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Development of a CubeSat-Scale Green Monopropellant Propulsion System for NASA's Lunar Flashlight Mission

Grayson Huggins*, Ali Talaksi†, E. Glenn Lightsey‡, Dawn Andrews
Georgia Institute of Technology, Atlanta, Georgia, 30313

Daniel Cavender, Carlos Diaz, Donald McQueen, Hunter Williams
Marshall Space Flight Center, Huntsville, Alabama, 35811

John Baker, Matthew Kowalkowski
Jet Propulsion Laboratory, California Institute of Technology

NASA's Lunar Flashlight is a low-cost 6U CubeSat whose mission is to search for ice and mineral deposits inside of the scattered craters at Moon's southern pole. To conduct its primary science mission, Lunar Flashlight must be placed in a stable lunar polar orbit which requires the utilization of an on-board propulsion system. However, to this date, most CubeSats have been propelled by cold-gas or electric propulsion systems that have proven to scale well but lack sufficient impulse to conduct large ΔV maneuvers such as orbit insertions. To this end, the Lunar Flashlight mission has chosen to utilize a custom-designed green monopropellant propulsion system developed by the Georgia Institute of Technology under the leadership of NASA's Marshall Space Flight Center and support from the Jet Propulsion Laboratory. The developed system is capable of providing more than the required propulsive capability for full mission success while fitting inside of a 2.5U volume and weighing less than six kilograms. The system utilizes the Advanced Spacecraft Energetic Non Toxic (ASCENT) green monopropellant that provides higher specific impulse compared to traditional hydrazine while also being safer to handle. If successful, the presented propulsion system will enable Lunar Flashlight to be the first CubeSat to reach the Moon, the first to conduct an orbit insertion, and will be the first CubeSat demonstration of the ASCENT propellant.

I. Lunar Flashlight Mission

Lunar Flashlight is an upcoming 6U CubeSat mission from NASA's Jet Propulsion Laboratory that will search for water-ice deposits and other volatiles near the lunar south pole from a highly-eccentric polar lunar orbit [1]. The spacecraft will fly on-board the Artemis I launch vehicle, NASA's first Space Launch System (SLS) rocket, as part of a group of small satellites that will be deployed throughout its journey around the Moon. Except for the JPL MarCO CubeSats that flew by Mars in November 2018, CubeSats have been mostly limited to Earth-orbiting missions until now. Lunar Flashlight aims to add to the flight experience of deep-space CubeSats and demonstrate their ability to conduct space science missions at a fraction of the cost and complexity of larger missions. The spacecraft will conduct an orbit insertion at the Moon using a green monopropellant propulsion system developed uniquely for this mission, fueled by the ASCENT propellant developed by the Air Force Research Laboratories (AFRL). The custom-designed propulsion system developed by a team from NASA's Marshall Spaceflight Center (MSFC) and Georgia Tech's Space Systems Design Laboratory (SSDL) delivers sufficient total impulse for the orbit insertion and necessary attitude maneuvers, fits within a 2.5U volume, and has a total wet mass under six kilograms. Upon completion, Lunar Flashlight may become the first CubeSat to achieve orbit around a planetary body besides the Earth, which is enabled by the new propulsion system.

The Lunar Flashlight Propulsion System (LFPS) consists of a propellant tank, propellant management device (PMD), manifold, pump, four ASCENT thrusters, and several micro-fluidic components developed by NASA MSFC. Additive manufacturing is utilized to fabricate the PMD and manifold to the scale that is necessary to fit within a CubeSat form factor, as these designs require a complex geometry that would be impossible to machine using traditional methods.

*Graduate Research Assistant, Daniel Guggenheim School of Aerospace Engineering, grayson.m.huggins@jpl.nasa.gov
†Graduate Research Assistant, Daniel Guggenheim School of Aerospace Engineering, atalaksi3@gatech.edu
‡Professor, Daniel Guggenheim School of Aerospace Engineering, glenn.lightsey@gatech.edu

Additionally, the manifold incorporates all necessary fluid paths and mechanical interfaces into a single continuous structure, which significantly decreases the total volume and mass of the system. The LFPS unit notional location in the Lunar Flashlight spacecraft is shown in Figure 1.

Fig. 1 Lunar Flashlight spacecraft, specifying the location of the propulsion system

A. ConOps

Lunar Flashlight is stowed during launch in a 6U CubeSat deployer in the second stage of the SLS rocket, underneath the Orion capsule. After lunar transfer orbit-insertion and Orion deployment, Lunar Flashlight's deployer will release the spacecraft on its journey around the Moon. The propulsion system will be turned on for the first time immediately following release, and conduct a small maneuver as a system checkout. The spacecraft will proceed to perform three fly-bys of the Moon over the next 90 days, occasionally performing impulsive maneuvers along the way. On the fourth trip around the Moon, the propulsion system will complete its largest maneuver to enter into polar Lunar orbit, with a perilune at the south pole of 15 kilometers and an orbital period around 7 days. Over the next two months, 10 science passes around the south pole will be conducted, where the spacecraft will utilize its instruments to collect and send data back to Earth. During this time the propulsion system will mainly be used for attitude maneuvers and momentum wheel desaturation. After the science goals of the mission have been concluded, including possible mission extension(s), the propulsion system will perform a final burn to place the spacecraft on an impact trajectory with the lunar surface for disposal.

B. Technology Demonstration

With CubeSat technology becoming more feasible for deep-space applications comes the need for more efficient and impulsive small-scale propulsion systems. As stated before, most CubeSats have been limited to low-Earth orbit but additional propulsive capability would allow this class of spacecraft to visit further destinations and extend mission lifetimes. As more CubeSat-scale propulsion systems are flown, the design process becomes more streamlined and allows for more rapid mission development that could help provide significant scientific data to study our solar system and beyond, as well prepare for future human expansion into space. The LFPS aims to be a pathfinder device for these CubeSat propulsion systems and add to flight heritage while also providing lessons learned.

The mission also serves as the first flight of custom micro-valves developed by NASA MSFC, with the intention that they will be used on many other NASA CubeSat propulsion systems after a successful demonstration on Lunar Flashlight. Additionally considered is the use of commercial-off-the-shelf (COTS) components in the design, which shows how these small-satellite systems can be built without designing the whole system from scratch. A few examples of this include the fluid pump, which is modified from a commercial micro-pump developed by Flight Works Inc., and the controller electronics boards, which are built from COTS components.

The LFPS is the also second planned flight of the ASCENT monopropellant that was first flown in 2019 on NASA's Green Propellant Infusion Mission (GPIM). Typical monopropellant systems are fueled by hydrazine, which has a high specific impulse but is very toxic to humans and is therefore difficult to handle. A large push in the propellants industry over the past few decades has been to develop a chemical substitute for hydrazine that is easier to handle while also providing improved performance. The LFPS project chose ASCENT due to its relatively high technology readiness level (TRL) at the beginning of the project, and to add flight heritage to the propellant and help prove its usefulness by hopefully being a successful demonstration of the propellant. With increased flight heritage, ASCENT may be considered for use on more spacecraft as well as larger missions.

Lunar Flashlight is a testament to how small satellites can act as testbeds for many new technologies in a rapid, cost-effective way while also expanding our understanding of our solar system and beyond. However, with new innovation comes new challenges, and this paper discusses some of the challenges that were faced in the various phases of the LFPS project to build the system to its scale and meet its goals.

II. Propulsion System

A. Propulsion Schematic and Requirements

Before beginning the design of the propulsion system, the LFPS project had to choose between a blowdown or pump-fed system by considering variables such as total mass, volume, performance, and overall system complexity. Additionally considered in this discussion and trade were safety and fracture control. The high pressures of a blowdown system coupled with the hazardous nature of the propellant would require significant structural analysis and testing to clear the necessary control review boards [2]. A pump-fed system reduces the system pressures to below the launch vehicle's pressure vessel classification, which significantly reduces the concern of safety control and fracture criticality. For these reasons, the LFPS team selected a pump-fed propulsion system, as shown in Figure 2. However, the project still conducted significant reviews to reclassify the propellant's risk from a catastrophic to critical hazard. This reduced risk classification allowed the design to remove a redundant isolation valve, and limited two-fault tolerant fluid seals to be necessary only to the propellant tank. Meanwhile, all component seals to the manifold could be designed to single-fault tolerance [2]. This classification was reviewed and approved due to the ASCENT propellant's high viscosity and practically non-existent vapor pressure that would prevent high leakage and self-pressurization, which could lead to safety or fracture hazards before and during launch [3]. The mechanical impacts this re-classification entailed significantly helped the design close by opening up useable space underneath the manifold for other system components.

In the selected pump-fed configuration, the propellant tank is filled with ASCENT, a gaseous nitrogen ullage for pressurization, and a PMD, as well as being equipped with a fill/drain valve, pressure transducer, and various heaters and thermocouples. The propellant tank is isolated from the rest of the system by the propellant isolation valve, which is one of the new micro-solenoid valves developed by NASA MSFC for CubeSat propulsion systems. When the isolation valve is opened, the combination of the ullage pressure and operating pump pull propellant from the tank and increase the fluid pressure from storage pressure to the thruster operating pressure. During firing, the propellant flows through the opened micro-solenoid thruster valves and into the thrusters. Prior to this event, the thruster valves are closed and the fluid instead flows through a recirculation loop that carries the propellant exiting the pump through a fixed orifice flow control device (FCD) and back to the pump inlet.

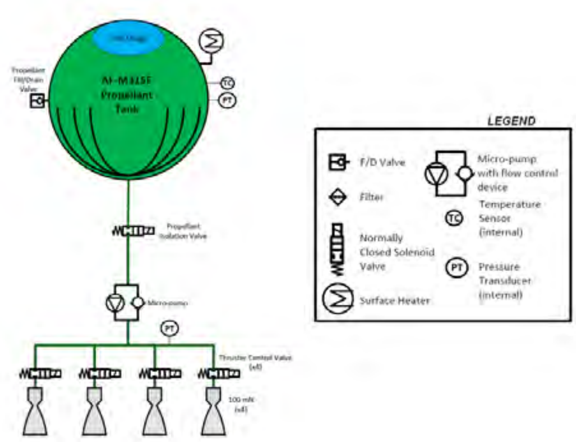


Fig. 2 Lunar Flashlight Propulsion System, fluid and mechanism propulsion schematic

Georgia Tech's SSDL was contracted to design the LFPS structure to conform to the required interfaces and envelopes that were previously established by the MSFC team. Table 1 lays out a few of the propulsion system requirements provided to Georgia Tech by MSFC. Figure 3 shows the LFPS flight configuration that meets all the requirements, and whose components are being manufactured and integrated at the time of this publication.

Table 1 LFPS Level 4 System Requirements (LFPS-SPEC-204)

Requirement	Description	Notes
LFPS-REQ-005	Wet Mass	The propulsion system's 'wet' mass shall not exceed 5.55kg
LFPS-REQ-006	Total Impulse	The total impulse capability for the system shall be no less than 1800 N-s
LFPS-REQ-011	Propellant Tank MDP	The propellant tank shall be designed for a Maximum Design Pressure (MDP) of 100 psia
LFPS-REQ-012	Manifold MDP	The manifold shall be designed for a Maximum Design Pressure (MDP) of 500 psia
LFPS-REQ-013	Design Factor	The propulsion system shall have all pressurized hardware designed, analyzed, and tested to the following pressures in accordance with NASA-STD-5001. Proof pressure = 1.5 times MDP, Burst Pressure = 2.5 times MDP
LFPS-REQ-025	System External Leakage Rate Allowable	The external leakage rate of the system shall be no greater than $5e^{-3}$ standard cubic centimeters per second of gaseous Helium at MDP

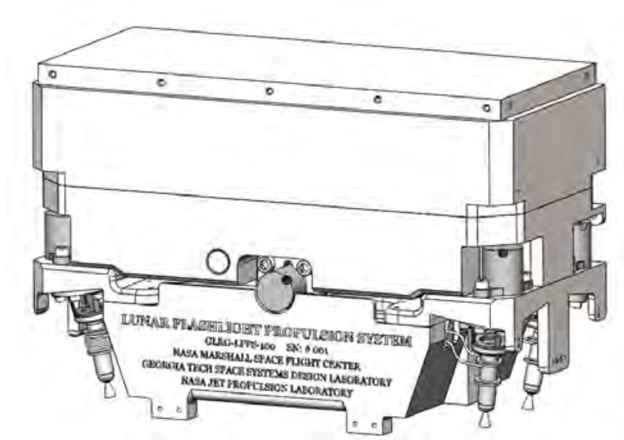


Fig. 3 Isometric view of the Lunar Flashlight Propulsion System model

B. Control

During nominal operation after the initial system checkout firing, the manifold fluid lines contain propellant between burns. The propulsion system begins its operation by commanding the thruster catalyst bed to heat up to operating temperatures via thermostatic control, called thruster conditioning, which could last for 10-30 minutes depending on the current thermal environment. Additionally, the tanks heaters can be turned on to increase the temperature of the propellant before it flows into the manifold. In the last minute of thruster conditioning, the pump accelerates to operating rotational velocity. During this transient, the thruster valves remain closed to prevent any propellant flowing to the thrusters, which would either be below operating pressure or below catalyst operating temperature. The thruster valves are only opened when the entire system is ready to fire, which the system performs via control from the spacecraft attitude control system (ACS). Therefore, during pump acceleration, the propellant inside of the manifold has nowhere to easily go. This issue is solved by creating a recirculation loop between the pump's outlet and inlet, where the fluid instead flows through a fixed orifice flow control device. The orifice adds resistance to the flow by restricting it to a small area, and when pressures or flow rates are high enough the fluid overcomes this resistance and flows through the orifice that routes back to the pump inlet. Figure 4 shows the recirculation loop and it's routing inside of the system.

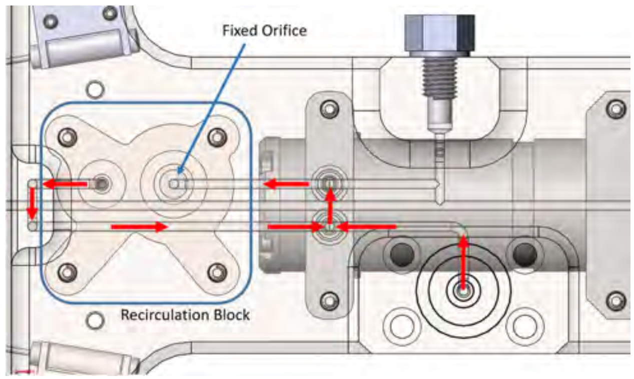


Fig. 4 Recirculation loop

During nominal firing, the propellant isolation valve and thruster valve(s) are opened. The outlet flow rates of the COTS pump are larger than what the four thrusters can handle, so a majority of the propellant flows through the recirculation loop during firing. However, a small portion of the propellant is now able to flow through passages in the manifold to each thruster valve. The open thruster valve exposes the propellant to space and pressure differential pushes the propellant through the heated thruster catalytic decomposition chamber and expels it, providing a nominal 100 mN thrust per thruster. During the mission lifetime, any number of the four thrusters are available to be operated simultaneously based on the desired maneuver, as controlled by a combination of software and the valve drive electronics.

C. System Performance

The system-level trade study to maximize performance depends heavily on the requirements outlined in Table 1. The right amount of propellant must be loaded to meet LFPS-REQ-005 and LFPS-REQ-006, which are inversely related. The useable propellant mass for this design is assumed to be 90% of the total propellant mass due to the PMD expulsion efficiency, the total volume of the manifold fluid lines from the tank to the thrusters, and the line losses. Typical hydrazine monopropellant systems utilizing a bladder or diaphragm can reach much higher expulsion efficiencies than 90%, but with the unknowns associated with ASCENT and its interactions with the custom-designed PMD, 90% is used as a conservative estimate. Additionally, there must be enough gaseous Nitrogen (GN2) pressurant loaded into the propellant tank prior to flight that the end of life pump inlet pressure is above the minimum operating pressure. If too little GN2 is loaded at low pressure, the drop in tank propellant volume due to mission firing operations may expand the GN2 ullage to the point that the back-pressure is below the pump's minimum operating pressure when accounting for pressure losses through the PMD, filter, iso-valve, and fluid lines. In this situation, there would be leftover useable propellant remaining in the tank that is unable to be fired due to the low GN2 pressure, decreasing the total impulse capability of the system. These restrictions inform the system performance trade study so that the amount of propellant and pressurant loaded on the ground meets the requirements.

At the time of publication of this paper, engineers at Georgia Tech estimate a wet mass less than 5.55kg. The total impulse is near 2850 N-s assuming a constant end of life thruster I_{sp} during the entirety of the mission, which is quite conservative. At the highest expected operating thruster I_{sp}, the total impulse becomes near 3300 N-s, giving the system a range of total impulse potentially exceeding 1.75 times the 1800 N-s requirement that was considered as an initial, guiding parameter for the design. The additional impulse over the requirement provides design margin and allows for the possibility of a mission extension.

Georgia Tech engineers are in the process of weighing each component as they arrive from manufacturing and are updating the dry and wet mass estimates accordingly. When the full system is integrated, Georgia Tech will provide MSFC and JPL a recommended ullage fill percentage, fill pressure, and total wet mass that meets the requirements outlined in Table 1.

III. Mechanical Design

A. Propellant Tank

All major structures of the propulsion system, including the propellant tank, are made from Grade 5 Titanium (Ti-6Al-4V) that has a high strength-to-weight ratio and is resistant to corrosion, which is necessary for long-term exposure with the ASCENT propellant. This titanium alloy has been used extensively on heritage monopropellant systems, as well as the GPIM propellant tank that was also filled with ASCENT [4].

An early idea considered for the tank design was to additively manufacture the propellant tank and manifold into one single continuous structure of printed Ti-6Al-4V. The as-printed structure would contain the propellant storage volume, necessary fluid passages and the PMD. Precision interfaces or thread-forms would be machined into the as-printed structure, typical of many metal printed parts. However, the striated nature of an additively manufactured part's macro-structure led to the concern of micro-fractures being introduced into the pressurized tank's material from project stages ranging from manufacturing to flight [5]. These micro-fractures could possibly lead to part failure during flight and this was deemed to be an unacceptable risk. Therefore, the LFPS propellant tank utilizes traditional manufacturing techniques. However, with upcoming technological advances and the expected increased flight heritage of AM, future CubeSat-scale propulsion systems could utilize more system-comprehensive additively manufactured structures that would greatly decrease the number of components and fluid seals necessary throughout the system.

The traditionally manufactured flight LFPS tank design consists of two halves that are electron beam welded together along the weld line shown in Figure 5. The tank top structure contains a majority of the Lunar Flashlight spacecraft interfaces along its outer edge, while internally featuring structural ribbing which prevents unacceptable deformation at MDP that could harm interfacing spacecraft components. In addition to structural support, the additional material of the ribs solves the issue of fastener drill depth that was encountered many times during the system's mechanical design. Adequate thread engagement is important for ensuring a strong and reliable mechanical connection while not stressing the fastener to plastic deformation or failure during torquing, vibration, or other loading. However, the small scale of the system often limited manufacturing tap and thread depth, in this case to keep a minimum wall thickness around the entire tank structure. By placing these ribs directly above the spacecraft interfaces, the interface fastener holes could be drilled and tapped further to allow proper thread engagement while maintaining wall thickness.

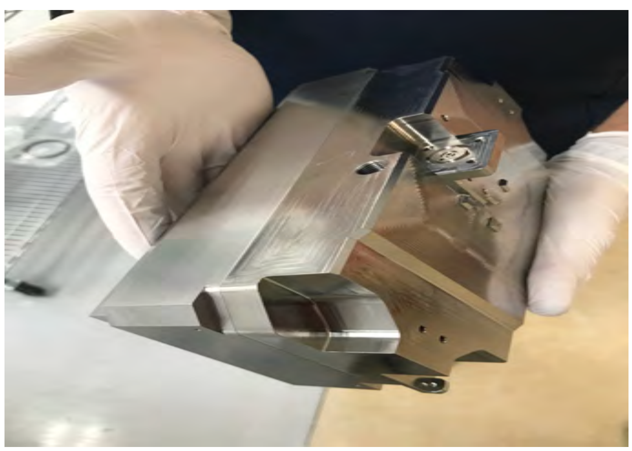


Fig. 5 Flight Propellant Tank Assembly Serial Number 001

The tank bottom structure is a complicated part for its size, containing interface features for nine separate subsystem and spacecraft parts while being designed for propellant and pressurant volume, as well as mass requirements. Externally, the tank bottom structure interfaces to the spacecraft and manifold, containing fastening features and small machined flow passages for propellant transfer during operation. The propellant isolation valve, fill/drain valve, and tank pressure transducer all connect to the exterior through custom-designed interfaces. Internally, the structure houses the passive PMD that directs propellant to the tank's fluid exit tube. The PMD addresses the issue of zero gravity fluid management, the physics of which have been studied and implemented on many spaceflight missions utilizing hydrazine [6]. However PMDs haven't been as extensively studied when interacting with ASCENT, so this remains an open research topic as PMDs are highly dependent on fluid properties. For proper fluid communication according to analysis conducted by NASA's Glenn Research Center, the parts are offset from the surface of the tank bottom structure. This consideration led to the design of ten fastening bosses symmetrically placed around the tank's internal structure. Finally, all internal convex edges are rounded to promote the PMD's operation by preventing surface tension causing the viscous propellant to pool around sharp corners, preventing flow to the tank's fluid exit. The PMD fits into the tank bottom as shown in Figure 6 below.

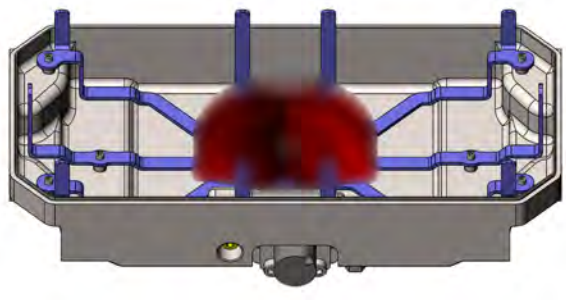


Fig. 6 Tank Bottom Subassembly, showing PMD sponge (red) and vanes (blue). Sponge intentionally blurred.

The LFPS PMD is made of two parts, the sponge (shown in red) and the vanes (shown in blue). The sponge forces propellant towards the fluid exit tube by the principle of liquid surface tension. The sponge only covers a portion of the tank's internals, so the PMD vanes are used to bring propellant from the outer edges of the tank to the PMD sponge to saturate it. Prior to exiting from the tank, the propellant must be filtered to prevent any possible foreign object debris (FOD) from entering the system's small fluid passages that could damage system components or clog the lines. A COTS ten micron grade 2 titanium filter is placed directly above the fluid exit passage inside of a cutout in the PMD sponge, and preload is applied to the filter using a stack of stainless steel curved disc springs that match the gap between the filter top face and the PMD sponge cutout face.

The complex PMD sponge geometry makes traditional machining extremely challenging. However, as the sponge is not subject to similar differential pressure loading that presented issues with printing the tank structure, the LFPS project chose to use laser-powder bed fusion (L-PBF) additive manufacturing of Ti-6Al-4V for the PMD sponge structure. Meanwhile, the vanes are relatively simple in mechanical design, so they are instead made from Ti-6Al-4V bent sheet metal, and interfaces between the fastening bosses and PMD sponge.

B. Manifold

The pump-fed propulsion schematic in Figure 2 requires that the fluid be delivered to the pump, thrusters, and a recirculation loop when necessary after exit from the propellant tank. Fluid tubing on traditionally sized propulsion systems typically use bent metal tubes of varying internal diameters to connect fluid components around the system, but a similar design would be difficult to implement on the LFPS while respecting system mass and envelope requirements.

Additive manufacturing (AM) presents a different way of approaching fluid tubing design when compared to these traditional methods. A main advantage of AM is the flexibility of design without having to consider many aspects of design for traditional manufacturing (TM). This is due to the nature of AM versus TM techniques, as the parts are built layer-by-layer rather than by being cut away from a metal stock. Therefore, AM has the ability to print complex, curving passages directly into a structure in a way that is impossible in traditional manufacturing. The GT SSDL has built many cold-gas propulsion systems that print fluid tubing directly into 3D-printed plastic structures, as seen for example on NASA's BioSentinel mission cold-gas propulsion system [7]. As a technology demonstration mission coupled with the SSDL's experience with AM on small-scale propulsion systems, the LFPS project chose to manufacture the manifold from L-PBF Ti-6Al-4V to greatly decrease the system complexity and add to the flight heritage of additively manufactured parts, while presenting a relatively low risk to the mission. A finalized CAD image of the manifold is shown in Figure 7 below.

While making the system's fluid tubing design much more streamlined by utilizing AM, the manifold remains a very complex part that required significant design effort due to the fact that the manifold also acts as the major interfacing structure of the propulsion system. Figure 8 shows the distribution of system components fastened directly to the manifold including the pump, thrusters, thruster valves, junction box blocks, recirculation block, controller boards, muffin tin, and solar panel hinges. These components all rely on traditional fastening and sealing methods such as thread forms and face-sealing o-ring grooves that require individually machined interfacing features. A major challenge of the

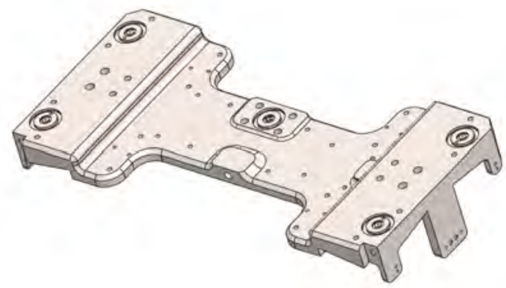


Fig. 7 CAD of the Lunar Flashlight manifold

manifold design was fitting all of these components and their interfaces nicely into a few square inches of space while ensuring structural stability during pressure and thermal loading throughout the mission. Additionally, the internal tubing must be large enough to handle propellant flow rates and pressure and be routed such that adequate material remained between the hollow tubes and the machined interfaces, all while ensuring that the tubing did not bias the system flow to certain thrusters.

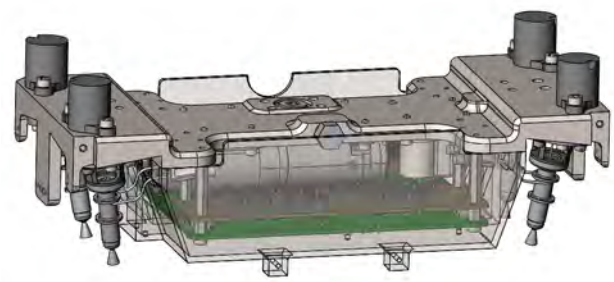


Fig. 8 Manifold interfacing components

C. Additional Hardware

While the propellant tank halves, PMD, and manifold are the major components of the propulsion system that took a majority of the design consideration, a few additional custom-designed parts are essential to the system's functionality, the first of which is the recirculation block. As discussed in Section II.B, a majority of the propellant flow travels through the recirculation loop during nominal conditioning and firing. For this recirculation loop to function as intended, a flow control device (fixed orifice in this case) is placed in the recirculation loop, as seen in the propulsion schematic in Figure 2. Typical COTS orifices are designed to be installed into fluid tubing for proper functionality, however, with the manifold having its fluid tubing 3D-printed directly into its structure, there is no location to install an orifice. Instead, the recirculation block is designed as a separate part to house the orifice and make installation easy, while not creating any discontinuities in the fluid loop. Figure 9 shows how the recirculation loop is built to curve out of the manifold and into the recirculation block, through the orifice, and back into the manifold. Therefore, the orifice can be installed into the recirculation block as it is designed, and then the recirculation block can be installed onto the manifold via a face-sealing o-ring to adapt to the system. However, the designed tubing path required that this part also be manufactured using AM.

The next piece of additional hardware is called the muffin tin, due to its similarity in shape to a cooking pan. The muffin tin acts as a protective thermal and radiation cover to shield the fragile electronic components during flight, such as the controller boards and pump. The ambient solar radiation from the spacecraft's lifetime in space will be the largest source of nuclear radiation the spacecraft receives, so as a barrier between the electronics and the space environment the muffin tin helps to mitigate the exposure of the electronics to that nuclear radiation. Additionally, the thrusters heat to +1600C during operation, which could harm the electronics that are in close proximity. Therefore, the muffin tin is also designed to limit the amount of heat transferred from the thrusters to the electronics. A thermal analysis

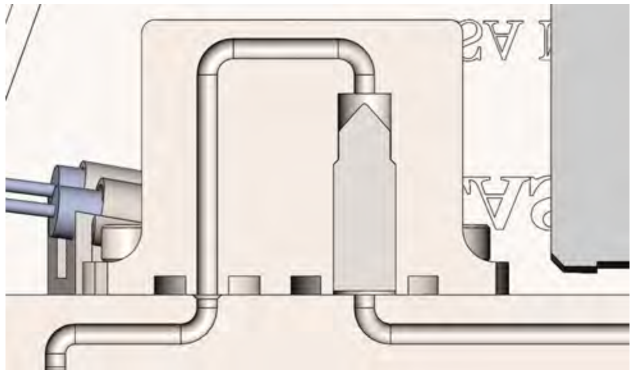


Fig. 9 Section view of the recirculation loop passing through the recirculation block

performed by MSFC showed that the muffin tin's angled walls near the thrusters absorb that energy well and prevents unintended warming. Finally, the bottom face of the muffin tin incorporates all of the spacecraft propulsion system +Z face interfaces, including mounting holes for the solar panels, low-gain antennas (LGAs), sun sensor, and limit switch.

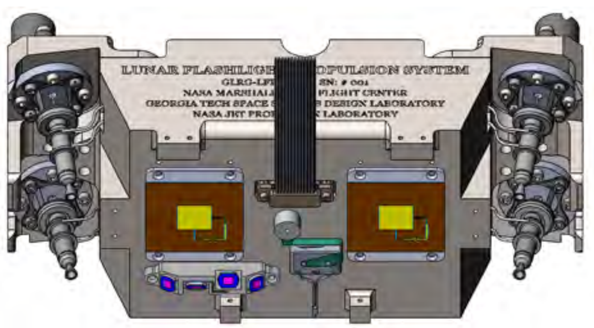


Fig. 10 Iso-view of the muffin tin showing a few of the spacecraft electronic components connected to the +Z face of the muffin tin. The angled walls of the muffin tin near each thruster are also shown.

IV. Manufacturing Processes

A. Additive Manufacturing and Lessons Learned

The L-PBF AM printing process, also called Direct Metal Laser Sintering (DMLS) focuses a high-powered laser onto a bed of fine metal powder, which melts a small area of the powder. Before the powder can cool and solidify, the laser melts an adjacent area and the melted powder cools together to form a solid piece of fused metal. This occurs continuously throughout one layer of the print. After one layer is complete, a new metal powder layer is added on top of the sintered material to repeat the process to form the next layer of the print. This process repeats until the parts are formed.

The LFPS project required the use of virgin metal powder on flight parts as some studies have shown that reuse of metal powder can lead to varying part material properties and performance, which is still a significant topic of research in the AM community [8]. Acquiring flight-grade virgin powder becomes quite expensive compared to recycled powder due to these effects, so the use of the virgin powder is desired to be minimized during the printing process. The printed part's support material is built directly out of this virgin powder during the print operation, so the flight parts should be printed in an orientation that minimizes the amount of support material to be used while also providing a stable base to prevent part failure during printing due to loss of structural support or thermal distortion. The support material, seen on the left-hand side of Figure 12, is built like scaffolding, intertwined together to support the overhanging material in a mass-effective way.

A notable difference between plastic and metal 3D-printing is the ability to machine the parts post-printing. Plastic parts are generally printed directly to their final configurations, while metal parts are not. As an example, the BioSentinel spacecraft's cold-gas propulsion system structure made of Accura Bluestone was printed directly to its flight configuration and any necessary mechanical interfaces with sensors and electronics boards were machined from separate metal plates using traditional techniques. However, the LFPS L-PBF manifold structure is the primary interfacing component of the propulsion system assembly, so many precision thread-forms, o-ring grooves, and machining datums need to be machined into the structure itself. Therefore, the structure that comes from the L-PBF machine is called the "as-printed" structure, and is sent for heat-treating, hot-isostatic pressing (HIP), and finally to a machine shop to add these features to create the flight-grade "as-machined" structure.

Additional material is designed on top of and around any machined interfaces in the as-printed structure so that the machine shop has room to shave away material to produce these features. Traditional machining processes require that features be dimensioned from established datums, but if the datums of a structure are covered in printed material that needs to be machined away, it is not obvious where these datums lie inside of the printed part. To this end, AM parts sometimes undergo structured-light scanning (SLS), which is a process that provides metrological data that the machine shop can use to determine how much material is needed to be removed to establish the major datums. The initial pathfinder manifold print was sent out for SLS for this reason, the measurements of which are precisely established to tens of thousandths of an inch. The results of the initial printing came back showing a 0.040"-0.060" warping throughout the center of each part in the +Z direction, seen in Figure 11. Due to the tight tolerancing around a majority of the manifold, these discrepancies were determined to be unfit for flight and could not be reworked into a useable flight grade part when considering the fluid sealing surfaces and proximity of the internal fluid passages to the exterior surfaces of the manifold.

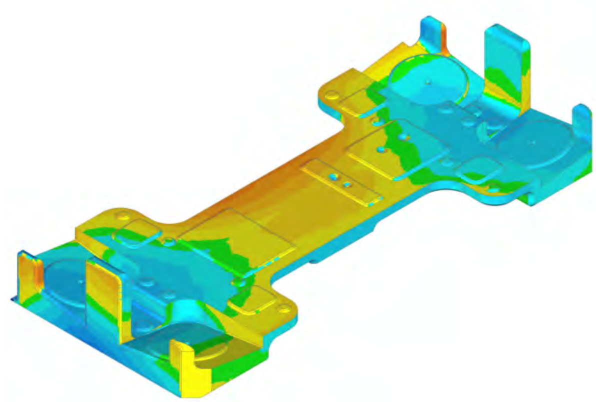
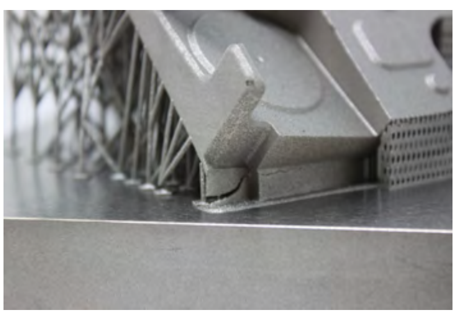


Fig. 11 Structured-light scanning results of the manifold post L-PBF printing. Green represents nominal dimensions; warmer and cooler colors indicate warping.

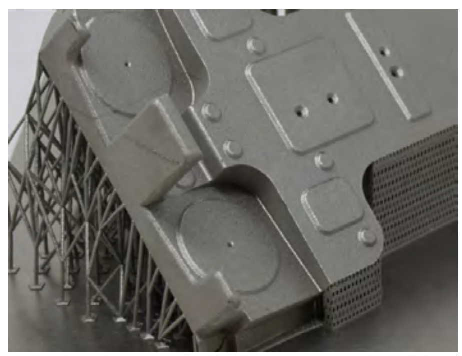
The initial investigation into this issue led the engineering team to believe that the heat treatment process, done prior to removing the support material from the printed part, was not set at a high enough temperature to adequately release the internal stress concentrations produced during the printing process. Therefore, when the support material was removed, the part's unrelieved internal stresses warped the part into what was seen in the SLS analysis. To solve this issue in the next round of printing and keep the project's manufacturing schedule, two printing orientations were devised: one very similar to the previous (see Figure 12) with slight structural modifications to make the part's support structure stiffer during printing while also increasing the heat treatment temperature; another, dubbed the "battleship method", where the part was built flat with very little concern for the amount of virgin powder used to ensure that at least one flight grade non-warped part would be properly produced. If the modified original print orientation produced acceptable to no warpage, the next flight grade manifolds would be printed in that orientation to save cost due to the large use of virgin powder for the battleship method. However, even with the modifications a slight warpage deemed to be unfit for flight was also seen after SLS. Therefore, the project chose to accept the additional cost of the battleship method manifold prints based on the fact that this method had the highest chance to minimize part warpage and produce flight grade manifolds.

Another issue encountered was support material failure during the initial pathfinder manifold print, as seen in Figure 13a, where there was a fracture near the build plate in a location that supported a majority of the left-hand side of the structure. A sharp corner was unintentionally designed into the interface between the support material and the build plate, which failed when the increasing weight of the part during printing created a stress concentration at the corner that exceeded the ultimate stress of the support material. The part shifted due to the failure and caused a discontinuity about halfway through the print, which is shown as a line that crosses the entire part along its build plane in Figure 13b. Future builds ensured that each sharp corner was rounded and thickened to spread the load and the provide necessary support structure.

Fig. 12 One of the four flight-grade manifolds after L-PBF printing, Image Credit: Volunteer Aerospace



(a) Support material failure



(b) Skipping line due to failure

Fig. 13 Failure seen in pathfinder manifold print.

The AM process on the manifold provided two valuable lessons to the LFPS team which could easily apply to other projects utilizing AM. One, that SLS should become an integral part of the acceptance and review process for small scale additively manufactured parts. SLS provides a quick way to gain significant metrological data on a printed part's inherent dimensional flaws prior to use or being sent for post-print manufacturing. In this way, SLS can help save significant time and money for a project, in addition to providing data and lessons learned that can be utilized in future designs for AM. The second takeaway is that support structure design and build orientation are significant challenges on small scale parts that require attention and detailed review. Complex and reliable computer programs are usually implemented to complete the support structure design quickly and efficiently, however as these programs grow in maturity on small and complex parts a review process should be conducted to check the computer's work and modify the support structure design where necessary.

B. Electron Beam (EB) Welding

The tank top and tank bottom structures are joined along a 360-degree weld-line due to the TM fabrication method of the tank halves. Electron beam welding was selected due to the factors of heat input during the welding process, reliable precision, and the weld joint's size. Processes like friction stir welding and tig welding input massive amounts of heat during the welding process, causing the metal to expand and then contract when cooled which can affect the material properties and overall dimensions that need to be exact for the small size of the LFPS. Electron beam welding, by comparison, does not use nearly as much heat, which diminishes this concern. Additionally, electron beam welding is automated and intended for high precision applications, while friction stir and tig welding are mainly utilized on much larger systems where the range of deformation is allowed to be larger.

The weld geometry itself is a lap-joint design that allows for adequate weld penetration while also preventing any FOD generated during the welding process from being blown into the tank, which could clog up the filter or fluid lines, or cause damage to the system components. Because the lap-joint goes 360 degrees around the weld line, the fit-up is heavily dependent on the tank top and tank bottom tolerancing. The horizontal gap between the tank top and tank bottom weld steps that form the lap-joint has a profile tolerance around the entirety of the weld line, which prevents this gap from ever closing and having the parts improperly interfere. This tolerance proved to be difficult to manufacture, with a profile tolerance nonconformance seen on one of the pathfinder tank top and tank bottom structures causing the two pieces to not fit together. Luckily, the manufacturing shop was able to fix this issue for the flight units and provide an additional conforming pathfinder tank build. Additionally, the lap-joint's vertical tolerance was designed knowing that the weld vendor was able to accept a small weld line gap.

One issue seen on the weld coupons was due to porosity and burn-through of the weld through the wall, which required adjusting the weld parameters. EB welding requires that a beam of electrons be balanced in terms of energy, amplitude, frequency, and waveform. The weld samples were tested to determine what combination of these parameters created the best weld for the project's geometry and application. The vendor initially found that when they got good penetration without burning through, they would find porosity throughout the weld, but when they would try to get rid of the porosity they would burn through the wall.

The solution to this issue came from suggestions by weld engineers at MSFC. The initial samples delivered to the vendor were two inches long and were fixtured and insulated at either end when welded. Typical welds happen in single or multiple long passes, where the heat applied at one end is usually so far from the opposite end that the heat is unable to soak through the weld length and affect it. However, if the samples are short enough and insulated on both sides, as seen in the original weld samples, the heat could soak and cause higher heat loading throughout the part than expected, potentially leading to burn-through. With longer passes (a longer sample, more like the LFPS propellant tank weld-line itself) enough heat can be applied to prevent porosity but very little heat will soak from one end of the line to the other, preventing burn-through due to higher than expected heat loading.

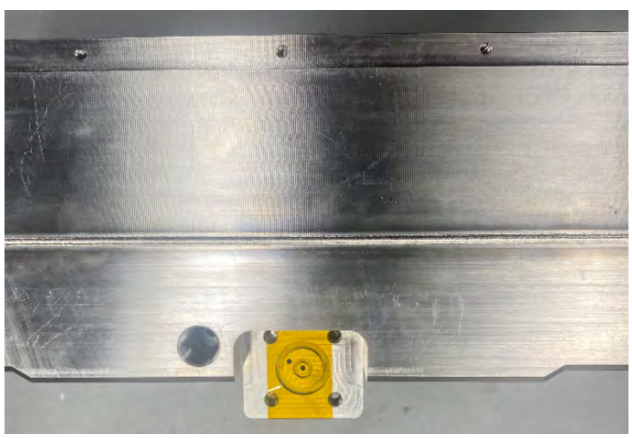


Fig. 14 EB weld of the pathfinder tank assembly

V. Integration and Test

The LFPS integration and test procedures were developed by the Georgia Tech SSDL with input from NASA MSFC. Part of the reason the GT SSDL was selected for the LFPS project was due to the SSDL's prior experience on the BioSentinel mission, which required the development of detailed integration procedures. The procedures focus on outlining necessary integration steps, quality assurance (QA) witness steps, torque value recordings for each fastener on the system, and a multitude of pictures to document the integration process. The procedures also list all necessary parts, equipment, and documentation needed, as well as specifying the qualities of a safe, clean environment for integration. The LFPS integration procedures were developed following these guidelines, and are called Assembly, Integration and Test Procedures (AITPs). The LFPS integration requires nine of these, which are outlined in Table 2.

Table 2 LFPS Assembly, Integration and Test Procedures

Procedure	Description
AITP-01	PMD sponge, vane, filter installation into tank bottom
AITP-02	Propellant tank EB-welding, proof and burst testing
AITP-03	Recirculation block orifice installation, proof and burst testing, precision cleaning
AITP-04	Recirculation block, thruster valves, pressure sensor, heater, TC installation into manifold, leak test
AITP-05	Fill/drain valve, pressure sensor, bulk prop iso-valve, heater, TC installation into welded tank sub-assembly, leak test
AITP-06	Tank and manifold sub-assembly mechanical connection
AITP-07	Pump installation, leak test
AITP-08	Controller installation, connector mating, electrical checkout
AITP-09	Thruster, muffin tin installation, system-level leak test

A major component of the project's integration plans are the test campaigns that go along with building the assembly and sub-assemblies. First, specific parts that were designed to be pressurized during flight (i.e. tanks, manifold, recirculation block) will be pressure tested prior to being delivered back to Georgia Tech. Pressure testing is a way of testing the strength of the system and validating the structural analysis, which is important for qualifying the propulsion system for flight. The LFPS project conducts pressure testing at the component level before integration with any other flight hardware. This is done to ensure that each pressurized component of the system will not damage other components when under pressure. Proof and burst testing are conducted per the Level 4 requirements seen in Table 1. To pass a proof test, the component is allowed to deform elastically but not plastically. Alternatively, burst testing allows the parts to plastically deform but does not allow to fracture. If the component passes the required burst pressure without failure, the test will proceed by increasing pressure until the part does fracture.

Other major tests to be conducted are regular leak tests with gaseous Helium at the end of each integration step involving newly-integrated components featuring fluid seals. Leak tests measure the rate of gaseous leakage of a fluid seal, and this rate is defined in the system-level requirements. If too much gas is allowed to leak, the system will depressurize over time and will either have reduced performance or stop working altogether. The LFPS project requires leak tests be performed at 1.1 times MDP (110 psia), which is over the Maximum Expected Operating Pressure (MEOP) of the system. A higher gas pressure than nominal will force more gas out of any small openings which increases the measured leak rate. If the system meets the leak requirement at elevated pressure, it will also meet it at a lower pressure, so this is a conservative method to ensure the system meets the requirement. Because of the complex steps involved with setting up a sniffer or mass spectrometer to a vacuum chamber for quantifying leak rates, many of the sub-assembly leak tests will be conducted qualitatively using a bubble test. The bubble test involves placing a bubbling liquid mixture around the externals of a fluid seal while the internals are pressurized, and any escaping gas will be caught in the mixture and create visual bubbles. Any visual bubbles seen will show a leak that is much too large to meet the requirement, and the seal will have to be fixed. The final system-level test in AITP-09 will require quantitative results to meet LFPS-REQ-025 as defined in Table 1. The results of the test are expected to be obtained using a mass spectrometer.

At the time of this publication, three flight propellant tank top and bottom structures have been delivered to Georgia Tech and AITP-01 has been completed on the flight, spare and burst units, one of which is shown in Figure 15. The pathfinder weld has finished heat treatment and is undergoing dye-penetrant inspection, with results expected in November 2020. The tank bottom half assemblies built in AITP-01, along with the tank top structures, plan to be shipped shortly to the weld vendor, following pathfinder weld results, for electron beam welding as a part of AITP-02. AITP-03 has been completed and is awaiting MSFC to proceed with proof and burst testing. The remainder of the project will include finishing the manufacturing process on the manifolds and ordering other hardware needed later in the assembly, particularly the muffin tin and junction box mounting blocks and brackets. Proof and burst pressure testing will be conducted in early 2021 at MSFC on the welded tank assemblies, manifolds, and recirculation blocks. As these processes finish, the Georgia Tech and MSFC teams will conduct AITP-04 through AITP-09 along with all necessary tests on hardware specific to the propulsion system, including structural components, microelectronic components, and the system controller. After all nine AITP's have been conducted, the completed assembly will be shipped to JPL in Pasadena, California where it will be integrated with the Lunar Flashlight spacecraft. Functional and environmental tests will be conducted on the full spacecraft assembly to prepare for flight. After transfer to JPL, the GT team will remain on the LFPS project to provide additional technical support as necessary, but all hardware will be delivered. The Lunar Flashlight spacecraft is on the launch manifest for the Artemis-1 SLS rocket, due to launch in late 2021.

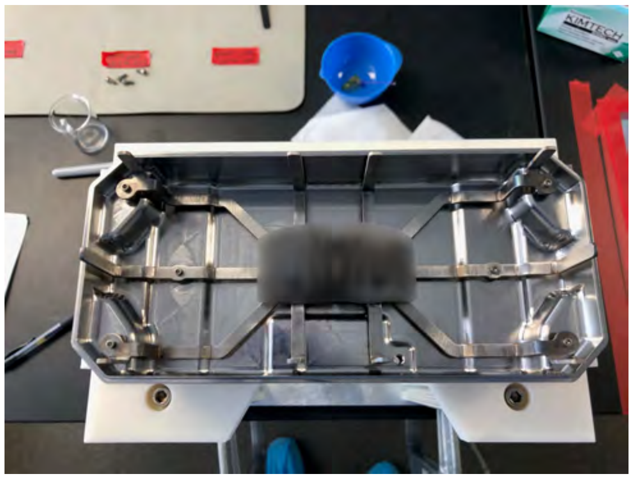


Fig. 15 Flight spare tank bottom and PMD integrated following AITP-01. Sponge intentionally blurred.

VI. Conclusions

An ASCENT green monopropellant system was developed by the Georgia Tech Space System Design Laboratory for NASA's Lunar Flashlight CubeSat mission under the leadership of NASA's Marshall Space Flight Center and support from the Jet Propulsion Laboratory. A pump-fed system is utilized so that the required pressures are low, reducing the risk of the propulsion system to the mission and facilitating the successful completion of safety and fracture control reviews. LFPS components are built using a combination of traditional and L-PBF additive manufacturing, with the AM manifold housing most of the fluid passages that are printed directly into the structure, adding to the spaceflight heritage of AM. Challenges during the design, fabrication, and assembly phase led to many learning opportunities, including overcoming difficulties seen with TM, AM, electron beam welding, and more that were specific to scaling a green monopropellant propulsion system to a size that will fit within a 6U CubeSat. Upon submission of this report, the project is completing the final stages of manufacturing and beginning the integration phase, with expected delivery for integration and testing at the spacecraft level in mid-2021. After launch on NASA's first Space Launch System rocket in late 2021, the custom-designed Lunar Flashlight Propulsion System will place the Lunar Flashlight spacecraft into polar Lunar orbit by early 2022 and allow for a 90-day science mission with the possibility for a mission extension.

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