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

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NASA's Lunar Flashlight is a 6U CubeSat that will be investigating the Lunar South Pole for water-ice. Propelling the spacecraft is a 2.5U green monopropellant propulsion system developed by the Georgia Tech Space Systems Design Laboratory in partnership with the NASA Marshall Spaceflight Center and NASA Jet Propulsion Laboratory. Lunar Flashlight will be the first interplanetary CubeSat to use green propulsion, and will be the first CubeSat to place itself into orbit around another planetary body. Utilizing a mix of traditional and additive manufacturing techniques to manufacture the propulsion system presented unique challenges for the project. In addition, the integration of precision flight hardware has required rapid design changes to parts to ensure that the system fits together as intended. However, as a pathfinder mission for future small satellite propulsion systems, the Lunar Flashlight Propulsion System will establish flight heritage of various components, including additively manufactured hardware, microfluidic components, custom-designed electronics, and unique cleanliness specifications.

I. Introduction

In recent years, as technology capabilities have increased for satellites, their size and form factors have decreased, ushering a new wave of small satellites known as CubeSats. While the mission timelines are short and their current capabilities are limited, these satellites can be designed, manufactured, and integrated at a fraction of the cost of traditional satellite systems. CubeSats currently are classified as orbiters that perform small-scale scientific research, while also serving as technology demonstration missions.

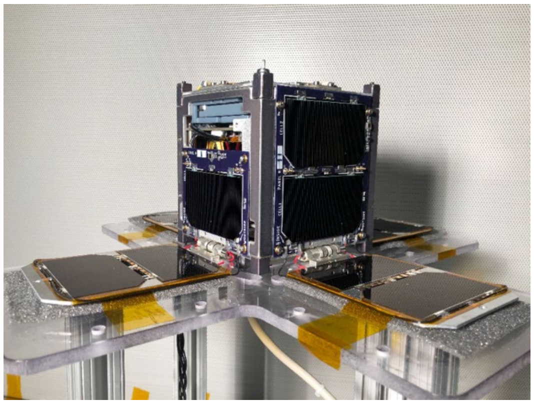

Figure 1. GT-1, a 1-U CubeSat being built by the GLRG as part of the GT SSDL

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A very significant topic of research in the area of small satellites is increasing the propulsive capabilities of CubeSats in order to increase the scope of missions that the satellite can perform. Cold gas systems are the most common choice of propulsion systems used on CubeSats currently due to their versatility in design and delta-V capabilities for attitude-control maneuvers. Since most Earth-orbiting CubeSats do not require a large delta-V capacity, these cold gas systems are sufficient. In order to increase the delta-V capabilities, a different propellant must be used to increase the propulsive efficiency and total impulse. Liquid monopropellant propulsion systems are used to achieve these higher specific impulse values. For satellites that require greater propulsive capabilities, hydrazine is a common propellant that is used. However, hydrazine is very toxic to humans, which makes the propellant difficult to store and handle. This in turn, drives up the cost of the propellant, and drastically increases the cost and complexity of hydrazine-based propulsion systems.

Green monopropellants, as they are known, have been developed to address the complications presented by hydrazine. These propellants have the capabilities to achieve specific impulse values similar, and even greater to that of hydrazine, and have a much lower hazard classification [1].

This paper discusses the manufacturing and integration of the green monopropellant propulsion system being designed by the Glenn Lightsey Research Group (GLRG) as part of the Georgia Tech Space Systems Design Laboratory (SSDL) for NASA's Lunar Flashlight mission. This report describes the various components of the system, the manufacturing techniques used to fabricate the major components, and the integration of the propulsion system.

II. Lunar Flashlight Mission

A. Mission Overview, Purpose, and Objectives

Lunar Flashlight is a 6U CubeSat that will be launched as a secondary payload on the Artemis I mission, which will also serve as NASA's Space Launch System's first flight. During the two-month mission timeline, the satellite will use lasers to search for water-ice in the Moon's craters close to the Lunar South Pole. These craters lie in permanently dark areas on the lunar surface, and the spacecraft's instruments will attempt to distinguish water-ice by observing the reflection of light off of the surface using a four-laser reflectometer [3,4].

In order to place itself in the lunar polar orbit required to perform the mission, the spacecraft will use a green monopropellant propulsion system to provide the necessary delta-V for the orbit insertion. The propellant used will be AFM315E (ASCENT), created by the Air Force Research Laboratories (AFRL). Lunar Flashlight will serve as a technology demonstration mission for the propulsion system, as the spacecraft will be the first interplanetary CubeSat to use green propulsion. In addition to the orbit insertion, the Lunar Flashlight Propulsion System (LFPS) will also be used for attitude control and orbit correction maneuvers. The Lunar Flashlight mission objectives are outlined in the table below [3]:

Table I. Lunar Flashlight Mission Objectives

1.	Demonstrate green propulsion system technology for planetary missions using a low-toxicity propellant that is simpler to handle while providing higher performance than hydrazine
2.	Demonstrate active laser spectroscopy that could differentiate between water-ice (or frost) and dry regolith on the Moon's surface
3.	Map the locations of exposed surface water-ice near the Moon's South Pole
4.	Determine the viability of a CubeSat platform for performing scientific measurements

B. Implications and Importance

As NASA aims to send astronauts to the Moon by 2024, it is imperative that water and other resources are found on the Moon's surface. Lunar Flashlight will aim to identify these areas, allowing NASA to plan processes and manned missions around locations that are rich with resources. Using Lunar Flashlight's potential discoveries, future missions could use some of the resources identified that are already present on the surface of the Moon, rather than having to bring them from Earth, drastically reducing future mission costs.

If successful, Lunar Flashlight will be a pathfinder mission for future interplanetary CubeSat missions, enabling other payloads fueled by green monopropellant propulsion systems. The mission aims to show that interplanetary

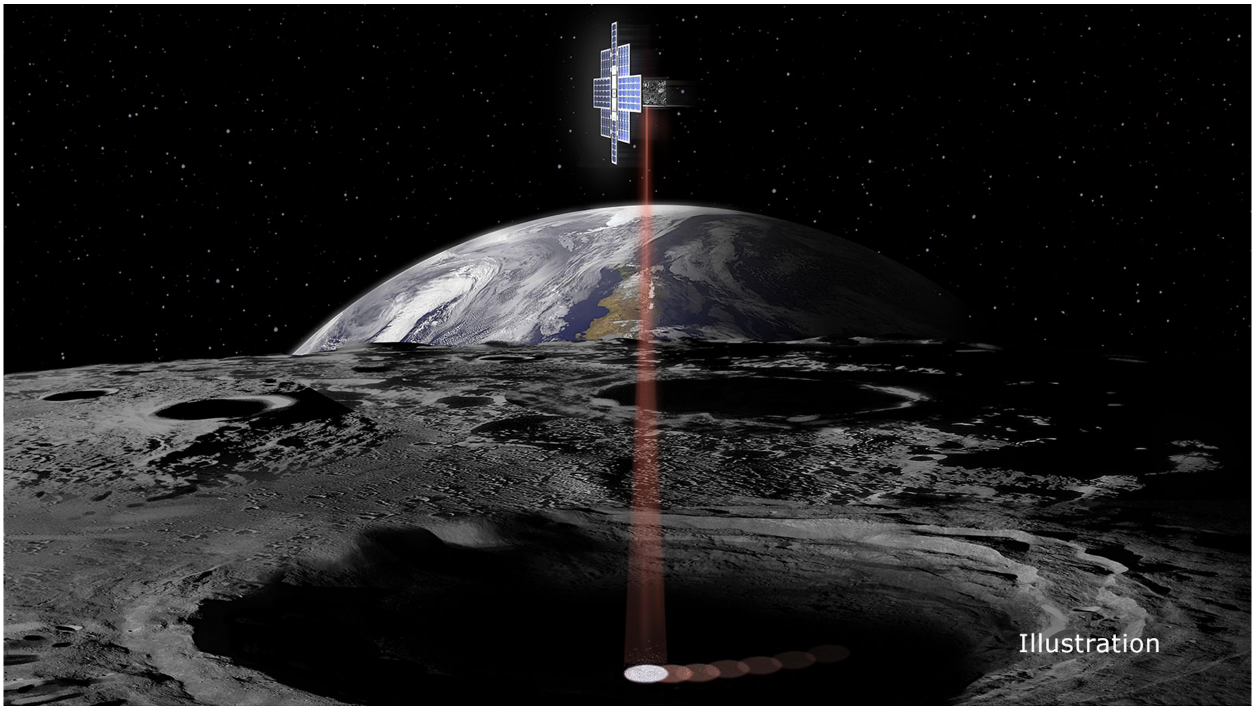

Figure 2. Artist's depiction of Lunar Flashlight over shadowed Moon crater [4]

CubeSat missions can be completed at a fraction of the cost of typical satellite missions.

III. Propulsion System Overview

The Lunar Flashlight Propulsion System consists of three major structural components: the propellant tank, the manifold, and the electronics radiation shield known as the "muffin tin." The system interior consists of various microfluidic components: the recirculation block, the pump, the pressure sensors, and the thrusters. Tertiary hardware consists of the micro-solenoid valves developed by NASA Marshall Spaceflight Center (MSFC), and the junction box block. Figure 3 shows the schematic of the Lunar Flashlight Propulsion System. LFPS is a pump-fed system, rather than a traditionally-used pressure-fed system. A schematic of this system is shown in Figure 3. This design choice, in part, is due to the geometry of the satellite. Most pressure-fed systems are utilized in tanks that are cylindrical in nature to provide for adequate pressure loading around the internals of the tank. Due to the "cubic" geometry of a CubeSat, rectangular-shaped tanks need to be used to maximize tank volume. In addition, the pump reduces the necessary system pressures that the system will need to operate to more manageable levels. This decreases the structural complexity of the propellant tank, and will decrease the overall system mass [2].

A. Propellant Tank

The Lunar Flashlight Propulsion System propellant tank consists of two tank halves that are electron beam welded together to form one part. Both halves are traditionally manufactured from Ti 6Al-4V, AMS 4928. This material was chosen due to its high strength-to-weight ratio, and due to its material compatibility with ASCENT. The total tank volume is 1521.699 cubic centimeters, with a total mass of 1841.72 grams (this number includes the propellant management device, discussed later). The propellant tank will not only house the liquid monopropellant, but will also house gaseous nitrogen that will be used as an ullage gas to keep pressure within the tank. The propulsion system will have a 24% ullage volume allotted for the gaseous nitrogen, meaning that the remaining volume will consist of ASCENT. Only 90% of the ASCENT within the tank will be accounted for as "usable propellant", as some of the liquid may stick to areas of the tank that are too far away from the tank/manifold interface, and are out of reach of the propellant management device. The propellant tank was designed to meet a maximum design pressure of 100 psia, a proof pressure of 150 psia, and a burst pressure of 250 psia.

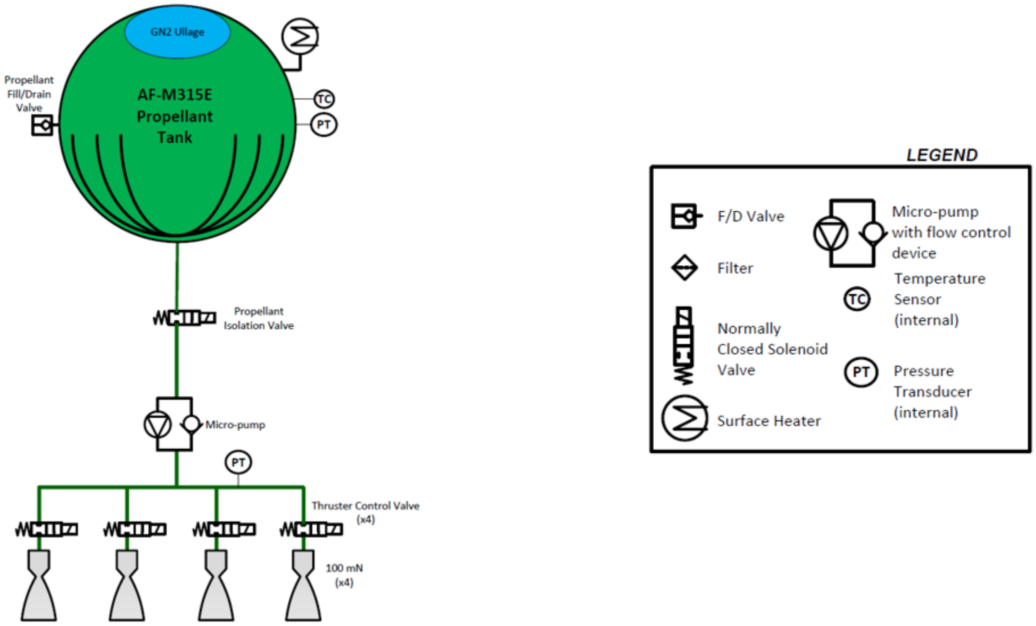

Figure 3. Lunar Flashlight Propulsion System Schematic

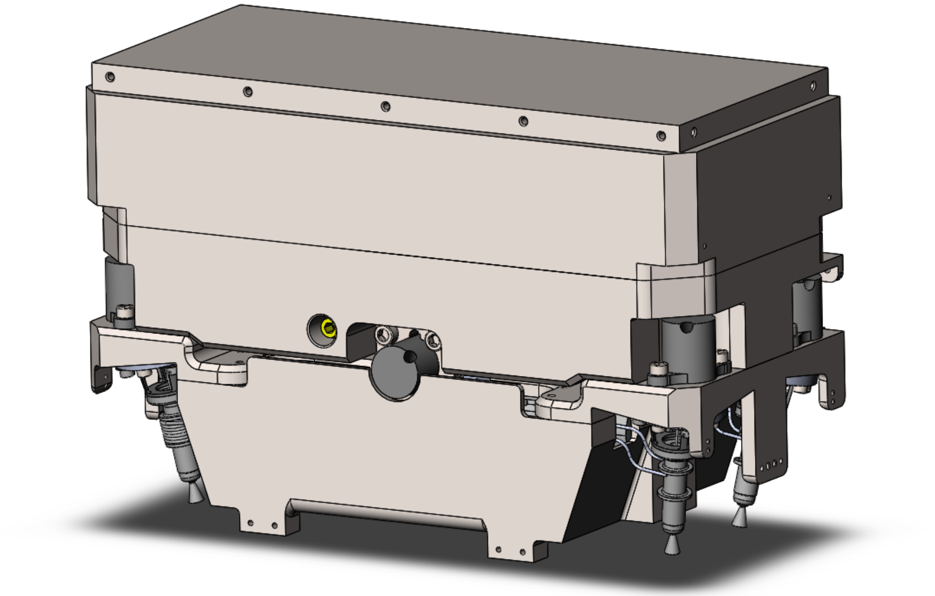

Figure 4. Lunar Flashlight Propulsion System CAD Model

The tank top is a much simpler to manufacture part relative to the tank bottom structure. The exterior of the tank top includes the Lunar Flashlight spacecraft interface holes, while the interior houses structural ribs that not only allow the tank top to have a higher stress margin, but also give a greater wall thickness to ensure that there will be no compromise of wall strength when accounting for the spacecraft interface fasteners.

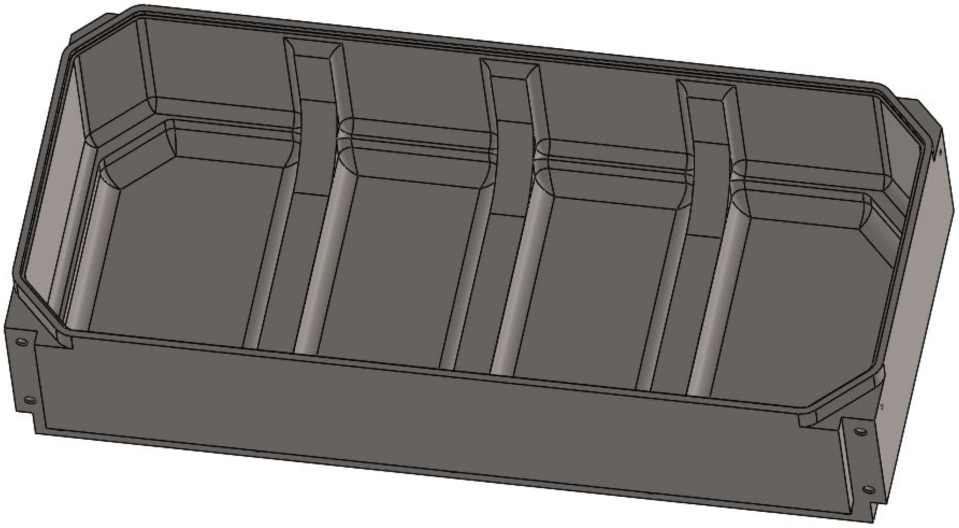

Figure 5. Tank Top Structure

The tank bottom is a much more difficult to machine part due to this component housing the propellant management device, as well as a ten micron titanium filter at the point of the tank/manifold passthrough. In order to interface with these components, a cutout for the filter was placed at the bottom of the tank, concentric with the tank/manifold passthrough. On the propulsion system, all fluid seals include double o-ring grooves to prevent any leakage of propellant. Early design of the filter "seat" included an o-ring at this interface. However, after the electron beam welding process, the propellant tank will go through a heat treat at 1100 degrees F (593 degrees C) for two hours in order to relieve residual stresses. This process would cause the o-ring to melt within the tank, and therefore, the o-ring and o-ring grooves were removed from the tank bottom. Threaded bosses were extruded from the bottom of the tank to provide a suitable mechanical interface for the propellant management device. Additionally, the tank bottom is the interfacing component with the manifold, and needs to include the spacecraft interface holes. Other hardware that interfaces with the tank bottom includes the fill/drain and isolation valves designed by MSFC, a pressure sensor that is inserted into the bottom of the part, and heaters that will be attached on the outside.

A.I. Propellant Management Device

Housed inside the propellant tank is the propellant management device (PMD). During the mission, in a zero-gravity environment, the propellant could be at any location within the tank. The purpose of this subassembly is to ensure that the liquid monopropellant is as close to the tank/manifold passthrough as possible. The propellant management device is comprised of two parts: the sponge and the ribbon vanes. Both of these components use liquid surface tension to direct the propellant in the direction of the tank/manifold passthrough. When looking at Figure 6, it is evident that the ribbon vanes stretch toward both the end walls and the corners of the tank in order to "grab" as much liquid as possible.

B. Manifold

The additively manufactured manifold is the most complex piece of hardware on the propulsion system. This part, manufactured from Ti 6Al-4V virgin powder, houses all the internal fluid passages that route the propellant from the tank to the recirculation block and to the thrusters. These fluid passages internal to the manifold would not be able to be created using traditional manufacturing techniques due to their complicated paths. Additive manufacturing enabled these passageways to be placed at a variety of locations within the part, and enabled them to connect various interfaces to each other. External to the manifold includes the tank/manifold interface, the muffin tin interface, and the holes for the JPL solar arrays that will provide power to the spacecraft. The manifold will increase the heritage of metal additively manufactured flight hardware, and will lead to opportunities for other additively manufactured flight hardware, including propellant tanks and tertiary hardware. The manifold was designed to a maximum design pressure of 500 psia, a proof pressure of 750 psia, and a burst pressure of 1050 psia.

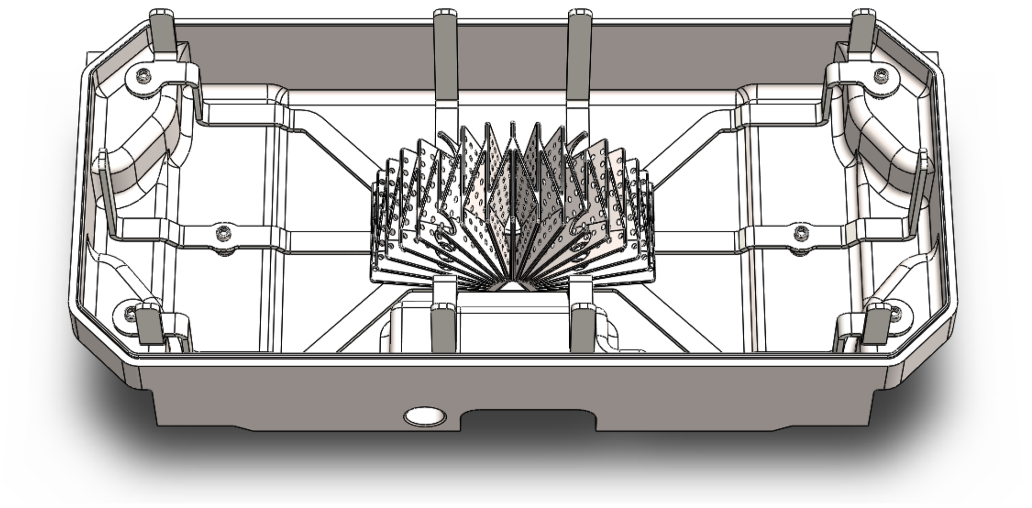

Figure 6. Tank Bottom with PMD inside

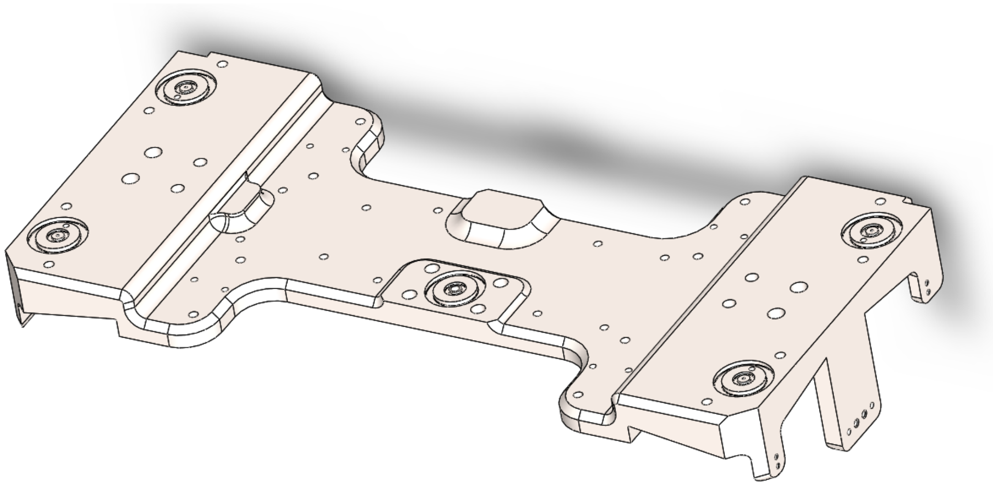

Figure 7. Manifold Structure

B.I. Recirculation Block

The recirculation block is a component that is critical to the successful operation of the system. Mated to the manifold, this component houses a flow control device, an orifice, that will provide a pressure drop for the monopropellant coming from the tank. This is to ensure that the system stays within operating pressure of the pump. During nominal conditioning and firing, most of the flow will travel through the recirculation block before traveling through the thrusters. This component was additively manufactured from Ti 6Al-4V virgin powder for the same reason as the manifold: the routing of the fluid passages would be impossible using traditional manufacturing techniques. Since the manifold has its fluid passages printed directly into the structure, it would be very difficult to place an orifice inside this tubing. Therefore, the recirculation block was created as a separate part to perform this function [2].

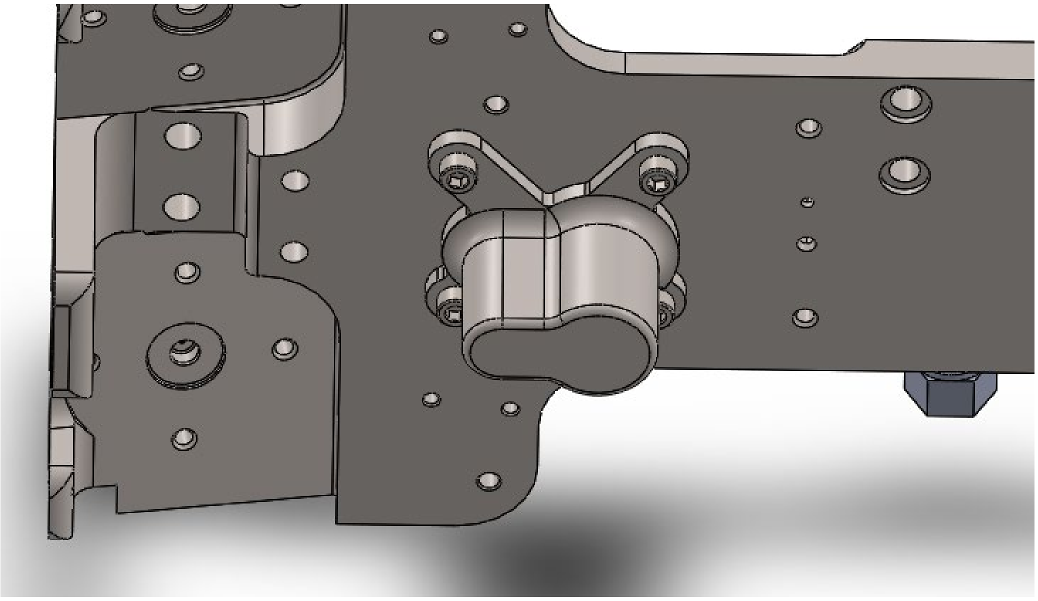

Figure 8. Recirculation Block mated to Manifold

B.II. Junction Box Block

The junction box block was created as a mount to hold the thruster junction boxes during flight. The junction boxes are part of the thruster assembly to allow for nominal operation. These components are metal cylindrical boxes that are connected to the thruster by a thin metal wire. Both of these boxes perform different functions: one of these boxes is a heater while the other is a thermocouple. When designing this part, the bend radii of the thin metal wires needed to be taken into account, as the location where the wire leaves the thruster and the location where the junction box block is mated to the manifold are on different planes, as shown in the figure below.

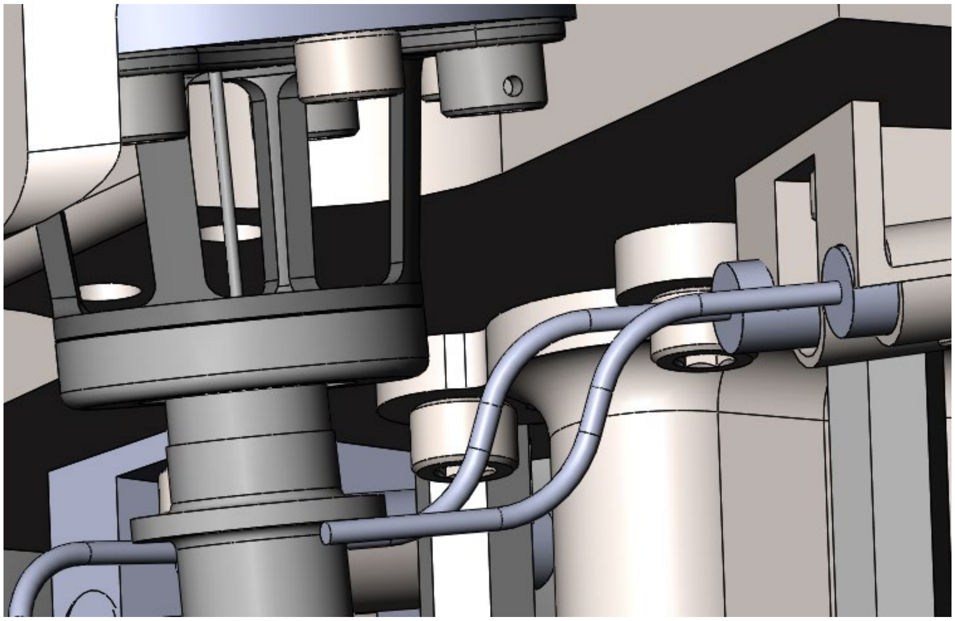

Figure 9. Wires connecting Junction Boxes and Thruster

The original requirement for this component was that the center axis of the block needed to be aligned with the center axis of the thruster. To meet this requirement, the top surface of the junction box block was canted at two different angles, and the block was made to a very complex geometry. However, after the SSDL designed this block, this requirement was relaxed by the thruster vendor. Since this part was originally supposed to be traditionally manufactured from Ti 6Al-4V AMS 4928, the geometry of this part would make machining difficult, and therefore, would drive up the cost of machining.

As a result, this component has been undergoing design iterations, as well as a potential change in material, to decrease the cost of machining. A potential technique that was considered was 3D printing this mount out of Somos PerFORM, a composite material that would allow for a potential weight saving on the system, and would eliminate the need for a simple geometry. One of the drawbacks with using this material is that each component would need to be individually tested before being integrated with the system. This is due to the potential difference in material properties between the PerFORM parts which could be caused by potential voids, delamination, and other point defects.

The project has decided to utilize traditional manufacturing techniques to machine the part, however the specific metal has not been selected at the time of this report. Aluminum and titanium are two metals that are currently being explored for this part. The final design is shown below in Figure 10.

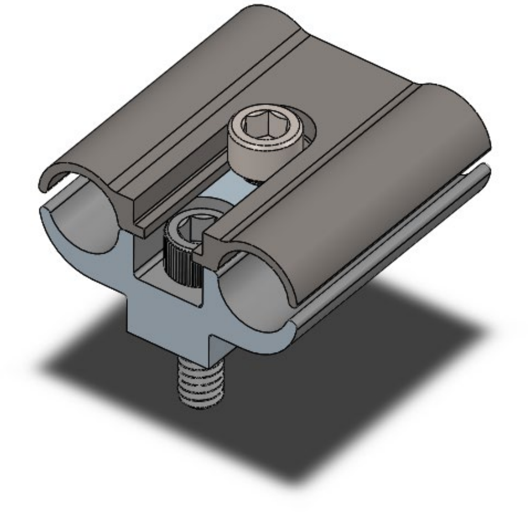

Figure 10. Junction Box Block

This assembly includes a mount plus bracket design that will allow the junction boxes to stay secured during the mission. The primary form of retention will be epoxy, while the bracket will act as a secondary form of support. A slot, instead of a single-hole design was chosen for the bracket, will allow the bracket to be placed on the junction box block after the controller is integrated if necessary.

C. Muffin Tin

The muffin tin is the name given to the radiation shield that covers the sensitive electronics that power the system. This part is traditionally manufactured from Ti 6Al-4V, and interfaces with the underside of the manifold. While not housing any fluid passages, the muffin tin is still a complex part due to the various interfacing components. The underside of the muffin tin is the major interface for critical spacecraft hardware, including: low-gain antennas, sun sensors, the deployment limit switch, and the solar panels. In addition, a cutout at the bottom of the muffin tin is included for a connector that will interface with Georgia Tech SSDL hardware.

While the largest source of radiation will be seen while the spacecraft travels through the van Allen belts, a significant dose of thermal radiation comes from the thrusters on the system. During firing, the thrusters can reach up to 1600 degrees C, and the radiation emitted can damage the electronics on the system if not directed properly. The canted walls near the thrusters absorb the energy and dissipate the heat, preventing the boards from reaching temperatures that are too high for operation [2]. At the bottom face of the muffin tin, a large filleted edge was placed on the exterior to allow for the routing of spacecraft wires. If this edge was sharp, this may have resulted in the breaking of some of these wires. Due to this feature addition on the exterior of the part, a variable fillet was placed on the inside of the muffin tin to allow for an increase in wall thickness in that specific area. Furthermore, internal fillets were added to the muffin tin to prevent the creation of any stress concentrations that could potentially cause a fracture during flight.

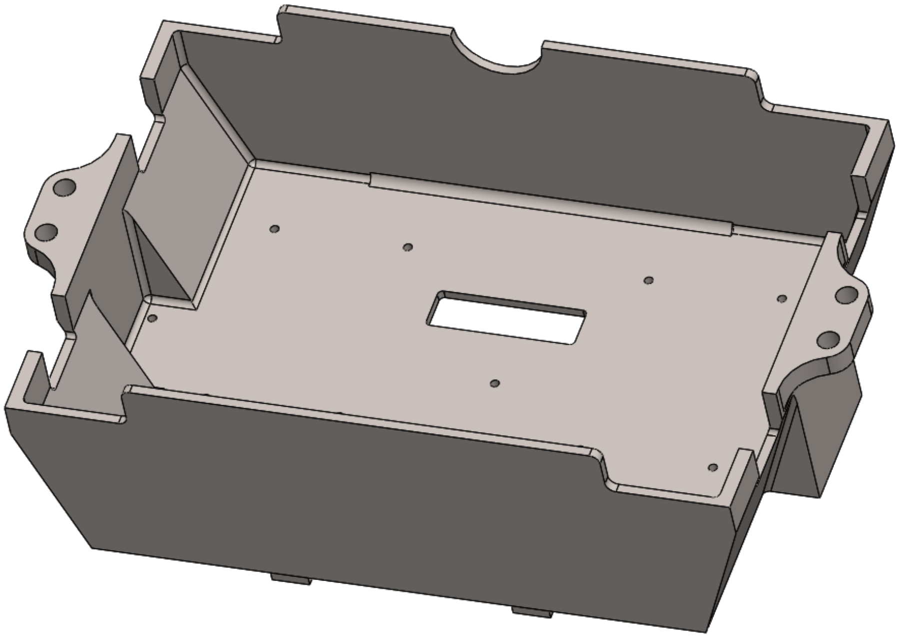

Figure 11. Muffin Tin Structure

IV. Manufacturing Techniques and Manufacturing Anomalies

A. Traditional Manufacturing

Traditional manufacturing, also known as subtractive manufacturing, is the process of removing material from a stock piece using different tools to create different features. While every part on the system uses traditional manufacturing during its manufacturing process, the components that were built completely using traditional manufacturing were the tank top, tank bottom, propellant management device ribbon vanes, muffin tin, and junction box block. Upon completion of each of the parts, a coordinate-measuring machine (CMM) inspection was performed by the machine shop to present the results of machining (i.e. how close the actual dimensions were to the dimensions called out on the engineering drawings provided). These inspection reports were beneficial for establishing which one of the individual parts would be the flight, spare, and burst units. The parts with the least amount of nonconformances were selected as the flight units.

Three tank tops and three tank bottoms were manufactured to provide three different propellant tanks: a flight unit, a spare unit, and a burst unit for qualification testing. As discussed in Section IV.A, the tank bottom was a much more complex part to machine than the tank top due to the internal and external geometries. As a result, it was evident that the machined tank bottoms would have a higher chance of having nonconformances than the tank tops. The tank tops returned zero nonconformances when compared to the drawing, while two out of three tank bottoms had nonconformances at the point of the MSFC fill/drain valve interface. This is a critical interface for the propellant tank, as it acts as a seal between the inside of the tank and the outside environment. The CMM inspections for these two tank bottoms showed that the o-ring groove dimension was 0.001” to 0.002” smaller than the lower end of the tolerance band. If this dimension was too small based on the tolerance stack up performed in that area compared to the outer diameter of the o-ring, this could cause o-ring clipping, which would compromise the fluid seal at that location. The Georgia Tech team performed a tolerance stack-up of the fill/drain valve interface and deemed that the project could accept all three tank bottoms. SN001, the tank bottom with zero nonconformances, is the flight unit, while SN002 and SN003 are either the spare or burst units.

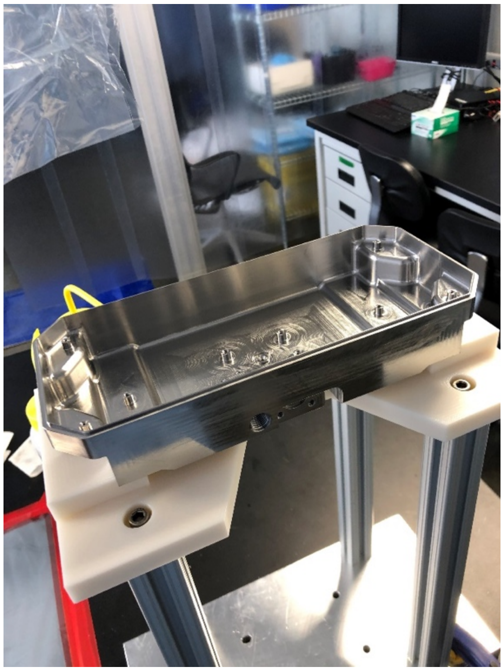

Figure 12. Flight Tank Bottom

Four PMD ribbon vanes were machined out of Ti 6Al-4V AMS 4928 stock material. This part includes four through holes for fasteners to mate to the tank bottom, and a larger circular cutout to allow for the filter to extrude upwards into the ribbon vanes and into the cutout in the additively manufactured PMD sponge. When the PMD sponge arrived back from printing, extra material was present on the bottom of the sponge that prevented the PMD ribbon vanes and PMD sponge from fitting together. Two options were considered to ensure that the parts would fit together: machining the extra material from the sponge or machining material from the ribbon vanes to account for the extra material on the sponge. The second option was chosen due to the simplicity of the machining that would need to be completed. 0.0285” of material was removed from a 0.900” x 0.450” square of material in the center of the part. Figure 13 shows the fit-up of the two parts after the machining operation was completed.

At the time of the writing of this report, the muffin tin structure has not been machined, however the final engineering drawings have been finalized. Two muffin tins, a flight and a spare unit, will be manufactured for the project.

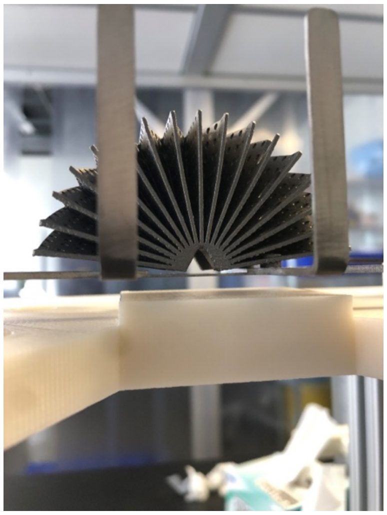

Figure 13. PMD Sponge/Ribbon Vanes fit-up after machining

A burst unit is not required for this part, as the muffin tin will not have propellant in it at any point during the mission. The muffin tin structure will be machined out of Ti 6Al-4V AMS 4928. This material was chosen to remove any difference in coefficient of thermal expansion (CTE) between different metals. Since the muffin tin is interfacing with the manifold, it is important that these two larger parts are the same material. Similarly, eight junction box blocks will be manufactured for the flight and the spare unit.

B. Additive Manufacturing

Additive manufacturing, or 3D printing, is the process of building a part by placing layers of material on top of each other to create different features. There are various techniques that can be used to additively manufacture a part that vary based upon the type of material being printed. For plastic materials, some of these techniques include material jetting, fused deposition modeling, and stereolithography [5]. For LFPS, metal additive manufacturing was utilized to manufacture the manifold, the recirculation block, and the propellant management device sponge. Specifically, laser powder bed fusion (L-PBF), also known as direct metal laser sintering (DMLS), was the technique utilized. During this process, a high-power laser is beamed onto a bed of metal powder. During each pulse, the laser melts a certain radius of powder. The melted powder then cools together to form a solid piece of fused metal [2]. The build then continues layer by layer, building upwards, until eventually a part with intricate features is created.

The manufacturing timeline of the manifold has been much longer than originally anticipated. Since the LFPS is a pathfinder mission for future propulsion systems, an important aspect is defining, and redefining, the manufacturing process for additively manufactured flight hardware. After the first flight manifolds were taken off the build stand and sent to the machine shop to be post-machined, the machinists were unable to define the datum structure based on the printed part. As a result, the printed manifold was sent out to be structured light scanned: a process in which the part is hit with different beams of light/shadow in order to determine how far-off nominal the printed part is from the CAD model from which it was made. Figure 14 shows some of the images with the data overlay for one of the flight manifolds. In the image, a more blue tone of color shows that there is material missing from that area, while a more red tone of color shows that there is additional material in that area. The light scanned data showed that there was warpage of up to +/- 0.050” in some areas. While in practice that is not a noticeable amount by the naked eye, on a system like the LFPS, a warpage of those proportions could potentially break a fluid seal or cause interference between two mating parts. The Georgia Tech team analyzed this data and looked at how this warpage would affect the overall system. One area of concern was the tank/manifold sealing face. During the design phase, the tank/manifold subassembly was designed such that, at nominal dimensioning, there would be a 0.010” gap between the manifold wings (the right and left sides of the manifold that house the thrusters and thruster valves), and the bottom of the tank. An additional amount of material at those faces on the manifold would result in a broken seal at the tank/manifold interface. The team also analyzed the addition of material around the thruster valves. In order to attempt to return the manifold to nominal dimensioning, material would need to be shaved off of the faces of the manifold. If material was shaved off along the wings, this would leave a very little amount of titanium between the o-ring grooves and the thruster fluid passage. Due to these nonconformances, the flight manifolds needed to be re-printed, while the least-warped manifold would be used as the burst unit for testing. For the burst unit manifold, to save machining costs, only holes that were required for blanking plate integration were machined.

To mitigate warpage on the manifold re-prints, a few changes were made to the manufacturing process. The first major change that was made was the build orientation of the manifold. As shown in Figure 15, the manifold was originally printed at a 45 degree angle with titanium support material extruded underneath. This build orientation was pursued to minimize the amount of support material that would need to be used for printing. However, this approach posed a problem during the heat treat process that occurred after the manifold finished printing. The build orientation led to a stress concentration when the geometry of the support material linked up during printing. As a result, the specified temperature of heat treat was not sufficient to allow removal from the plate, causing warpage in different areas of the manifold. As shown in Figure 16, the build orientation of the manifold was changed for the new flight reprints. Deemed the “battleship” approach, this new flat orientation eliminated stress concentrations due to material link up and removed the original build standoffs from the 45 degree orientation. At the interface between the build plate and the beginning of the support material, fillets were added to prevent any stress concentrations,

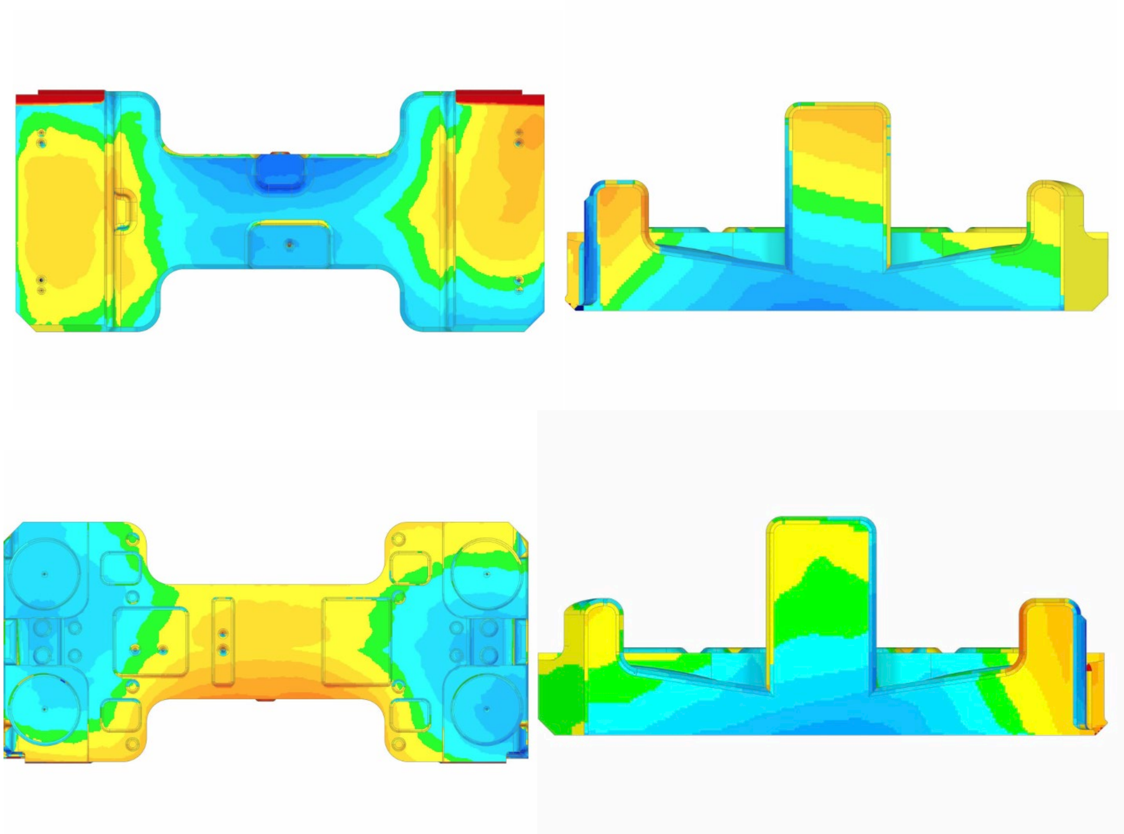

Figure 14. First Print, Manifold Light Scanning Images (Credit: Volunteer Aerospace)

Figure 15. Original Manifold Print Orientation

and a thicker build plate to minimize warpage during stress relief. As part of the heat treat process, instead of cutting the manifold off the build plate before heat treat, the manifold went through heat treat on the build plate to maintain accuracy of the part.

During the reprinting of the first flight-grade manifold, a crack propagated along the bottom of the support material, as shown in Figure 16. Even though it was identified that the crack did not propagate upwards into the part itself, to mitigate this for the second flight-grade manifold, a larger fillet was added to the bottom of the interface between the support material and the build plate. To further mitigate this risk, small fillets were added to the as-machined part to further reduce any potential stress concentrations. Figure 17 shows these added fillets in light blue.

Figure 16. Manifold Reprint I – Crack Propagation (Credit: Volunteer Aerospace)

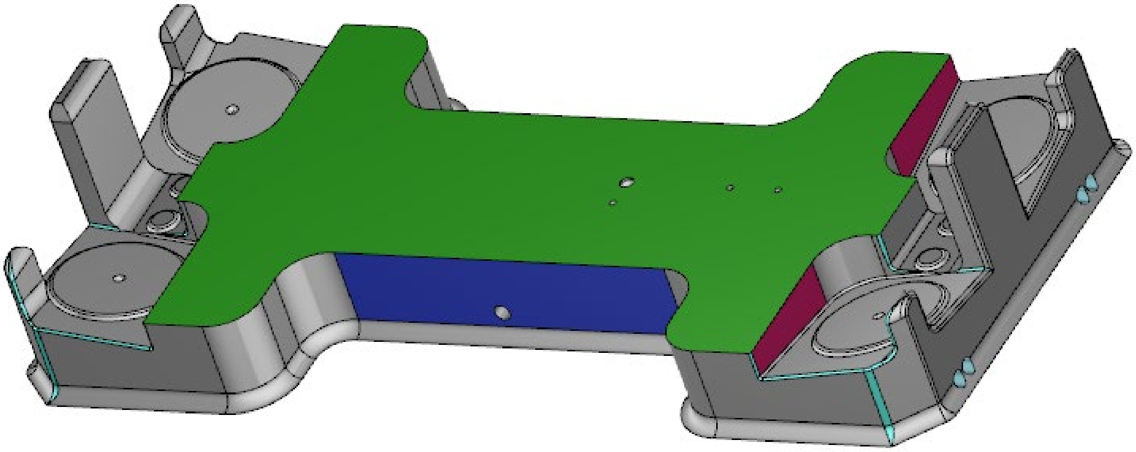

Figure 17. Fillets added to Flight Manifolds

The results of the structured light scanning of the reprinted flight-grade manifolds showed much less warpage than originally seen in the first prints. It is evident that the changes to the manufacturing process resulted in a much more uniform part.

The recirculation blocks and PMD sponges were both additively manufactured without any significant warpage. The CMM inspection reports from those parts were used to identify which parts were deemed acceptable for flight.

Each piece of additively manufactured hardware was designed to include an “as-printed” and “as-machined” configuration. Upon completion of the printing of the flight hardware, post-machining was performed on the hardware in order to machine features such as interface holes, interface surfaces, and o-ring grooves. All threaded holes were post-machined due to the lack of reliability with printing threaded holes directly into the structure. When a specific surface finish was needed for interfacing hardware, the area around this component included extra printed titanium to be shaved down to achieve that specific surface finish. As shown in Figure 16, pads of titanium were included above the thruster interfaces to achieve the specific surface finish called out by the thruster vendor.

C. Electron Beam Welding

Electron beam (EB) welding was the welding technique chosen to mate the tank top and tank bottom components to create a sealed pressure vessel. EB welding is a process by which, in a vacuum environment, a high-velocity beam of electrons is accelerated in order to create heat through kinetic energy, welding and fusing the two materials together. For small, precise applications, EB welding provides the controlled process necessary and an acceptable amount of heat for the part. There are many advantages to this welding technique over other techniques such as tungsten inert gas (TIG) or metal inert gas (MIG) welding. One major advantage of EB welding is the weld depth that the technique can achieve. If needed, EB welding can provide up to two inches of weld penetration. As mentioned previously, EB welding results in a small heat affected zone, rather than the much larger zone generated with other techniques. Furthermore, EB welding has a very high reliability with strength margin, retaining up to 95% of the strength of the base materials. Most importantly, for LFPS, EB welding ensures a high level of purity during the welding process. Due to the vacuum environment in which the process is performed, impurities are removed and eliminated, providing for a clean weld [6].

The geometry along the weld line for both the tank top and tank bottom was designed specifically for an electron beam weld. Figure 18 shows the weld lap-joint geometry for the tank top and tank bottom. For weld qualification by the vendor, the Georgia Tech team designed four inch long weld coupons that mirrored the exact weld geometry. This allowed the vendor to design the specific welding process and test fixtures for LFPS. At the time of writing, the flight tanks are being welded and will be delivered to Georgia Tech late December 2020.

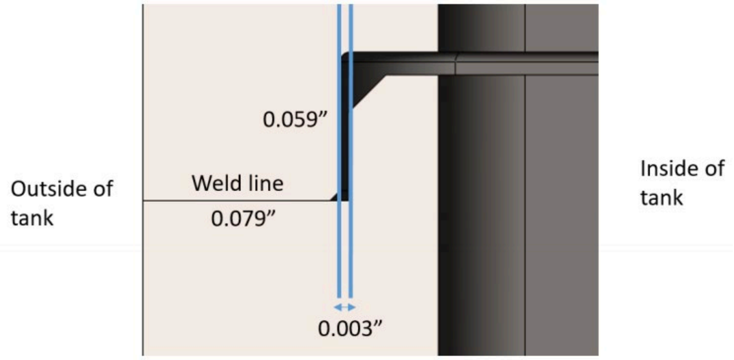

Figure 18. EB Weld Lap-Joint Geometry [2]

D. Pathfinder Hardware

Before any final flight hardware was manufactured, preliminary models and drawings were sent to vendors in order to practice and perfect the manufacturing process for the various hardware before applying those processes to the flight pieces. Pathfinder hardware was created for the tank top, tank bottom, and manifold. Going through the various processes for the pathfinder pieces allowed the Georgia Tech and MSFC teams to iterate and make slight design changes to the hardware that would ensure that the flight hardware would be the exact hardware that was needed for mission success. This hardware was originally intended to be the Georgia Tech team’s first attempt at integration for the propulsion system. However, fabricating this hardware took longer than originally expected, and the pieces did not arrive at Georgia Tech until much later in the mission development timeline.

Fabricating the pathfinder tank top and tank bottom allowed the EB weld vendor to further qualify the weld for LFPS. Furthermore, fabricating the pathfinder manifold ensured that structured light scanning was added to the manufacturing process for additively manufactured hardware. Figure 19 shows the pathfinder tank top and tank bottom welded together, while Figure 20 shows the pathfinder manifold.

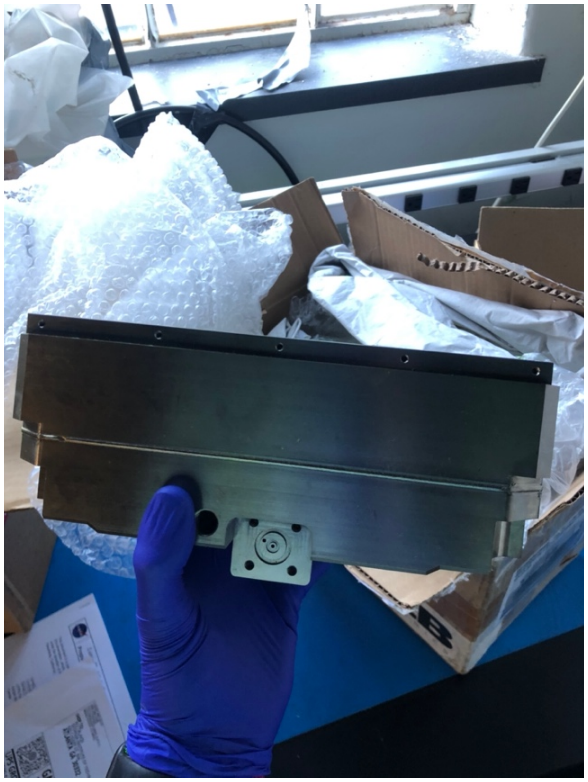

Figure 19. Pathfinder Propellant Tank

Figure 20. Pathfinder Manifold

E. Cleanliness Requirements

When working with space flight hardware, it is important to ensure that the hardware is clean of any foreign object debris (FOD) before final integration. FOD inside the propulsion system has the potential to cause mission failure. Should any FOD cause a negative reaction when coming in contact with the propellant during flight, this could compromise performance of the propellant, and thus, the entire propulsion system. Before entering the class 100,000 cleanroom in the GT SSDL, all wetted hardware (hardware that will come into contact with propellant) was precision cleaned to the following specification: "Level 100, no particles greater than 50 microns." Non-wetted hardware is cleaned to the GLRG-SOP-01-Flight Hardware Cleanliness specification as defined by the GLRG.

During the Georgia Tech team's first attempt at AITP-01 (discussed later), the team found a black, oily substance that was coming off the PMD ribbon vanes after flushing the part with isopropyl alcohol (IPA), as shown in Figure 21. After this was seen, the MSFC team amended the cleanliness specification to be "Level 100A, no particles greater than 50 microns," and the team sent the ribbon vanes out to be precision cleaned again. The letter "A" added to the "100" in the specification signifies the removal of non-volatile residue (NVR) during the precision cleaning process. Without the addition of this to the specification, the precision clean shop did not perform any invasive cleaning of the part.

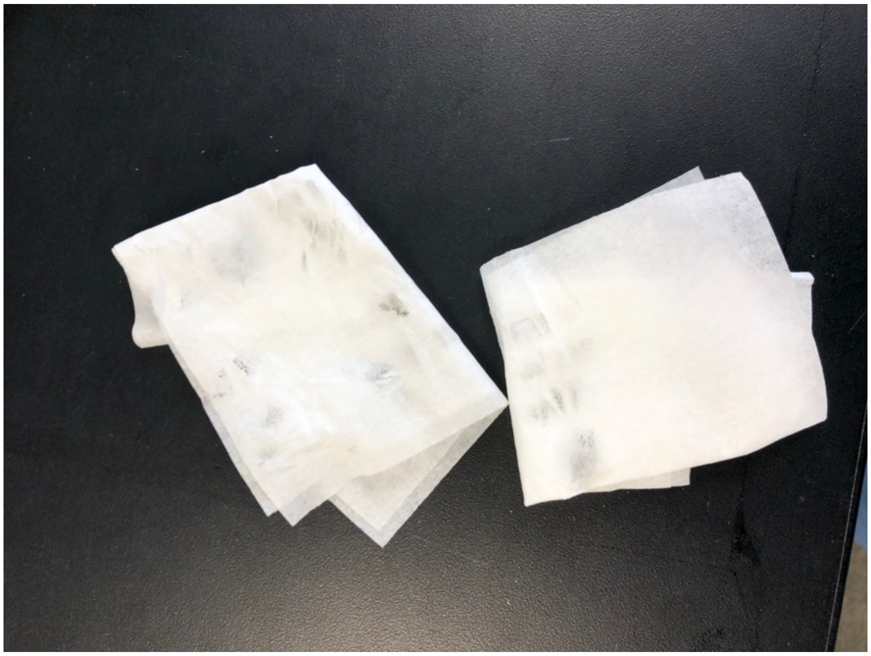

Figure 21. NVR from PMD Ribbon Vanes

VI. Integration and Test

Integration procedures for the Lunar Flashlight Propulsion System were designed by both the Georgia Tech SSDL and NASA MSFC. Nine Assembly, Integration, and Test Procedures (AITPs) were designed for full LFPS assembly. Each AITP document defines the procedure, documentation required, hardware required, and tools required to complete the necessary subassembly. In order to complete an AITP, an assembler and a quality assurance (QA) witness must be present. Torque values for each fastener were provided by NASA MSFC. In order to pressure test all the parts that will contain fluid, all of the openings and interfaces of that specific part need to be sealed to prevent leakage. Engineers at NASA MSFC designed blanking plates for this purpose for the propellant tank, the manifold, and the recirculation block. Table III outlines each of the nine AITPs.

Table III. LFPS AITP Outline

AITP-01	Propellant management device installation into tank bottom
AITP-02	Tank top/bottom electron beam weldment, blanking plate installation onto tank, proof and burst testing
AITP-03	Orifice installation into recirculation block, recirculation block blanking plate installation, proof and burst testing
AITP-04	Blanking plate installation onto manifold, proof and burst testing, recirculation block installation, pressure sensor installation, thermocouple installation, thruster valve installation onto manifold, 1.1x MDP pressure test, leak test
AITP-05	Fill/drain valve installation, isolation valve installation, isolation valve bracket installation, pressure sensor installation, heaters installation onto tank, 1.1x MDP pressure test, leak test
AITP-06	Tank/manifold mating
AITP-07	Pump installation, leak test
AITP-08	Controller installation
AITP-09	Thruster valve installation, thruster valve installation, muffin tin installation, electrical and mechanism liveliness test, thruster cover installation

A. Mechanical Ground Support Equipment (MGSE)

In order to integrate the various subassemblies within the propulsion system, it was important to ensure that the subassembly was placed on a fixture in order to torque the various fasteners down without the part moving. However, for a system as complex as LFPS, multiple fixtures would need to be created to accommodate the tank, the manifold, and the two parts mated together. The Georgia Tech team designed a standard fixture using aluminum t-slotted rails tapped on either end with ¼-20 threadform. The bottom of these rails interface with a one-inch-thick aluminum plate that is clamped to the table for integration.

The flexible design capability of this fixture comes from the plastic 3D printed plate that interfaces with the top of the aluminum rails. Manufactured from ABS plastic, this 3D printed plate is the interfacing component between the subassembly being integrated and the MGSE fixture. This plate can be interchanged with other printed plates in order to interface with different parts from LFPS. Figure 22 shows a flight tank bottom interfacing with the MGSE fixture created. To mate with the 3D printed plastic plate, for the tank bottom specifically, the manifold interface holes on the right and left side of the part were used. When placing the fasteners into the thread, it was important to handthread the fasteners into the threads rather than torqueing them down using a wrench. Loading and de-loading the threads

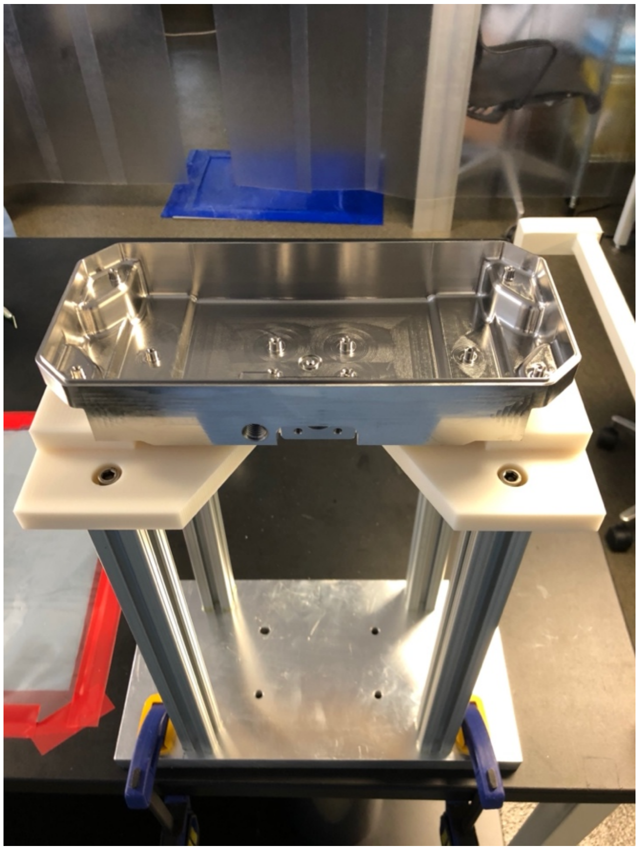

Figure 22. Tank Bottom mated to MGSE Fixture

could potentially induce fatigue, and over-torqueing the fasteners could cause galling within the threads. Either of these mechanical defects would decrease the strength of these threads, and thus would weaken the seal between the two parts.

When looking at the bottom aluminum plate, there are four threaded holes that were not used. This was due to the Georgia Tech team finding that four aluminum rails created a strong enough fixture and eliminated the need to create a 3D printed plate that had eight interfacing thru holes instead of four.

B. AITP-01

As part of AITP-01 completion, three flight tank bottoms needed to have PMDs integrated inside of them. This involved the PMD vanes, the PMD sponge, the 10-micron filter, the curved disc springs, and the fasteners that allow the PMD to interface with the tank bottom. The CMM inspection reports were referenced when selecting which of the various PMD sponges and ribbon vanes would be the flight, spare, and burst unit pieces.

When designing the PMD, an intentional gap was left between the PMD sponge cavity and the top of the filter. In order to eliminate chatter and account for the maximum loading that will be seen during launch, stainless steel curved disc springs from McMaster-Carr were selected. However, the number of springs that would be placed on top of the filter to close the gap is subject to change based upon the various dimensions of the different parts. The following formula was developed by the Georgia Tech team to select one of the filters out of the 10 available:

$$\Delta = y_{cavity} + y_{vane} + y_{post} + y_{seat} - y_{filter}$$

where y represents the dimension of the feature. The filter with the lowest positive Δ that was greater than 0.005” was selected for each tank bottom. The following criteria was provided by MSFC for the number of springs to place on top of the filter based upon the value of Δ:

If 0.005”< Δ < 0.010”, add 1 spring

If 0.010”< Δ < 0.025”, stack 2 springs
If 0.025”< Δ < 0.040”, stack 4 springs
If 0.040”< Δ < 0.055”, stack 6 springs
If 0.055”< Δ < 0.065”, stack 7 springs

For all tank bottom structures, four springs were placed on top of the filter. Figure 23 shows the springs stacked on top of the filter during installation.

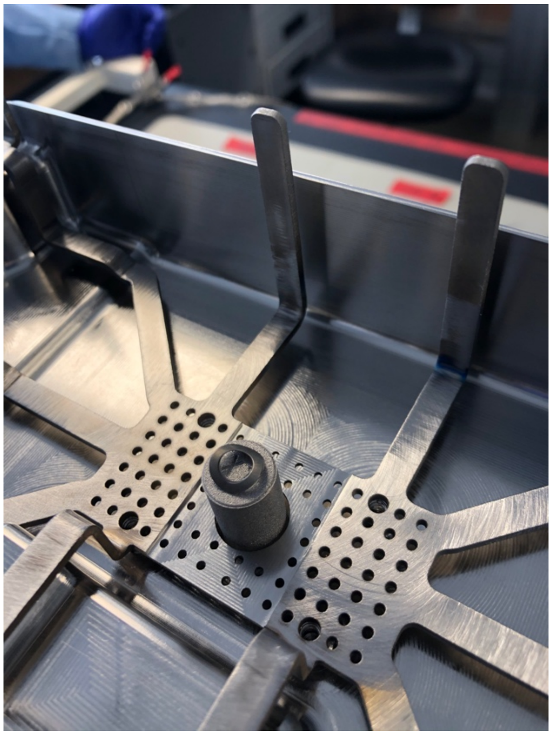

Figure 23. Curved Disc Springs stacked on top of 10-micron Filter

B.I. AITP-01 Integration Anomalies

As mentioned above in Section V.E, the team’s first two attempts to complete AITP-01 for a flight tank bottom were scrubbed due to the NVR still present on the PMD ribbon vanes. This required the Georgia Tech team to send out the ribbon vanes to a shop to be precision cleaned. The team was also required to install four #2-56 helicoils into tank bottoms SN001 and SN003 since the manufacturing shop did not install them as part of the manufacturing process. Figure 24 shows a member of the Georgia Tech team installing the flight helicoils into the tank bottom.

While the team was completing the assembly of tank bottom SN002, the initial fasteners placed in the tank were under-torqued due to the running torque of each of the fasteners being too low. As a result, each fastener had to be backed out in order to re-install with the correct amount of torque. Since the torque values for these specific fasteners were very small (8-9 in-lbs), there was not much concern with backing out and re-installing the fasteners. When the team was backing out the #4-40 fasteners that mate the PMD sponge, the PMD ribbon vanes, and the tank bottom extruded bosses, a loud “popping” noise was observed when attempting to remove one of the fasteners. This sound was not heard for the other three interfacing fasteners. It was observed that the first bolt was stuck, mated to the tank bottom, the PMD sponge, and the PMD ribbon vane. The team decided to de-torque the #2-56 bolts, which were also holding down the ribbon vanes, in order to provide enough “wiggle room” to de-mate the bolt. Upon the eventual removal, the team noticed the PMD sponge and PMD ribbon vanes were held together by the fastener itself, as the helicoil had been removed onto the fastener, as shown in Figure 25. In addition, a piece of metal was seen inside the tank bottom threads. At first, the team thought that this small piece of metal was a piece of a thread on the fastener that had been removed. However, upon removal of the helicoil from the fastener, the team observed that this small piece of metal was in fact a part of the bottom of the ribbon vanes that had sheared off during the removal process.

This is shown in Figure 25. The team did a visual check to ensure that none of the tank bottom threads had been stripped, and found that the threads were still completely intact within the tank bottom boss.

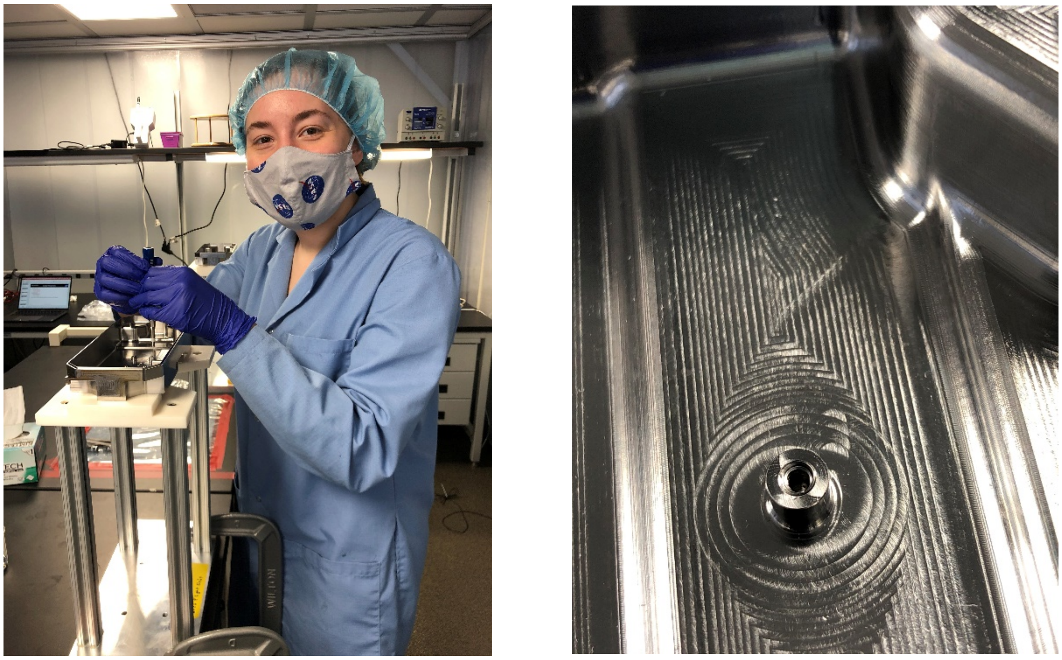

Figure 24. #2-56 Helicoil Installation Process

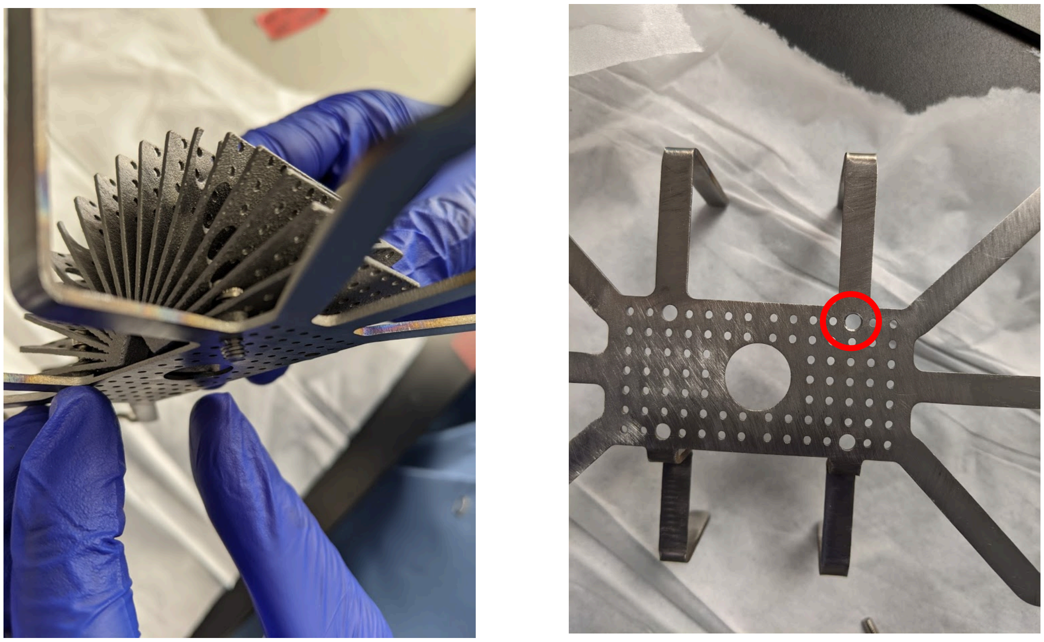

Figure 25. PMD De-Mate Anomaly

Upon identifying this issue, the Georgia Tech team decided to repeat AITP-01 using a new set of both PMD ribbon vanes, PMD sponge, and fasteners in order to eliminate the use of any damaged hardware. Furthermore, the team was required to install a new helicoil, while pushing another helicoil further into a boss due to the semi-backing out that occurred during the PMD de-mate process. Figure 26 shows a completed tank bottom assembly.

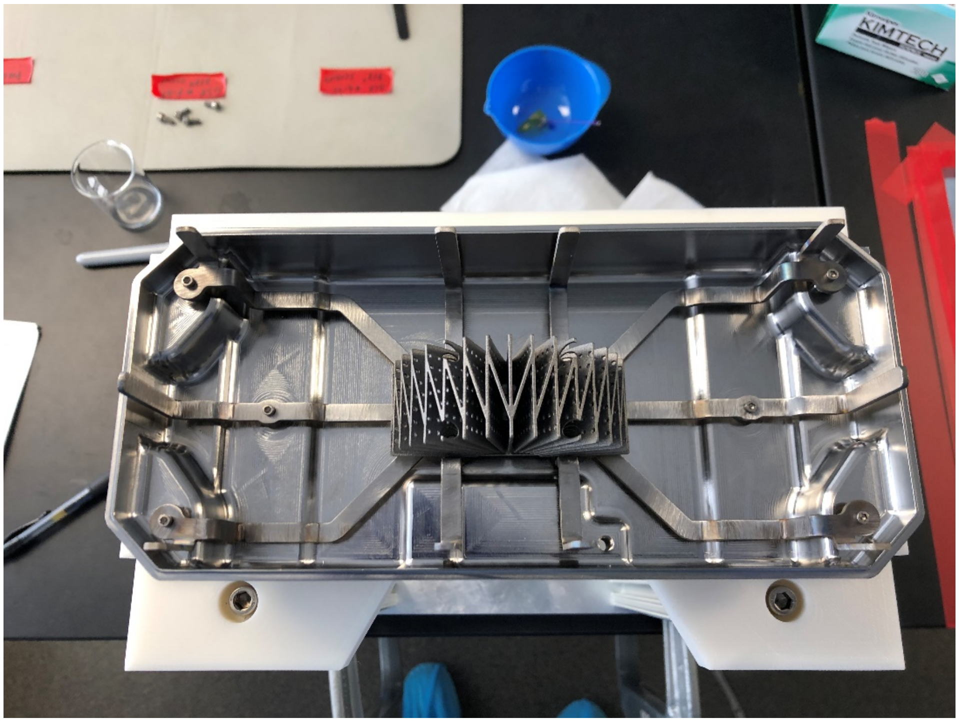

Figure 26. Tank Bottom Subassembly

C. AITP-02

This AITP involves the completion of three welded propellant tanks and the accompanying proof and burst testing. Table IV shows what was required from the project management side to qualify the flight tank welds:

Table IV. Requirements for Pathfinder and Flight Tank Welds

Unit	Green Light to Welding
Pathfinder Tank	• Coupons pass inspection (dye pen, visual, & x-ray) pre & post heat treat. • Tank manufacturing vendor verified material certs • WPS signed (signatures from weld engineer and QE, and a 'thumbs up' from GT)
All Flight Tanks	• NASA/GT received and concurs with the weld coupon & pathfinder tank PQR • GT has received and examined the Pathfinder tank; post welding task • Pathfinder passes inspection (dye pen & visual); pre and post stress relief • WPS is validated or revised and signed after pathfinder tank weld task

The Weld Procedure Specification (WPS) is a document that contains all the information necessary to produce welds that consistently meet the strength and quality requirements as defined by NASA MSFC. The Procedure Qualification Record (PQR) that must be provided by the vendor is used to document all the test results performed to qualify the WPS. The PQR also includes all the inspection/test reports from the welding process. Table V shows the specific procedure that will be followed when welding the flight tanks.

Table V. Flight Tank Weld Procedure

Task	Description	Details
1	Pre-weld coupon (1)	Purpose: to screen for porosity prior to flight tank welds. To be performed same day as tank welds; no need for heat treatment. Should welding continue to next day, pre-weld coupon needed before any flight tanks are welded.
2	All flight tanks (3)	In succession; no coupons between tanks.
3	Post-weld coupon (1)	Purpose: to screen for porosity after flight tank welds. To be performed same day as tank welds; no need for heat treatment.
4	Inspections	Flight tank dye-pen and visual inspection, post heat treatment.

After the tank top and bottom are welded together, the welded tank is sent to be stress relieved. This involves the tank assembly being relieved at 1100 degrees for 2 hours in a vacuum environment. After this, the Georgia Tech team will install the blanking plates onto the tank. The propellant tanks will then be sent to MSFC to be dye penetrant inspected and proof and burst tested. At the current time of writing, the weld vendor is welding the three flight tanks, with delivery to Georgia Tech scheduled for late December 2020.

D. AITP-03

AITP-03 involves the assembly, blanking plate integration, proof and burst testing, and precision cleaning of the recirculation blocks. As mentioned in Section III.B.I, an internal orifice was placed into the larger port of the recirculation block in order to provide a pressure drop for the system. After this step was completed by a vendor, the Georgia Tech integration team installed the single blanking plate onto the four recirculation blocks for pressure testing. Due to nonconformances with respect to the true positional tolerances of the o-ring grooves, two of the recirculation blocks are classified as test units, while the other two are classified as flight units. Figure 27 shows the blanking plate integrated onto the recirculation block. At the time of writing, the recirculation blocks are undergoing testing at NASA MSFC. Figure 28 shows the burst unit recirculation block being pressure tested. Upon completion of the testing, the recirculation blocks will be sent out to be precision cleaned to the required project specification.

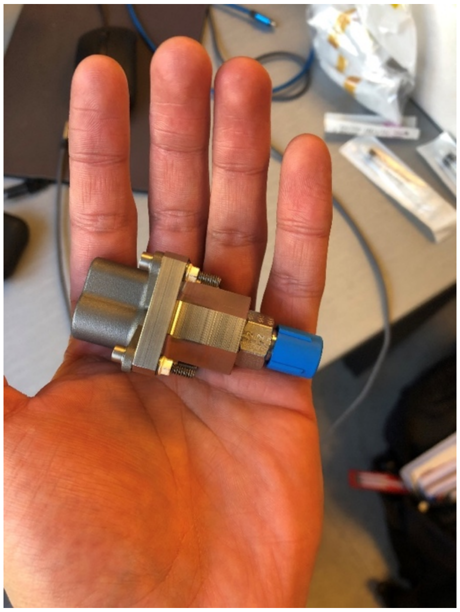

Figure 27. Recirculation Block with Blanking Plate Attached

Figure 28. Recirculation Block Burst Pressure Test

E. AITP-04

While the flight manifolds have not been delivered to Georgia Tech, as mentioned above, the least-warped manifold was accepted as the burst unit. Blanking plates were created to cover the interfaces for the thrusters, the thruster valves, the pump, the recirculation block, the pressure port sensor, and the tank/manifold passthrough. Figure 29 shows the blanking plates integrated onto the burst unit manifold.

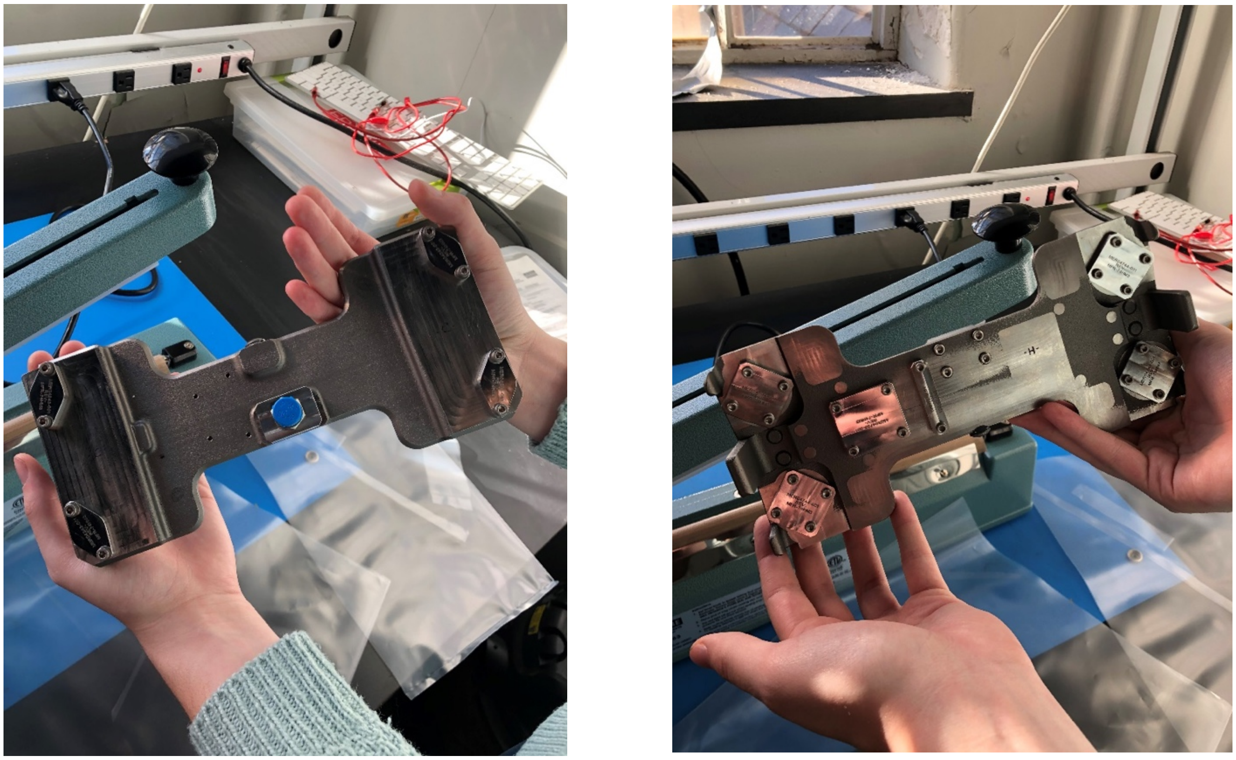

Figure 29. Burst Unit Manifold with Blanking Plates Attached

During post-machining of the burst unit, due to the warpage of the datums on the part, additional material was removed from the pressure sensor port area. To accommodate this, instead of a blanking plate sealing that interface, a screw plus epoxy combination was used. The epoxy selected was 3M Scotch-Weld Apoxy Adhesive, and was applied to the internal threads, the screw threads, and was used to fill the remaining area between the screw head and the manifold surface. Figure 30 shows the technique used to create a seal. At the current time of writing, the burst unit manifold has passed burst testing at NASA MSFC, which is shown in Figure 31.

Once the flight manifolds arrive at Georgia Tech, they will be fitted with blanking plates and proof pressure tested. After being precision cleaned, the recirculation block, the thruster valves, and the pressure sensor will be mated to the manifold. For the tank/manifold and thruster interfaces, the blanking plates will remain mated to the manifold until further in the assembly process.

F. Future AITPs

The rest of the propulsion system assembly is shown in Table V. At the current time of writing, the welded flight tanks will arrive at Georgia Tech late-December 2020, and the flight manifolds are scheduled to arrive at Georgia Tech mid-December 2020. Current delivery of the propulsion system to NASA JPL is scheduled for April 2021. At this point in the project timeline, all flight hardware will be out of the Georgia Tech SSDL, and the team will remain on the LFPS project as support when needed.

Figure 30. Epoxy plus Screw Seal for Pressure Sensor Interface

Figure 31. Manifold Burst Pressure Test

VII. Testing

A. Proof and Burst Testing

In order to qualify flight hardware, proof and burst testing is required for all components that will hold fluid: the propellant tank, the manifold, and the recirculation block. This testing is important in order to ensure that the hardware will be able to survive worst-case values to ensure peak performance at nominal pressures that will be seen during flight. Proof pressure is defined as 1.5 times the maximum design pressure (MDP), while burst pressure is defined as 2.5 times MDP. To qualify a part for burst pressure, there are two different techniques for performing this test. The first technique is by increasing the pressure in the part until the part physically bursts, while the second technique involves taking the part up to a maximum pressure bound that is very high, and assuming that the part does not burst, stopping the test at this point. For LFPS, the second technique was used to qualify the parts, and the maximum pressure seen was 5000 psi.

B. Leak Testing

While it is important to check the maximum pressures that the flight hardware can survive, it is equally as important to perform assembly level leak testing in order to check the strength and quality of sealing interfaces. This leak test will involve bringing the pressure of the system up to 1.1 times 1.06 times the MDP pressure. The 1.06 form factor is the environmental correction factor (ECF) which accounts for a maximum temperature of 140 degrees Fahrenheit.

There are two different leak tests that can be used to qualify the system: a qualitative test or a quantitative test. Quantitative leak tests measure the amount of gas that escapes through an unintended opening in the system using a "sniffer" or mass spectrometer, which is a device that is able to measure the amount of gas that escapes the system over time to find the average leak rate [2]. However, due to the complications and cost of developing a quantitative test, the LFPS project decided to proceed with a qualitative bubble test. For this test, a bubbling liquid will be placed around the externals of the interface locations. While gas flows through the system, any gas that is escaping will create bubbles from the solution. Any bubbles will show that a breach in the seal is present, and the seal will have to be either torqued down more, or fixed in another manner. Figure 32 shows the leak test schematic that will be used for LFPS.

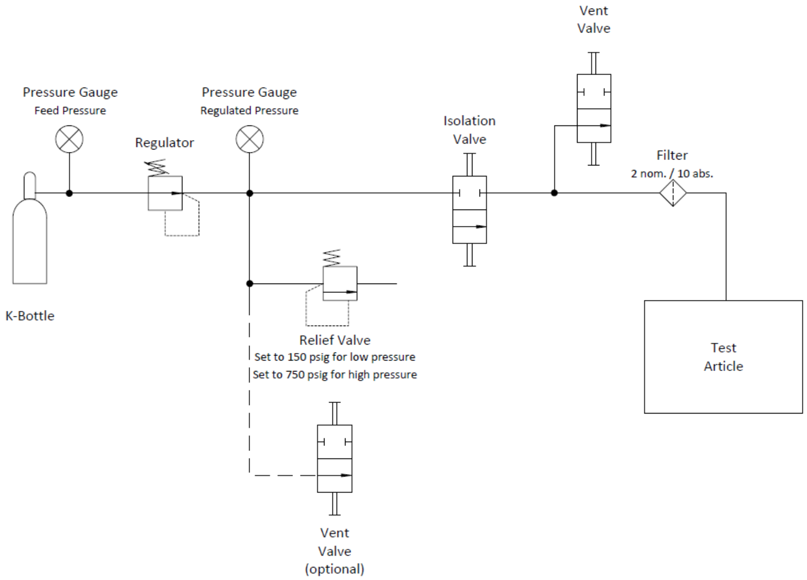

Figure 32. LFPS Leak Test Schematic

VIII. Conclusion

The Lunar Flashlight Propulsion System is a green monopropellant propulsion system that is a leading pathfinder project for future small satellite propulsion systems. In conjunction with the use of ASCENT propellant, LFPS combines traditional and additive manufacturing techniques in order to create a system that is capable of producing over 2500 N-s of total impulse for orbit insertion around the Moon and for attitude maneuvers that the spacecraft will need to perform during the mission lifetime. Critical lessons have been learned during the manufacturing phase of the project that will enable future missions to complete a similar propulsion system in a shorter amount of time. With the support of NASA Marshall Spaceflight Center and NASA Jet Propulsion Laboratory, the Glenn Lightsey Research Group as part of the Georgia Tech Space Systems Design Laboratory has been able lead the mechanical design for the propulsion system. This project will provide the necessary experience for the GLRG to design future green monopropellant small satellite propulsion systems.

IX. Acknowledgements

I would like to conclude this paper by expressing my gratitude towards the multitude of individuals that have made this paper possible. First, my family: Farid, Ruksana, Omar, and Nadia Talaksi, for the constant support while I was chasing my dreams. Thank you all for everything.

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