Assembly, Integration, and Testing of a Green Monopropellant Propulsion System for NASA's Lunar Flashlight Mission

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Lunar Flashlight is a NASA 6U CubeSat that will orbit the moon. The objective of the mission is to investigate deep, permanently shaded craters for surface level water-ice. The satellite will be equipped with a 2.5U green monopropellant propulsion system (LFPS) capable of injecting the satellite into lunar orbit from a free return trajectory. This propulsion system will enable Lunar Flashlight to be the first CubeSat to be placed into orbit around a body other than Earth and will provide flight heritage for multiple micro-scale propulsion technologies that are on board. Design, manufacturing, integration, and testing of the propulsion system has been a joint effort between the Georgia Tech Space Systems Design Laboratory, NASA Marshall Space Flight Center, and the Jet Propulsion Laboratory. Assembly of any space system requires extreme care, but the small size of the LFPS makes precision integration particularly important. All of the components were subject to tight tolerancing, and most had to be assembled in a Class 100,000 clean room. As parts were successfully integrated, a simultaneous testing campaign was performed to confirm dimensional requirements, establish bursting pressures, check for leaks, ensure electrical liveliness, and determine flight-like performance.

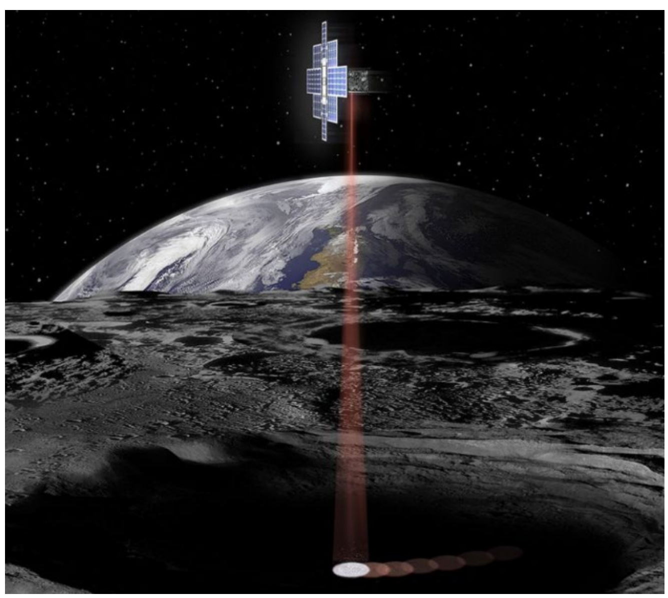

Fig. 1 Lunar Flashlight Concept Art [4]

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I. Introduction

CubeSats are becoming increasingly popular in the space industry, as their small scale makes them lighter, cheaper, and faster to develop than traditional satellite missions. They range in configurable sizes from a 1U, or 10 cubic centimeter satellite, to 27U. Their low cost enables more types of payloads and experiments to be launched without significant financial investment. They also allow for multiple science missions to launch simultaneously or "rideshare" with larger missions due to their relatively small mass. Consequently, Lunar Flashlight is one of 13 CubeSats that will be deployed together on the first launch of NASA's Space Launch System, known as Artemis 1.

As more CubeSat missions come into production, many technologies are being miniaturized to work in smaller form factors. Propulsion systems and the electronics that control them have previously been too large for CubeSats, but earlier innovations made by Dr. Lightsey's research lab at Georgia Tech and the Space System Design Laboratory (SSDL) have led to the design of multiple Cold Gas systems [6] and the monopropellant LFPS [7]. The extra mobility granted by these propulsion systems expand the scope of missions that can be accomplished by small satellites. Orbital adjustment, reaction wheel desaturation, station keeping, and formation flying are just a few examples of possible mission functions that are enabled by onboard propulsion.

The Lunar Flashlight Propulsion System (LFPS) is the latest completed propulsion project from the SSDL. If successful, Lunar Flashlight will become the first CubeSat to be inserted into orbit around the moon. Previous reports have detailed the design and manufacturing of the system [1][2][3]. This report addresses the assembly and testing process, including the problems and solutions that were encountered along the way to delivery.

II. Lunar Flashlight Mission

Lunar Flashlight is a technology demonstration mission for NASA that will make scientific discoveries to address identified Strategic Knowledge Gaps about the moon, such as the location of lunar water-ice. It will provide flight heritage for green monopropulsion and active laser spectroscopy at the CubeSat scale [5]. In searching for water-ice in permanently shaded craters of the moon, Lunar Flashlight will be able to identify the "potential utility of water as a resource to human exploration" [5].

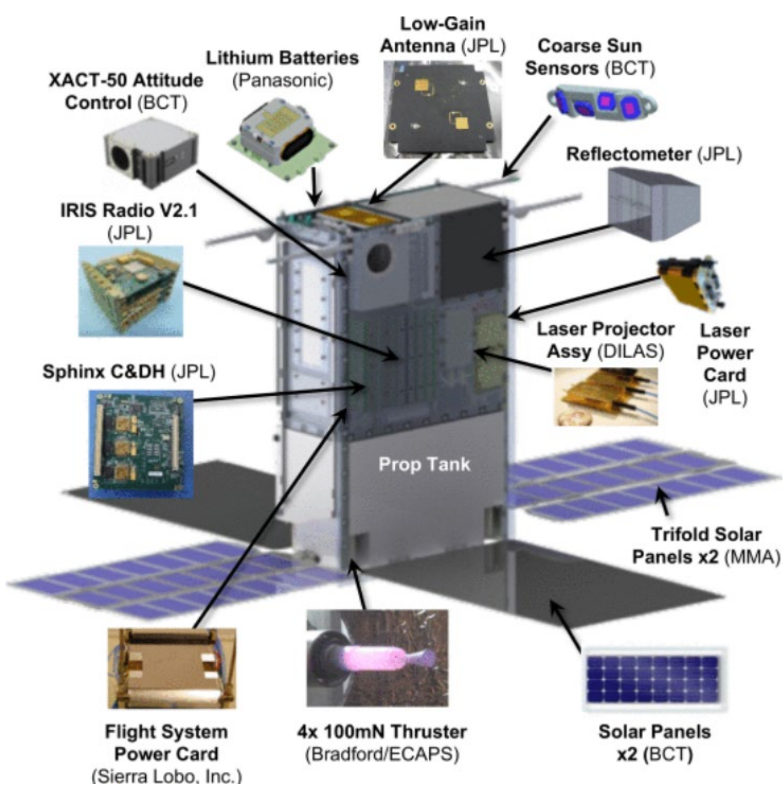

Fig. 2 Lunar Flashlight Component Breakdown [5]

Onboard the spacecraft are four lasers that each operate at different wavelengths, and a 4-band point reflectometer. The combination of these instruments will detect lunar surface reflectance. The reflectance amount directly relates to the amount of water and ice present. Using lasers in this fashion to search for water-ice is a new technology and Lunar Flashlight will be the first mission to use it. There are also two expandable HaWK solar arrays and two 2U x 3U solar panels, for a total of four panels. The HaWK arrays are folded into thirds during launch, then later deployed. The attitude control system is an XACT built by Blue Canyon Technologies and will directly command the propulsion system when it is necessary to execute maneuvers. There is also an IRIS radio that will communicate with the Deep Space Network (DSN) on X-band. The telemetry will be routed to the Mission Operations Center (MOC) at Georgia Tech. All commands to the spacecraft will also flow from the Georgia Tech MOC, to the DSN, to Lunar Flashlight.

The mission will start after being deployed from the Space Launch System. It will then cruise for 4 months and perform a series of Trajectory Correction Maneuvers (TCM's). The satellite will perform a Lunar Orbit Insertion (LOI), then be in a Near Rectilinear Halo Orbit (NRHO) with a perilune at the south pole of 10-20 km and apolune of about 65,000 km. With an orbital period of about 6 days, the satellite will perform a minimum of 10 orbits over 2 months while observing Permanently Shaded Regions (PSR's).

III. Propulsion System

The Lunar Flashlight Propulsion System is a 5.5 kg, pump-fed, monopropellant system capable of delivering more than 230 m/s of total velocity change (delta V). To accomplish this performance, the LFPS features a unique mix of traditionally machined and 3D printed titanium parts that work together in a small 2.5U volume. A summary of the propulsion system is presented here. For a more detailed description of the design of the LFPS, see [1], [2], and [3].

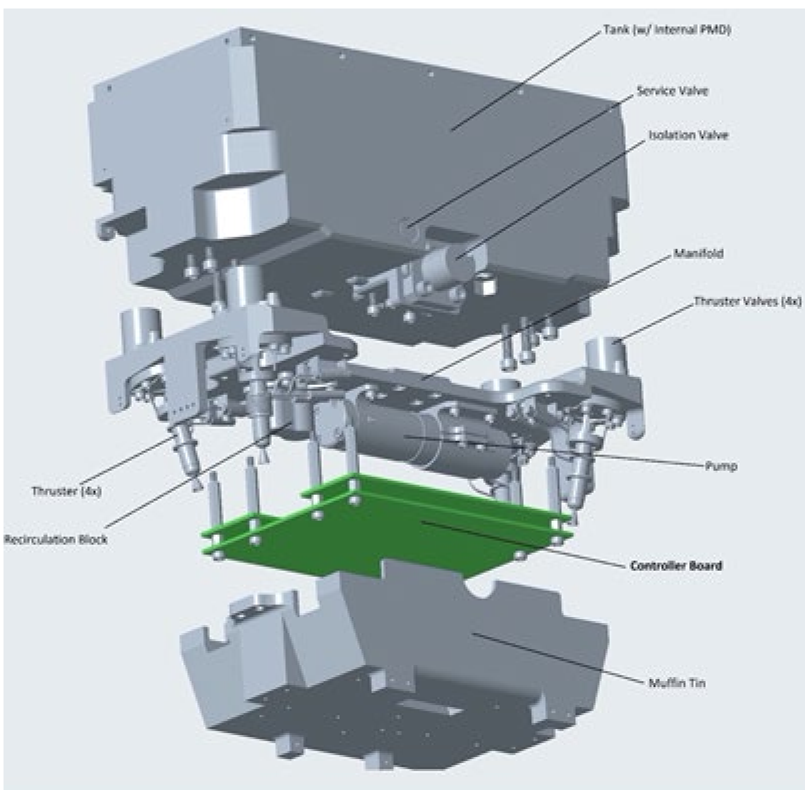

Fig. 3 Lunar Flashlight Propulsion System Component Breakdown

A. Tank

The tank is made of two traditionally machined titanium halves that are welded together in the middle. Inside the tank, a Propellant Management Device (PMD) uses surface tension to hold the propellant close to the outlet while in zero gravity. The PMD consists of two pieces, one set of titanium “ribbon vanes” that fit close to the wall, and a 3D printed “sponge” device that is designed to hold the liquid in place near the outlet. Inside the PMD sponge is a small ten micron filter that will prevent any contaminants from reaching the delicately small fuel channels and thruster supply lines downstream. Attached to the outside of the tank is one bulk propellant isolation valve (Iso-valve) that has the ability to both provide and shut off fuel supply to the rest of the system. There is a fill-drain valve designed by Marshall Space Flight Center (MSFC). This valve is a needle device that fits snuggly with a matching ground half valve to fill the tank with nitrogen and propellant.

The tank will hold 1521cc of gaseous nitrogen and liquid AFM315E, a green monopropellant developed by Air Force Research Laboratories (AFRL). The nitrogen is an ullage gas that will maintain pressure in the tank and allow for a higher expulsion efficiency. There is also a pump downstream that will pull propellant out of the tank. The combination of a pump and nitrogen buffer should allow the tank to expel about 80% of its stored fuel. The pump has an added benefit of lowering the overall pressure needed to produce this expulsion efficiency. With the pump, the tank is only required to be held at 100 PSI.

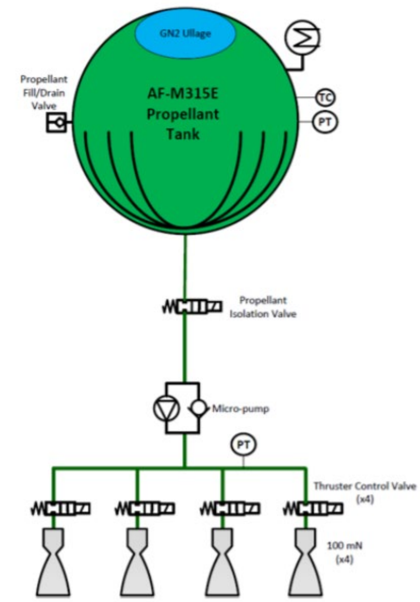

Fig. 4 Lunar Flashlight Propulsion System Fluid Schematic

B. Manifold

The manifold is the most connected part of the LFPS, as it contains the most fluid interfaces to other parts. It is attached to the tank, recirculation block, pump, thrusters, thruster junction boxes, and controller board standoffs. Referencing the fluid schematic, the manifold is directly below the isolation valve and connects the outlet of the tank to the pump circulation loop and distributes fuel to each of the four thrusters. There are four custom designed micro-valves that control fluid flow to each thruster. In order to accomplish this, the part has a web of small internal fluid passages. which had to be 3D printed. The printing process is not precise enough for interfacing with other parts, so every opening was later traditionally machined on a CNC mill. In addition, every fluid interface has a double o-ring seal to prevent any leakages.

A critical piece attached to the manifold is the recirculation block. This block contains an orifice that influences the pressure downstream of the pump in the operational case where the pump is running while all of the valves are closed. The recirculation loop prevents the pump from pulling a vacuum upstream and drastically increasing the pressure downstream. The orifice changes the pressure within the loop to maintain proper inlet and outlet pressures on the pump itself. The recirculation block is also 3D printed because of the channels inside of it.

Also connected to the manifold are junction box mounting brackets. The thrusters each have two cables that provide heat to the catalyst bed and a temperature reading to the controller. Both cables have a junction that converts the cable from a flexible wire to a rigid metal line. The conversion, especially from the heater line, flows back a lot of residual heat from the thruster that needs to be dissipated. The junctions also need to be held firmly in place to prevent overly stressing the rigid metal line to the thruster. The solution to these issues was to create a custom mounting bracket out of titanium that can securely hold the junctions and conduct heat to the manifold. These brackets were traditionally manufactured on a CNC.

C. Controller

The controller built into the propulsion system is a completely custom board designed by Georgia Tech to control and monitor the propulsion system [9]. It has three boards, a sensor connect board, driver connect board, and the main board. The board includes mostly Commercial Off The Shelf (COTS) parts that allowed for rapid development and testing. These COTS parts are all radiation tolerant and capable of operating in the required 5 to 40 degree C operational range.

Every electrical component on the propulsion system is connected to the controller. It reads data from all of the thermocouples and pressure sensors and controls all of the valves, heaters, and the pump. It has built-in firmware called F-Prime that was developed by JPL, which is currently being used by the Ingenuity helicopter on Mars. The custom avionics allow for active control algorithms that adjust to the pressure and temperature of the system. The propulsion system is connected to the XACT computer inside Lunar Flashlight with one cable that sends commands and telemetry.

D. Thrusters

There are four 100 mN thrusters on board that are designed by Plasma Processes (PPI). These thrusters are uniquely small and are the first of their size to be used in conjunction with a micropump. They work by heating up the AFM315E fuel, which starts an exothermic chemical decomposition process. It is a replacement for Hydrazine that is safer to handle and has a higher specific impulse.

Each of the four thrusters on the system is slanted inwards slightly to allow for multi-axis control of the rest of the satellite. Firing all four simultaneously will propel the satellite forwards, while selecting only one or a combination will produce roll, pitch, and yaw.

E. Muffin Tin

The last major part of the propulsion system is the muffin tin. The muffin tin provides thermal and radiative shielding to the vitally important controller boards underneath. This part is traditionally manufactured titanium and is wrapped in reflective metal stickers to help improve its shielding properties. Because the thrusters can reach up to 1600 degrees C while firing, the muffin tin is incredibly important to sustain the life of the controller, which can only operate up to 40 C. The muffin tin's bottom face also provides a mount for several external parts provided by JPL, including the Low-Gain Antennas (LGA), the sun sensor, and a deployment limit switch. Additionally, it is engraved inside and outside with information about the Lunar Flashlight Propulsion System and its engineers.

IV. Integration and Testing

Integration was accomplished in nine major phases. The ordering of each phase accounted for sub-component lead times, when testing could be completed to fulfill requirements, and how everything had to mechanically fit together. Each phase included a meticulously prepared procedure for how to assemble and test the sub-assemblies down to each individual screw. At a high level, the integration plan started by building the tank first, then building the manifold, attaching them together, and finally installing the thrusters and muffin tin. Figure 4 is the Product Breakdown Structure that shows every part number, which sub-assembly it belongs to, and in what order it was assembled (from bottom to top).

Each phase had its own associated Assembly, Integration, and Test Procedure (AITP). Every AITP required at least two Electro-Static Discharge (ESD) and Cleanroom trained personnel to assemble the hardware and provide

Quality Assurance (QA) inspections. The procedures included detailed step by step instructions, including how much to torque down bolts, where to apply adhesives, and when to perform tests.

Some of the sub-assemblies were built multiple times. The extra copies allowed for a partial engineering unit, practice articles, and test units. Ideally, a complete extra unit would have been built at the same time; however, there were not enough critical parts manufactured in time to support the effort. The second unit is currently in construction and will be finished at a later date when the parts are available to complete it.

All anomalies and non-conformances were tracked and reported in corresponding Anomaly Reports (AR) and Non-Conformance Reports (NCR). Each issue was addressed by a panel of GT and MSFC engineers to determine solutions and verify the article's flight worthiness. Those integration issues and their workarounds are discussed in each section below.

When problems did happen, all efforts to keep working were taken in order to meet the delivery deadline for the project. The integration team at Georgia Tech was given some liberty to perform assembly steps out of order if it made sense to expedite the overall process. Some examples of this protocol were combining epoxy staking steps to limit the amount of overnight drying sessions and preparing materials for future AITP procedures while waiting for hardware to be delivered for the current one. The team easily saved a few weeks of time by being flexible enough to perform steps out of order and take advantage of the materials on hand at any given time.

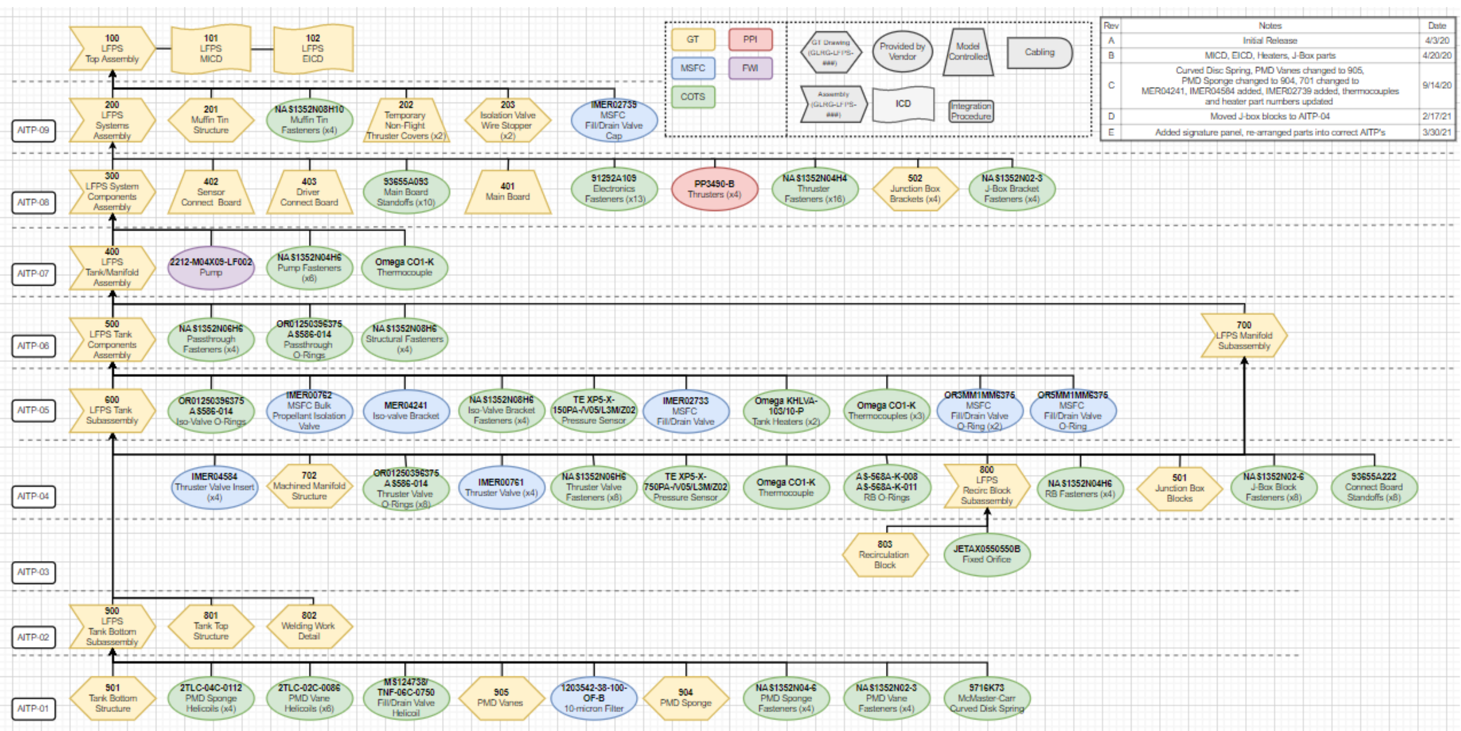

Fig. 5 Lunar Flashlight Propulsion System Product Breakdown Structure

A. AITP-01 Tank Bottom Component Assembly

The first procedure detailed the installation of everything inside of the tank. There are propellant management device (PMD) Ribbon Vanes, a PMD Sponge, a filter, and disk springs. The ribbon vanes and sponge were screwed into helicoils in the tank bottom, and the filter was placed over the outlet port and held in place by the sponge and springs. This tank bottom sub-assembly was made a total of 3 times, all of which were treated like flight-hardware. One was used as a burst unit to determine the rupture pressure of the tank, one is a spare, and the third will fly in space.

All items were held to strict cleanliness requirements to prevent future contamination of fuel or clogging of fuel lines. This requirement became an issue immediately when the three ribbon vanes were inspected and found to have a greasy coating on them. They had to be returned and professionally cleaned again, while specifying a higher level of cleanliness than before. The new requirement for flight hardware that comes into contact with fuel was to be "Level 100A, No particles greater than 50 microns". The practice of visually verifying and wiping down every part with Iso-Propyl Alcohol (IPA) was also introduced to ensure that every piece was visually clean.

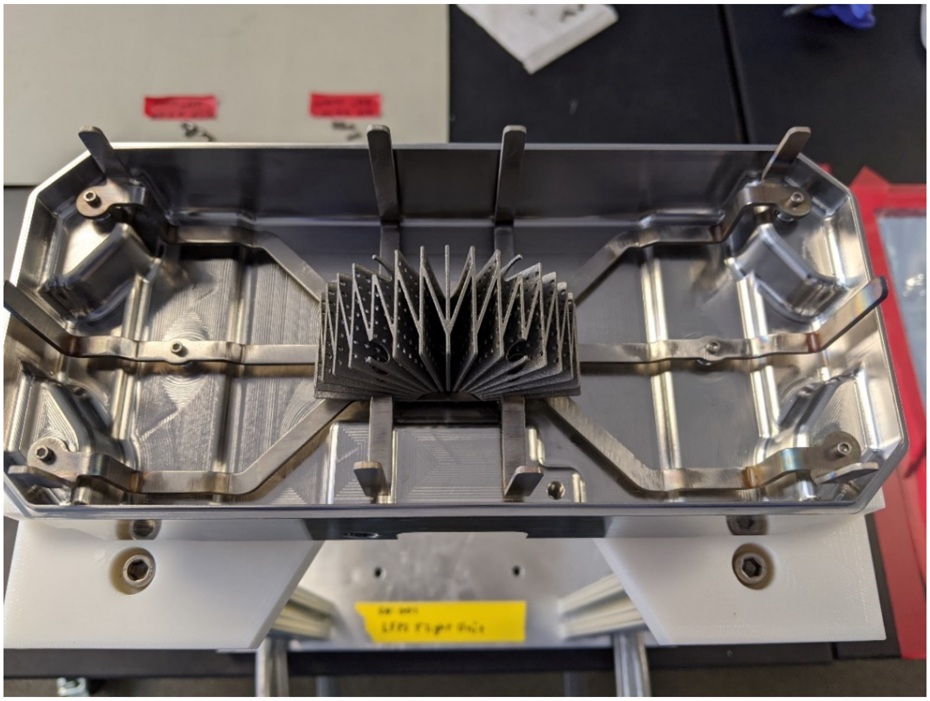

Fig. 6 Completed Tank Bottom Sub-Assembly

B. AITP-02 Tank Welding

The three tank bottoms with the PMD parts installed were individually packaged and labeled, then sent to EB industries along with matching tank tops. They were welded together, then sent for heat treatment at a separate facility to stress-relieve the weld line. At this point, the identification tags attached to each part were mistakenly removed, making it impossible to determine which tank was which. They are all identical on the outside, so the best guess was made to re-label them by looking for tiny differences in mass. The lesson learned from this loss of traceability was to label or engrave every piece before sending it to external companies to ensure that parts can always be re-identified.

Fig. 7 Three Welded Tanks without Identification

Once the tanks had been welded, they were sent back to Georgia Tech to install blanking plates, or plugs, over all of the orifices for pressure testing. An issue had also been identified in the CAD model that required re-working some of the tabs on the tanks. The wires on the valves were bigger and stiffer than expected, so a channel had to be machined into the tank in order to fit them in. The fit-up was tested on a plastic 3D printed model first, and once it was shown to fit, the exact same cut was made on the real units. All the tanks had two semi-circle notches machined into them on a mill in order to make the valve wires fit properly.

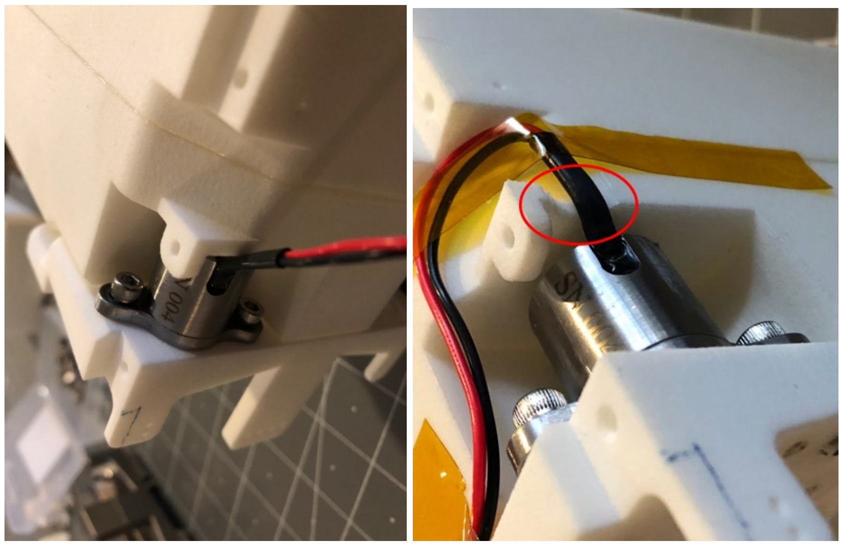

Fig. 8 Valve Wire Fit-up Issue and the Proposed Solution

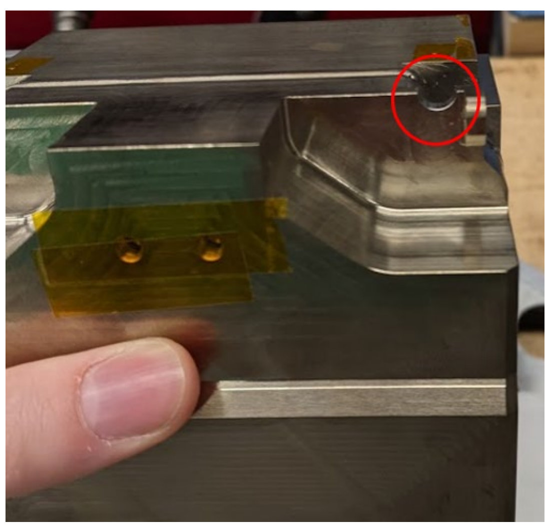

Fig. 9 Wire Notch Cut into the Flight Tank

After stress relief and the hardware modifications, the weld lines were all visually inspected with fluorescent dye-penetrant to check for gaps or crack-like indications. Unfortunately, all three tanks had very slight surface-level cracks around the corners. They were easily fixed by filing down the corners and re-inspecting several times until the cracks no longer appeared on the dye-penetrant test.

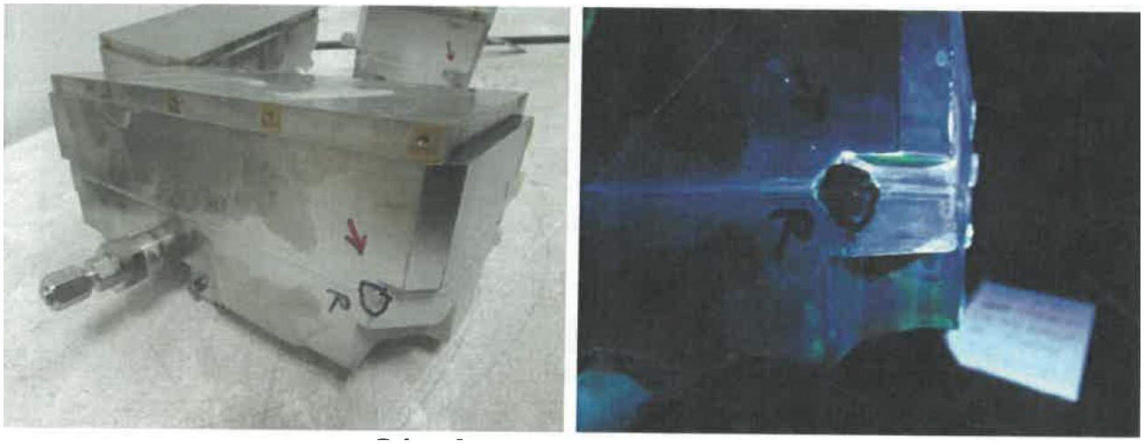

Fig. 10 Crack Indications on Tank Weld Line during Dye-Penetrant Inspection

Once the tanks all passed their dye-penetrant testing, they each had to pass proof pressure tests, and one of them was burst to determine the pressure required to structurally fail the system. The proof pressure is performed to prove that the system can hold its Maximum Design Pressure (MDP) without leaking. In order to do this, each tank was filled with Nitrogen, which is a very small but inert gaseous molecule that will be able to find any leaks easier than air and won't chemically react with the fuel later on. For this system, the MDP is 160 PSIG, and all three tanks were held at this pressure for 5 minutes. After 5 minutes, a visual inspection was performed for any deformations. No deformations were noticed, and therefore all the tanks passed their proof pressure testing.

One tank was selected to undergo the burst test. First this tank was connected to a water supply and held at its predicted burst pressure of 300 PSIG for 5 minutes. With no signs of deformation, the pressure was slowly pumped higher and higher until it ruptured at 2200 PSIG. This pressure greatly exceeded its design requirements and therefore the design passed.

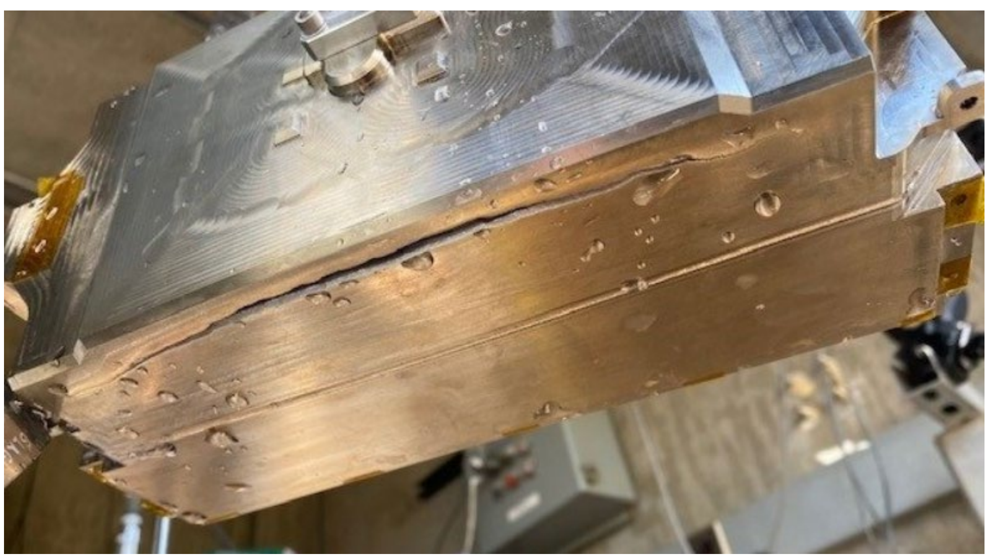

Fig. 11 Burst Tank after Rupture at 2200 PSIG

Finally, the remaining two tanks were sent to be professionally cleaned at the same "Level 100A, No particles greater than 50 microns" requirement. The inside was inspected with a boroscope and chemically tested for residues before and after being flushed to ensure that nothing remained in the tank. It was then sent back to Georgia Tech as a flight ready article to be mounted to the rest of the system.

C. AITP-03 Recirculation Block

The recirculation block's primary purpose is to hold a small orifice inside of it that will increase the pressure when the pump is running with all the valves closed. Once the orifice was hammered into place, the assembly had to be proof tested to its MDP and burst tested until failure. There were three recirculation blocks, one flight, one spare, and one burst unit. Both the flight and spare units survived a MDP of 759 PSIG for 5 minutes without deforming. The burst unit was only required to survive 1325 PSIG, but went to 5000 PSIG without deforming. This was the maximum pressure the test rig was capable of outputting, and therefore the strength of the block exceeded the rig's ability.

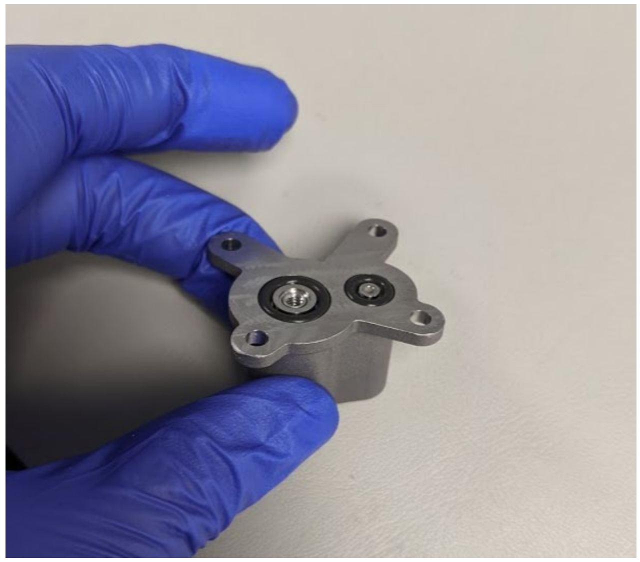

Fig. 12 Recirculation Block with Orifice Installed

D. AITP-04 Manifold Components Subassembly

The manifold is a 3D printed titanium part that has all tightly toleranced areas, like fluid interfaces and screw holes, which are traditionally machined after printing. Unfortunately, there were multiple issues with the manifold fabrication process that left the team with only one usable flight part. The first issue was warpage of the manifold during printing. In order to achieve a flat and square part, the manifold had to be printed over-sized and have all the flat surfaces machined down afterwards. This led to difficulties with establishing reference points on the CNC machines. The datums had to be machined in, and some of the features were out of tolerance with respect to the new surfaces. A total of six manifolds were created, four of them were too warped off of the print bed to be useful, one was machined incorrectly, and the last one had a few non-conformances but was still good enough to be used as a flight part. For this reason, this and the following assemblies were only performed once for the flight unit.

One of the warped manifolds served as a burst unit. It held at its proof pressure of 759 PSIG for 5 minutes without deformation, then held steady to 5000 PSIG without any deformation. This was the maximum pressure capable of the testing rig. The warped manifold proved that the manifold design was sound and would not rupture in space at any pressure expected to be seen in flight.

During the assembly procedure for the flight unit, the recirculation block, pressure sensor, and thruster valves were all installed onto the manifold before being pressure and leak tested. Before integration, the part was wiped clean with IPA, and all of the tiny fluid channels were blown clean with a can of compressed CO_2. This was done to ensure every passage was clean and free of debris before securing the parts on top. All electrical pieces had to be handled in an Electro-Static Discharge (ESD) safe fashion, and each one had to have their wires cut and crimped with DF11 crimps. Each valve also had a small insert carefully placed onto the outlet port, and then the valve was lowered on top.

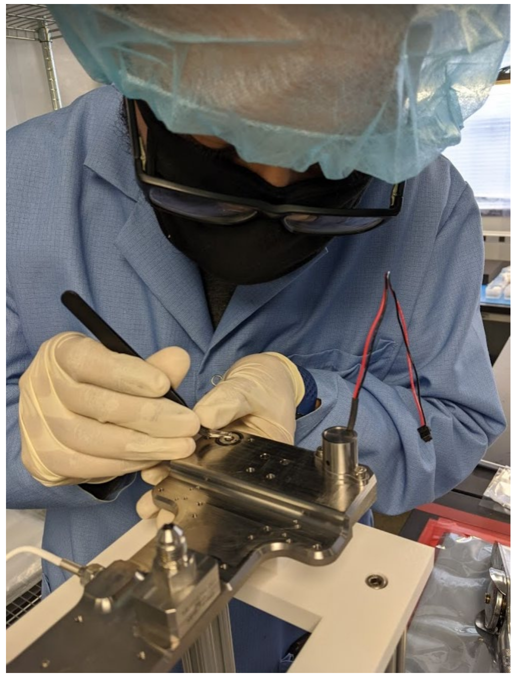

Fig. 13 Careful Installation of Valve Inserts

The flight manifold had to pass a pre-proof leak test, proof pressure test, and post-proof leak test. The pump interface and tank mounting face were covered with blanking plates in order to block air flow during the test, then helium was flowed into the system for all three tests. Helium is an inert gas that will not interact with the propellant, and will leak through any potential gaps much easier than the propellant would. This makes it a good test gas. In order to test for leaks, a liquid called Snoop was used that will bubble when introduced to small air flows.

Marshall Space Flight Center provided pressure regulator boxes, precision cleaned tubing, pressure sensors, and a filter to assist with the pressure testing campaign. The helium supply bottle was connected to the regulator which allowed the pressure to be carefully controlled to within a fraction of a PSI. The regulator box itself had a mechanical gauge, and downstream of the box was a calibrated electronic pressure gauge. Directly upstream of the test article was a 2 micron filter to prevent and potential debris from contaminating the inside of the precision cleaned hardware.

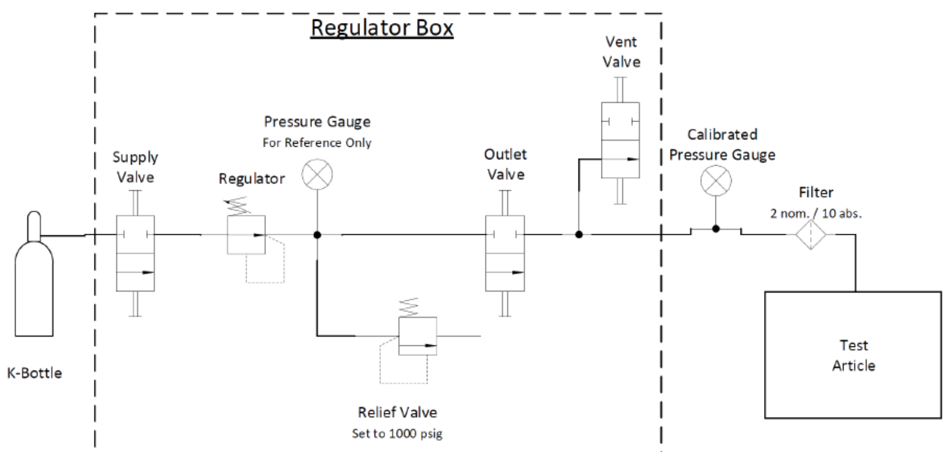

Fig. 14 Pressure Testing Fluid Schematic

The flight manifold leak test was performed at Maximum Expected Operating Pressure (MEOP) of 500 PSIG and was verified with Snoop. The snoop was sprayed around every fluid interface and observed until it was evident that no bubbles or leaks were present. Once it passed its pre-proof leak test, the manifold was raised to a proof pressure of 795 PSIG and held for 5 minutes. No deformation was found, and the post-proof leak test at 500 PSIG also showed no leaks with the snoop.

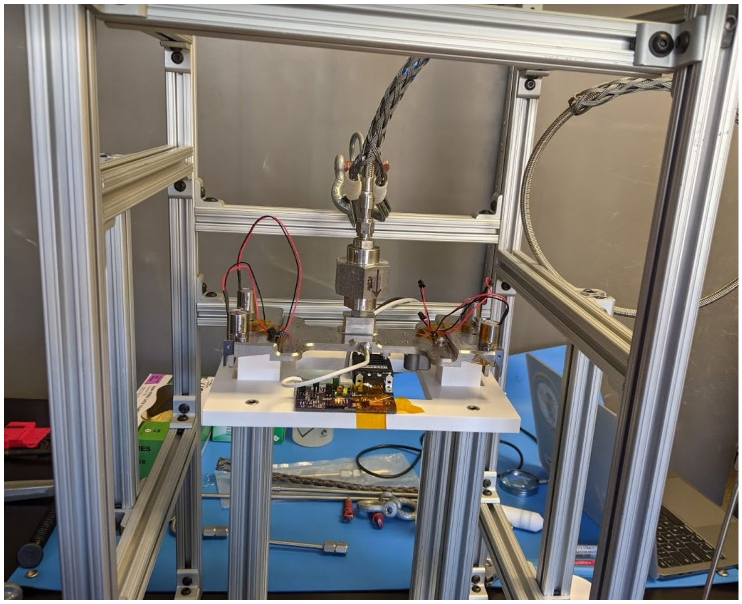

Fig. 15 Flight Manifold During Proof and Leak Testing

Once the pressure testing passed successfully, the junction box brackets and controller standoffs could be attached. The junction box brackets are designed to hold the heater and thermocouple junctions for each thruster. They serve a dual purpose of keeping them secured and allowing them to drain some heat away from the junctions to the rest of the manifold. The controller standoffs are mounts for the electronic boards that control the propulsion system. They were installed in this step to prepare for their integration later.

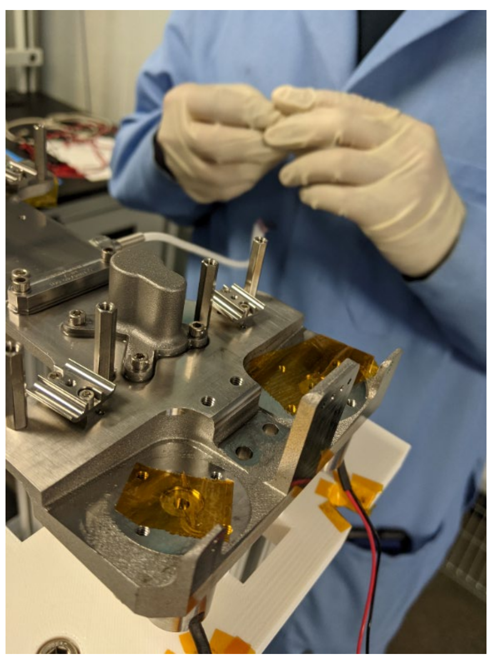

Fig. 16 Controller Standoffs and Junction Box Brackets Installed

The last step of this assembly procedure was to attach a thermocouple to one of the four thruster valves. This thermocouple will help monitor the thermal health of the system in flight and make sure that the valves are not operated when they are too hot, which could damage them. To attach the thermocouple, a custom clamp was 3D printed to fit the surface of the valve precisely and hold it tightly until the epoxy dried.

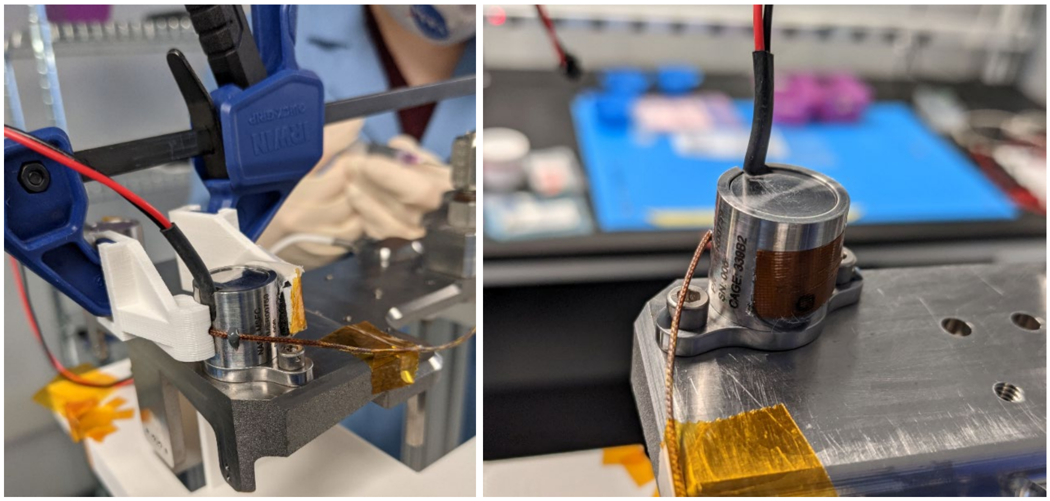

Fig. 17 Valve Thermocouple Installation with Custom Clamp

E. AITP-05 Tank Components Subassembly

During this procedure, the tank was prepared with the final items before connecting it to the manifold. This included heaters and thermocouples, the fill-drain valve, and a pressure sensor. The tank required two thin Kapton tape heaters to keep the fuel inside warm for maneuvers. The two heaters were applied by laying a thin strip of epoxy down and clamping them to the surface of the tank overnight. Their effectiveness was checked with a Flir thermal imaging camera to observe it had good thermal contact with the tank and was distributing heat well. The heaters were then staked on top as well to ensure that none of the edges would peel up.

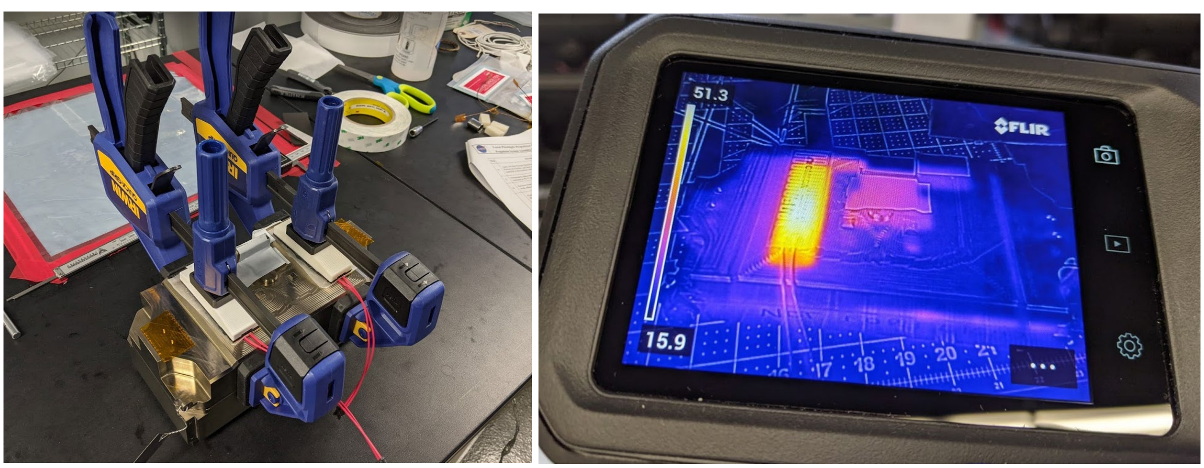

Fig. 18 Tank Heater Installation and Thermal Imaging Test

The propellant isolation valve was attached in this step with a bracket. The bracket allows for four screws to hold on this critical valve instead of two. The fill-drain valve was also inserted into the fill-drain port. This valve is a small insert with a matching ground-half valve that can insert inside and fuel the tank. The fill-drain valve is otherwise leak proof.

The tank pressure sensor was screwed into its port at the bottom of the tank. At this stage, it was important to check the functionality of the pressure sensor to ensure that it was reading accurately and was not damaged during the installation process. The sensor works by having a sensitive tip that will compress and change its resistance properties in higher pressures. The change in resistance is detectable and related to a precise pressure reading. However, when this sensor was tested at ambient atmospheric conditions, it read 0 PSI instead of an expected 14.7 PSI. This error was found to be because of the range of the sensor itself. The sensor's ideal operating range is close to 100 PSI where it is most accurate but will give readings that are significantly off at lower pressures. Because of this result, an offset was made in the controller logic that helps to counteract the incorrect measurements.

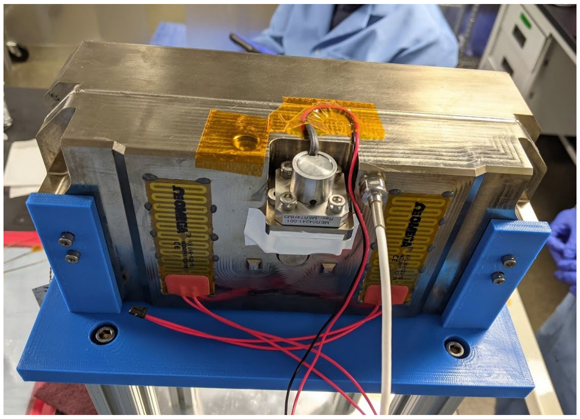

Fig. 19 Tank Subassembly with Iso-Valve, Heaters, and Pressure Sensor Installed

Three thermocouples were also added to the tank bottom. There is one on each heater, and one in the middle. The two on the heaters will allow the controller to check that each one is functioning properly, and the one in the middle will ensure that the tank itself, and hence the fuel inside, is getting warmer.

With all of these electronic devices now installed on the hardware, it became very important to consider wire routing. The wires had to be laid in a way that they were capable of reaching their ports on the controller board, without having too much slack. They also had to be staked down at least once per inch in order to keep them in place during the harsh vibration environment of launch. A plastic 3D printed model was used to test the cable routing and management plan before it was implemented on the real system, and this allowed all of the wires to be cut to exact lengths before putting anything on the system. It worked really well.

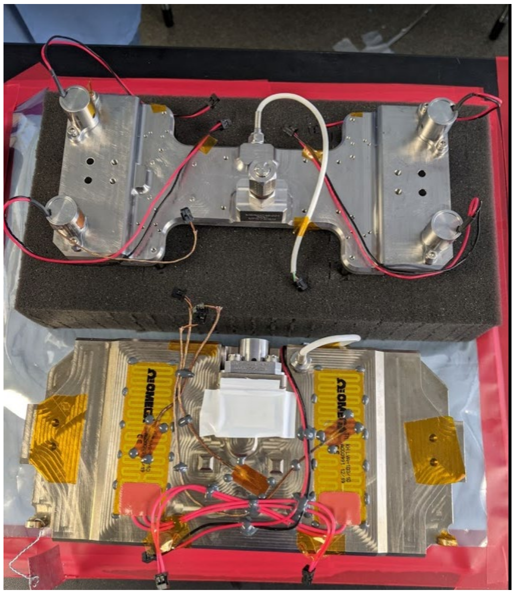

Fig. 20 Completed Tank Subassembly with Wires Routed Next to the Manifold

F. AITP-06 Tank and Manifold Mounting

Mating the tank and manifold together was a very tightly toleranced task. There are 12 holes on the two pieces that must be exactly aligned to within .01” in order to attach the solar panel mounts. This alignment requirement posed many issues, beginning with the need to locate each hole’s location on the overall part. The machinists that manufactured the part provided an inspection report to verify the accuracy of their work to be within the given requirements, however it did not include information about each hole’s absolute position relative to X and Y body planes. Therefore, it was necessary to measure each hole’s location by hand on a mill.

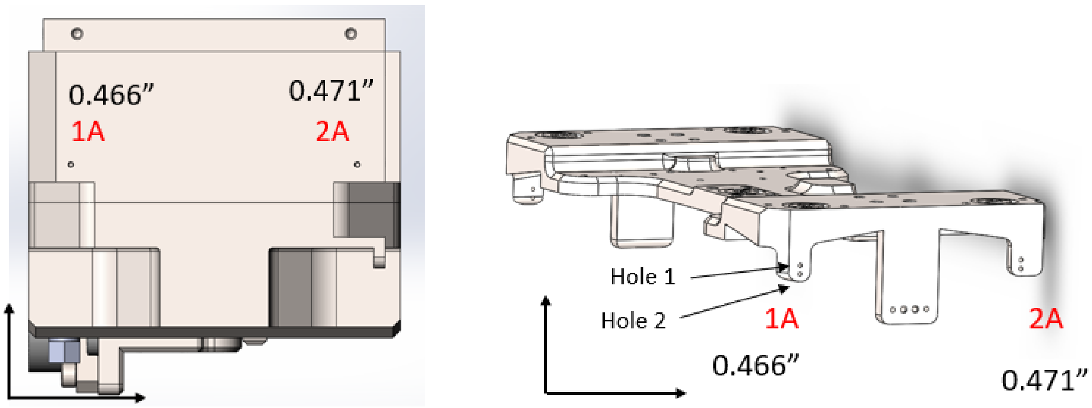

Fig. 21 Tank and Manifold Solar Panel Mounting Hole Locations

The manifold and tank both had all openings covered with Kapton tape for cleanliness and were taken to the Aerospace Engineering (AE) machine shop to indicate each hole location and find its position. Once all of the measurements were taken, geometric calculations were done to determine how much to offset the tank and manifold in order for their holes to be precisely aligned. The two faces could not simply be held flat, each face needed to be offset a specific amount.

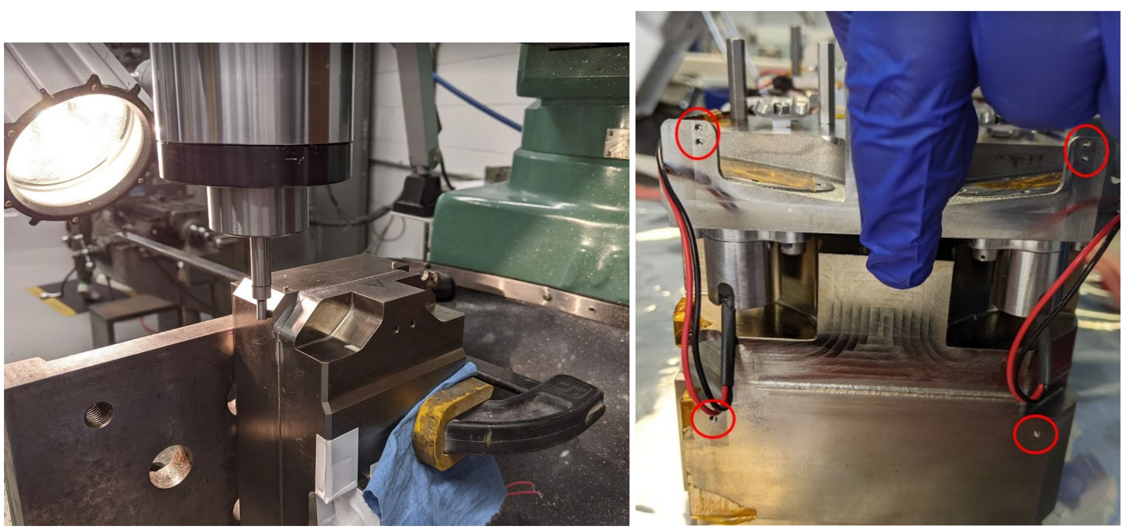

Fig. 22 Tank and Manifold Measurements and Test Fit

A fixture was 3D printed to hold precision squares and parallels, as well as fine threaded screws to push out the surfaces to the correct position relative to each other. The tank and manifold were each clamped to the screw mounted setup and held very tightly in place while the eight connecting screws were torqued down into place. It was a multiple-person effort to measure and hold everything in place, but once it was finally attached, the holes were all successfully aligned to within the .01” margin.

Fig. 23 Tank and Manifold Mounting Fixture

G. AITP-07 Pump Installation and Leak Test

The FlightWorks Micro-pump that was installed on the system also had a thermocouple attached to it for health monitoring during flight. The thermocouple used another set of custom made 3D printed clamps to hold the thermocouple in place while the epoxy dried. Once the thermocouple was attached, a set of double o-rings around the inlet and outlet port were placed in grooves on the pump's face. A thermal pad was nestled inside a cutout in the pump mounting block the improve the thermal conductivity in between the pump to the manifold.

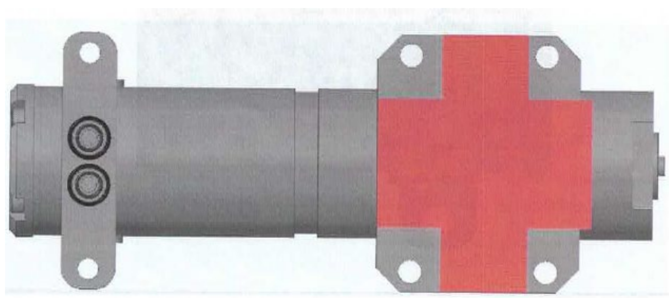

Fig. 24 Underside of the Pump with O-rings and Thermal Pad

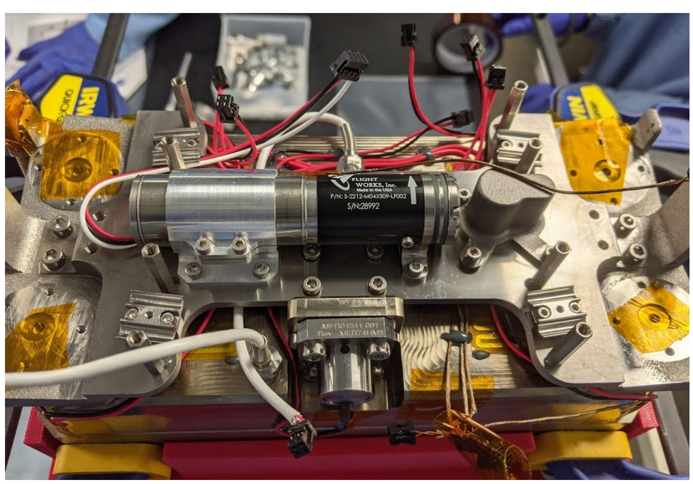

Fig. 25 Tank and Manifold Subassembly with the Pump Attached

Once the pump was installed, the system subassembly underwent another leak test to check the connections between the tank, manifold, and manifold parts. The same helium testing rig and procedure was used for this test as the flight manifold proof and leak test. The system used the ground half fill drain valve this time to fill the tank with helium, then the isolation valve was opened to also fill the manifold. The entire system was raised to 100 PSIG for a pre-proof snoop leak test, then was filled to a proof pressure of 117 PSIG. This was held for 10 minutes before decreasing back to 100 PSIG, where a final snoop leak test was performed. All of the connections were sealed tight and had no indication of leakage with the snoop test. This completed another successful pressure testing campaign with the flight unit.

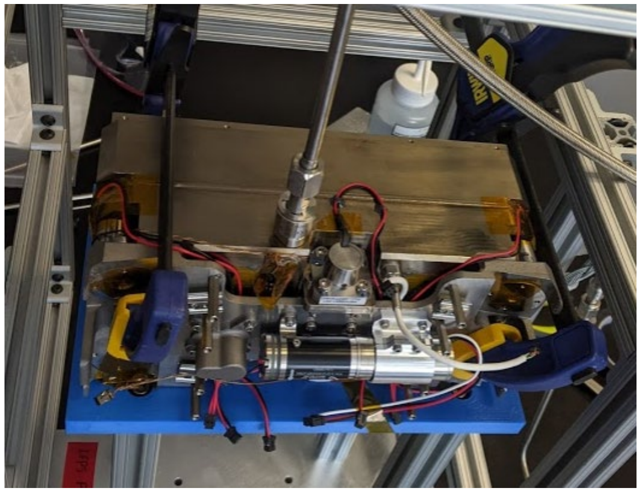

Fig. 26 Tank and Manifold Subassembly During Pressure Testing

H. AITP-08 Thruster and Controller Installation

The original Assembly and Integration flow plan required the controller to be attached before the thrusters. When the plan was made, it was thought that the thrusters would be delivered after the controller, so the controller would need to go on first to save time. However, the thrusters were finished and delivered sooner than expected, and it was found to be easier to attach the junction box brackets before putting the controller boards on. For these reasons, the thrusters were installed first.

Tomas Hasanof from Plasma Processes came to Georgia Tech to help install and flow test the thrusters. Each thruster had its wires cut to the appropriate length before being integrated. It is interesting to note that cutting the excess wire off of the thrusters removed 30 grams of mass per thruster for a total mass reduction of 120 grams. This was much more of a mass saving than expected.

The junction boxes all need to thermally conduct to their mounts and the manifold beneath them in order to stay in an operable temperature range. They needed to have some sort of thermally conductive and compressive material that could provide as much surface contact as possible in between the junctions and their mounts. Originally, the idea was to use a thin strip of indium, which is highly conductive and similar to aluminum foil. These indium sheets were cut to size with an xacto knife, but came with an acrylic backing on them that had to be removed by soaking in acetone. Once the strips were dipped into the acetone, they were so small and fragile that they immediately disintegrated. The indium foil was thinner than gold leaf, and would have been nearly impossible to install. The solution was to replace the indium strips with thermal vacuum grease. The project managers were contacted to help make this last minute decision before performing the installation, and it was approved.

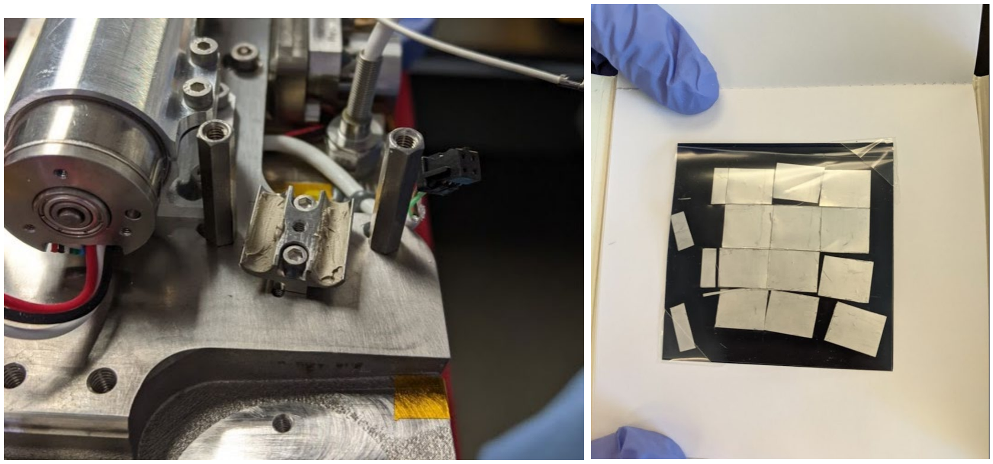

Fig. 27 Junction Box Mount with Thermal Grease versus the Indium Strips

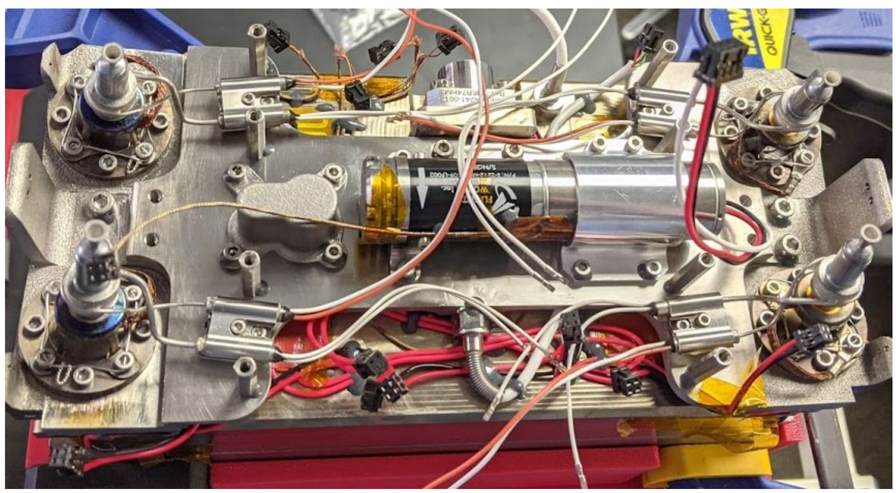

Fig. 28 Tank Assembly with Thrusters and Junction Box Brackets Installed

After being integrated, the thrusters all needed to be flow and leak tested. The flow test verified that all of the internal passageways through the system were not clogged and that each thruster was passing its expected mass flow rate for the given input pressure. This test was accomplished by pressurizing the tank with helium again, opening the isolation valve, and opening a thruster valve one at a time while a rotameter was attached to it. All four thrusters had a flow rate of 27 mL/min of He when pressurized to 100 PSIG, which was directly in the middle of their acceptable range. Therefore, they all passed without issues. Then, with the tank pressurized with helium, all of the valves were closed and the entire system was placed into a vacuum chamber connected to a helium mass spectrometer. The vacuum chamber was depressurized, and the mass spectrometer attempted to detect any helium that could be leaking from the system. So little was detected that it was actually lower than the control measurement taken without the tank being inside. These two tests verified that the system was completely airtight and the thrusters were successfully connected to the fuel lines without any obstructions.

Fig. 29 Thruster Leak Test and Flow Test

The controller boards were the last major piece to be integrated onto the propulsion system. All of the wires were staked into their final places, and the boards were carefully screwed onto their mounting brackets. All of the DF-11 sockets were pushed into their appropriate connectors, while checking multiple times to ensure that each wire went from the right component to the right port. With all the wires connected, the top board was mounted into place. The boards were connected with spring loaded plated pins, and those pins had to be precisely in line for good contact. To check that they were aligned, a mirror was used to look for perfectly straight lines.

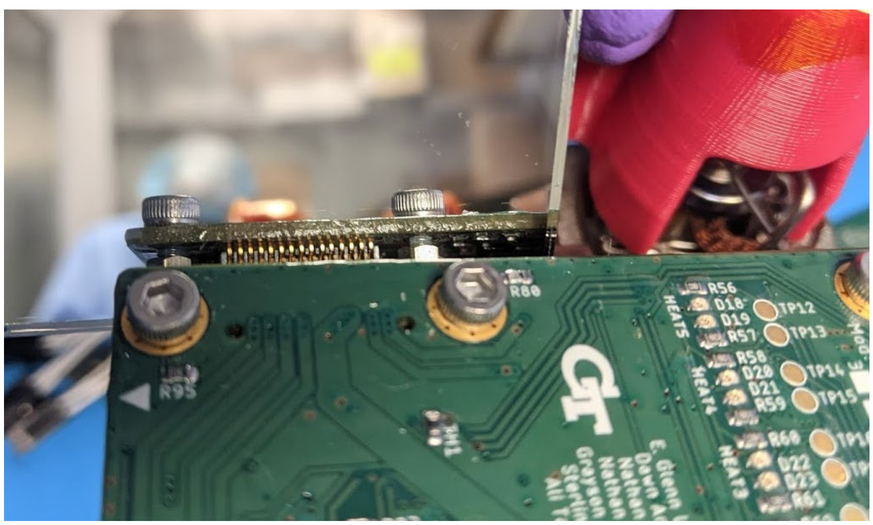

Fig. 30 Mirror Inspection of Controller Board Connector Pins

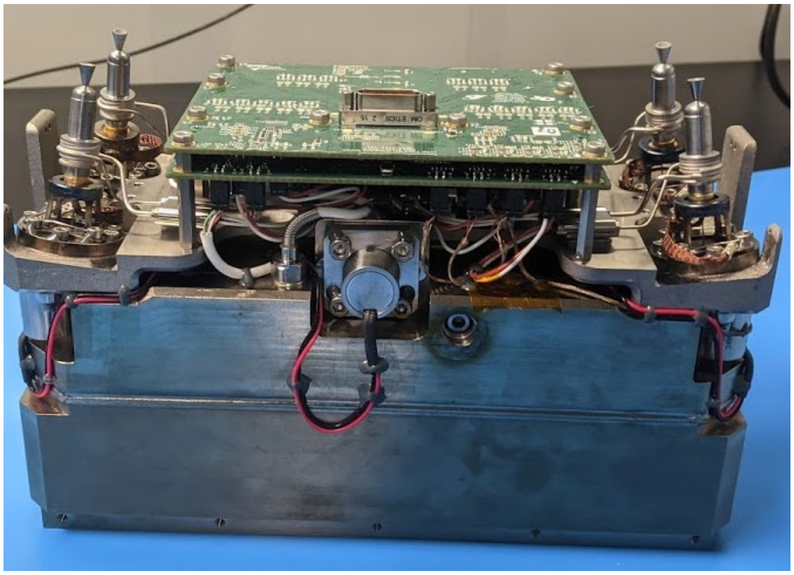

Fig. 31 System with Controller Boards Installed

I. AITP-09 Muffin Tin Installation

The muffin tin went on very easily on top of the system, and perfectly boxed up the propulsion system. After fixing it on, all the major flat faces of the system were wrapped in reflective material to help the system match the thermal properties deemed the best by the LFPS thermal model. Then the last step was to put stoppers onto the front to protect the isolation valve wire from being bumped by the solar panels that will rest against that face. The wire stoppers were made out of epoxy that was molded in a rubber washer and later popped out and sanded flat. This simple solution prevented the team from having to add another part or material to the materials list.

Fig. 32 Isolation Valve Wire Stoppers Being Molded

Because of how fragile the thrusters are, a need was identified to protect them from being bumped or jostled during carrying and integration activities. A set of plastic 3D printed covers were made that fit snuggly onto the manifold and protect all four thrusters without touching them.

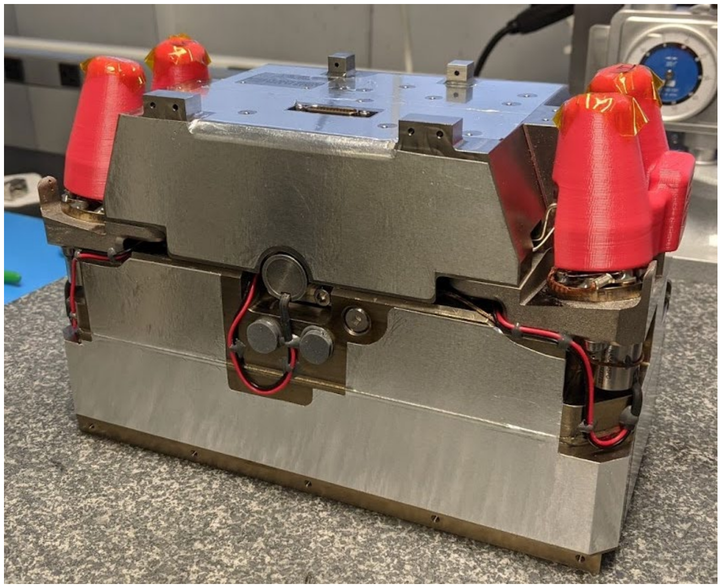

Fig. 33 Final System with Thruster Covers Attached

The final step of the LFPS assembly process was to complete functional acceptance testing. During this test, the propulsion system was placed in the thermal vacuum chamber to complete a series of checkouts, and to run the thruster heaters on the system for the first time. The system was liveness tested, which meant turning on each component and reading values from all of the sensors to see that they all worked. Then the thruster heaters were turned on to pre-heat, and determined how much power they drew, how quickly they got to temperature, and how altering the duty cycle affected the heater parameters.

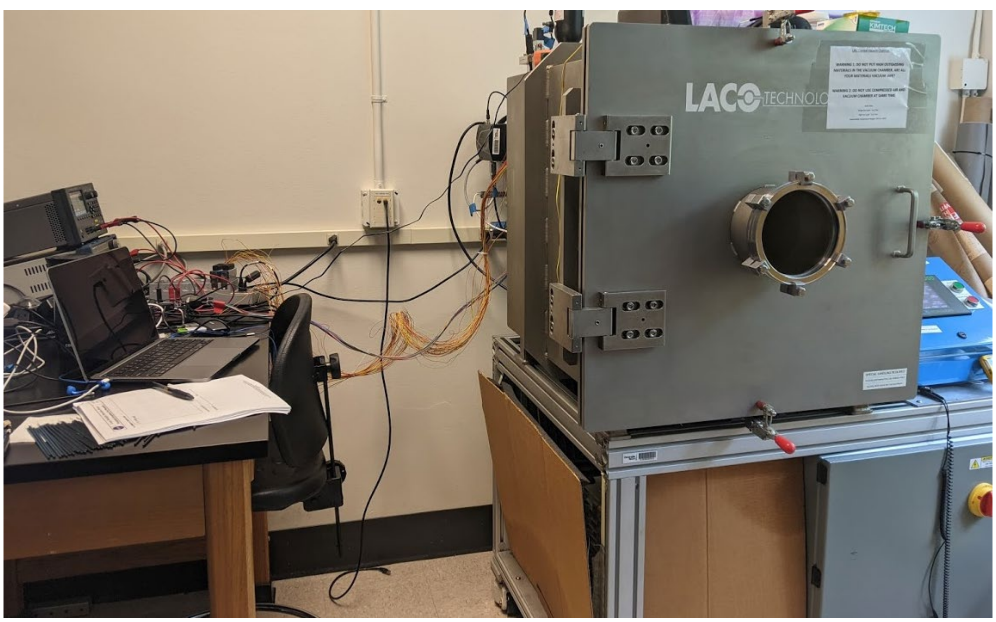

Fig. 34 Thermal Vacuum Chamber with Connected Laptop for Functional Checkouts

This test was particularly significant because it provided flight-like data for how the controller operated. The thruster thermostatic heater control was tested by commanding a minimum and maximum temperature setpoint and allowing the controller to power the heaters until they were hot enough. This functionality had a lot of variability depending on multiple confounding variables. The controller is capable of heating all four heaters at the same time, or alternating them one, two, or three at a time in order to limit the overall power draw. For example, if only two heaters are ever powered at once, they draw less power than if all four are on together. The number of heaters that were allowed to be on at once affected how quickly the heat ramped up, but also limited the ability to reach the target temperature. The “off” time for each heater while in between cycles would eventually lose the additional heat gained during the “on” phase. Another variable that changed the results was how much power was provided to the system. The Lunar Flashlight Propulsion System is designed to be able to function with a range of voltage from 9V to 12V. Because the heaters are resistors, they behaved differently depending on the input voltage. The combination of all of these led to some changes in how the heater control algorithm worked in order for it to function as desired in all cases.

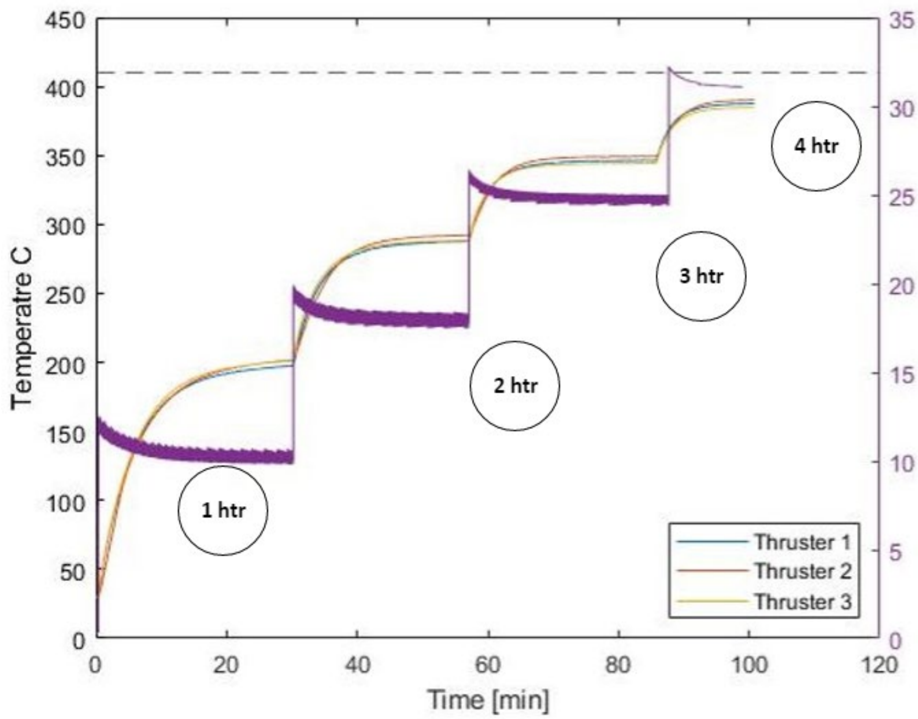

Fig. 35 Thermal Test Data During Functional Checkouts

V. Performance Analysis

As the system was being built, all of the parts were weighed individually, and the assembly as a whole was weighed at the end. The mass of the system is very important, because the mass is limited by the launch vehicle, and influences the amount of propellant that can be carried onboard the spacecraft. During the design phase, an expected mass list was created that detailed the anticipated mass of each individual component. NASA has a standard to add a certain percentage of Growth Allowance to each part dependent on their maturity level in order to avoid under-estimating mass during the design phase. However, this growth allowance was found to be fairly extreme when used on the small spacecraft scale. As a result, the system came in under mass, and allowed for a higher amount of propellant to be stored than previously expected.

In addition to the reduced mass, data from the testing campaign showed that the system overall should not only meet its requirements, but overperform. An analysis report indicated a low bound estimate that the PMD should be able to provide a propellent expulsion efficiency of about 80%. The thrust capability of the thrusters was proven during thruster qualification testing to show that the system will meet it’s design goal of 3000 N-s.With the assumption that 80% of the total fuel on board will be used, it was determined that the system will be able to provide 3132 N-s of total impulse and 242 m/s of Delta V. This value becomes even greater if the expulsion efficiency is higher than expect.

TABLE I:
PROPULSION SYSTEM PERFORMANCE

PROPULSION SYSTEM SPECIFICATIONS	
SYSTEM PERFORMANCE	
PROPELLANT:	AF-M315E
ULLAGE:	GN2
NOMINAL THRUST PER THRUSTER:	100 mN +/- 10mN
TANK MEOP:	90 psia
MANIFOLD MEOP:	275 psia
TANK MDP:	100 psia
MANIFOLD MDP:	500 psia
TANK PROOF PRESSURE:	157 psia
MANIFOLD PROOF PRESSURE:	795 psia
TANK SUBASSEMBLY BURST PRESSURE:	258 psia
MANIFOLD SUBASSEMBLY BURST PRESSURE:	1250 psia
TANK VOLUME:	1521 cc
PROPELLANT VOLUME (17% ULLAGE):	1262 cc
EXTERNAL LEAKAGE:	<= 5 x 10-3 sccs GHe @ MDP
OPERATING TEMP:	5°C to 40°C
NON-OPERATING TEMP:	-15°C to 60°C
MINIMUM SPECIFIC IMPULSE:	210s
ASSUMED USEABLE PROPELLANT:	>80%
TOTAL IMPULSE (17% ULLAGE):	>3030 N-s
ESTIMATED DELTA-V (14KG SPACECRAFT):	>230 m/s
DRY MASS:	3.608 kg
WET MASS	5.448 kg

Fig. 36 Final System Performance Capabilities

VI. Conclusion

In conclusion, the Lunar Flashlight Propulsion System is a groundbreaking system that will advance the future of in-space propulsion capabilities for small satellites. The entire process, from design to manufacturing to assembly and testing was completed in just two years and has been incredibly successful. The new technologies built into the system, including the combined use of additive and traditional manufacturing, new micro-thrusters that utilize green monopropellant, a COTS built controller board, and a micro-pump, will all receive flight heritage on this mission and will be a leading pathfinder for future missions. The Glenn Lightsey Research Group as part of the Georgia Tech Space Systems Design Laboratory along with a team at Marshall Spaceflight Center are already using the lessons learned and experience from this system to design a new propulsion system for a spacecraft called Spectre.

VII. Acknowledgements

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I would also like to say thank you to the entire MSFC team. Daniel Cavender and Carlos Diaz, your mentorship has been incredible. I have learned more from you both than I thought possible, and have genuinely enjoyed working together with you and finishing this system.

Finally, I would like to thank Dr. Glenn Lightsey for making all of this possible. Thank you for believing in me, bringing me into your lab as a graduate student, and providing me the ability to work on this satellite going to the moon. I could not be here without you.

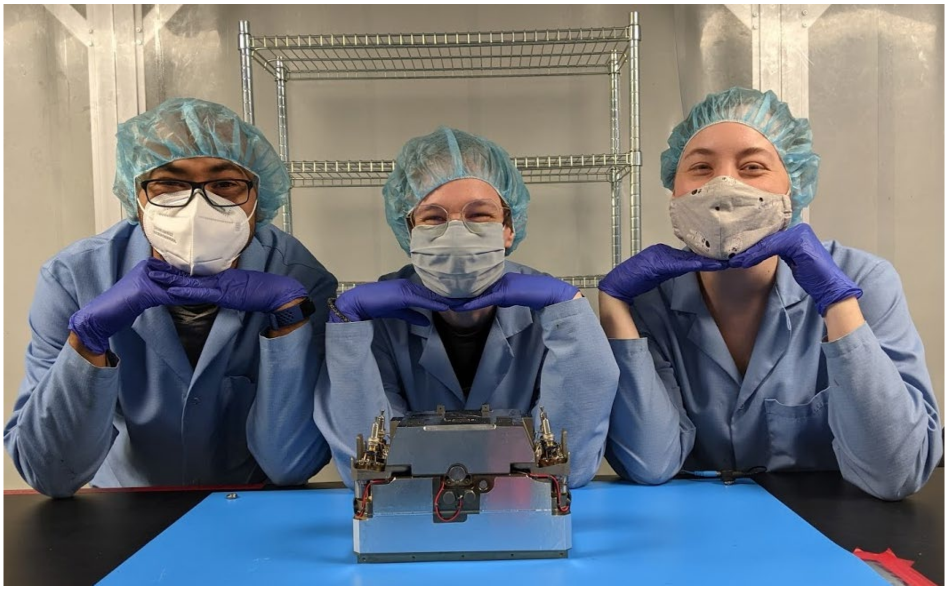

Fig. 37 (left to right) Brandon Colon, Celeste Smith, and Lacey Littleton with the completed Lunar Flashlight Propulsion System

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