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Design of a Green Monopropellant Propulsion System for the Lunar Flashlight CubeSat Mission

Dawn Andrews
Georgia Institute of Technology
305 Gull St, Manhattan Beach, CA 90266; (678) 634-9542
dawnandrews4@gatech.edu

Grayson Huggins
Georgia Institute of Technology
1952 Cheyanne Dr SE, Smyrna, GA 30080; (404) 483-8519
ghuggins3@gatech.edu

E. Glenn Lightsey, Nathan Cheek, Nathan Daniel Lee, Ali Talaksi, Sterling Peet, Lacey Littleton, Sahaj Patel, Logan Skidmore, Mackenzie Glaser
Georgia Institute of Technology
620 Cherry St NW, Atlanta, GA 30332; (404) 385-4146
glenn.lightsey@gatech.edu

Daniel Cavender, Hunter Williams, Don McQueen
NASA Marshall Space Flight Center

John Baker, Matt Kowalkowski
NASA Jet Propulsion Laboratory

ABSTRACT

Lunar Flashlight is a 6U CubeSat mission from NASA's Jet Propulsion Laboratory that will search for water-ice deposits near the lunar south pole. Lunar Flashlight aims to add to the flight experience of deep-space CubeSats by demonstrating an orbit insertion using a green monopropellant propulsion system designed uniquely for this mission. Developed by NASA Marshall Spaceflight Center (MSFC) and Georgia Tech's Space Systems Design Laboratory (SSDL), the Lunar Flashlight Propulsion System (LFPS) delivers over 2500 N-s of total impulse for the orbit insertion and necessary attitude maneuvers. The custom propulsion system fits within a 2.5U volume and has a total wet mass of less than six kilograms. It will be fueled by AF-M315E, which is a green monopropellant developed by the Air Force Research Laboratory (AFRL) as a safer alternative to hydrazine. Additive manufacturing is utilized to fabricate several components of its primary structure. Upon completion, Lunar Flashlight may become the first CubeSat to achieve orbit around a celestial body besides Earth. The LFPS aims to be a pathfinder device for CubeSat missions by demonstrating how monopropellant systems, green monopropellant fuel, and additive manufacturing can be utilized to expand the reach of small satellite space exploration.

INTRODUCTION

The inclusion of propulsion systems on small satellites adds significant capability to their missions, allowing them maneuverability, momentum control, and orbit adjustment. However, the design of small satellite propulsion systems can be challenging due to their miniature size, custom architecture, and inclusion of cutting-edge technologies necessary for their success.

Under sponsorship by the NASA Marshall Space Flight Center and the NASA Jet Propulsion Laboratory, the Glenn Lightsey Research Group was awarded responsibility for the design, manufacturing, test, and delivery of the Lunar Flashlight mission's propulsion system. The Critical Design Review of the Lunar Flashlight Propulsion System (LFPS) was successfully completed in January of 2020, and the project has since proceeded into the manufacturing and integration phase.

Lunar Flashlight Mission

The Lunar Flashlight mission is a 6U CubeSat that aims to investigate the South pole of the Moon for volatiles including water ice.[1] It will ride along with the Artemis-1 mission on the Space Launch System (SLS) as part of the United States' national effort to reestablish a human presence on the moon. The Lunar Flashlight Propulsion System accounts for approximately one half of the spacecraft, filling about 2.5 of the total 6U. This propulsion system will be responsible for momentum unloading as well as the insertion maneuver into the science orbit. Upon the successful completion of this mission, Lunar Flashlight could become the first CubeSat to perform an orbit insertion and, subsequently, the first CubeSat to explore the Moon.

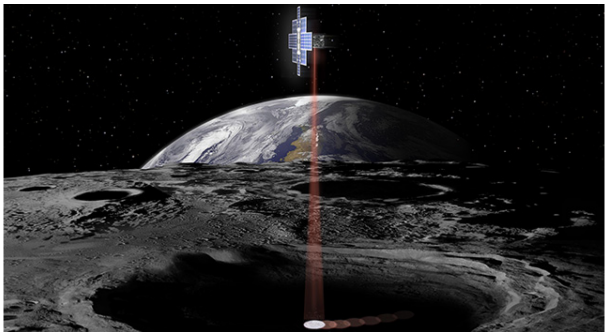

Figure 1: Concept Artwork of the Lunar Flashlight Mission[2]

In addition to the main science objectives, the mission will add to the flight heritage of green monopropellant propulsion and be a technology demonstration for several of its supporting components. The microvalves, micropump, and 100 mN thrusters will experience their first spaceflight, increasing their Technology Readiness Level (TRL) to 7. The inclusion of additive manufacturing in the flight hardware's fluid manifold structure and Propellant Management Device will both contribute to the growing number of use cases of additively manufactured materials in space. Finally, this system will be the first implementation of green monopropellant propulsion on a CubeSat platform, demonstrating this technology's significant potential to expand the scope of exploration that is accessible to small satellite platforms.

Green Monopropellant Propulsion

Monopropellant propulsion is a decomposition-based form of chemical propulsion. The stored propellant is heated and flowed over a catalyst bed that triggers an exothermic reaction. This results in a high-temperature gaseous medium that may be accelerated out of a nozzle to produce thrust.

Hydrazine has been in use for a very long time as a monopropellant, dating back to use as a rocket propellant in the 1930's.[4] However, it is also notorious for being extremely toxic, carcinogenic, corrosive, flammable, and explosive.[5] In NASA's 2020 Technology Taxonomy, hydrazine alternatives were identified as a key technology, specifically mentioning candidates such as LMP-103S and AF-M315E. Both of these are 'green monopropellants,' or hydroxylammonium nitrate-based alternatives whose most notable advantages include decreased toxicity and significantly safer storage and handling properties compared to Hydrazine.[6] The LFPS uses AF-M315E, which has also been designed to improve on the performance of hydrazine as shown in Table 1.

Table 1: Comparison of Hydrazine and AF-M315E Propellants

	Hydrazine	AF-M315E
Specific Gravity	1.01[5]	1.46[7]
Specific Impulse	190 seconds[8]	231 seconds[9]
Hazard Classification	8[5]	1.4C[7]

The AF-M315E green monopropellant has flight heritage from one prior mission: the Green Propellant Infusion Mission (GPIM). GPIM was also managed by NASA MSFC, and it included engineering efforts by Aerojet Rocketdyne and Ball Aerospace. Its primary objective was the technology demonstration of its AF-M315E propulsion system. It launched on June 25th, 2019 as part of the STP-2 mission on a Falcon Heavy rocket in a Ball Aerospace SmallSat platform.[10] A week later, it reported successful firing of all five of its thrusters as part of system checkouts and an orbit lowering maneuver.[11]

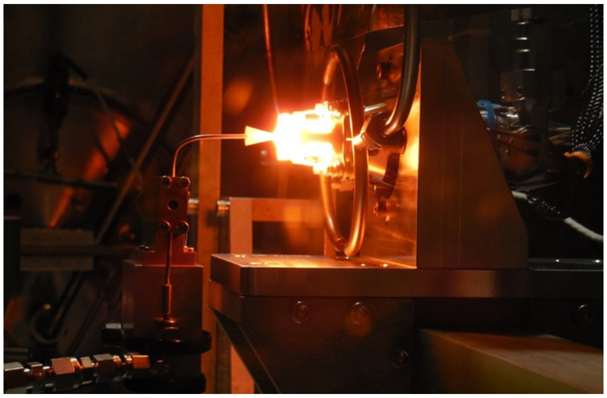

Figure 2: Test Fire of the GPIM Mission Thrusters[12]

SYSTEM REQUIREMENTS

The Lunar Flashlight Propulsion System was allocated approximately 2 x 1 x 1.5 U volume within Lunar Flashlight's total 6U (where 1U is equivalent to 10cm or 1000ccm) and was required to follow strict specifications on its mechanical and electrical interfacing to the rest of the spacecraft. The three major requirements for the LFPS are shown in Table 2. Additional requirements included expected environmental loads, pre-determined interfaces, quality standards, and more.

Table 2: Main Design Requirements

Requirement	Value
Wet Mass	5.5 kg
Propellant Volume	1500 cc
Total Impulse	3000 N-s

The design solution, which is shown in Figure 3, includes a titanium structure that is split between a tank subassembly and a manifold subassembly. The manifold structure leverages the use of Laser Powder Bed Fusion (L-PBF) additive manufacturing.

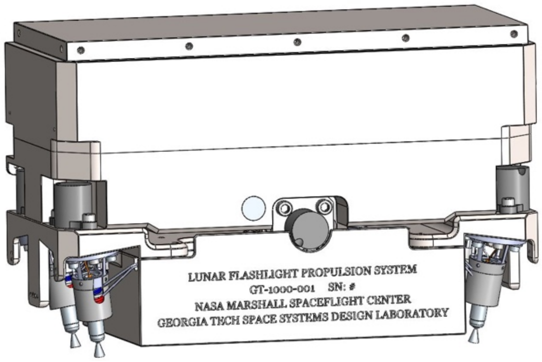

Figure 3: External Structure, As Presented at the LFPS Critical Design Review.

Figure 4 shows the functional elements of the LFPS shown in the style of a Piping and Instrumentation Diagram (P&ID). Notable elements include the pump and recirculation circuit, all sensor locations, and valve responsibilities for 1) bulk propellant isolation within the tank and 2) controlled propellant feed to the thrusters.

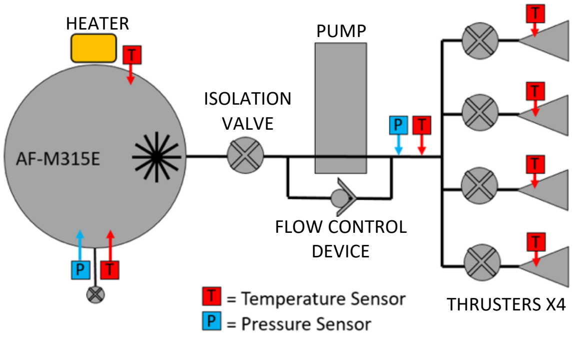

Figure 4: Piping & Instrumentation Diagram

The pump-fed system allows the propellant to be stored at low pressures in the tank before being fed into the thruster interface at the much higher required inlet pressures. This allows the entire system to be low pressure (<100psi) when fully fueled, which simplifies and reduces risk for all ground handling and launch events.

Tank Design

The primary responsibility of the LFPS tank is to store the propellant through launch and during operation of the spacecraft. It contains the AF-M315E propellant and a Nitrogen ullage, as well as all components related to propellant filling, monitoring, and control in zero-gravity. Its design was largely driven by strength and deformation requirements under static pressure loading. The flight design is a Titanium 6Al-4V (Grade 5) machined piece, joined by an EB weld seam through the center of the part. Within it is the full required internal propellant and ullage volume, as well as a Propellant Management Device (PMD) for on-orbit fluid management. On its exterior are mounting locations for the joint between spacecraft and propulsion system, between the tank and manifold, various sensors and the fill/drain port.

Manifold Design

In addition to the tank, the LFPS includes a manifold structure that houses all of the valves and fluid passages that are typical of many propulsion systems. The manifold is responsible for all fluid handling downstream of the tank and its isolation valve. It structurally connects the tank, all four thrusters, the four thruster valves, and the pump and recirculation lines. Internally, it contains all of the fluid passages that route between those components.

A functionally equivalent system made from traditional machining methods would require special equipment for the miniscule flow passages, and several critical welds would be required. To make a similar design out of tubing and connectors, upwards of 40 non-standard components would be required, vastly increasing mass, cost, and complexity. Instead, L-PBF additive manufacturing was chosen so that the manifold structure could be designed as a single, continuous part. This allows the manifold to include structural supports and fluid passages that would otherwise be impossible to machine, while also reducing part count and avoiding welds altogether. Fluid channels were routed organically without machining limitations, and components were placed with significantly more flexibility. The additive manufacturing approach also provided the most efficient packaging of the fluid system in terms of mass and volume, which were the most important requirements to satisfy for the system as a whole.

ADDITIONAL DESIGN CONSIDERATIONS

Thermal Control

The viscosity of AF-M315E is heavily dependent on its temperature, so it requires that the propulsion system include careful thermal monitoring and temperature control. However, at its lower bounds, the propellant does not run the risk of freezing, and instead experiences a glass transition.[8] This is a major advantage over other monopropellants like Hydrazine, which must be actively controlled at all times to prevent freezing damage to wetted components. Instead, an AF-M315E system can simply rest dormant until it is warmed up for firing.

When the system is operational, thermal inputs to the fluid must be monitored because certain cases could lead to thermal expansion while the propellant is constrained to a fixed volume. Similar to an engine experiencing hydraulic lock, this can be an extremely destructive failure scenario. To mitigate this risk, the LFPS includes seven fluid temperature sensors in critical locations to monitor fluid temperatures during operation.

Fluid Control

In the tanks, a propellant management device was included to handle the liquid propellant once the spacecraft is in orbit. The tank carries both liquid propellant and a gaseous ullage, so it is important to protect the downstream components from ingesting bubbles that could cause damage or decreased performance. Common methods for in space fluid control include pistons, elastomeric diaphragms, or balloon designs, although these require soft goods and actuated components that can be difficult to resolve with AF-M315E material compatibility requirements.[13] LFPS instead chose a passive method, which leverages capillary action to ensure that propellant always stays suspended over the tank orifice. These designs often use veins, screens, and/or sponge structures inside the tank, and must be customized to the fluid properties of the propellant.

The amount of fluid volume itself ended up becoming an important decision for the control of the system overall. An analysis was performed early in the design process to determine correct fill percentages of ullage and propellant. Constraints included the project's requirements for volume, mass, performance, and feed pressure to components, all of which directly compete with each other for determining the appropriate tank fill.

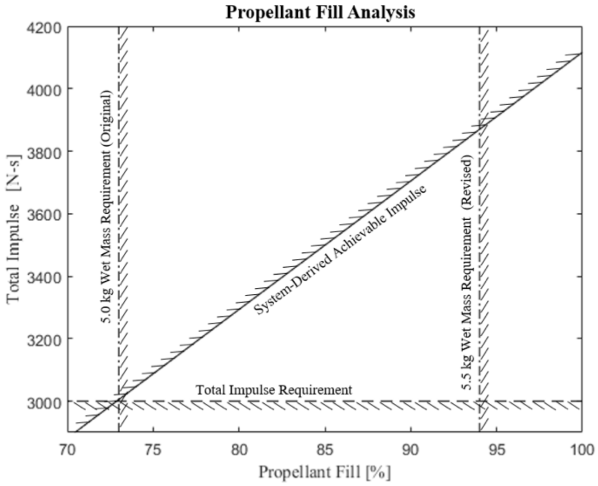

Figure 5: Propellant Fill Analysis

The initial results of the study are shown in Figure 5. This study conservatively assumed worst case environmental conditions and required that the ullage pressurization never exceed the 100psi threshold that would classify the tank as a pressure vessel. It also assumed that there would be no dissipation of the gaseous ullage into the liquid propellant at high pressures, thus making the simplified analysis into a series of ideal gas law calculations. One of the competing constraints was the minimum total impulse performance requirement, which increased linearly with propellant mass. The other was the maximum wet mass of the system, which preferred ullage for its lesser density. Under the original requirements, the analysis found the acceptable range of propellant fill to require a precision of .1%, or approximately 100mL, and left no mass margin for any of the remaining design. After presenting this at the Preliminary Design Review, and with support of the NASA MSFC team, the LFPS wet mass budget was increased from 5.0 kg to 5.55 kg. This significantly improved the structural mass and fluid mass margins for the rest of the design.

Additive Manufacturing

Direct Metal Laser Sintering is a form of additive manufacturing that uses a directed laser to fuse metal powder together layer by layer. It provides designers with incredible flexibility to create continuous parts with internal features, complex geometries, and otherwise unmachinable structures. L-PBF prints have a minimum feature size of .006", and are most commonly seen for Stainless Steel, Nickel alloys, Aluminum, and Titanium material choices.[6] During the design of the LFPS, four key rules were recommended for consideration to the additive manufacturing process.

Firstly, the laser sintering process creates thermal gradients during printing. Sharp concave corners should be avoided, since their thermal gradients cause stress concentrations that can develop into true cracks as the part cools. Thermal gradients may also cause warping between abrupt changes in part thickness, as seen in Figure 6.

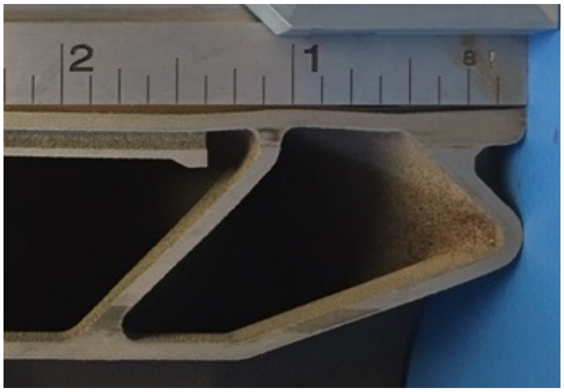

Figure 6: Example of Warping Across Changes in Part Thickness

Secondly, internal cavities must have a clear route for removing unsintered powder. Since the fusion bed starts with a clean layer of powder across each layer, internal features will be filled with powder that must be removed when the part is complete. And, any powder left in contact with surface areas retaining significant heat may partially fuse into the main structure. This can be seen in Figure 7, where the darker coloration indicates partially fused powder. To some extent, print settings can be adjusted to mitigate this effect, but it is best to avoid small concave features in thick-walled structures that may exacerbate this issue.

Figure 7: Example of Partial Fusion of Unsintered Powder

Third, for any features requiring machining such as tapped holes, surface finishing, or other post-processing, it is necessary to leave a clean line of sight for machinability. While additively manufactured parts give great freedom to feature placement, it is often necessary to finish these pieces with post-print machining processes that still must account for tooling paths on traditional machines.

Fourth, the material properties of L-PBF printed parts tend to be highly orthotropic, meaning that one axis's properties differ greatly from those of its perpendicular axes. This can be addressed through a combination of decisions made during designing as well as printing. Choosing a particular print orientation early in the design can allow for control over how the material strength axes align with the major axes of the part.

Safety

In-space propulsion systems are often subjected to strict safety control criteria due to their inclusion of high-risk components, particularly pressure vessels and hazardous fluids in the case of Lunar Flashlight. At the beginning of the project, the tank design raised concerns about fracture criticality, specifically for the high pressures that it required in its original configuration as a blow-down pressurization system. The hazardous nature of the propellant at high pressure required significant additional analysis and testing in order to clear fracture requirements. However, when the design matured to a pump-fed system, the need for stored pressure was significantly reduced and the pressure vessel designation no longer applied.

One key takeaway from these initial concerns about fracture was that the use of additive manufacturing would be extremely disadvantageous for fracture-controlled hardware. The naturally striated macro-structure of layer-by-layer printed materials would be considered microfractures and would require extensive material testing to receive approval from the SLS's Fracture Control Board. As a solution, the traditional machining of the tanks from stock material would pass much more easily through fracture control as long as they included careful vetting of the weld in the design.

Additionally, the Lunar Flashlight system went through several appeals to safety boards over fault-tolerance to leakage. Initially, dual-fault tolerance was required throughout the entire system. This included series-redundant valves to protect from in-line component failure as well as concentric o-rings on all seals to protect from breaches. However, the LFPS project used several strategies to mitigate these risks and reduce the complexity related to leakage. Firstly, the propellant's own high viscosity at its designed low storage pressure meant that it had a very low likelihood to leak through small gaps. It also has practically no vapor pressure, and thus "[would] not self-pressurize or evaporate through small fissures."[15] Then, with the tank and its auxiliary components being the only wetted parts during launch, it was possible to isolate any safety requirements to the tank subassembly. This allowed the manifold, and its significant number of fluid interfaces, to decide its own redundancy requirements instead of following the strict launch vehicle safety requirements.

CONCLUSION

In summary, the Lunar Flashlight Propulsion System project has developed the design of a green monopropellant propulsion system for a mission whose flight would be a major accomplishment for the small satellite community. In addition to enabling Lunar Flashlight to become the first CubeSat to reach the moon, the propulsion system will add critical flight heritage to green monopropellants and be their first demonstration on a CubeSat platform. It ultimately exemplifies a massive increase in capability for small satellite missions and paves the way for additional interplanetary CubeSat missions to come.

ACKNOWLEDGMENTS

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