Cycle Automated Mass Flow (CAMFlow) System for Hall Thrusters

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Abstract: The Cycle Automated Mass Flow (CAMFlow) system is a compact, reliable, and well-regulated flow control unit for electric propulsion systems. CAMFlow uses a control scheme that enables stable operation using fixed frequency valve openings with variable duration (Boolean valve states), even for 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 the fixed operational frequency, allows for a direct correlation between system life and valve cycle life. Through the use of inexpensive space-rated components, CAMFlow technology provides a reliable low-cost flow controller that is well-suited for sub-kilowatt Hall/ion thrusters. The CAMFlow-1 unit and control scheme were successfully implemented, tested, and validated on a 600-Watt Hall thruster in the Large Vacuum Test Facility at the University of Michigan. This systems-level demonstration included open loop, closed loop, and cold start operations. In separate testing, the control valves were cycled > 120 million pulses demonstrating long-life potential. CAMFlow units are presently focused on smaller Hall effect or gridded-ion electric propulsion systems having a flow rate in the 0 – 8 mg/s range. However, the technology is widely applicable over a larger range of flow rates for a broader commercial market. CAMFlow-2 is a 1U-sized system including dual XFCs and a pressure management assembly (PMA) and was developed for NASA's Jet Propulsion Laboratory. The CAMFlow-2 system will accept up to 2,500 psia of input pressure and control the output flow rate of 0 – 5 mg/s to within ±3% of the desired flow rate.

I. 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]. Operationally, these thrusters typically employ xenon as a propellant with discharge voltages ranging from 200-300 V and currents from 0 – 5 A. Given the Hall thruster rule of thumb that 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 this solicitation, i.e., 0-5 mg/s. An additional 7-10% of this anode must be supplied to the electron source for the device, the cathode. In terms of total propellant

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throughout, 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 extending 20 khrs [Conversano, 2017b]. Similarly, the number of cycles on the system (for start-up and shut-down) can be >10,000.

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. With the acceleration of commercial launches for satellites having Hall and ion thrusters, reliable low-cost options for the xenon flow control (XFC) and propellant management assembly (PMA) modules are demanded. Relevant requirements are listed for VACCO's XFC module in Cardin *et al.* [Cardin, 2013]. To supplement the qualification standards desired in the development of this XFC, we also include fault tolerance required informed by Class-D mission requirements as well as specifications for the XFC currently under development for the 13 kW Hall thruster system under development for the NASA-sponsored Advanced Electric Propulsion System (AEPS) [Jackson, 2017]. Some general requirements for an XFC for a sub-kW class propulsion system are presented in **Table 1**.

Table 1: Xenon flow controller (XFC) requirements for sub-kW class propulsion system.

Requirement	Goals
Flow rate (anode)	0 – 5 mg/s
Flow rate (cathode)	0 – 0.5 mg/s
Flow rate error	< 3%
Single point failure	Permissible if demonstrated through testing and use of high reliability parts
Anode backpressure	< 2 psia
XFC inlet pressure	40 ±3 psia
Total throughput	100 kg
Working gas	Xenon
Gas cleanliness	15-micron inline filter

Over the course of the efforts described herein a more general set of requirements was developed for operating the CU Aerospace (CUA) Cycle Automated Mass Flow (CAMFlow) system in conjunction with flight proven PMAs. As many PMAs rely on proportional valves to provide an XFC that accepts tank pressure, CAMFlow is more likely to be used in conjunction with mechanical regulators like the flight proven options from Stanford MU.

A device that could meet these requirements is the µFCU from German company AST [Harman, 2013]. This uses a pulsed valve with a tortuous path to control flow down to the 0-5 mg/s level with a valve similar to the VACCO valve. Key differences are the control scheme and valve pulse rate, and the CUA system strives to increase valve life with lower frequency operation. The µFCU valves claim an impressive 300 million operational cycles, so even at higher pulse rate they can enable a large quantity of propellant throughput. Further, Maxar is working with Moog [Lenguito, 2019] on an extended range of operation XFC using a proportional flow control valve (PFCV) and includes a latching valve that can switch between two cathode flow fractions, but PFCVs are susceptible to more failure modes over many cycles than the Lee Co. valves used in CUA's CAMFlow system. Note that CAMFlow is readily adapted to have additional flow line splits to enable switching between different cathode flow fractions.

II. CAMFlow-1 Design and Flow Testing

2.1. Hardware Design

Figure 1 shows a schematic of the hardware configuration for the brassboard CAMFlow-1 system. The orifice configuration around the pulsed Lee Co. IEP valve was adjusted to enable lower pressure operation, enabling better end-of-life performance as the main propellant tank drains, as well as faster controller response when exposed to the typical 40 psia of mechanical regulators. Not shown in this diagram are additional sensors, such as temperature for a flight unit. The CAMFlow-1 brassboard system as shown has what CUA feels is a bare minimum in filtration and redundancy. The flight-like CAMFlow-2 design baselines parallel redundant pulsed and shutoff valves (discussed in **Section V**). **Figures 2** and **3** show both the simplified CAD drawing of the brassboard and the assembled brassboard unit sent to team partner the University of Michigan (UM) for thruster testing (**Section IV**), respectively.

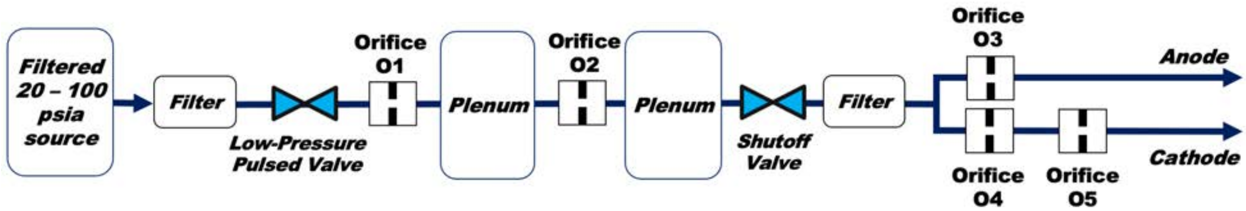

Figure 1. Schematic of the CAMFlow-1 system with all valves and orifices and a 9% cathode-anode flow split.

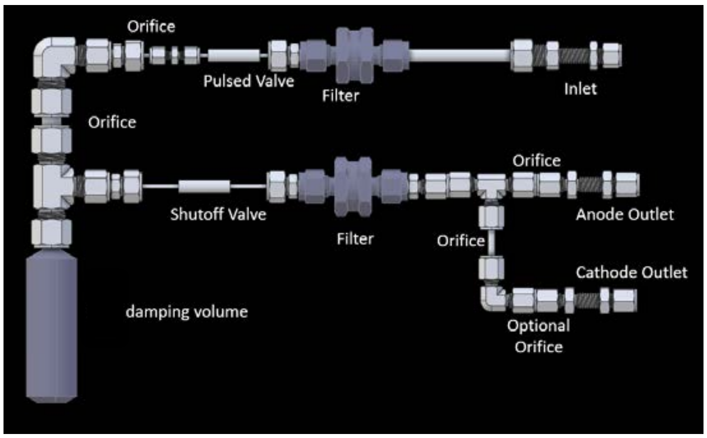

Figure 2. CAD model of the breadboard system.

Figure 3. Breadboard CAMFlow-1 system with additional pressure sensor monitoring.

Some downstream features, specifically the plenum pressure and corresponding exit orifices were driven by the requirements from team partner UM for the BHT-600. A passively controlled flow split of 7-10% was desirable to remove system complexity, and this arrangement of commercially available orifices provide the cathode with 8.3% of the total flow, or 9% of the anode flow. Furthermore, these are sized to provide a majority of the flow range (~1-5 mg/s) without plenum pressure dropping below 4 psia. This ensures orifice flow is choked for both anode and cathode feeds with anode pressure as high as ~ 2 psia, making the flow distribution *independent* of downstream pressure. In the event long flow lines are necessary for the anode output, the final orifice O5 in the cathode leg shown in **Figure 1** was used to approximate the pressure drop in the anode line, forcing the cathode orifice to run with similar backpressure to the anode orifice.

CAMFlow can scale to a variety of systems and flow rates by changing only the outlet orifices, with only major flow rate adjustments requiring upstream orifice changes. This flexibility was demonstrated when UM needed to replace the first cathode orifice O4 for their BHT-600 with one requiring ~15% of the anode flow instead of 9%. This was necessary as UM changed the hollow cathode from the baseline design for the integrated test.

2.2. Flow Controller Simulations

A quasi-1D time stepping simulation was developed to help size the plenum gas volumes and orifices, along with developing a control scheme for the system. This model was a modified version of the simulation code developed during CUA's Cubesat High Impulse Propulsion System (CHIPS) thruster program [Hejmanowski, 2015; Hejmanowski, 2016]. Mass is tracked throughout the system while using gas properties to determine pressures and mass flow rates. Both choked and unchoked flow is considered through the valve and each orifice based on pressure ratio. The resulting control scheme was a fixed frequency, variable duty cycle system, **Figure 4**. Historical CUA systems use pressure feedback from the gas plenum for the control loop, which varies duty cycle via a modified PID scheme. **Figure 4** shows the end product of the simulations – the controller running on hardware for the CUA CHIPS thruster. This is operating with 4 Hz valve actuations.

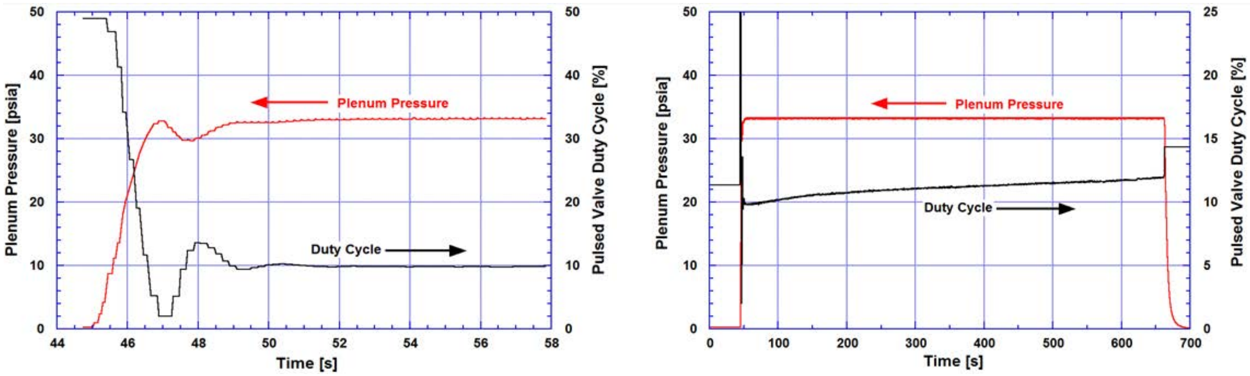

Figure 4. CUA CHIPS hardware running control loops tuned in simulation software. System cooling is driving the increase in duty cycle, and the control loop continues to maintain constant plenum pressure.

To lower the total number of valve actuations required for the CAMFlow system to flow the desired amount of 100 kg of propellant (**Table 1**), this system was tuned to operate at a lower valve actuation rate of 1 Hz. Also, rather than pressure feedback, CAMFlow utilizes mass flow rate as the process variable, as that is proportional to Hall thruster current. Testing showed that a traditional PID performed best for CAMFlow than the previous CHIPS implementation. **Figure 5** shows a simulation of the system shown in **Figure 1** at 1 Hz with a highly tuned controller, enabling ~10 second rise time. Simulations were run for a variety of conditions representative of what may be required for a true Hall thruster in the 0 – 5 mg/s mass flow rate range.

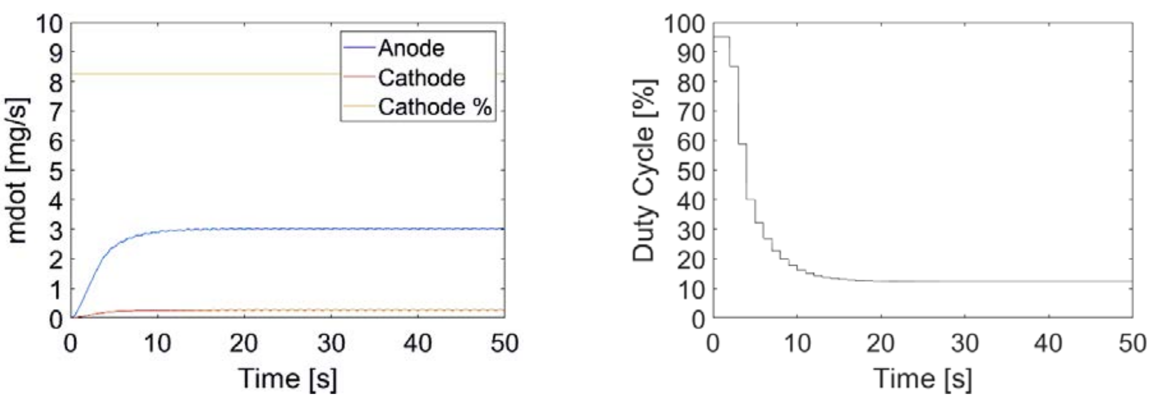

Figure 5. CAMFlow simulation using closed loop control on calculated mass flow rate. Setpoint is 3 mg/s.

More specific system requirements were provided to CUA by UM for the BHT-600 and were entered into CUA's flow control simulation model to fine tune the hardware design. The primary challenges for this system revolve around the inherent ripple and resulting control stability issues. While ripple can be adjusted with valve actuation rate, orifices, and damping volumes, a control scheme unaffected by ripple was strongly desired to decouple the problem. Two iterations of the breadboard flow control system were designed and fabricated, with the first serving to validate the model, and the second to test a more accurate configuration. While the first two breadboards functioned reasonably well, precise orifice sizing control was critical and simulation results suggested an additional orifice would provide some improvements to controller response and ripple. These breadboard iterations led to a brassboard that was packaged in a shippable form factor, **Figure 3**, using higher quality calibrated orifices. While originally slated to use a single microvalve, a secondary shut off valve was added to better represent a flight-like system. For the unit sent to UM for testing on the BHT-600 a set of custom valve driver boards was produced to better emulate a flight system's controller.

UM desired the flow controller to be capable of operating in both open and closed loop mode. In the closed loop mode, thruster discharge current is used for feedback. The flow is adjusted to match a given current set point as is consistent with most SOA XFCs. The controller operates at the same rate as the valve, with the valve driver circuit providing a timing signal to help synchronize the controller as illustrated in **Figure 4**. Open loop control requires some pre-calibration and characterization to determine the correct duty cycle as a function of source pressure and desired flow rate. **Figure 6** shows an example closed loop simulation for 3 mg/s using the updated flow split for UM. **Tables 2** and **3** show predicted minimum and maximum flow rates of CAMFlow over a wide range of inlet pressures and gas temperatures (presently assumed constant from inlet to exit).

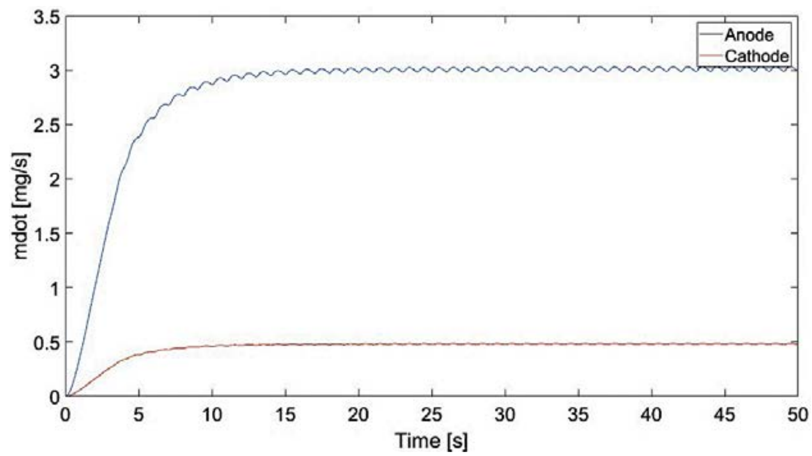

Figure 6. Simulation results for CAMFlow-1 brassboard including updated orifice split for UM (cathode gets ~15% of anode flow).

Table 2. Minimum flow rate (mg/s, 0.7% duty cycle, 0 PSIA backpressure). Red boxes indicate conditions for which the controller cannot quite meet minimum flow rate requirements. Underlined numbers are nominal.

	Inlet Pressure [PSIA]				
Temperature [C]	**20**	***40***	**60**	**80**	**100**
-20	0.21	***0.43***	0.64	0.86	1.07
-10	0.21	***0.42***	0.62	0.83	1.04
0	0.20	***0.40***	0.61	0.81	1.01
10	0.20	***0.39***	0.59	0.79	0.98
20	0.19	***0.38***	0.57	0.77	0.96
30	0.19	***0.37***	0.56	0.75	0.93
40	0.18	***0.36***	0.55	0.73	0.91
50	0.18	***0.36***	0.53	0.71	0.89
60	0.17	***0.35***	0.52	0.69	0.87

Table 3. Maximum flow rate (mg/s, 99% duty cycle, 0 PSIA backpressure). Red boxes indicate conditions for which the controller cannot quite meet maximum flow rate requirements. Underlined numbers are nominal.

	Inlet Pressure [PSIA]							
Temperature [C]	20	20.5	21	21.5	40	60	80	100
-20	5.14	5.26	5.41	5.53	10.3	15.4	20.5	25.7
-10	5.04	5.16	5.29	5.42	10.1	15.1	20.2	25.2
0	4.95	5.07	5.20	5.32	9.9	14.8	19.8	24.7
10	4.86	4.98	5.10	5.23	9.7	14.6	19.5	24.3
20	4.78	4.90	5.02	5.14	9.6	14.4	19.1	23.9
30	4.69	4.81	4.93	5.05	9.4	14.1	18.8	23.5
40	4.63	4.75	4.86	4.96	9.3	13.9	18.5	23.1
50	4.55	4.66	4.78	4.90	9.1	13.6	18.2	22.8
60	4.48	4.59	4.70	4.82	9.0	13.4	17.9	22.4

Note that the 40 psia condition is underlined because it was the baseline anticipated initial configuration of CAMFlow – being coupled with a 40 psia mechanical regulator. Maximum flow rates below 5 mg/s and minimum flow rates above 1 mg/s are highlighted in red, indicating they do not meet a rough initial requirement flow rates between 1 and 5 mg/s. With the addition of anode backpressure, both minimum and maximum flow rates may be reduced, resulting in better low flow rate conformance and worse high flow rate conformance by a small margin.

2.2. Brassboard Electronics and Control

It was necessary to provide a valve driver solution that integrated easily with Hall thruster systems expecting a proportional valve. A general valve driver board that accepts a Boolean on / off signal was a necessity, as the valves operate on a hit and hold methodology, with 12V hit and ~2V hold for reduced power consumption. This driver board is functionally equivalent to the demo board provided by Lee, except it has a fixed hit time of 5 ms. All components have rad hard equivalents for integration into future flight-like and flight units. A more complex pulsed valve board was produced to enable throttling proportional to an analog signal. Essentially, 0V input corresponds to operating at 1 Hz, minimum duty cycle (0.7%), and 3.3V corresponds to 1 Hz, maximum duty cycle (~70% for this model). The completed boards are shown in **Figure 7** and are each roughly 1 in^2. If a hall thruster PPU has sufficient timing capabilities and computational headroom, it could operate CAMFlow with only the general valve drivers. **Figure 8** shows a black box diagram of each of the valve drivers. Signals represented by a dotted line represent those which are altered by the host device, or by the driver circuit. Like the general, shutoff valve driver, the pulsed valve circuit contains all parts available in rad hard packages. Further, no microcontrollers are used, only 555 timers using R/C circuits and transistor switching.

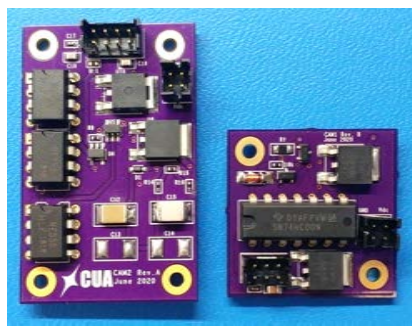

Figure 7. Fabricated CAMFlow PCB controller boards.

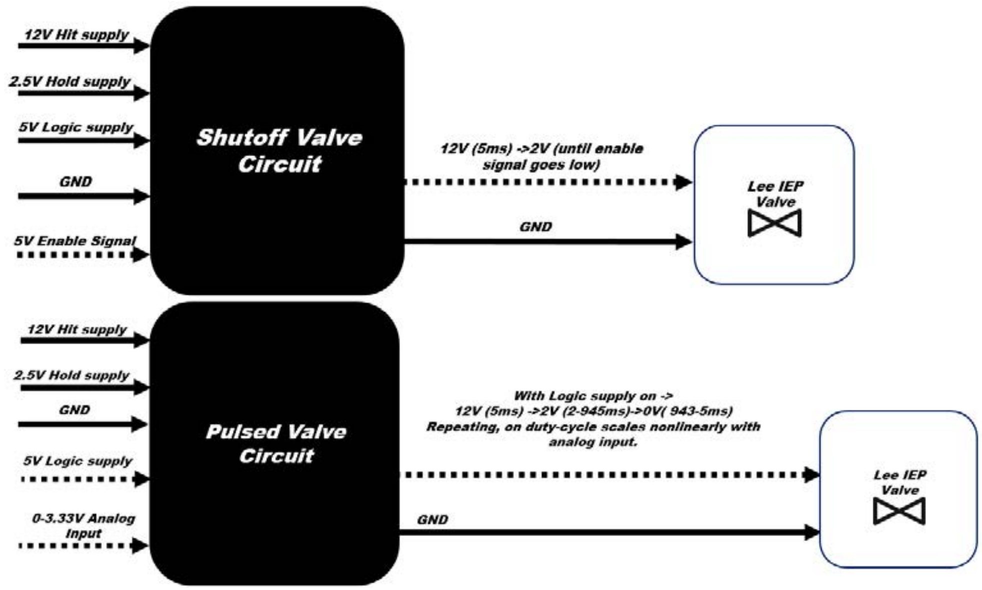

Figure 8. Black box diagram for valve driver circuits.

The key feature of the pulsed valve circuit is a nonlinear correlation between duty cycle and input voltage. While the boundaries of 0.7% and up to 95% are fixed, intermediate duty cycles are not. This is due to much of the flow controller's operation residing in duty cycles below 20%, and higher desired resolution for those cases. Not unlike the logarithmic output of an ion gauge pressure sensor, this allows an analog output device to more accurately control CAMFlow. **Figure 9(a)** compares the flow rate vs. duty cycle for CAMFlow as a function of feed pressure, and **Figure 9(b)** flow rate vs. analog voltage as a function of feed pressure, which incorporates the nonlinear correlation to provide better analog resolution.

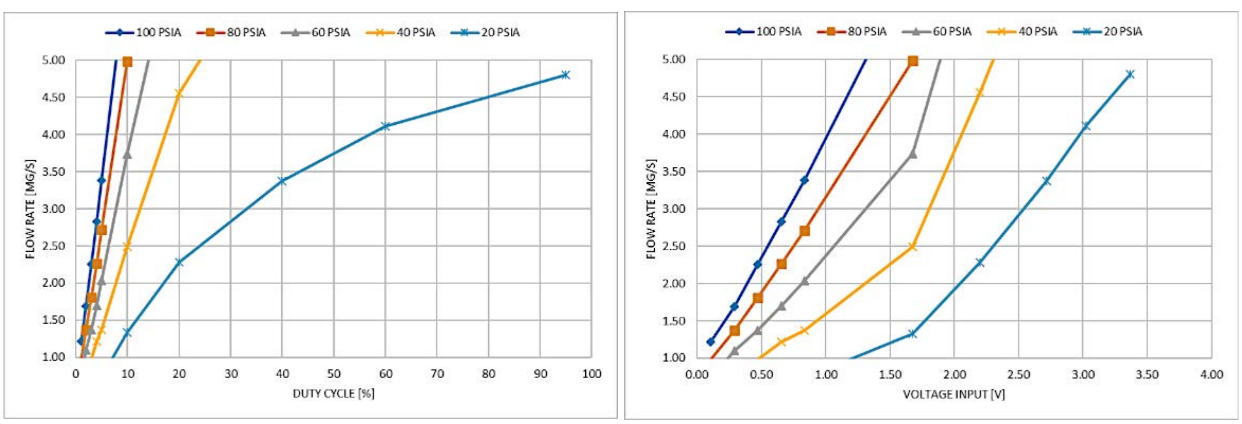

Figure 9. (a) flow rate vs. duty cycle, and (b) flow rate vs. analog input voltage.

III. CAMFlow Valve Life Testing

Given a roughly 100 kg target propellant throughput, valve life is the primary risk of the program. At 1 Hz operation point, this required 40 million valve actuations if the average flow rate is 2.5 mg/s. A device similar to CAMFlow in some ways is the µFCU from a German company called AST [Harman, 2013]. This uses a pulsed valve with a tortuous path to control flow down to the 0-5 mg/s level, but not at a fixed frequency, and is higher than 1 Hz.

The µFCU valves claim an impressive 300 million operational cycles, but with the variable frequency life it is harder to estimate.

Even with easier life estimation for CAMFlow, 40 million actuations are significant, therefore an accelerated life test was desired. A test apparatus was designed to automate the cycling process of two Lee Co. IEP valves, one with an EPDM seal and one with an FFKM seal. For convenience of automated overnight operation, dry compressed air was used as a surrogate to test the valve cycling and total mass flow. The cycling was controlled by a duplicate of one of CUA's shutoff valve drivers built for the breadboard CAMFlow system. Heat sinks were added to the valves along with a cooling fan and thermocouples. The valves were pulsed at 75 Hz, which allows for 5 ms between firings. While we did not experimentally determine the valve is fully opening and closing at this rate, the valve specification indicates sub-millisecond actuation speeds. **Figure 10** shows a pulse sequence and illustrates settling time between pulses. It also shows the hit signal followed by the hold signal.

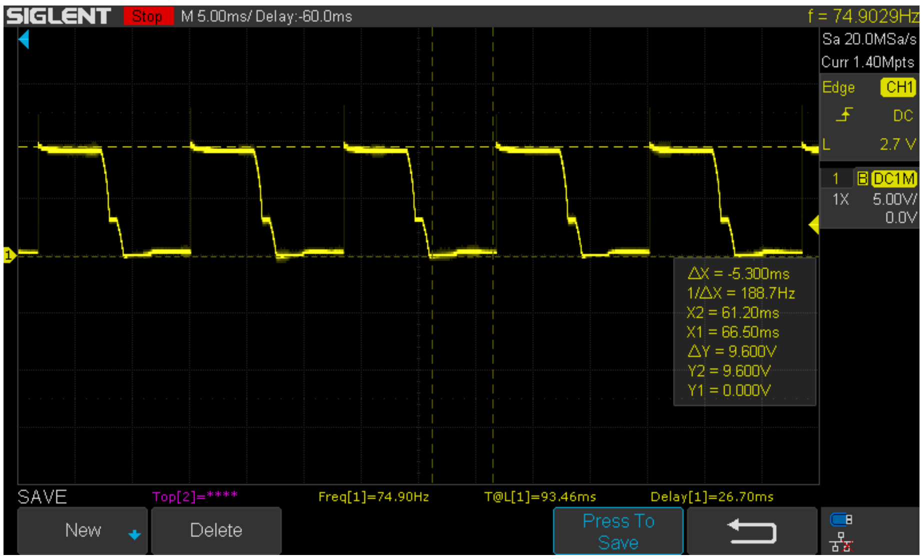

Figure 10. Pulse sequence at 75 Hz showing enough settling time for complete open-close valve actuation.

Figure 11 shows the history of leak rate of the two Lee valves in parallel. It is important to note that the two Lee valves were placed in parallel, which means that any measured leak rates represent the sum of both valves rather than the leak rate for each valve. Further, the setup utilizes compression fittings and plastic tubing, so the measured leak rate also likely includes leaks from these fittings. An advantage to this methodology was quick leak testing via a pressure blowdown method, and this did not require decoupling any fittings that could change the external leakage. It is important to note that because the CAMFlow system would be fed by a pressure management assembly (PMA) having a main shutoff valve, and has a downstream shutoff valve, it is only necessary for the CAMFlow system to maintain a leak rate that is a small percentage of the minimum thruster flow rate. As measured, this test setup maintained a leak rate of 0.19% of the minimum flow (including system leaks and parallel valves). *Overall, the valves performed extremely well for > 120 million actuations.*

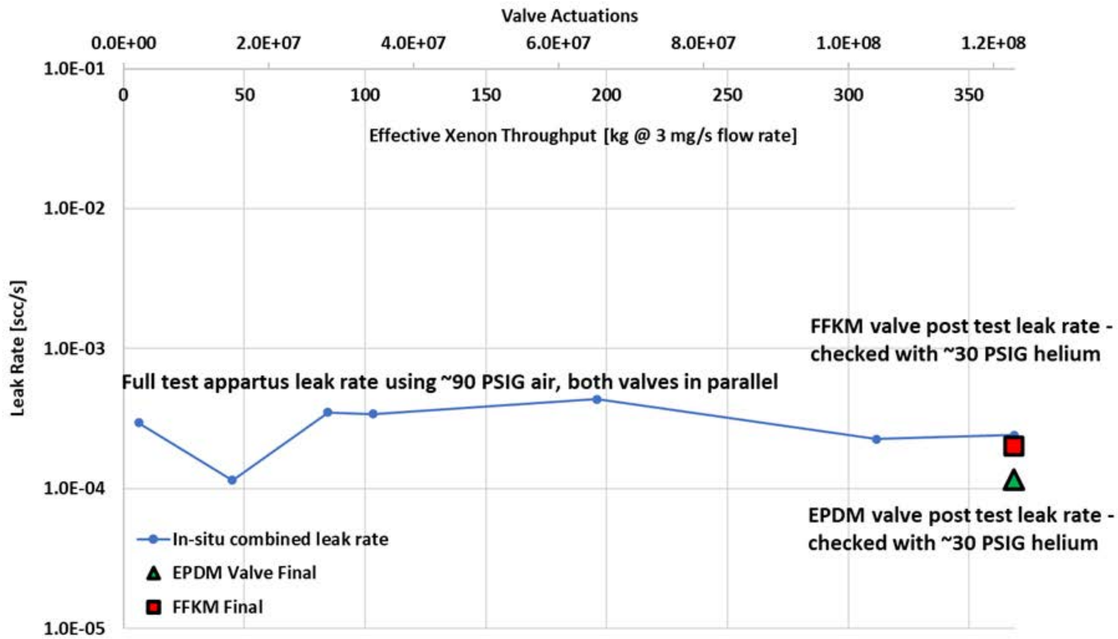

Figure 11. Measured total leak rate from two valves and fittings as a function of mass throughput and valve actuations.

When the life test was completed a final in-situ leak check was performed. This still showed no appreciable change in performance from the start of the testing. For a final check, the valves were removed from the life-test setup and connected with Swagelok fittings to a significantly smaller system consisting of a manual isolation valve, a quarter inch diameter stainless tube, and a digital pressure sensor. The internal volume of this configuration was measured by filling and draining with ethanol, resulting in 3.5 cubic centimeters. A leak check of this new system was performed via a pressure blowdown method – first capped off for a control, then with the FFKM valve, and finally with the EPDM valve. The pressure sensor data were recorded, and curve fits were created to provide an accurate pressure slope. With a 30-psig source pressure, this resulted in a leak rate of 1.77e-5 sccs for the "control" setup, 2.18e-4 sccs for the FFKM setup, and 1.33e-4 sccs for the EPDM setup. Subtracting off the baseline leak rate, the post-test helium leak rate for the FFKM valve is 2.00e-4 sccs helium and for the EPDM valve it is 1.15e-4 sccs helium. Again, it is important to note that a compression fitting was utilized to connect the Lee valve to the control setup, therefore the leak rates presented are worst case. *To within the error bar of the measurement, the measured EPDM leak rate is within the Lee Co. specification of ≤1e-4 sccs helium after >120 million.*

IV. Hall Thruster Testing with CAMFlow System

To demonstrate the ability of the CUA CAMFlow-1 XFC to operate a sub-kW class Hall thruster, the CAMFlow-1 system was sent to team partner UM to interface the developed XFC with a 600 W thruster. The experimental setup, telemetry, and results from this task are described below. The key technical objectives, which were accomplished over a week-long test campaign performed at UM, were designed to mirror the anticipated requirements for a flight like system:

1. Demonstrate XFC ability to command cold flow (thruster off) in open loop mode
2. Demonstrate ability to start thruster in open loop mode with XFC
3. Demonstrate thruster throttling with XFC in open loop mode: set flow manually in XFC software to adjust thruster current
4. Demonstrate thruster throttling with XFC in closed loop mode: set target discharge current in software and allow XFC to control to setpoint
5. Demonstrate "hard start" and shut down in closed loop mode

Large Vacuum Test Facility (LVTF)

UM employed the 6 m × 9 m Large Vacuum Test Facility (LVTF) for performing the thruster testing. It is cryogenically-pumped by 19 re-entrant helium pumps and capable of achieving an effective pumping speed of 550 kl/s on xenon and base pressure < 10^{-7} Torr. LVTF has been employed to test several forms of electric propulsion systems and basic plasma experiments over the past three decades. It is equipped with a flow manifold, break out box, power supplies, and optically-isolated telemetry system configured for operating and running Hall thrusters.

600 W Hall thruster

UM employed the 600-W class, BHT-600 Hall thruster built by Busek Co. for the systems level test. The University of Michigan owns a four-element array of BHT-600s (**Figure 12**) that were originally procured in 2005. Nominally, each thruster employs a barium oxide cathode, operates on xenon, and discharges at 200-400 V with powers ranging from 200 W to 800 W. This power range corresponds to flow rates from 0.6-4 mg/s. For this program, only one of these units was once operated and interfaced with the flow system.

Before the start of this effort, the BHT-600 cluster at UM was originally obtained in 2005 [Jorns, 2018] and had been in storage for over ten years. An initial check out test therefore was performed at UM in the first months while the XFC was being constructed at CUA. It was discovered through this test that all the cathodes in the cluster had poisoned during storage and were not recoverable. As a work around, a 20-A class laboratory LaB6 hollow cathode was substituted (**Figure 12**). The thruster was shown to operate stably over the throttling range with this cathode, and this configuration subsequently was adopted for the systems level test.

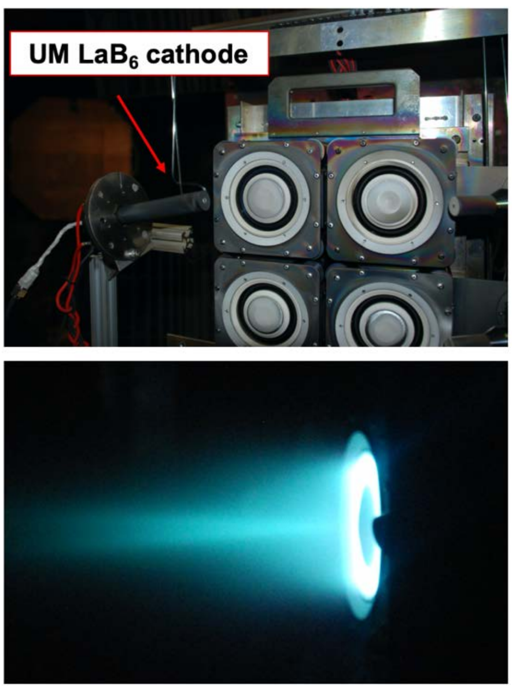

Figure 12. (Top) BHT-600 cluster at UM with the LaB6 cathode installed. (Bottom) thruster operating in UM vacuum facility.

Table 4 shows the thruster throttle points we employed for this investigation. The cathode flow fraction was 15% for all conditions. This generous split was necessitated by the fact that the replacement LaB6 cathode was not designed to operate at the standard 8% flow rate used when the thruster runs with its nominal cathode. We also note from this table that the flow rate and discharge current are linearly related. This is consistent with most state-of-the-art (SOA) Hall thrusters.

Table 4. BHT-600 throttling points in this test series. The cathode flow fraction was 15% for all conditions.

Voltage	Current [A]	Power [W]	Anode mass flow [mg/s]
300	2	600	2.53
300	2.2	660	2.67
300	2.5	750	2.98
300	1.8	540	2.23
300	1.5	450	1.88
200	3	600	3.4
200	3.3	660	3.67
200	3.8	760	3.95
200	2.7	540	3.11
200	2.2	440	2.58
400	1.5	600	1.69
400	1.7	680	2.15
400	1.9	760	2.38
400	1.3	520	1.53
400	1.1	440	1.50

Flow system

UM has a dedicated flow manifold that regulates high pressure (800 psi) xenon through commercial flow controllers to deliver gas to thruster test articles inside LVTF. This laboratory flow system was used for the initial thruster checkouts. For the integrated test, the laboratory flow controllers were bypassed, and the CUA CAMFlow-1 controller was installed in series with two lines—one for the anode and one for the cathode (**Figure 13**). The input pressure to the CUA was regulated down from the Xe bottle to 30-40 psi. Two pressure transducers also were installed on the anode and cathode lines immediately adjacent to the thruster.

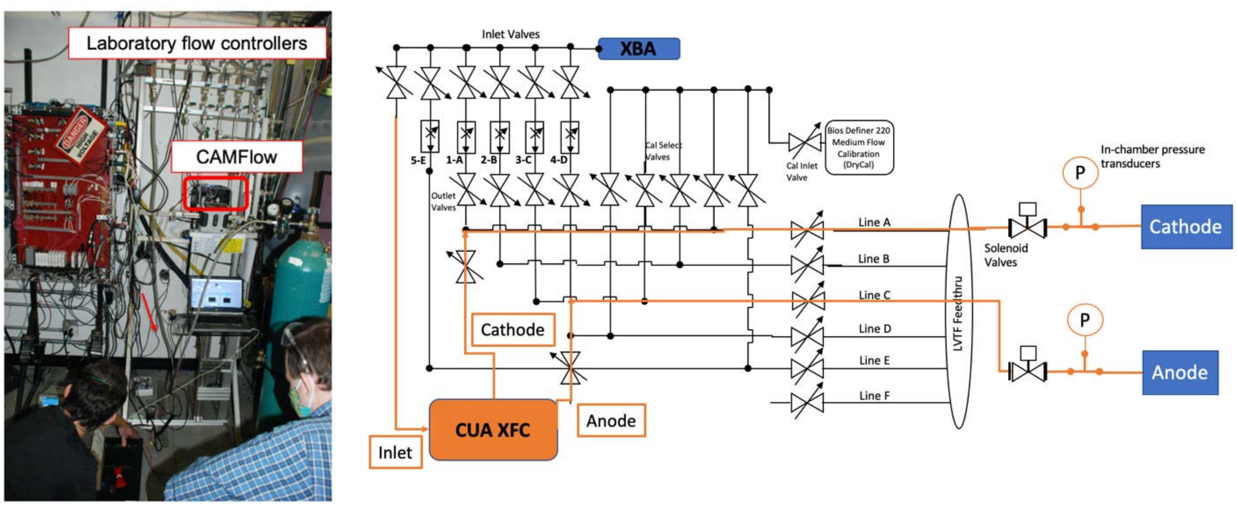

Figure 13. (Left) CUA XFC (CAMFlow-1) system integrated into the laboratory flow manifold at UM. (Right) Schematic of UM flow system showing where the CUA system was located. Lines for the cathode and anode flow were utilized

Power supplies

The thruster was operated on laboratory power supplies located at UM. The discharge power supply consisted of a Magna-power electronics 60 kW system with a maximum output voltage of 1000 V. The power for the cathode heater, keeper, and electromagnets was provided by a series of TDK Lambda power supplies.

Telemetry system

Telemetry was monitored in two ways during the systems level test: through the UM in-house data-logger---an optically isolated telemetry system---and with a control computer provided by CUA. The data reported here is from the CUA measurements. Key telemetry included the thruster discharge current, the flow rate, and the discharge current set points for the controller. **Figure 14** shows the I/O layout for the flow controller. The discharge current feedback was provided from a current shunt measurement located in the UM's facility breakout box.

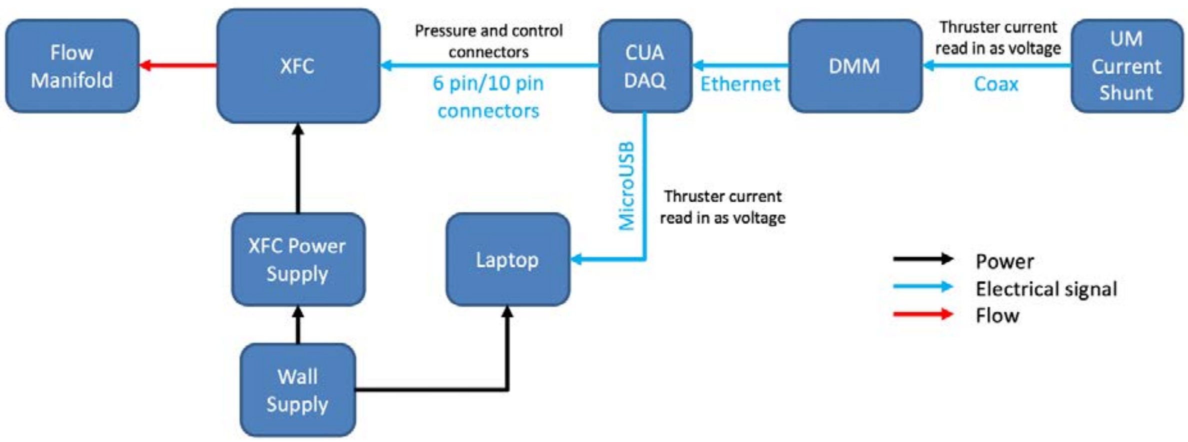

Figure 14. I/O configuration for the CUA CAMFlow controller (XFC) during the system integrated test.

Results of Thruster Testing with CAMFlow

The systems level test was completed at UM over one week of testing. The CUA XFC was delivered to UM and integrated with the laboratory flow system by UM personnel. This process was supervised by CUA through video conference. *The first three objectives were demonstrated in the first two days of testing.* It was shown that the XFC could operate in open-loop mode, serving the same function as a standard laboratory flow controller. We were able to adjust the flow rate in a controlled way and in turn start the thruster and throttle the discharge current over the conditions shown in **Table 4**.

In the remaining part of the test, we focused on demonstrating the capabilities of the XFC operating in closed loop mode. In this case, we commanded a set point for discharge current, and the controller employed a PID feedback loop to adjust flow to the thruster (which scales linear with discharge current) until this set point was achieved. We show in **Figure 15** the results of the closed loop test. This depicts the set point as commanded to the thruster and the corresponding measured discharge current. Not shown for brevity, but the data also showed how the discharge current and flow rate were directly linked during thruster operation.

At the beginning of the test, the thruster was started and outgassed in open loop mode. This is why the set point in **Figure 15** is zero for the first 30 minutes of testing. After this point, the closed loop was engaged. As can be seen here, the controller initially was poorly conditioned. This is because the flow controller's PID settings originally had been configured during benchtop testing at CUA where the simulated flow manifold had significantly less volume than the laboratory flow system at UM. The controller's response at first therefore was too fast for controlling the thruster. Over the next 30 minutes, as shown in **Figure 15**, the PID settings were systematically adjusted to slow the controller response.

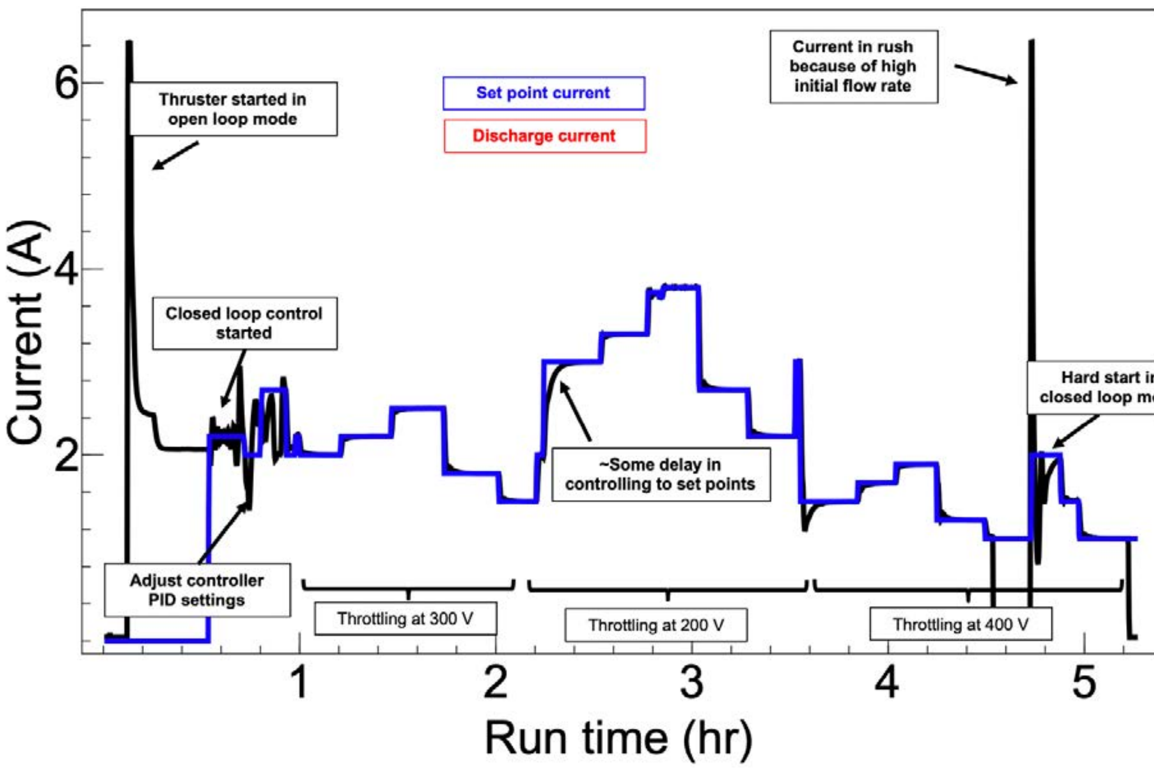

Figure 15. Telemetry from closed loop test. The commanded discharge current set point and the measured discharge current are shown.

Once the new settings were established, the set point was systematically adjusted over the next 3.5 hours of run time to demonstrate the ability to throttle across all of the operating conditions shown in **Table 4**. In all cases, the thruster and controller operation both remained stable. **Figure 16(left)** shows in finer detail one of these changes in the set point. As can be seen, the controller was able to stably achieve the set point, though the response was slightly underdamped and required 1-3 minutes of settling time. This response time could have been reduced with additional adjustment, though it was deemed sufficiently short for this Phase I proof of concept.

After successful demonstration of controlled throttling (Objective 4), the thruster was shut down 4.5 hours into the run, and a hard start was performed in closed-loop mode. This is shown in finer detail on the righthand side of **Figure 16(right)**. In this case, no voltage was applied to the thruster, but the discharge current setpoint was commanded to 1 A. The controller responded by opening the flow fully to the thruster. The voltage was then applied and the thruster “hard-started” leading to an inrush in current. *Objective 5 was demonstrated by the controller responding successfully and stably, reducing the flow to achieve the nominal discharge current set point.*

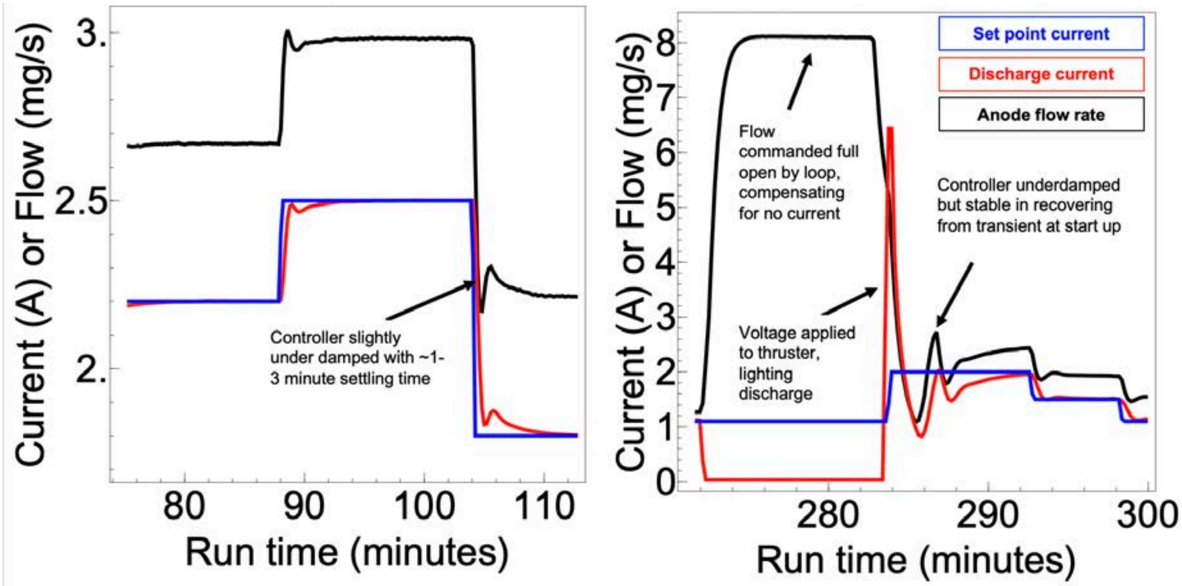

Figure 16. (Left) Zoomed in view of a controlled transition in the discharge current set point. (Right) Zoomed in view of a controlled hard start.

As a final result, we show in **Figure 17** the discharge current and the flow rate during the systems level test. This illustrates the same features as shown in **Figure 15**; however, we explicitly see here how the discharge current and flow rate were directly linked during thruster operation.

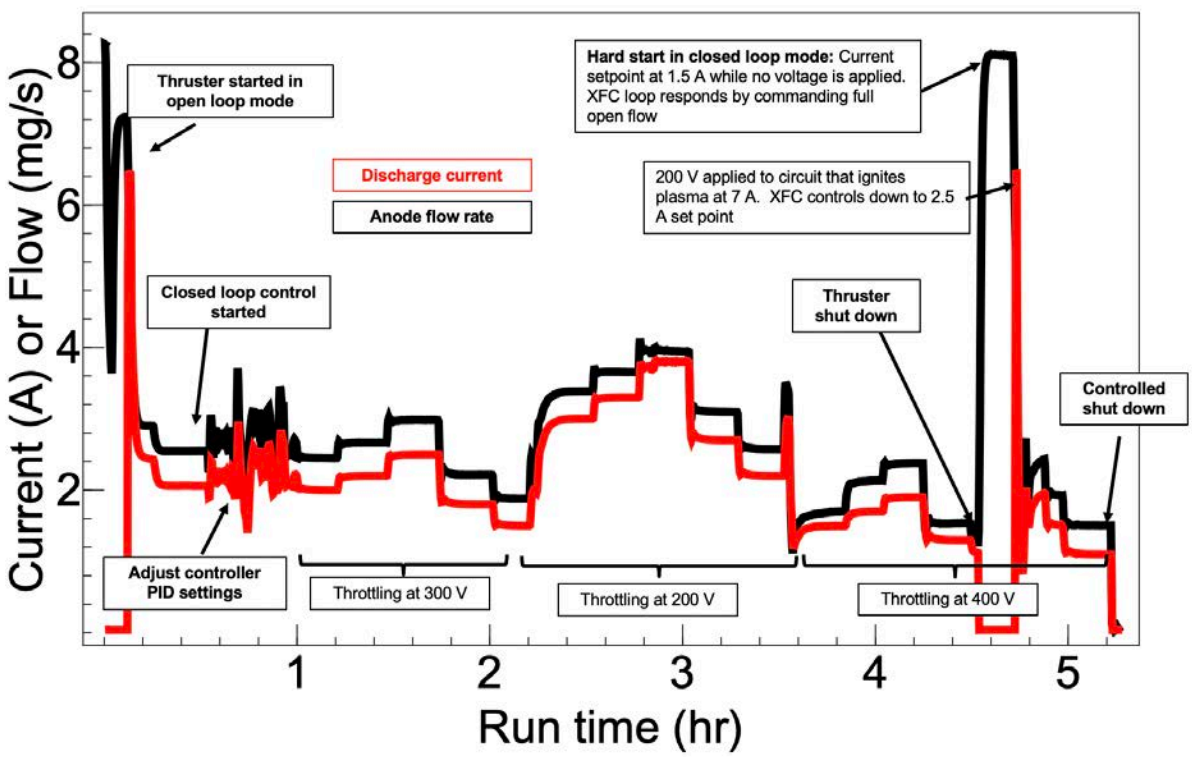

Figure 17. Telemetry from closed loop test. The commanded flow rate and the measured discharge current are shown.

V. Design and Fabrication of Compact CAMFlow-2 System

NASA's Jet Propulsion Laboratory (JPL) and multiple manufacturers of Hall thrusters expressed strong interest in the addition of a PMA to our core CAMFlow technology. As such, CUA included the development of PMA technology into the system built for JPL. There is an appropriate Lee Co. direct acting solenoid valve that can handle the desired pressure rating for the propellant tank and our preliminary PMA design and hardware build was based upon that valve. A flow schematic of the CAMFlow-2 system built for NASA's JPL is shown in **Figure 18**. The CAMFlow-2 design also includes redundant parallel valving to reduce risk of valve failure and thereby having increased reliability. Since the valves themselves are relatively inexpensive, the addition of redundancy was viewed as an opportunity to provide greater value/reliability and lower risk to the customer at a relatively marginal price increase. Further, an advantage to the redundant valves is that the flow rate can be increased if all valves are operating simultaneously.

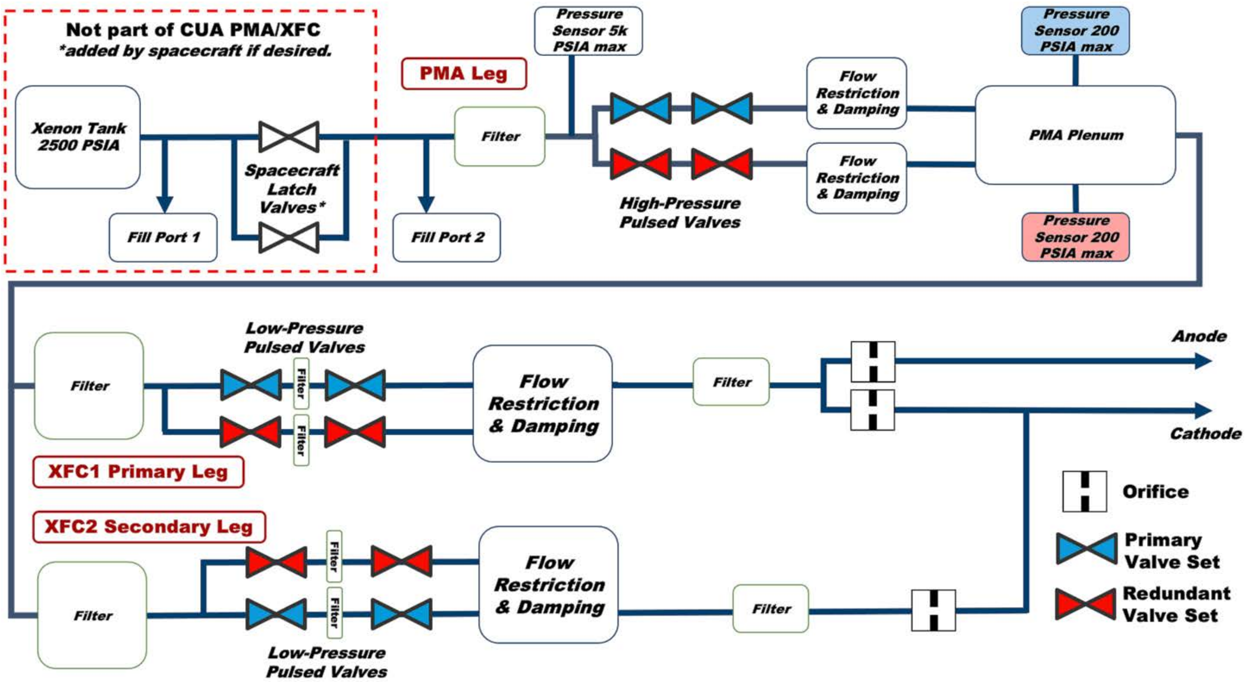

Figure 18. CAMFlow-2 system including 1 PMA and 2 XFCs built for JPL with all volumes & orifices and a 9% cathode-anode flow split.

A hardware scheme was used for the PMA leg as for the primary XFC leg; however, the control scheme is simplified. Furthermore, the PMA will not require nearly the same number of actuations as the CAMFlow XFC because the CAMFlow system is already designed to accommodate varying source pressure. Functionality (before redundancy) can be achieved by a single high-pressure valve, high pressure orifice, and small low-pressure plenum. Leveraging the ability of CAMFlow to accept input pressure transients, the low-pressure tank is refilled and drained with minimal logic – refilled to a setpoint when a minimum pressure threshold is reached. This is repeated until end of life. The maximum pressure rise time has been initially set to ~10 seconds, what should be approaching the maximum control authority of CAMFlow. As the high-pressure storage tank blows down, this rise time decreases to the benefit of CAMFlow. Blowdown time is consistent, and presently tuned to roughly 20 minutes. Given a delta propellant mass of ~5 grams between refilling, this equates to 20,000 valve actuations for every 100 kg propellant. A high-pressure valve also from Lee is under consideration for future CAMFlow models with a rated 100,000 valve actuations.

CUA's simulation tool was used to model the PMA. **Figure 19(left)** shows the fill and blowdown characteristics of the PMA at different high pressure storage tank pressures, assuming CAMFlow is drawing 5 mg/s. **Figure 19(right)** shows a close-up view of the recharge from the 40 psia threshold pressure. Note that the timings are slightly different among source pressures; this is a result of the volume between the valve and the orifice.

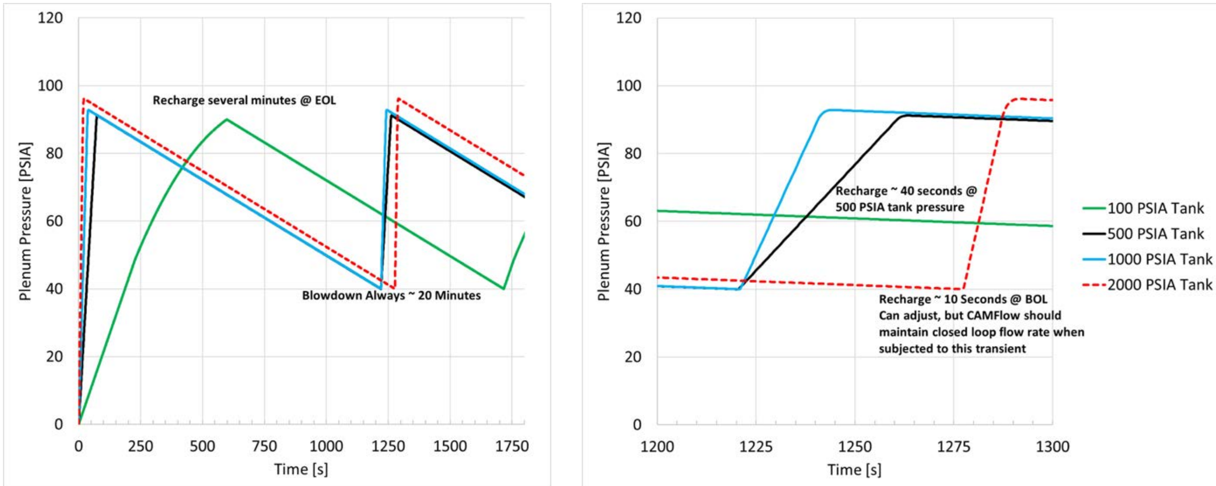

Figure 19. Pressure versus time fill and blowdown simulations of functional diagram of PMA schematic shown in Figure 18. (Left) complete cycle, (Right) close-up view of recharge from 40 psia.

A solid model design of the all-welded compact CAMFlow-2 unit delivered to JPL is shown in **Figure 20** and the actual hardware is shown in **Figure 21**. The electronics boards are located between the XFCs and PMA behind cover plates. The XFC and PMA materials are all stainless steel while the brackets and cover plates are aluminum. Excluding the mounting brackets and extended tubing, the dimensions are 113 mm x 115 mm x 170 mm (2.2 liters) for the entire package containing two XFCs and one PMA. It should be noted that there is a lot of available open volume in the CAMFlow-2 package and the next iteration should further reduce in size to ~1.5 liters. System performance information is provided in **Table 5**.

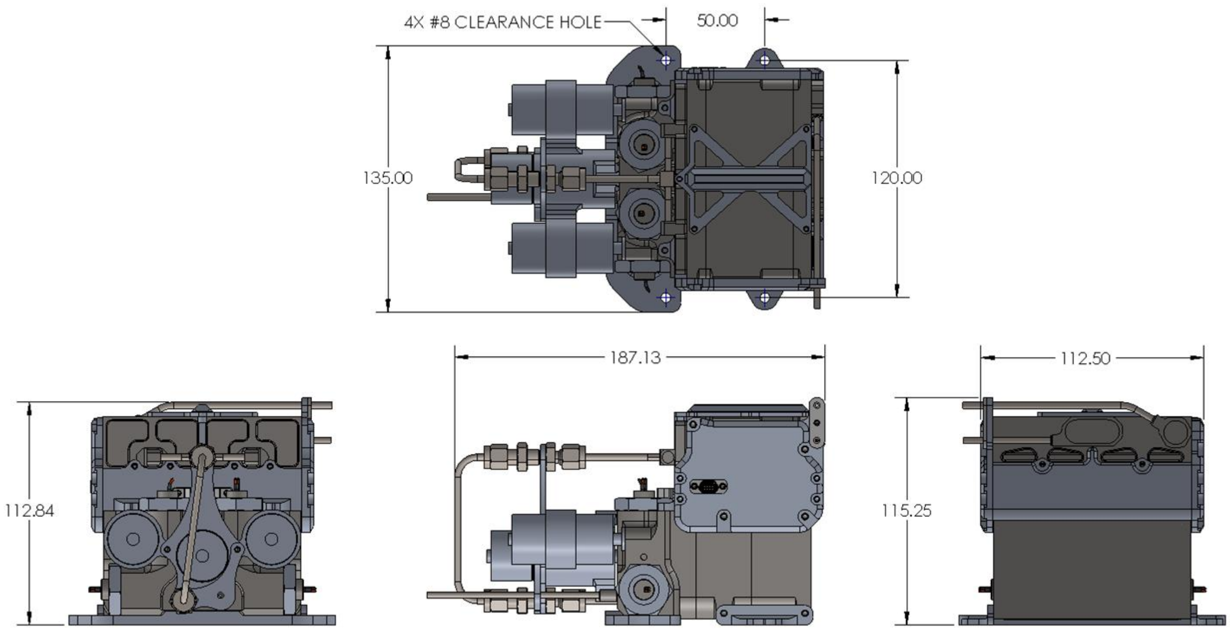

Figure 20. Dimensions of the baseline CAMFlow-2 unit. The large PMA pressure sensors can be substituted with smaller higher cost sensors as desired to shrink the size. Future versions will be further compacted, and remaining fittings replaced with welded tube connections. [Units are mm].

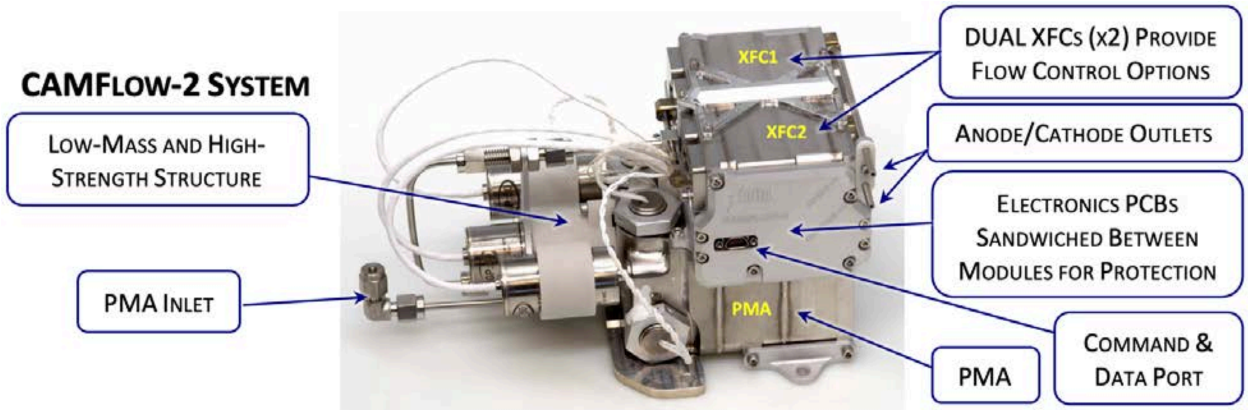

Figure 22. The CAMFlow-2 system with mass of 2.2 kg consists of multiple modular sections: (1) the Pressure Management Assembly (PMA) accepts up to 2,500 psia of input pressure; (2) the primary Xenon Flow Controller (XFC) controls the output flow rate to < ±3%; and (3) a secondary, optional XFC provides an initial boost to the cathode flow leg and allows operation with heaterless cathodes.

Table 5. CAMFlow-2 performance information.
[*Fixed setpoint (customer option), †Requires second XFC]

CAMFlow-2 Performance	PMA	XFC
Anode Flow Rate [mg/s]*	0 – 8	0 – 8
Flow Split to Cathode*	N/A	0 – 15%
Heaterless Cathode Start Flow Rate†	0 – 8	0 – 8
Flow Pressure Variation at Outlet	100 +20/–80	< 3%
On/Off Cycles	> 20,000	> 1×10^6
Inlet Pressure [psia]	40 – 3000	40 – 100
Outlet Pressure [psia]	40 – 100	< 2
Total Throughput [kg]	>100	>100
Working Gases (others possible)	Xe, Kr	Xe, Kr
Gas Cleanliness – Inline Filter [μm]	10	10
Mass [kg]	1.5	0.7
Volume [liters]	0.7	0.4
Internal Leakage [scc/s of He]	< 1×10^{-4}	< 1×10^{-4}
External Leakage [scc/s of He]	< 1×10^{-6}	< 1×10^{-6}

Preliminary acceptance testing of the CAMFlow-2 system was completed and the system delivered to JPL. More detailed performance and environmental characterization testing of the CAMFlow-2 system still needs to be performed.

VI. Concluding Remarks

CUA's CAMFlow system is a highly reliable, fixed-frequency flow controller for electric propulsion systems. CAMFlow uses an innovative control scheme that enables stable operation, even for the low flow rates necessary for sub-kW Hall effect thrusters. This methodology reduces system complexity, places the onus of reliability on valve cycle life, and allows for a direct correlation between system life and valve cycle life. The CAMFlow-1 system was assembled and sent to UM for testing. Additionally, during this work, two Lee Co. IEP control valves were cycled >120 million pulses (the equivalent of 350 kg Xe throughput at 3 mg/s) while maintaining a very low leak rate of approximately 1e-4 sccs helium.

The CAMFlow control scheme was successfully tested and validated on a 600-Watt Hall thruster at UM. This included open loop, closed loop, and cold cathode "hard" start operations. All the planned objectives for the

CAMFlow-1 systems level test were met during this effort. UM successfully demonstrated the ability of the developed flow controller to integrate in a laboratory setting with a low power Hall thruster and to control its operation. This work also served to highlight potential paths for improving the technology's maturity including:

- Optimizing the feedback loop for a flight-like configuration. This will require moving the controller close to the thruster—as might be found in a small spacecraft bus---to reduce overall line capacitance
- Adjusting the start-up and shut down sequences to limit current in rush and transients
- Testing the system in a relevant environment, e.g., in vacuum and with realistic thermal loads.

The CAMFlow-2 system was designed and fabricated for JPL. This compacted system includes a PMA leg and two XFCs, the second XFC used for heaterless cold start in Hall thruster systems such as MaSMi and ASTRAEUS. Preliminary acceptance testing of the CAMFlow-2 system was completed, but more detailed performance and environmental characterization testing of the CAMFlow-2 system still needs to be performed.

While CAMFlow units are presently focused on smaller Hall-effect or gridded-ion electric propulsion systems having a flow rate in the 0 – 8 mg/s range, the technology is scalable and can be adapted for a large range of flow rates. Future versions of the electronics boards can be mounted directly to the CAMFlow unit or could be incorporated with the PPU for the propulsion system. For deep space missions the electronics would need to be in an enclosure for protection and radiation hard components would have to be chosen. Thermal analyses will likely influence the placement of the electronics. The packaging of the CAMFlow system elements is flexible and ultimately it will be the customers who will drive the preferred electronics placement and packaging.

A follow-on NASA-funded Phase II STTR effort is now underway to further mature the CAMFlow system and technology. The primary technical objectives of Phase II are to prove stable, reliable operation of a flight-like XFC+PMA control system, obtain detailed performance data from a UM Hall thruster, perform thermal modeling, and to design, assemble, acceptance test (including environmental testing), and deliver a compact integrated TRL 6 CAMFlow system.

VII. Acknowledgments

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