# Monofilament Vaporization Propulsion (MVP) Flight-like System Performance

## IEPC 2022-575

*Presented at the 37th International Electric Propulsion Conference*
*Massachusetts Institute of Technology, Cambridge, MA USA*
*June 19-23, 2022*

Curtis A. Woodruff[1], Magdalena Parta[2], Darren M. King[3], Andrew L. Woodruff[4],
Rodney L. Burton[5], and David L. Carroll[6]
*CU Aerospace (CUA), Champaign, IL 61822*

**Abstract: CU Aerospace (CUA) has developed an electrothermal thruster which consumes an inert polymer filament propellant and which has been tested to TRL 6. This technology retains performance characteristics competitive with other warm gas systems, but enables more accessibility to micropropulsion via dramatically reduced cost and the elimination of range safety concerns. CUA's Monofilament Vaporization Propulsion (MVP) draws from extrusion 3D printer technology to feed and melt polymer propellant in preparation for evaporation and heating to > 900K in a micro-resistojet. The base design uses Delrin™ propellant that is spooled inside a 1U package. Despite undergoing depolymerization and two separate phase changes, the system power requirements are manageable (operating at 13.5 W average power draw with 45 W peak power when firing), demonstrating a "flight-like" system design thrust of 4.5 mN, and a specific impulse of 66 s. A 180% life-test of a prototype superheater unit was successful. A 100% life-test of the flight-like propellant feed subsystem was also successful. The MVP flight-like unit demonstrated stable, reliable operation, including the ability to restart consistently without plugging. Off-design conditions can decrease thrust for specific impulses exceeding 100 s at the expense of thruster lifetime. The 1.1U flight-like system performance exceeds 330 N-s total impulse for the life tested conditions. Straightforward design improvements recognized during the flight-like unit testing were made on a follow-on "flight" MVP system to increase performance and efficiency. A 0.93U MVP with 280 N-s of total impulse is being integrated for flight on CUA's NASA-funded Dual Propulsion Experiment (DUPLEX) CubeSat, presently manifested for launch in Q1 2023. CUA sees MVP technology as a compelling option to meet many micropropulsion needs including collision avoidance maneuvers, limited orbit raising/lowering, drag makeup, and deorbiting.**

## I. Introduction

Several liquid propellant CubeSat propulsion systems exist today having a range of TRLs with the goal of providing moderate $I_{sp}$ and high specific thrust in a compact form factor. Unfortunately, the expense involved with pressure vessels and valving, along with range safety requirements, has limited the use of these liquid propellant systems. Affordable micropropulsion systems for CubeSats are desired to provide a "responsible space" option to existing and future satellite manufacturers, especially for collision avoidance and deorbiting to help avoid the escalation of the growing orbital debris problem.

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[1] Senior Engineer, woodruff@cuaerospace.com, AIAA Member.
[2] Staff Engineer, magda@cuaerospace.com, AIAA Member.
[3] Laboratory Director, king@cuaerospace.com, AIAA Senior Member.
[4] Staff Engineer, alwoodruff@cuaerospace.com.
[5] VP for Research, burton@cuaerospace.com, AIAA Associate Fellow.
[6] President, carroll@cuaerospace.com, AIAA Fellow.

Propulsion systems for CubeSats are evolving with a wide variety of thrust, specific impulse, and power draw levels and corresponding trade-offs, but still very few have flown to date. A good summary of CubeSat propulsion systems through 2016 is provided by Lemmer [2017]. Monofilament Vaporization Propulsion (MVP) is an effort by CUA (Champaign-Urbana Aerospace) to increase availability and ease of launch for CubeSat propulsion. Liquid propellant systems with pressurized vessels and valving are costly and may not be accepted by range safety. One potential option dating back to the earliest electric propulsion systems, the PPT, is not always applicable as the high specific impulse results in a low specific thrust, not to mention the inherently low electrical efficiency. MVP is an electrothermal system, rather than electromagnetic, using modified subsystems from extrusion based 3d printing to store and flow large quantities of polymer propellant in filament form. The propellant, polyoxymethylene (POM, tradename Delrin), has a high storage density of 1.4 g/cc (at demonstrated 89% packing factor when spooled). Furthermore, it is a low outgassing plastic already used in space applications. Current efforts aim to package the technology in a 1U propulsion system, providing approximately 300 N-s total impulse.

## II. Technology Description

### *2.1. Hardware Design*

MVP development focused on four major subsystems: propellant storage, a mechanical feed system, temperature-controlled extruder, and a micro-resistojet superheater. Propellant is stored on a spool, and fed with a mechanical feed into a temperature-controlled extruder to melt the propellant. All of those subsystems are already available as commercial-off-the-shelf (COTS) parts for 3d printers, and were utilized in development and testing. The evaporation and heating of the propellant had more inherent risk, as it is a new process. **Figure 1** shows a system block diagram with the four major subsystems. Detailed descriptions will follow, going from "cold" filament to "hot" exhaust. A render of the flight hardware is shown in **Figure 2** with a transparent casing illustrating how the Delrin propellant fiber is spooled around the core in which the propellant is fed, extruded (melted), and vaporized.

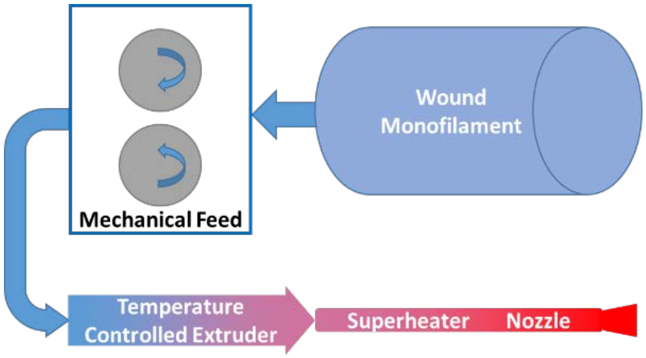


**Figure 1. Schematic of the MVP system.**

**Figure 2. Solid model rendering of flight-like MVP assembly. Note that the outside housing is rendered as a clear plastic, whereas the actual unit will have an aluminum housing.**

### *Feed and Storage*

Proof of concept for the spooled propellant storage was completed early in the Phase I program. MVP utilizes a fixed spool, and the feed rate is relatively small, so that torques on the spacecraft are minimized. Propellant is unspooled towards the back of the thruster in a manner similar to an open-faced fishing reel, and it is then drawn back through the spool core, where the rest of the subsystems are located, **Figure 2**.

An experiment using a COTS 3d printer feed motor helped define internal tolerances for the 1U system. A propellant load was unspooled without tangles or binding [Woodruff, 2018; Woodruff, 2020]. The motor is located inside the spool, and thrust is along the axis of the spool. A COTS geared brushes motor with vacuum lubricant options fits within the core of the system and drives the propellant. The prototype flight-like feed system is shown in **Figure 3**. Testing revealed that it was important to have a "standard" (non-thin-film) space-rated lubricant fill in the gearbox to achieve 100% life. It has demonstrated successful propellant fiber feed and draws less than 0.5 W.

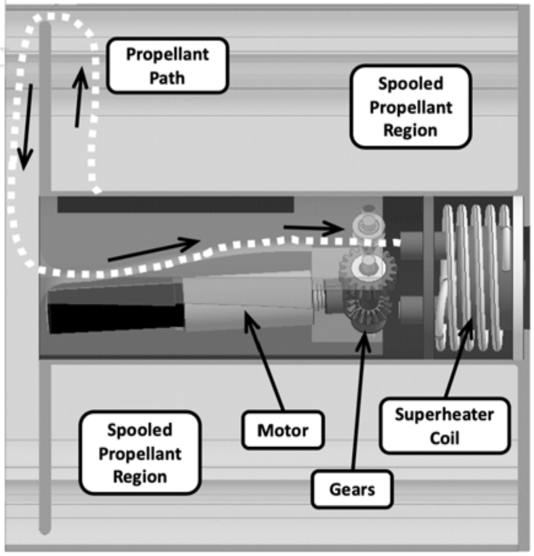


**Figure 3. Illustration of the internal packaged MVP layout showing spooled propellant region around core body, the coiled superheater, feed motor, gears, and propellant filament feed path to enter the melt block upstream of the superheater.**

*Melt and Evaporation*

Extrusion 3d printers use the mechanical feed to push propellant through a barrel into a heated nozzle. The barrel contains a thermal gradient wherein the propellant melts. After melting, a 3d printer uses a nozzle to dispense the melted polymer for printing, but MVP directly couples a resistively heated tube to further heat and evaporate the propellant. This "superheater" is based upon CUA's CHIPS micro-resistojet technology [Hejmanowski, 2015; Hejmanowski, 2016; Hejmanowski, 2018]. A diagram showing the transition is shown in **Figure 4**. These components, along with the drive motor can be seen in **Figure 3** and in the breadboard apparatus used for thrust stand testing, **Figure 5** [Woodruff, 2018].

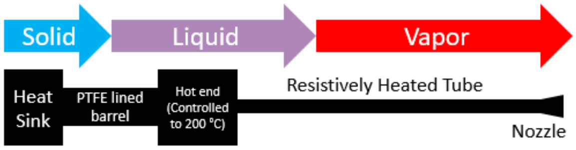


**Figure 4. Phase transition in MVP.**

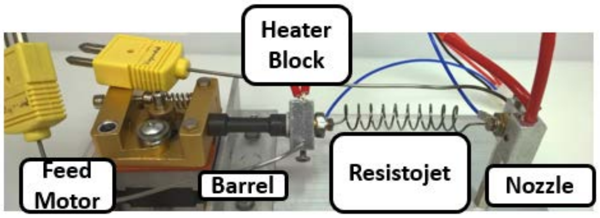


**Figure 5. MVP breadboard test apparatus.**

## 2.2. Flight-Like Hardware Design

The flight-like feed system was designed to have significantly more COTS parts. Wire-locking fasteners were added throughout and connections to the superheater assembly were refined. **Figure 6** shows the spool core with electronics mock-up, ceramic mounting plate, and the new rear bulkhead (transparent cyan) behind the coiled superheater tube. **Figure 7** shows these components installed inside the spool and propulsion system housing. Several parts will be 3D printed in aluminum as the complexity of the part and tolerances are well suited for 3D metal printing shop capabilities. A final CAD render was produced and is shown in **Figure 2.** The illustrated clear body is not used for flight units, but could be used in the future as a show model.

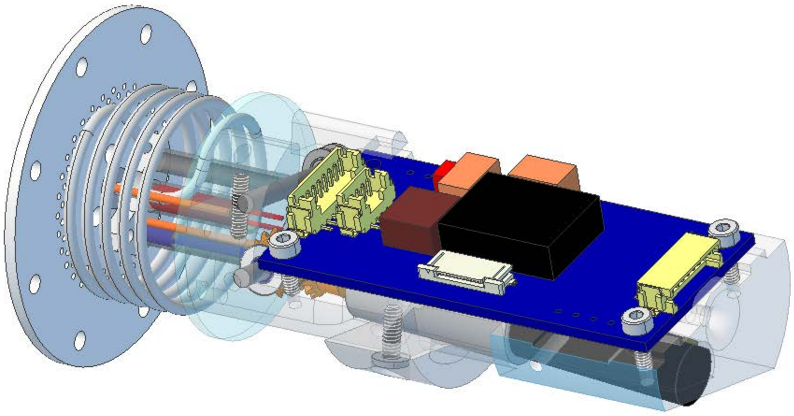


**Figure 6: Final assembled core design (PCB side shown). PCB screws are vented and will be staked.**

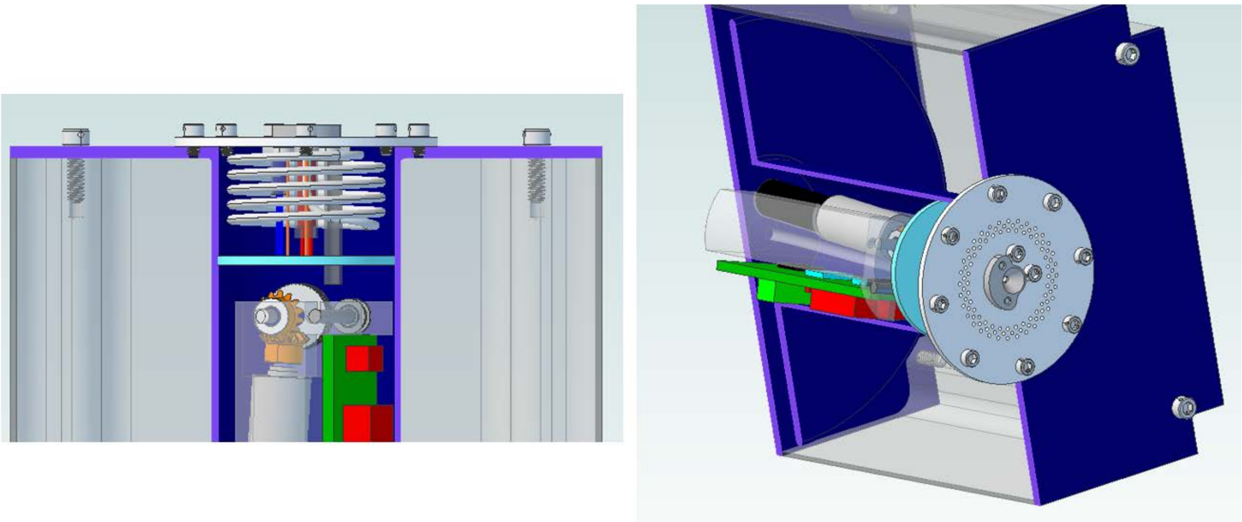


**Figure 7. Components within spool and housing.**

## III. MVP Flight-Like Hardware and Operating Characteristics

### *3.1. Fabricated Flight-Like Hardware*

Based upon life test experiments and nozzle modeling results, the micro-nozzles were designed having a 0.042” throat. To best accommodate readily available tooling, the half angle of the micro-nozzle is 41° degrees, which is still within the optimal region suggested by the BLAZE modeling [Woodruff, 2018]. The large half-angle nozzle is more optimal for low mass flow rate nozzles to minimize the impact of boundary layer effects [Williams, 2017; Woodruff, 2018]. The fabricated nozzle part is shown in **Figure 8**.

**Figure 8: Fabricated micro-nozzle installed in the ceramic insulator plate and MVP housing: (left) shown with a coin for scale, and (right) shown with light shining through backside to illuminate the installed superheater assembly behind the nozzle.**

**Figure 9** shows a photograph of the completed core assembly (see **Figure 6** for comparison with the solid model design) and the machined aluminum fiber spool into which the core assembled is mounted.

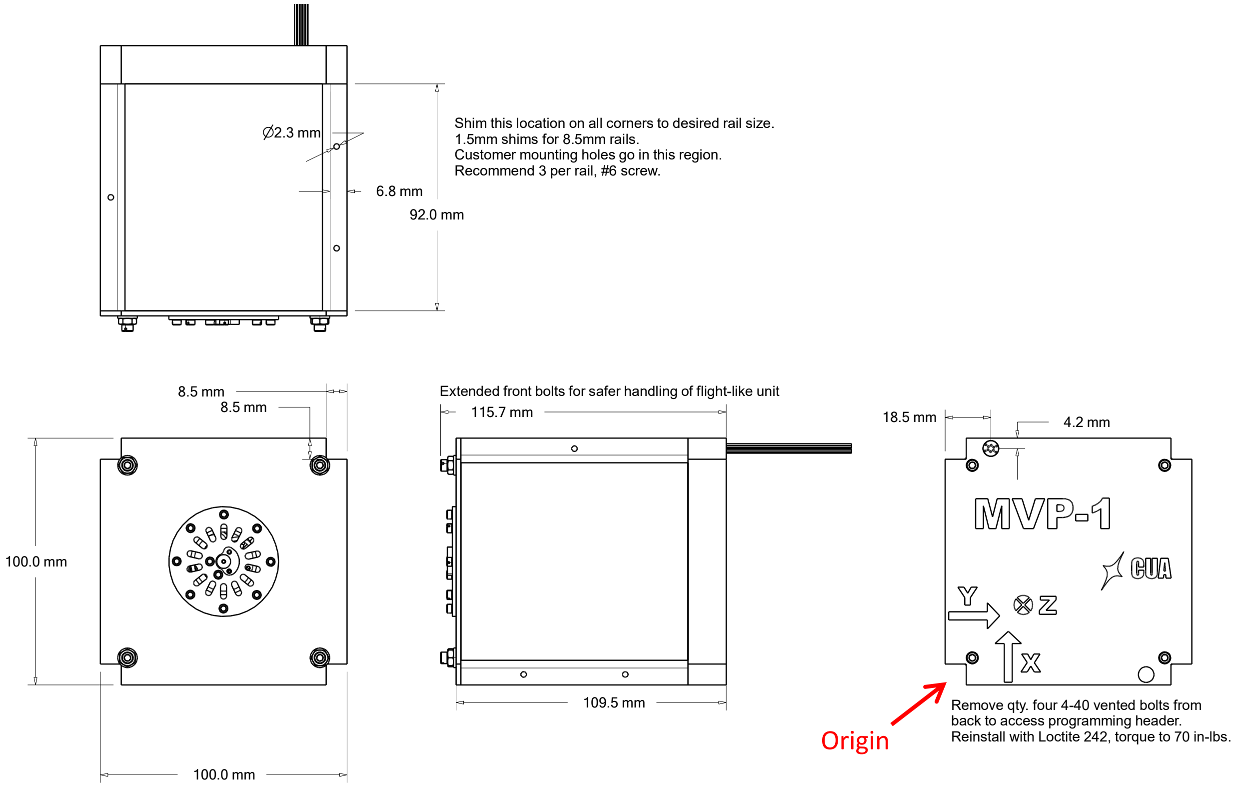
**Figure 9. Final core assembly (left side of image) during insertion into and integration with fiber spool (right side of image).**

Testing of the original integrated unit having a simple flat back plate (as illustrated in **Figures 2, 3, and 7**) unveiled a propellant feed issue. The 6.2 mm gap between the back rim of the spool and the flat backplate created a turn (bend) radius for the propellant filament and into the core assembly that proved to be too small, and the filament stuck early in the life testing of the integrated unit. This issue was resolved by changing the simple 2 mm thick backplate into a 15.5 mm back-housing and including a torus-shaped propellant guide attached to the back end of the circular spool rim to increase the bend radius. While the thicker back-housing adds length to the overall MVP thruster system, it still fits within the 130 mm length permitted by the standard CubeSat specification. The final MVP integrated "flight-like" unit is shown in **Figure 10** and subsequent testing proved that the propellant feed issue was resolved. Dimensioned drawings of the unit exterior are shown in **Figure 11**.

After assembly, the flight-like unit was inspected and passed. An ambient functionals check procedure was established that checks for proper current draw, heater operation, superheater operation, and data streaming. Basic electrical ambient functionality was confirmed before sending for vibration (**Section 4.1**) and thermal-vacuum testing (**Section 4.2**). The ambient functionals procedure checked functionality of all subsystems.

**(a) Front** **(b) Side** **(c) Back**

**Figure 10: Photographs of the fully assembled MVP flight-like thruster showing the (a) front, (b) side, and (c) back including the electrical wire harness that is located at a back corner of the housing. Note that the "Origin" is located at the virtual corner of the system, where the corner notch is cut out for mounting.**



Shim this location on all corners to desired rail size.
1.5mm shims for 8.5mm rails.
Customer mounting holes go in this region.
Recommend 3 per rail, #6 screw.

Extended front bolts for safer handling of flight-like unit

Remove qty. four 4-40 vented bolts from back to access programming header.
Reinstall with Loctite 242, torque to 70 in-lbs.

**Figure 11: Dimensioned drawings of external housing. Note that the "Origin" reference point for center of gravity measurements is located at the virtual corner of the system, where the corner notch is cut out for mounting to 3U rails.**

### *3.2. Fabricated Hardware Center of Gravity Measurement*

Center of gravity (CG) measurements were made on the MVP flight-like unit for both the dry (no propellant) system and the fully loaded wet mass, **Table 1**. The axes and "origin" position are marked in the "back" side photograph shown in **Figures 10c** and **11**. The geometric center is located at +1.9685" in the X- and Y-axes and +2.2776" in the Z-axis from the "origin" corner position. When the MVP unit is dry, the CG offset in the +X direction is an artifact of the wire harness mass, but the CG shifts in the –X direction when loaded with propellant. As anticipated, the CG shifts away from the back side of the thruster towards the front (+Z direction) when loaded with propellant. Regardless, in all cases the CG of the thruster is < 0.35" offset from the geometric center.

**Table 1: Measurements for center of gravity for dry and wet MVP systems. Position is relative to the origin point at the virtual corner on the back cover, and the offset refers to the geometric center of the unit.**

| | Dry System | Wet System | Units | Notes |
|---|---|---|---|---|
| Mass | 622 | 1138 | grams | Propellant load = 516 g |
| X+ Position from Origin | 2.3079 | 1.8444 | inches | Offset due to mass imbalance from wire harness |
| Y+ Position from Origin | 1.9057 | 1.9112 | inches | |
| Z+ Position from Origin | 1.9757 | 2.2362 | inches | |
| X+ Offset from Geometric Center | 0.3394 | – 0.1241 | inches | CG shifts in –X direction when loaded w/ propellant |
| Y+ Offset from Geometric Center | – 0.0628 | – 0.0573 | inches | |
| Z+ Offset from Geometric Center | – 0.2978 | – 0.0303 | inches | CG shifts in +Z direction when loaded w/ propellant |

### *3.3. Power Modes Analyses*

Operating power modes were evaluated with the "flight-like" MVP thruster system. These include the operational power to the superheater power processing unit (PPU), **Table 2**, as well as to the melt pre-heater, **Table 3**. The superheater PPU efficiency was found to decrease slightly with increasing power, but most importantly is that the PPU efficiency averages ~76% which was significantly lower than the desired 85%. It is believed that the DC buck converter has the greatest inefficiency of the designed PPU board. Recent testing on prototype next generation circuit boards have shown this efficiency increase, and approach 90%. The integrated flight-like boards are undergoing testing now and not presented.

**Table 2: Power modes table for superheater PPU.**

| Bus Voltage (V) | Superheater Current (A) | Bus Power to Superheater (W) | Superheater Power (W) | Superheater PPU Efficiency |
|---|---|---|---|---|
| 6.0 | 4.50 | 27.0 | 20.0 | 74.1 % |
| 7.2 | 3.62 | 26.1 | 20.0 | 76.7 % |
| 7.2 | 4.55 | 32.8 | 25.0 | 76.3 % |
| 7.2 | 5.6 | 40.3 | 30.0 | 74.4 % |
| 8.4 | 3.02 | 25.4 | 20.0 | 78.8 % |
| 8.4 | 3.85 | 32.3 | 25.0 | 77.3 % |
| 8.4 | 4.70 | 39.5 | 30.0 | 76.0 % |

**Table 3: Power modes table for propellant melt pre-heater.**

| Bus Voltage (V) | Average Current (A) | Max Pre-Heater Power (W) | Duty Cycle (%) | Average Pre-Heater Power (W) |
|---|---|---|---|---|
| 6.0 | 1.11 | 6.7 | ~ 50.0 | 3.2 |
| 7.2 | 0.60 | 4.3 | ~ 50.0 | 2.2 |
| 7.2 | 0.95 | 6.8 | ~ 50.0 | 3.4 |
| 7.2 | 1.33 | 9.6 | ~ 50.0 | 4.8 |
| 8.4 | 0.75 | 6.3 | ~ 50.0 | 3.2 |
| 8.4 | 1.20 | 10.1 | ~ 50.0 | 5.0 |
| 8.4 | 1.55 | 13.0 | ~ 50.0 | 6.5 |

The melt pre-heater had an efficiency close to 100% as expected and adds an average of ~4.5 W of power draw. The circuitry for this simple cartridge heater as well as the use of established COTS parts helped maintain a high efficiency. However, better thermal management that retains the heat in this region would result in a lower duty cycle and consequently lower power draw. Future design will attempt to improve the thermal management.

With the lower limit of the unregulated bus power voltage of 6 V, the fixed resistance of the superheater tube, and inefficiencies in the buck converter, the maximum power that the PPU can provide to the superheater tube is approximately 30 W in the flight-like design. In the "flight" redesign, higher power should be achievable with more efficient PPU electronics and/or higher superheater tube resistance (either a longer tube or a thinner walled tube, or both).

### *3.4. Electronics Subsystem Life Test*

Subsystem life testing was also performed on the final flight-like electronics and propellant feed motor/gear mechanism. For the electronics board, a 40-hr test was run that represents ~ 200% life of the flight-like unit. An average power input of 25 W was maintained for the entire test with an average board temperature of 80°C ± 5°C, **Figure 12**.

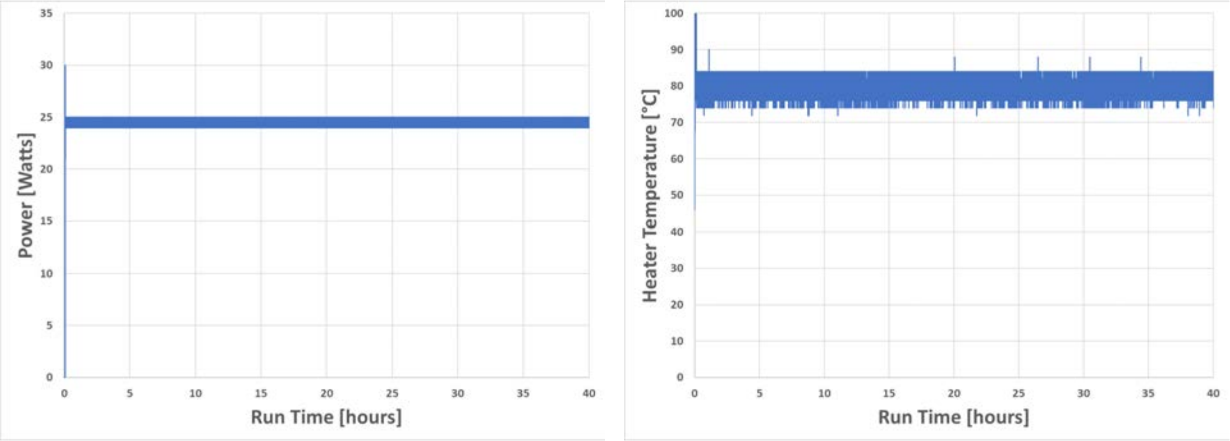


**Figure 12. Subsystem 40-hr life-test on electronics board. (Left) Power input, and (right) board temperature.**

### *3.5. Operational Characteristics*

The thruster warm-up time to a melt-tube temperature of 200°C with a full load of propellant was approximately 4 minutes. Prior measurements with an unloaded MVP showed that the warm-up time was only ~2 minutes, therefore the warm-up time required will decrease as the thruster uses its propellant due to the progressive reduction in thermal mass, as anticipated. Once the melt-tube is warmed up it can be maintained at 200-220°C for an indefinite amount of time so long as ~3 W of average power are provided to the cartridge heater.

The operational duty cycle was found to be ~ 30% at the baseline design operating conditions when thermally isolated. For example, for a 10-minute on/off cycle, during a 3-minute continuous firing the electronics board will increase in temperature from ~50°C to ~75°C, followed by a 7-minute cool down period during which the board temperature drops to back to approximately ~50°C. This process can be repeated indefinitely so long as power (and propellant) can be supplied. The baseline cutoff temperature is 85°C and power to the superheater circuit will automatically shut off if this board temperature is reached. Note that it may be possible to increase this on/off duty cycle when the thruster is thermally connected to the spacecraft bus, but this was not tested during this program. The longest continuous firing tested was at a 6 mg/s flow rate for 5 minutes starting from a board temperature of 32°C and reaching 78°C.

It should also be noted that while the entire thruster system will draw ~45 W of power during operation. During the course of in-space operations the system would only draw an average of less than 15 W because of the ~30% operational duty cycle. This power may be larger with good thermal connection to the spacecraft bus, but it is a power draw that is manageable by a 3U CubeSat with deployable solar panels.

# IV. Environmental Testing

## *4.1. Vibration Testing*

The 1U MVP flight-like unit was subjected to a vibration environment per CUA specification at Engineered Testing Systems (ETS) in Indianapolis, IN on 7 Jan. 2020. The ETS Vibration Exciter was programmed in accordance with the customer specification using NASA standard vibration profiles for satellites of 50-lb or lower with a qualification level of 14.1 Grms (GFSC-STD-7000). The vibration tests were performed in three mutually perpendicular axes for a total duration of 1 minute per axis. The system was monitored visually for problems. The test sample was not operating during the test. The test equipment used for this test is listed in **Table 4**.

**Table 4: Test equipment used by ETS for vibration testing.**

| Equipment | Manufacture | Model Number | Serial Number | Calibration Date |
|---|---|---|---|---|
| Vibration Exciter | Unholtz-Dickie | T1000 | 219 | CNR |
| Vibration Exciter | Unholtz-Dickie | T1000 | 341 | CNR |
| Controller | Vibration Research | VR9500 | 950AC1E2 | 7/23/21 |
| Accelerometer | PCB | 353B04 | 90500 | 3/31/21 |

**Figures 13 and 14** show the MVP flight-like unit placed in a mounting frame on a plate attached to ETS's two vibration tables (one horizontal, one vertical). A sample of the data taken for the x-axis ("axis 1") is shown in **Figure 15**. Data taken for the y- and z-axes are essentially identical and are not shown for brevity. No visual anomalies were detected during the test effort. Post-test ambient functionals were taken with no observed abnormalities.

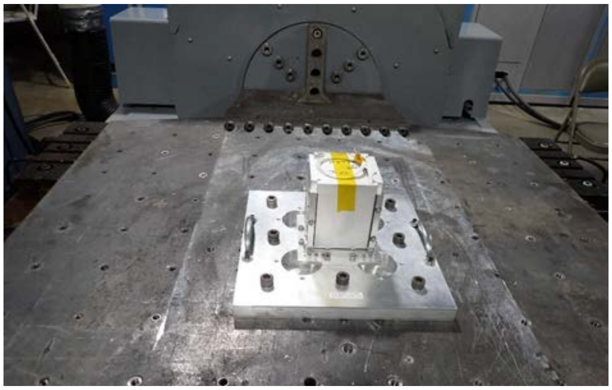


**Figure 13: Flight-like MVP in vibe test apparatus for x- / y-axis horizontal testing. Test shown is for x-axis; mounting plate rotated 90° for y-axis vibe.**

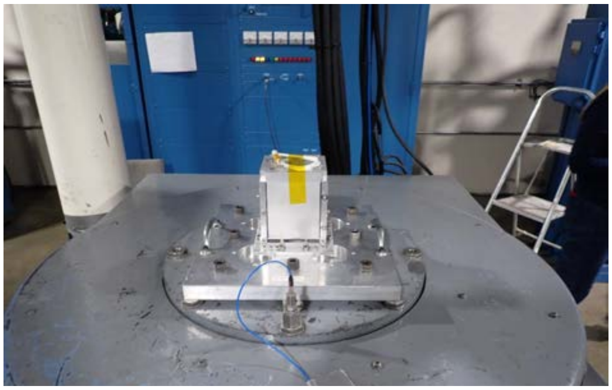


**Figure 14: Flight-like MVP in vibration test apparatus for z-axis vertical testing (up and down).**

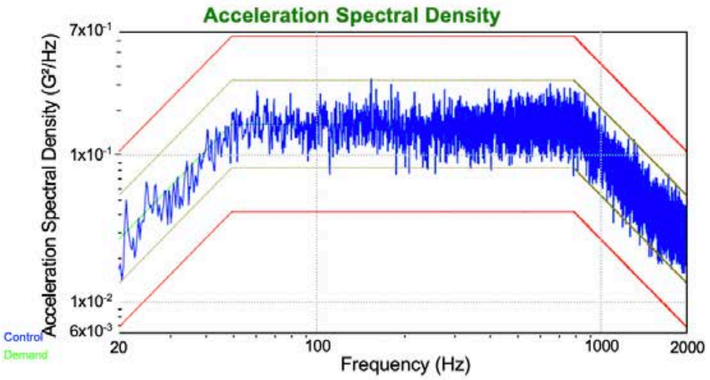


**Figure 15: MVP vibration test data for x-axis horizontal testing at ETS in January 2020 with MVP flight-like unit. Test data for the y- and z-axes were essentially identical and not shown for brevity.**

### *4.2. Thermal Vacuum (TVAC) Testing*

Thermal vacuum testing was performed at the University of Illinois' Laboratory for Advanced Space Systems at Illinois (LASSI) facilities. The test was performed to NASA LSP-REQ-317.01 Rev. B acceptance standards, **Table 5**. Actual test conditions that were applied during the test were compatible with the standards, **Table 5**. Thermocouples were attached to the thruster's upper plate and one of the side plates. There was also a temperature sensor measuring the electronics board temperature inside of the unit during the test; the electronics board was powered on and provided telemetry throughout the test series. The testing showed that the MVP system achieved an almost uniform temperature during the dwell times at 60°C and −20°C with a chamber pressure < $10^{-4}$ Torr.

**Table 5: TVAC testing standard followed and applied test conditions.**

| | **NASA LSP-REQ-317.01 Rev. B Acceptance Standards** | **Applied Test Conditions** |
|---|---|---|
| **Chamber Pressure** | $13.3\times10^{-5}$ Pa ($10^{-4}$ Torr) | between $10^{-6}$ and $10^{-4}$ Torr |
| **Temperature Margins** | 5°C | 5°C |
| **Number of Cycles** | 2 | 2 |
| **Temperature Range** | – | 60°C and –20°C |
| **Dwell Time** | 1 Hour | 1 Hour at 60°C and –20°C |

Two cycles were performed in October of 2019. Starting at ambient conditions, the temperature was lowered to −20°C, held for one hour, and then ramped (at a rate that did not exceed 5°C/min) to 60°C, again with a one-hour dwell time. **Figures 16 and 17** plot the temperature measured by the thermocouple on the top plate of the thruster (black line) and by the thermocouple on the bottom plate of the thruster (red line) with respect to time for the first cycle. After TVAC testing, the flight-like unit was again inspected and passed. Basic electrical ambient functionality was again confirmed before performing a series of operational tests described in **Section V**.

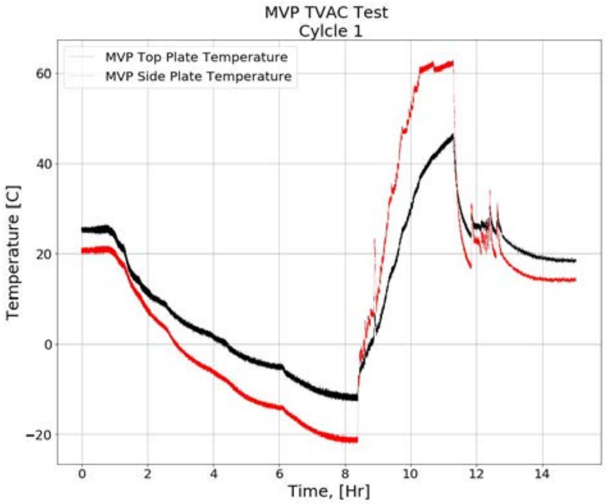


**Figure 16: TVAC test cycle #1 showing MVP top plate temperature (black) and side plate temperature (red).**

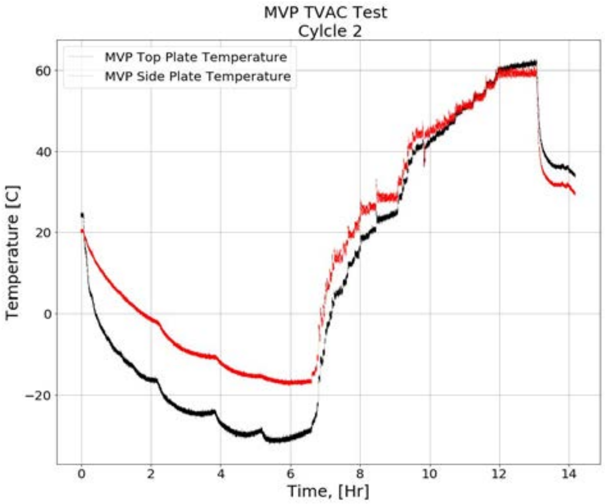


**Figure 17: TVAC test cycle #2 showing MVP top plate temperature (black) and side plate temperature (red).**

## V. Thrust Stand Performance Testing

Thrust stand measurements were made with the flight-like unit to validate performance relative to prototype testing. These measurements were made after the unit had been subject to the second series of vibration testing and all components had gone through TVAC testing. All data is taken on the CUA's replica of a Watt's inverted pendulum compact thrust stand described in [Hejmanowski, 2015]. A typical calibration trace and a thrust stand measurement trace (for a 4-minute firing) are shown in **Figure 18**. Two features of note in the thrust trace are (i) a small initial thrust spike resulting from the purging of propellant melt from the prior firing, and (ii) a thrust oscillation with approximately a ±11% variation from the average; this fluctuation in performance is believed to occur in MVP due to the natural ebb-and-flow of the feed-melt-depolymerization-vaporization process coupled to the internal motor control loop. After reducing the thrust stand data, to within experimental error, the flight-like unit replicated prior breadboard data, **Figures 19**. A short series of tests were also performed as a function of mass flow rate, **Figure 20**.

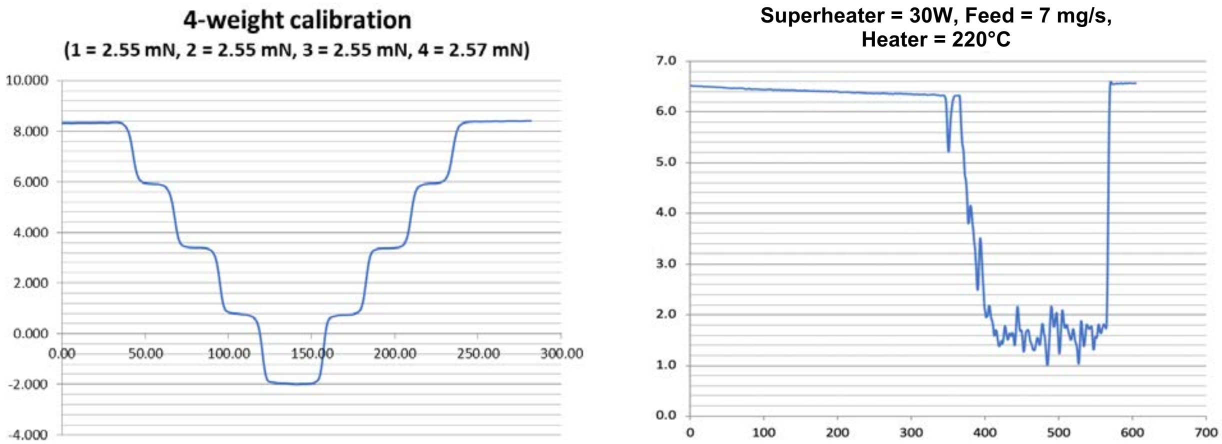


**Figure 18: Thrust stand calibration (left) and measurement (right) for a typical MVP thrust test. The calibration factor was measured to be 1.00 mN/V. This test measured an average thrust of 4.60 mN and specific impulse of 66.9 s during a 4-minute continuous test.**

As discussed in **Section 2**, the propellant fiber is mechanically drawn from a fixed spool into the extruder where it evaporates. While the propellant metering is precise, but evaporation time results in "softer" starts and stops. Consequently, minimum impulse bits were not measured because they are inherently much larger than gaseous propulsion systems with fast-actuating valves. The softer start-stop is generally considered an acceptable trade-off for the reduced system cost, simplicity, and low risk that MVP offers.

**(a)**

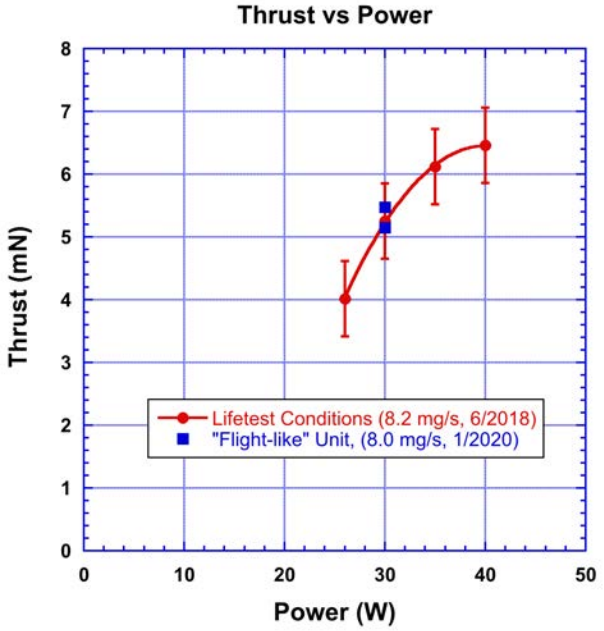
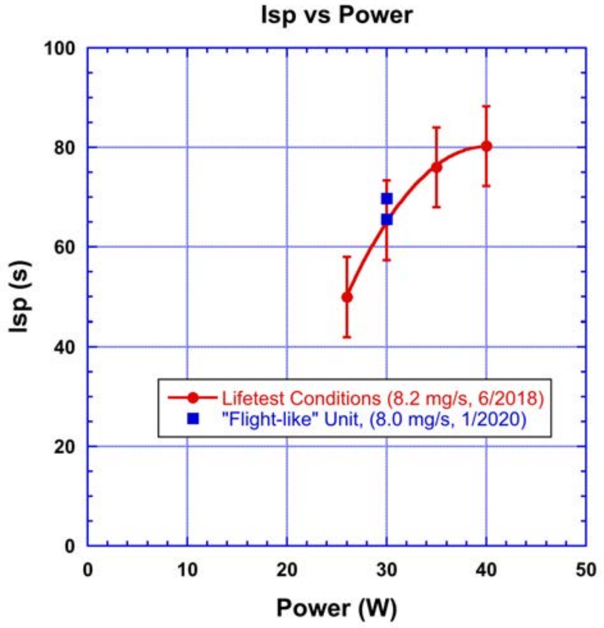
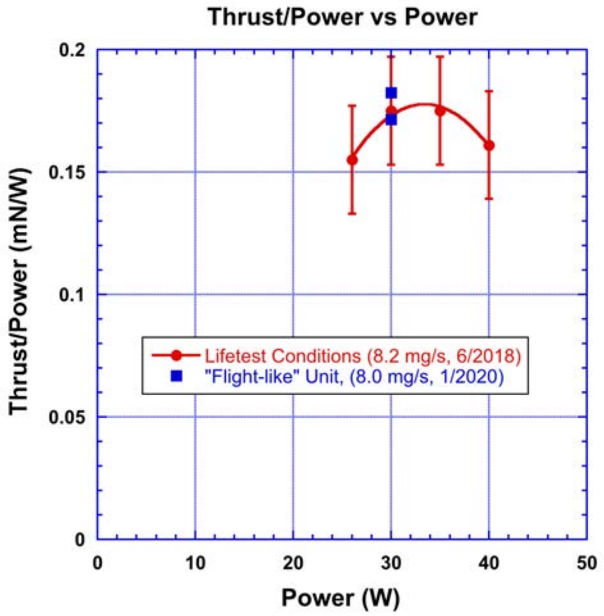


**Figure 19: Thrust stand measurements taken in June 2018 with breadboard system and January 2020 with flight-like MVP unit. (a) Thrust vs power input, (b) specific impulse vs power input, and (c) thrust/power vs power input. Mass flow rate for all data was 8.0-8.2 mg/s. Power input values are the power input to the superheater.**



**(b)**



**(c)**

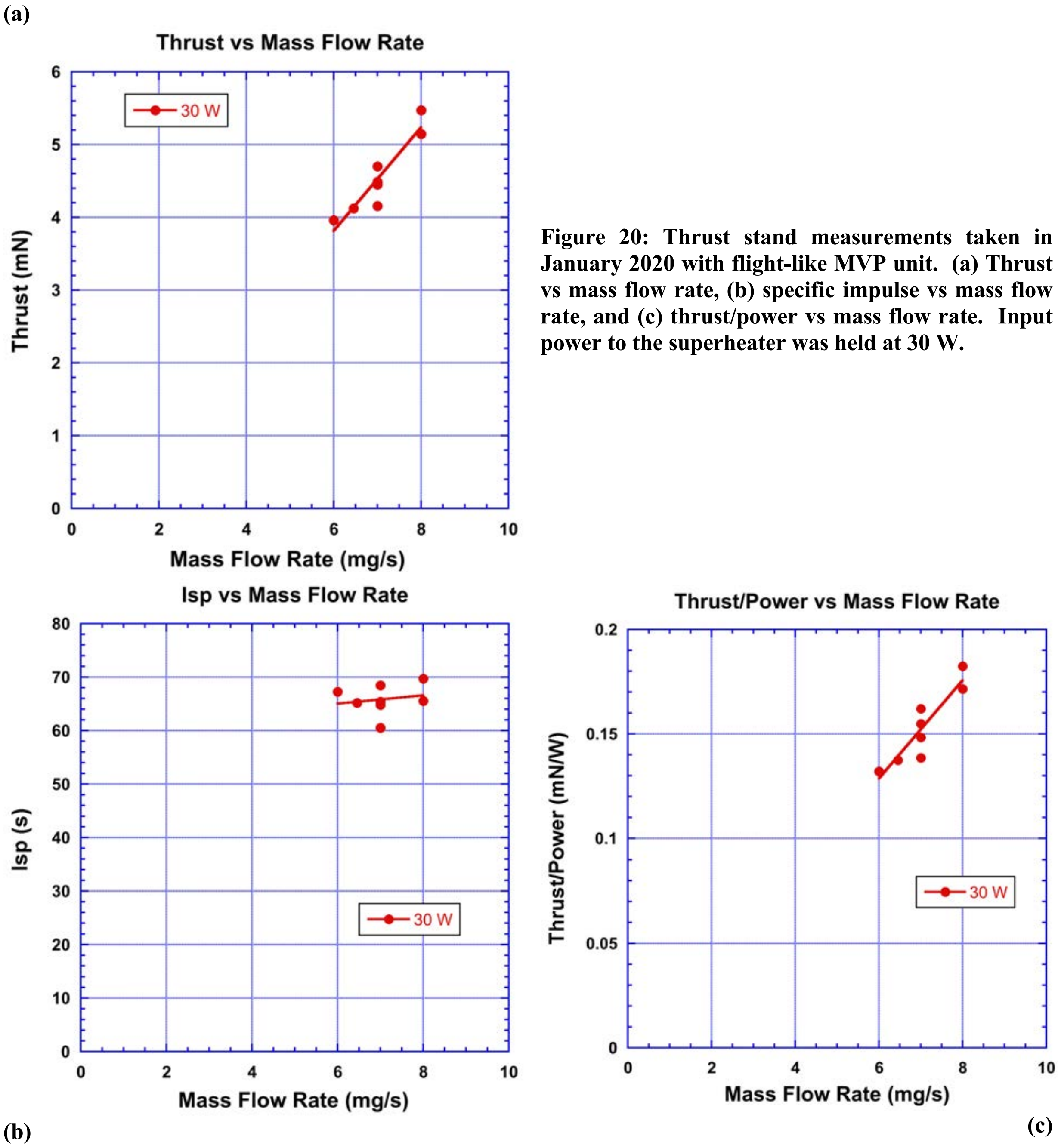


**Figure 20: Thrust stand measurements taken in January 2020 with flight-like MVP unit. (a) Thrust vs mass flow rate, (b) specific impulse vs mass flow rate, and (c) thrust/power vs mass flow rate. Input power to the superheater was held at 30 W.**

## VI. Design and Fabrication of Flight MVP-2 System for DUPLEX CubeSat

CUA was selected for a NASA STMD Tipping Point award to fabricate and fly the 6U "Dual Propulsion Experiment (DUPLEX)" CubeSat with one MVP flight unit and another CUA thruster technology, the Fiber-fed Pulsed Plasma Thruster (FPPT) [Woodruff, 2019; Burton, 2019]. The DUPLEX mission is manifested for launch in Q1 2023 to be deployed from the NG-19 Cygnus resupply vehicle, followed by in-space operations with the MVP thruster. This mission will reduce risk, provide flight heritage, take the technology to TRL 8-9, and encourage customer acceptance of MVP.

### *6.1. Design Modifications for Flight Unit*

Straight forward design modifications and improvements recognized during the flight-like unit testing were implemented on the follow-on “flight” MVP system for the DUPLEX mission. These include:

- The flight-like unit was designed to slide into the end of a 3U CubeSat with notches cut out in the corners, **Figures 10 and 11**. To fit inside the 6U DUPLEX CubeSat bus housing, a requirement of 90 mm was imposed on the MVP flight unit, **Figures 21 and 22**; this significantly lowered available tank volume for propellant winding and consequently a drop in propellant mass from 516 g to 433 g.
- The flight-like MVP system was set up for either RS422 or $I^2C$ communication protocol, but $I^2C$ was traded for TTL in the flight unit for the DUPLEX CubeSat bus flight processor.
- The superheater power converter (DC buck converter) used in the flight-like unit was much less efficient than desired. A software-controlled power supply has been implemented rather than the integrated unit, resulting in increased efficiency and better radiation tolerance. The previous power converter was a multi-purpose chip for providing a smooth DC output. As the superheater operates as a resistive heater, the software-controlled power supply only seeks to minimize ripple in current consumption and allows the voltage and current through the superheater to oscillate.
- A drop-in replacement stepper motor for the existing brushless motor is a desirable modification, but the waste heat generated by the stepper has been problematic. The brushless motor remains for this iteration of the thruster system. Component shortages may force the stepper switch in future builds.
- The flight-like design used a ceramic insulator with notched holes to provide electrical isolation for the superheater with minimal mass impact. These holes have been removed to provide better radiation shielding for the electronics core. Thermal isolation is still provided by shimming the ceramic away from the aluminum.
- The wiring harness in the flight-like unit took volume away from the propellant spooled around it. A 1-mm deep channel on the propellant spool was added to the flight unit to recess the electronics wiring harness into the core cylinder. This allows for more efficient winding of the propellant on the spool and increases the propellant load slightly. Further, this should correct the center of gravity issues seen in the first unit.
- The micronozzle on the flight unit was electro-polished for increased smoothness and lower frictional losses. Past experience with polishing micronozzles typically results in an Isp increase of 1-2 seconds.

### *6.2. Operating Characteristics for Flight MVP Unit*

As discussed in **Section 3.5**, a preheat is required for the MVP system before firing (~3 minutes), but once warmed the “ready” state is maintained with minimal power draw and thermal loading. When firing, the micro-resistojet uses approximately 30 W and the whole system uses a total power of < 45 W.

It should also be noted that while the entire thruster system will draw ~45 W of power during operation, during the course of in-space operations the system would only draw an average of less than 15 W because of the ~30% operational duty cycle. This power may be larger with good thermal connection to the spacecraft bus, but it is a power draw that is manageable by a CubeSat with deployable solar panels.

### *6.3. Flight MVP Unit for DUPLEX 6U CubeSat*

A 0.93U MVP with 280 N-s of total impulse is being integrated for flight on CUA’s DUPLEX CubeSat. Dimensioned drawings of the unit exterior are shown in **Figure 21**. The DUPLEX MVP Flight Unit is now being assembled and performance data will be presented in the future when available. Estimated performance is provided in **Table 6**.

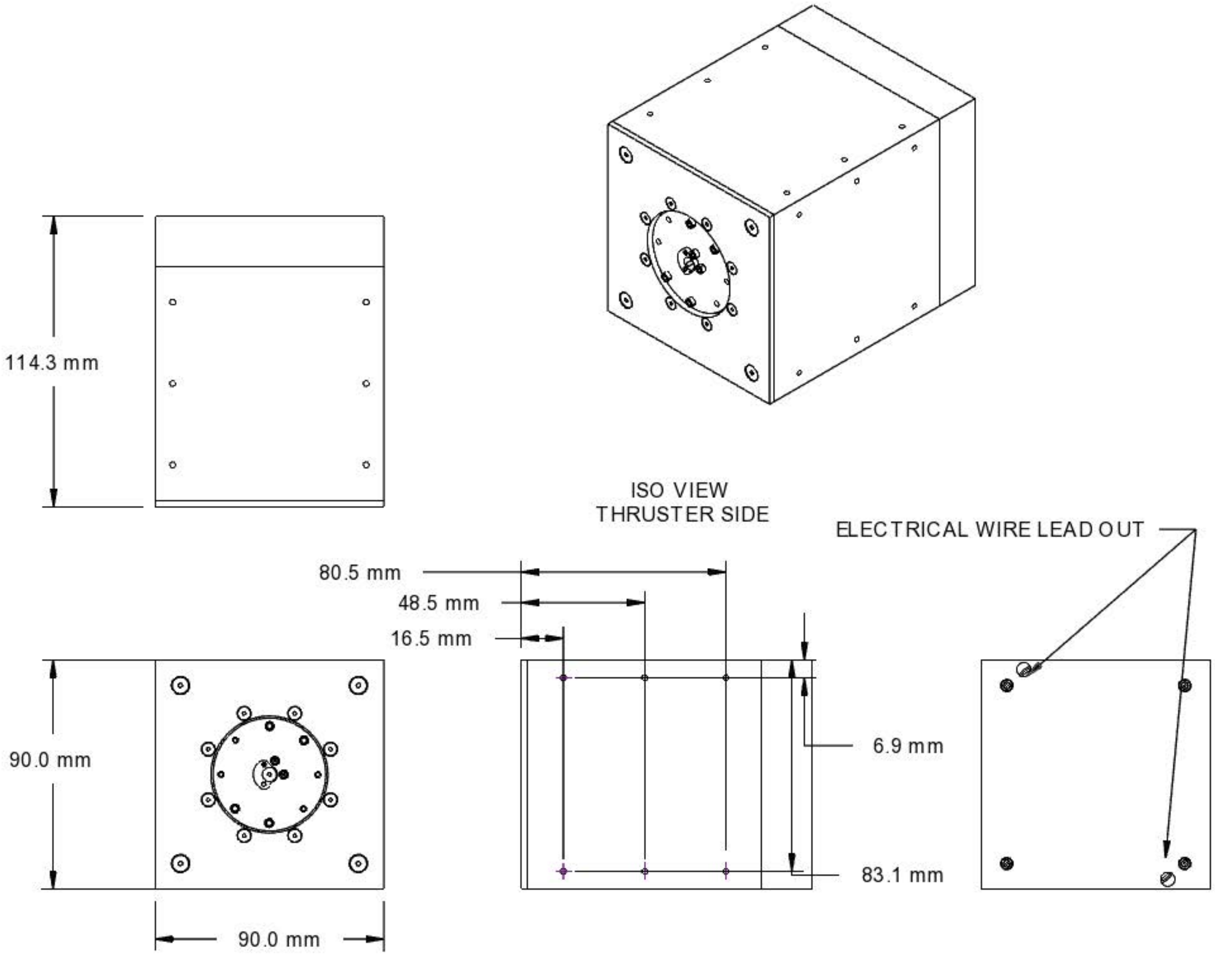


**Figure 21: Dimensioned drawings of external housing of the MVP flight thruster for the DUPLEX 6U CubeSat mission.**

**Table 6: System performance of a 1U MVP: Measured performance of "flight-like" MVP from SBIR effort and performance of the "flight" system built for DUPLEX 6U CubeSat.**

| Item | "Flight-like" MVP Performance | "Flight" MVP Performance |
|---|---|---|
| Propulsion system dimensions | 10.0 x 10.0 x 11.57 $cm^3$ | 9.0 x 9.0 x 11.43 $cm^3$ |
| Propulsion system volume | 1157 $cm^3$ | 926 $cm^3$ |
| System lifetime | Not propellant limited | |
| Spacecraft temperature range | Not propellant limited (survived – 20°C to + 70°C) | |
| Propellant | POM (Delrin), gaseous MW = 30 | |
| Power to MVP system when firing | 45 W | 39 W |
| Power to superheater PPU | 40 W | 36 W |
| PPU efficiency | 0.74 | 0.85 |
| Power to superheater | 30 W | 30.6 W |
| Duty Cycle | 30% (3 min on, 7 min off) | 30% (3 min on, 7 min off) |
| Propellant Mass | 516 g | 433 g |
| Dry Mass | 622 g | 622 g |
| Total propulsion wet mass | 1138 g | 1055 g |
| Nominal mass flow rate | 7 mg/s | 7 mg/s |
| Total thrust time | 20.5 hr | 17.2 hr |
| Specific Impulse | 66 s | 66 s |
| Primary Thrust | 4.5 mN | 4.5 mN |
| Total impulse | 334 N-s | 280 N-s |
| Volumetric total impulse | 290 N-s/liter | 302 N-s/liter |
| Spacecraft ΔV, M(initial) = 4 kg | 89 m/s | 75 m/s |

## VII. Concluding Remarks

CUA has made major strides forward in developing the MVP electrothermal thruster which consumes an inert polymer propellant fiber. This technology retains performance characteristics competitive with other warm gas systems, but enables more accessibility to micropropulsion via dramatically reduced cost and the elimination of range safety concerns (no pressure vessel and an inert propellant). The MVP system draws from extrusion 3D printer technology and CUA's micro-resistojet CHIPS technology. Despite undergoing depolymerization and two separate phase changes, the system power requirements are manageable, demonstrating typical specific thrusts of 0.17 mN/W, and a long-term stable specific impulse of 66 s. Higher specific impulse is achievable [Woodruff, 2018], but at the cost of significantly reduced operational life and total impulse. CUA has now developed a self-contained flight system that can be modified to best meet customer needs.

Future modifications that can be performed with a longer-term effort and testing are:

- A higher resistance superheater would allow higher power to the superheater for the same current draw, resulting in a thruster performance increase for thrust and specific impulse. Additional resistance can be accomplished by either a longer superheater tube, or a thinner walled tube.
    - These options require long duration testing with potentially alternative tube coatings.
    - It may be possible to incorporate other superheater geometries into the core.
    - Flow conditions that achieve a 150% life condition may be different with a different superheater tube and this can require some effort to determine.
- A contoured micronozzle can be designed to more efficiently direct the exhaust flow in the thrust direction and remove velocity components in the ±X and ±Y directions. Past experience with contoured micronozzles typically results in an Isp increase of 2-4 seconds. This enhancement would have to be traded against an increase in cost for the contoured nozzle. Polishing costs may also further increase to avoid changing the

shape of the contour during the polishing process.
- Identification of a lower flow rate operational mode can allow for reduced peak power. This will also reduce thrust, and possibly specific impulse. Life tests on the MVP system are difficult as polymer vapors must be captured to preserve pumping systems, as well as for safety and environmental concerns. As a result, operating conditions have yet to deviate from the successful life test.

A 0.93U MVP with 280 N-s of total impulse is being integrated for flight on CUA's NASA-funded DUPLEX CubeSat, presently manifested for launch in Q1 2023. CUA sees MVP technology as a compelling option to meet many micropropulsion needs including collision avoidance maneuvers, limited orbit raising/lowering, drag makeup, and deorbiting.

## VIII. Acknowledgments

This work was supported by NASA's SBIR program on contract numbers NNX16CC70P and NNX17CC11C (technical monitor Thomas Haag at Glenn Research Center), by NASA's Space Technology Mission Directorate on contract # 80ARC020C0001 (technical monitor Ali Guarneros Luna at Ames Research Center) for the DUPLEX CubeSat program, and by CUA Internal Research and Development funds.

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