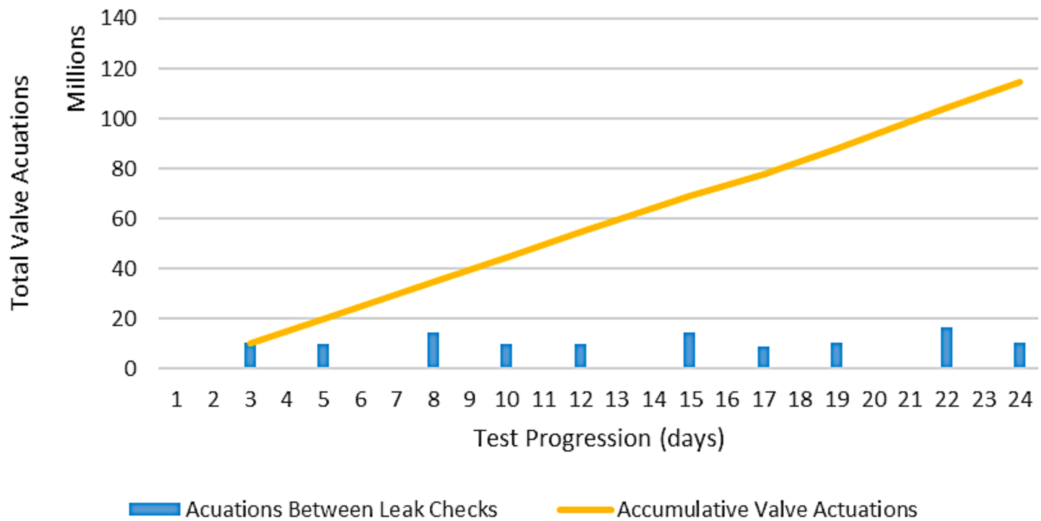

Figure 7. XFC Valve life test progression.

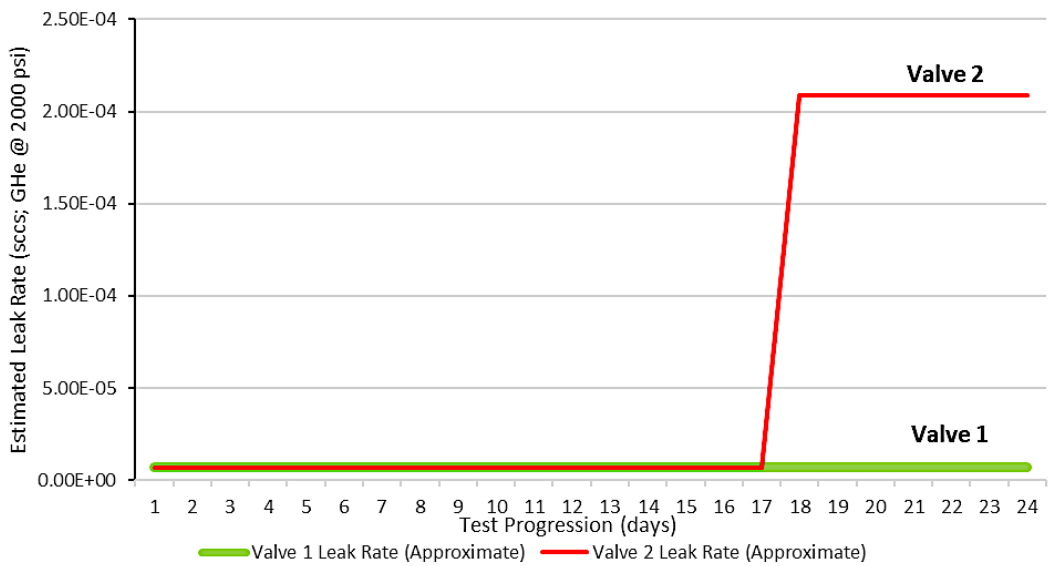

Figure 8. XFC valve leak rates.

The valves performed better than their rated leak rate on the order of 1x10-4 sccs helium. In each leak check, valves were independently tested long enough to ensure leaks were less than 7×10^{-6} sccs helium. Ultimately, the downstream valve began leaking slightly, but was still within the manufacturer specifications after ~120 million cycles. This was likely due to some debris generated by the upstream valve. Within the CAMFlow system, sintered flow restrictors are utilized to ensure debris will not clog any internal orifices. Further, later testing showed that at lower valve cycle rates with corresponding lower power and temperature levels, the debris generated by the valves is reduced substantially.

The PMA valves are operated with significantly longer opening durations than the XFC valves, however their total required cycles for system life are also greatly reduced. A spare set of CAMFlow-3 power electronics was used to operate this life test, and an artificial pressure reading was made with a function generator to cause the valves to cycle appropriately. High pressure (2000 PSI) Argon was used in this test, and flow was once again through similar flow restrictors to the real system. Leak checks were performed again with the bubble method and helium at a similarly high pressure. **Figure 9** shows the test progression of the PMA valves.

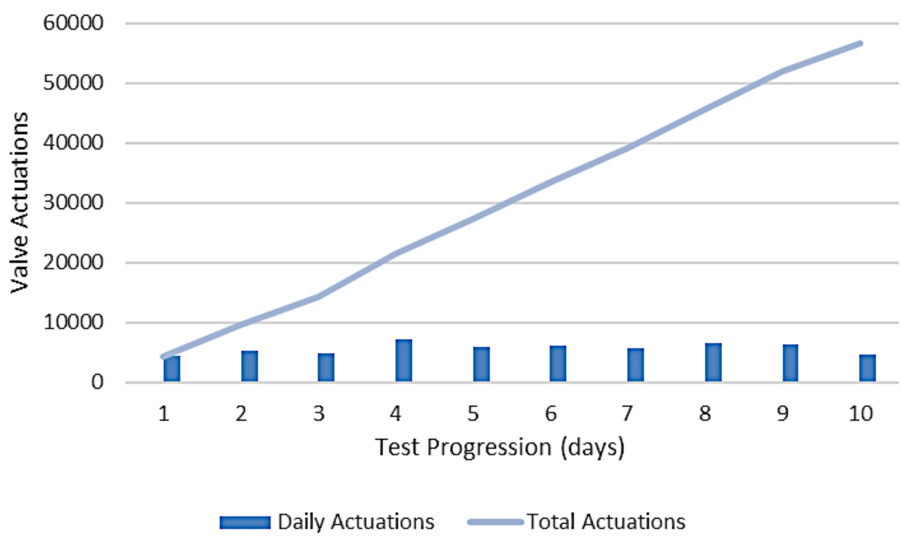

Figure 9. PMA Life test progression.

Unlike the XFC valves, leak rates above 7×10^{-6} sccs helium were never observed, and at the conclusion of the test the valves appeared to perform like new. While this may appear to be an experimental error, a 1×10^{-4} sccs helium leak rate presents itself as regular bubbles flowing from the device, with each forming visibly and multiple released each minute. Leaking and damaged valves are frequently verified at CU Aerospace (CUA) with this method, and the PMA valves simply did not leak. A gas analyzer could perform an accurate leak rate measurement for the valves, but they are so far below the requirements that it was not deemed necessary.

More critical to the valve leak rates than shedding or cycle life is the system cleanliness. CUA cleaned the internals of each unit to at least level 100A, with level 50A the target for any flight hardware. Further, filters are in place to protect the valves form contamination.

<u>FLOW TESTING</u>

CAMFlow-3 was successfully tested on a BHT-600, however this set of laboratory data better represents the full flow capabilities of the system. **Figure 10** shows the laboratory setup for general flow rate testing. The system exhausts into a vacuum pump, simulating realistic exit conditions.

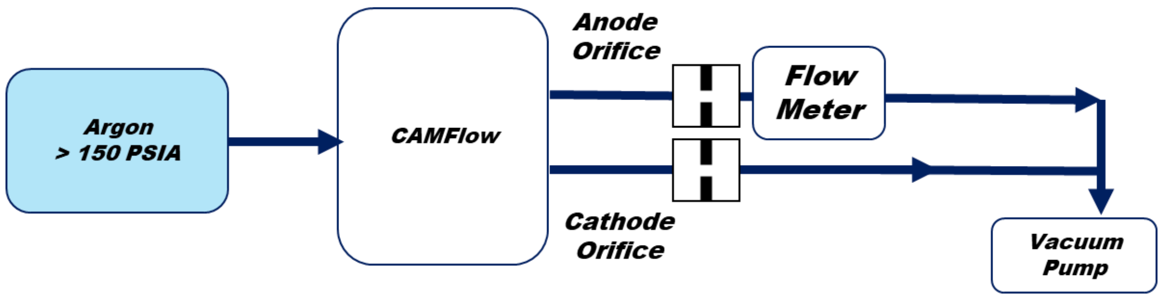

Figure 10. Lab flow test setup.

The baseline exit orifice for CAMFlow is a 100 µm orifice. This allows for flow rates below 1 mg/s Xenon, the expected minimum operating point for the system. **Table 5** below shows several data points collected with Argon and their equivalent Xenon result. PMA pressure is the exit pressure of the PMA, inlet pressure for the XFC. The XFC voltage is essentially the throttle value. The XFC is disabled below 0.5V and flow rate scales roughly linearly between 0.5V and 5V, which is the maximum throttle.

Table 5. 100 µm anode orifice testing

PMA Pressure [PSIA]	XFC Voltage [V]	Argon Flow [mg/s]	Eq. Xe Flow [mg/s]
50	0.6	0.258	0.47
42	0.67	0.5	0.91
40	1.6	2	3.64
55	2.1	4	7.28
46	5	4.6	8.37
25	5	3.6	6.55

The calibration of the CAMFlow unit resulted in the PMA operating between 25 and 55 PSIA. As this fills and drains, conditions presented to the XFC vary. For example, a true "maximum" flow rate should be taken at the minimum PMA pressure, as that is the highest flow rate achievable at all PMA pressures. As the table shows, a true maximum of roughly 6.5 mg/s and a minimum below 1 mg/s are possible in this configuration. Cathode flow rate is not shown here. In the default configuration, it is a 30 µm orifice and running < 10% of the anode flow. This is much more difficult to measure, but the orifices are purchased with calibration and can be more accurately characterized for a flight system.

As the exit orifices are interchangeable on this system, especially since they were not welded, a 200 µm anode exit orifice was also tested. While CUA has done extensive simulations to predict internal pressures and flow rates, the level of control at the low flow rates with this larger exit orifice was unexpected. **Table 6** shows these results.

Table 6. 200 µm anode orifice testing.

PMA Pressure [PSIA]	XFC Voltage [V]	Argon Flow [mg/s]	Eq. Xe Flow [mg/s]
40	0.54	0.22	0.4
30	0.8	0.5	0.91
30	0.95	1	1.82
53	1.1	2	3.64
41	1.5	3	5.46
40	1.85	4	7.28
33	2.3	5	9.1
35	2.5	6	10.92
30	2.9	7	12.74
50	2.5	7	12.74
25	5	8.4	15.29
30	5	9.5	17.29

While minimum flow rates were similar to the 100 µm orifice, maximum flows more than doubled, with ~15 mg/s Xenon possible at the minimum PMA pressure. This could be useful for a higher power system, although for a low power hall thruster, the lower limit on flow rate could reduce risk in the event of a control instability.

Closed loop control is implemented in the LabView interface, allowing the XFC to be throttled to attain a target flow rate. The long run presented in **Figure 11** shows an investigation of minimum and maximum flow rates between 0 and 150 seconds. Following this, the closed loop gains were adjusted for steady operation, and then flow targets of ~1 mg/s up through 13 mg/s Xenon were set and attained, all while the PMA drains and fills were occurring.

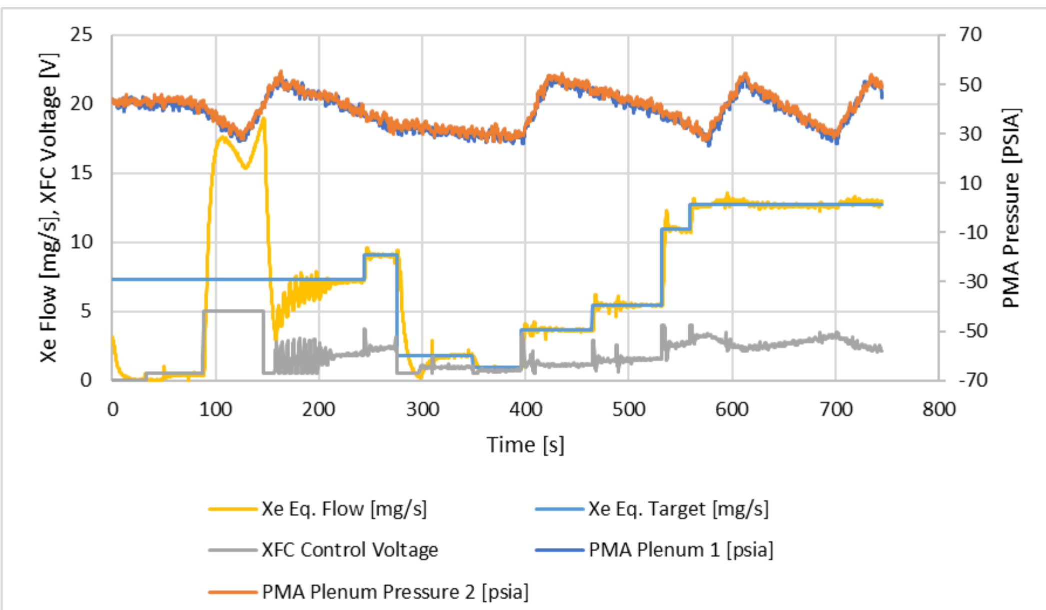

Figure 11. Flow test with multiple targets and varying input pressure.

SUMMARY AND CONCLUSIONS

A flight-like CAMFlow was designed, built, and tested successfully in a laboratory setting. The system was also successfully tested on a BHT-600 by the University of Michigan before and after environmental testing (to be detailed in a separate publication [Woodruff, 2024]). Life testing suggests the system can provide at least 100 kg Xenon throughput with margin, and the flow rate range and stability suggests CAMFlow will be compatible with most small Hall thrusters with little to no modifications.

ACKNOWLEDGMENTS

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