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

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Abstract

The Lunar Flashlight Mission is a lunar-bound small satellite that will investigate the Moon's poles for water ice. Aboard the spacecraft is a green monopropellant propulsion system that has been designed by the Georgia Institute of Technology under sponsorship and guidance by the NASA Marshall Space Flight Center. Green monopropellant propulsion is a forthcoming technology that promises improvements in performance and safety over existing monopropellant systems such as Hydrazine, making it a very desirable new technology, and Lunar Flashlight will be the first mission to utilize this propulsion on a CubeSat platform. The design solution for the Lunar Flashlight Propulsion System will be shared, as well as the story behind its evolution through the design process. Additionally, several key aspects of its design that are fundamental to green monopropellant propulsion will be collected in contribution to a design methodology for future iterations. This project is intended to continue on to launch with the Artemis-1 Mission, at which point the propulsion system would complete its objectives of contributing flight heritage to this technology while acting as a critical component for the Lunar Flashlight Mission.

Nomenclature

μ	Dynamic viscosity
ρ	Density
σ	$= 5.67 * 10^{-8} \frac{W}{m^2 K^4}$, Stefan-Boltzmann constant
σ_c	Circumferential stress
A	Area
AFM315E	Air Force Monopropellant 315E
CDR	Critical Design Review
D	Diameter
DMLS	Direct Metal Laser Sintering
dT	Temperature difference
f	Darcy-Weisbach friction factor
FEA	Finite Element Analysis
g	$= 9.81 \frac{m}{s^2}$, Earth gravitational acceleration

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GPIM	Green Propellant Infusion Mission
I_{tot}	Total Impulse
ICD	Interface Control Document
k	Thermal conductivity
L	Length
LFPS	Lunar Flashlight Propulsion System
LMP-103s	Liquid MonoPropellant 103S
m_{prop}	Mass of propellant
MDP	Maximum Design Pressure
MRR	Manufacturing Readiness Review
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NDE	Non-Destructive Evaluation
P	Pressure
p	Pressure
P&ID	Piping and Instrumentation Diagram
PDR	Preliminary Design Review
PMD	Propellant Management Device
Q	Volumetric flow rate
q	Heat transfer
r	Radius
R236fa	Refrigerant 236fa
Re	Reynolds number
SLA	Stereolithography Apparatus
SLS	Space Launch System
t	Thickness
TRL	Technology Readiness Level
TTR	Table Top Review
U	Unit, a standardized CubeSat volume of 10x10x10 cm

Contents

1 Introduction

In recent years, small satellites have become a popular tool for accessing space. CubeSats in particular offer a standardized platform for ride-along access to space, carrying payloads for space-based science research or technology demonstrations. These systems are typically on the order of less than a cubic meter in volume and weigh only tens of kilograms, and yet their capabilities continue to increase in scope along with the advancement of technologies suited to miniaturized space systems.

One such key technology is the advancement of in-space propulsion. The inclusion of propulsion systems on small satellites adds significant capability to their missions, allowing them maneuverability, momentum control, and orbit adjustment. The development of such a propulsion system requires considerable design effort due to their miniature size, custom architecture, and inclusion of cutting-edge technologies necessary for their success.

In particular, this report will focus on the design of a green monopropellant propulsion system suited for CubeSats, specifically drawing on experience from the Lunar Flashlight Mission. Under sponsorship by the NASA Marshall Space Flight Center and the NASA Jet Propulsion Laboratory, the Glenn Lightsey Research Group was awarded responsibility for creating the Lunar Flashlight Mission's propulsion system. As the major contribution associated with this research, the design of the Lunar Flashlight Propulsion System (LFPS) was completed in 2019. The design and methodology of this system will be discussed, as well as several critical aspects of the new technologies demonstrated by this project.

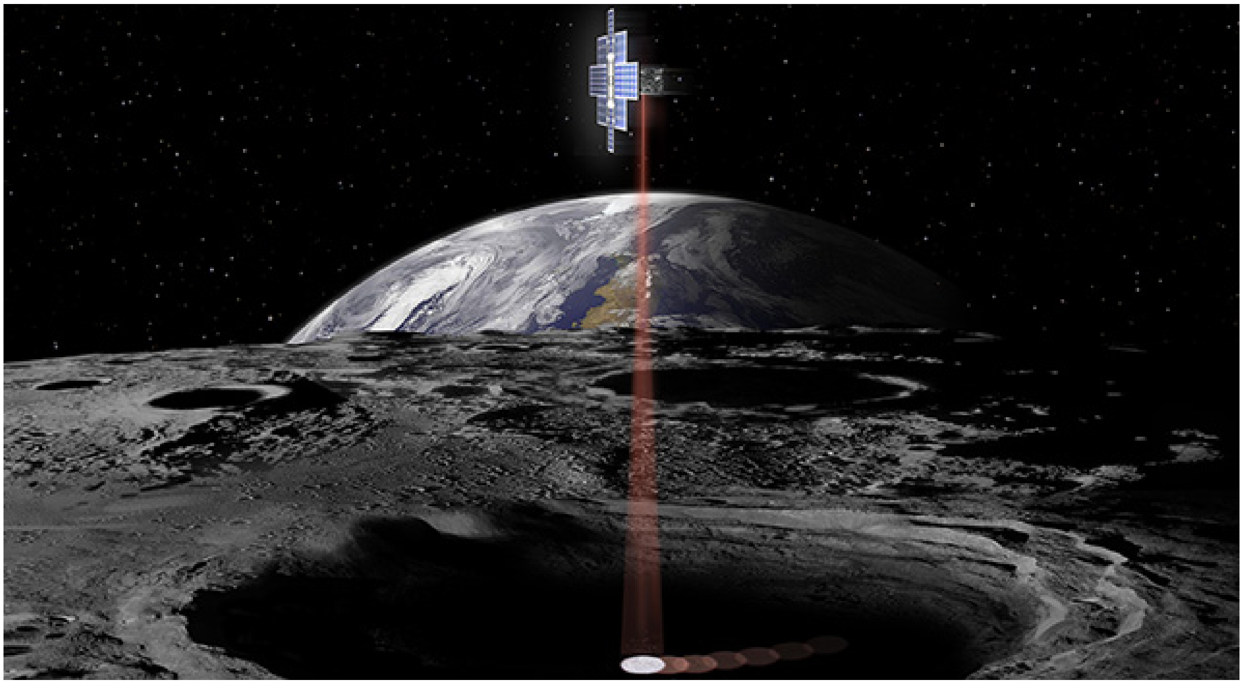

Figure 1: Concept artwork of the Lunar Flashlight Mission. [1]

1.1 Key Technologies

The fundamental subject matter of this research incorporates several key technologies considered desirable by the field. In NASA's 2020 Technology Taxonomy which "identifies, organizes, and communicates technology areas relevant to advancing the agency's mission," in-space propulsion is the very first technology area to be included. As part of the taxonomy, it has thus been indicated as a discipline "needed to enable future space missions," and one which may be referenced to "inform decisions on NASA's ... strategic investments." [2]

Futhermore, six of the ten examples for in-space propulsion listed under TX01.1.1 Integrated Systems and Ancillary Technologies are directly applicable to the design effort made in this research.[3]

- CubeSat propulsion
- Propellant Management Devices (PMDs)
- Pressure regulation mechanisms
- Propellant thermal control systems
- Long-duration propellant-compatible materials
- Low-impulse attitude-control systems

Additionally, the choice of propellant on the LFPS has involved two of the exact examples included under TX01.1.2 Earth Storable propellants. Both of the example green monopropellants mentioned (AF-M315E and LMP-103S) have been considered in the design of the LFPS. Both are also hydroxylammonium nitrate based propellants that offer improvements on storage, handling, and performance over heritage propellants such as Hydrazine, making them a very desirable technology in and of themselves.

Beyond the NASA-identified Taxonomy, the Lunar Flashlight Propulsion System also makes use of critical new technologies such as additive manufacturing, microfluidic components, and custom electronics. These characteristics of the design come from experience on previous flight projects from the Glenn Lightsey Research Group and have become essential aspects of this system as well.

2 Background

Small satellites traditionally do not carry any propulsion capability due to constraints on volume, mass, budget, and risk as a secondary payload. The complexity of propulsion subsystems makes them difficult to scale down to a CubeSat's form factor. Doing so often requires custom solutions that are expensive to produce and may depend on low-TRL components. This difficulty designing small propulsion systems often trades off with performance. Most small propulsion systems offer thrust on the order of millinewtons. Total impulse capability is a direct trade between propellant storage and the limited volume available on CubeSats. And in their miniaturized form, pressure losses through microfluidic components often significantly impacts the efficiency of these propulsion systems. Additionally, propulsion systems by nature must store some amount of energetic potential, usually through pressure, volatile chemicals, or a combination of the two. This makes them dangerous to handle and difficult to certify for flight, ultimately adding risk to the mission, launch vehicle, and all involved personnel. Since CubeSats are currently only launched as ride-along secondary payloads, they are strictly regulated against including high-risk elements such as hazardous chemicals, high pressures, pyrotechnic components, and various others typically associated with a propulsion system.

Thus, small propulsion systems must strike an appropriate balance between design difficulty, performance returns, and associated risks. Major advancements in design and manufacturing have closed the gap to make in-space propulsion accessible to small satellites. And, as small propulsion systems are developed and improved, CubeSats are able to extend their realm of performance. For example, where small satellites in Low Earth Orbit typically rely on Earth's magnetic field for momentum management, active propulsion can provide attitude control independently and on command anywhere in space. Active propulsion is also necessary for any delta-V maneuvers, such as those for station keeping, rendezvous, or orbit adjustment.

2.1 Cold Gas Systems

The Glenn Lightsey Research Group has been involved on several previous flight hardware projects in the realm of in-space propulsion. Through work by former students Steven Arestie, Travis Imken, Terry Stevenson, and Matthew Wilk, the Glenn Lightsey Research Group has developed a concise methodology for creating cold gas thrusters. In many ways, the Lunar Flashlight project and its associated design methodology for green monopropellant systems have been an evolution off of this work.

Cold gas systems provide propulsion through the expulsion of a gas stored at pressure, achieving acceleration by expanding it through a nozzle across the pressure difference between storage and space. Former projects from this lab have utilized a two-tank layout as shown in Figure 2: the first tank provides bulk storage of a two-phase fluid in a primarily liquid state, and the second plenum provides a controlled volume for expansion to ensure that only gaseous propellant is sent through the nozzle and out into space. Additive manufacturing is used to consolidate the entire tank and tubing into a continuous structure that requires no machining or welding. Specifically, Stereolithography Apparatus (SLA) manufacturing is used on a quasi-ceramic material to create a complex structure that allows for propellant volume optimization and total customization to the spacecraft interface.

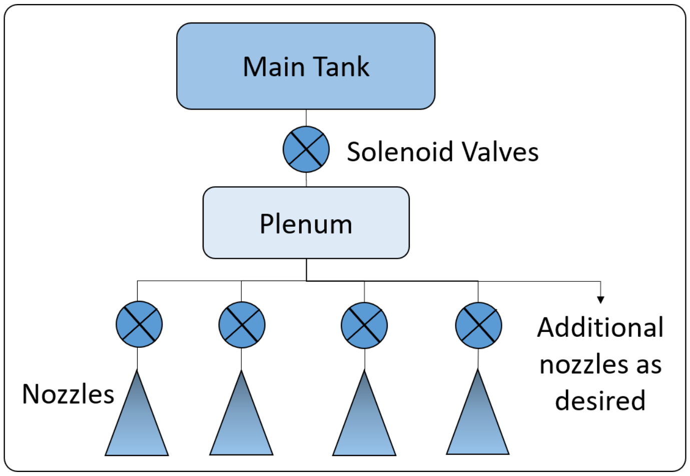

Figure 2: Example schematic of a cold gas propulsion system.

The system is equipped with temperature and pressure sensors to monitor the fluid conditions inside the tanks, and the valves are the sole controlled component used to “fire” these cold gas thrusters. A custom electronics suite and software handles all monitoring and telecommand so that the entire unit is an independent embedded system. The fluid used is the refrigerant R236fa, which is a two-phase fluid with a few distinct advantages behind its choice as the propellant. First, its vapor pressure at worst-case environmental temperature conditions is just below the maximum limit for secondary payloads on most launch providers. This allows the system to avoid many of the risks associated with carrying a classified pressure vessel as a secondary payload. All of these design choices come together to deliver a “capable, simple, and inexpensive cold-gas propulsion system that can be applied to many small satellite platforms.” [4]

Summarized in Figure 3 are several examples of cold gas propulsion systems developed by the Glenn Lightsey Research Group, with their specifications outlined in Table 1. The success of these former projects was a direct contributor to the award of the Lunar Flashlight contract, so it is essential to acknowledge the lineage of cold gas propulsion flight projects that has led up to the development of green monopropellant systems by this lab. In fact, some of the design decisions from previous cold gas projects have been adopted

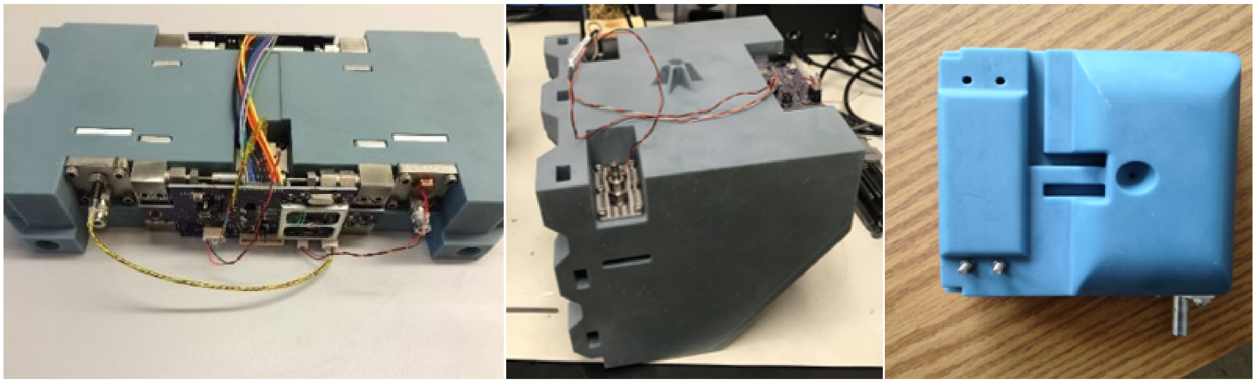

Figure 3: Former cold gas propulsion systems from the Glenn Lightsey Research Group. From left to right: BioSentinel, Prox-1, and Bevo-2. [4]

	BioSentinel	Prox-1	Bevo-2
Customer	NASA Ames	Georgia Tech	UT Austin
Delivery Year	2017	2015	2012
Total Mass	1.265 kg	6.000 kg	0.380 kg
Volume Envelope	4 x 21 x 11 cm	20 x 16 x 18 cm	10 x 9 x 4.4 cm
Total Impulse	36 N-s	998.9 N-s	48.9 N-s
Use Case	Attitude Control	Delta V	Delta V

Table 1: Comparison of the specifications and performance capability of the three aforementioned cold gas propulsion systems.

for use on green monopropellant systems as part of the Lunar Flashlight project, allowing the system to take full advantage of development efforts and lessons learned on these heritage systems.

2.2 Green Monopropellant Systems

The Lunar Flashlight Mission will be the Glenn Lightsey Research Group's first experience with monopropellant propulsion. Therefore, rather than discussing heritage projects and their established methodology, it is necessary to begin with a fundamental understanding of monopropellant propulsion as well as the desire to transition to "Green Monopropellant" systems. Much of the methodology around the design of the LFPS originated from intrinsic needs of monopropellant propulsion systems. Additionally, the one other mission that has successfully flown a green monopropellant propulsion system will be discussed for context in the design of these systems.

2.2.1 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 the decomposition. The decomposition itself is an exothermic reaction that releases chemical energy, resulting 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.[5] However, it is also notorious for being extremely toxic, carcinogenic, corrosive, flammable, and explosive.[6] As mentioned in NASA's identified key technologies, it is highly desirable to seek alternatives to hydrazine because it is such a dangerous and volatile chemical. Green monopropellants such as LMP-103S and AF-M315E are hydroxylammonium nitrate-based alternatives. In comparison to Hydrazine, green monopropellants most notable advantages include decreased toxicity and significantly safer storage and handling. In fact, their 'green' moniker originates from the fact that they are so much less toxic that they can be "[safely handled] in open containers for unlimited durations."[7] Green monopropellants also have been designed to improve on the performance of hydrazine as compared in Table 2 below.

In addition to design considerations for the propellant and the system safety, the Lunar Flashlight system included design consideration for fluid and thermal management. These are inherent elements of monopropellant systems that were first broached in the transition from previous cold gas projects to the Lunar

	Hydrazine	AF-M315E
Specific Gravity	1.01 [6]	1.46 [8]
Specific Impulse	190 s [9]	231 s [10]
Hazard Classification	8 [6]	1.4C [8]

Table 2: Comparison of three separate architectures within identical constraints on mass and volume.

Flashlight project. And, in continuing with additive manufacturing, material compatibility with the propellant demanded a switch from quasi-ceramic to metal structures. All together, these design considerations were major contributions to the growing GLRG methodology for designing monopropellant thrusters. They will all be covered in more detail in Section 5.

2.2.2 Similar Missions

There is only one prior instance of AF-M315E used as an in-space propulsion system: the Green Propellant Infusion Mission (GPIM). This mission was also managed by NASA Marshall, and included engineering efforts by Aerojet Rocketdyne and Ball Aerospace. Its primary objective was the technology demonstration of its AF-M315E propulsion system. This system carried five thrusters for orientation control and orbit maneuvering, which are seen in Figure 4. It launched on June 25th, 2019 as part of the STP-2 mission on a Falcon Heavy rocket in a Ball Aerospace SmallSat platform.[11] A week later, it reported successful firing of all five of its thrusters as part of system checkouts and an orbit lowering maneuver. [12]

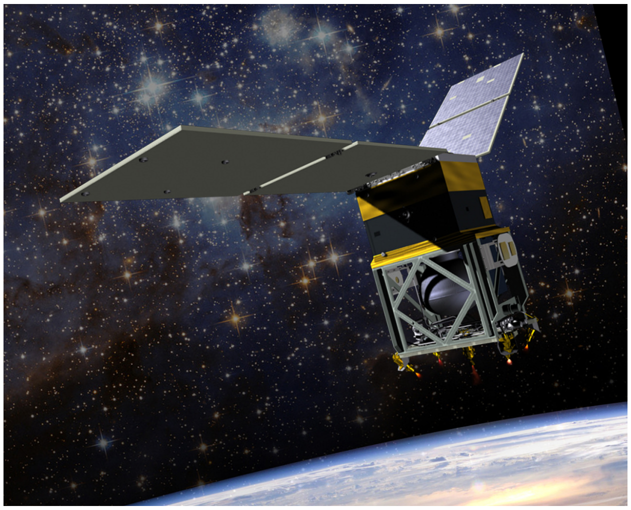

Figure 4: Concept artwork of the GPIM Mission. [13]

3 Lunar Flashlight Mission

The Lunar Flashlight mission is a 6U Cubesat that aims to investigate the poles of the Moon for volatiles including water ice. 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. It will be a technology demonstration of green monopropellant propulsion, and will contain all supporting hardware such that the entire subsystem is a functional standalone component.

The NASA Jet Propulsion Laboratory is responsible for the full mission, and the NASA Marshall Space Flight Center was contracted for the provision of the propulsion system. Georgia Tech's involvement is in collaboration with NASA Marshall over the design, manufacturing, test, and delivery of the full Lunar Flashlight Propulsion System flight hardware.

3.1 Project Context

At the award of Georgia Tech's contract in June of 2019, the Lunar Flashlight Propulsion System had already been under work by a previous contractor. From this original design, the Lunar Flashlight Propulsion System intended to use the LMP-103S green monopropellant in a blow-down pressurization system. Additionally, due to the maturation of the design of the rest of the spacecraft around this first design, the system ICD held

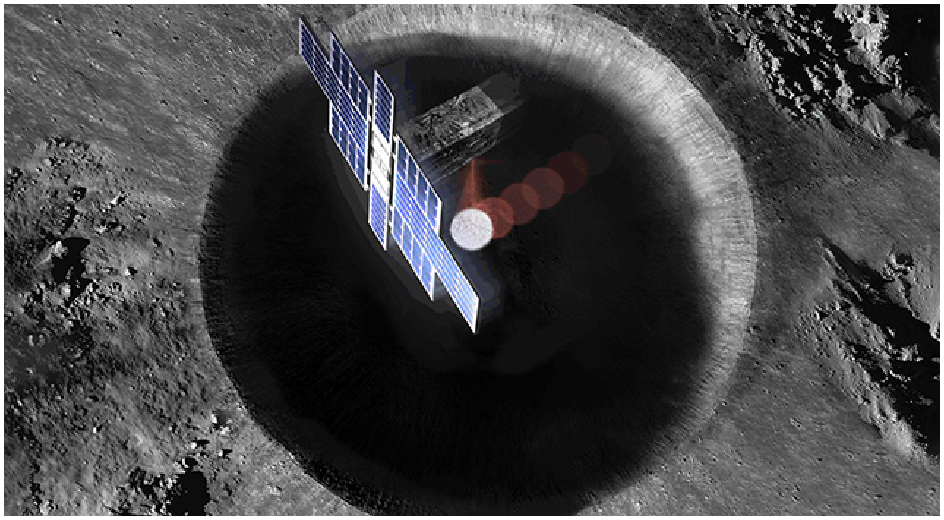

Figure 5: Concept artwork of the Lunar Flashlight Mission. [1]

strict mechanical and electrical interfacing requirements in order to perfectly match the previous contractor's system. However, after the change in contracts, the acquisition of major components such as the valves, pumps, and thrusters was moved under the responsibility of NASA Marshall. One exception to this was the ownership of the electronics design, which was put under parallel-path development effort by both NASA Marshall and Georgia Tech.

In July of 2019, the system design underwent a major rework decision by MSFC to switch to the AF-M315E green monopropellant in a pump-fed pressurization system. Then, following the conclusion of the Preliminary Design Review in September of 2019, the dual-path controller effort ruled in favor of the Georgia Tech effort, which held a significantly smaller volume envelope and could adapt to drive the new components included in the pump-fed pressurization system. These changes are important for context around the design of the LFPS since the Georgia Tech solution was simultaneously constrained to the expectations of the previous system while being asked to incorporate a vastly differently architecture and suite of components from the original design.

3.2 Objectives

The main objective of the Lunar Flashlight Propulsion System project is to provide a functioning and flight-worthy green monopropellant propulsion system for use on the Lunar Flashlight Mission. It will be responsible for attitude control and momentum dumping maneuvers during flight, as well as orbit-adjusting delta-V maneuvers in order to achieve the mission's desired science orbit. All the constraints of the Interface Control Document (ICD) shall be met, along with all requirements levied by NASA Marshall. The system shall be treated with all the rigor of a space-faring hardware project, with formal NASA design reviews throughout the design process and full campaigns of analysis, testing, and quality assurance to follow.

As of December 2019, the LFPS design has successfully passed its Table Top Review, its Preliminary Design Review, and its Manufacturing Readiness Review. It is on track to enter its Critical Design Review in January of 2020, currently showing all requirements completed and all margins positive. The manufacturing, integration, and testing plans have been laid out in preparation of work to be completed in spring and summer of 2020, to begin immediately after the conclusion of the Critical Design Review.

3.3 Contributions to the Field

Upon the successful completion of this mission, Lunar Flashlight would become the first CubeSat to reach the Moon and the first CubeSat to achieve orbit around a celestial body other than the Earth. Both of these accomplishments are directly dependent on the contribution of the propulsion system. Additionally, the propulsion system design includes several technology demonstrations that will directly gain flight heritage from this mission. The microvalves, micropump, and PPI 100 mN thrusters will be on their first flight, hoping to increase their TRL from 6 to 9. The inclusion of additive manufacturing in the flight hardware's main structure and Propellant Management Device will be unprecedented design decisions, each contributing to the various use cases of additively manufactured materials in space. Finally, this will be the first demonstration of green monopropellant propulsion on a CubeSat platform, making major strides in increasing the accessibility of space via small satellite platforms.

4 Lunar Flashlight Propulsion System Design

The Lunar Flashlight Propulsion System is a Green Monopropellant Propulsion system that uses pump-fed pressurization and the AF-M315E propellant.[1] It occupies approximately 2 x 1 x 1.5 U within the Lunar Flashlight's total 6U (where 1U is equivalent to 10cm), with strict specifications on the mechanical and electrical interfacing to the rest of the spacecraft. The three most major requirements for the LFPS are shown in Table 3. In addition to these design metrics, the project also holds to additional requirements on expected environmental loads, interfacing needs, quality standards, and more.

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

Table 3: Requirements for the Lunar Flashlight Propulsion System design.

Developed in response to the Lunar Flashlight Project's requirements, Figure 6 shows all functional elements included in the LFPS system shown in the style of a piping and instrumentation diagram (P&ID). This schematic addresses many elements of the system-level propulsion design, as it includes the pump and relief circuit, all sensor locations, and valve responsibilities for 1) bulk propellant isolation within the tank and 2) controlled propellant feed to the thrusters. However, unlike a traditional propulsion system, the majority of the "piping" within this P&ID is captured within the continuous structure of the manifold piece.

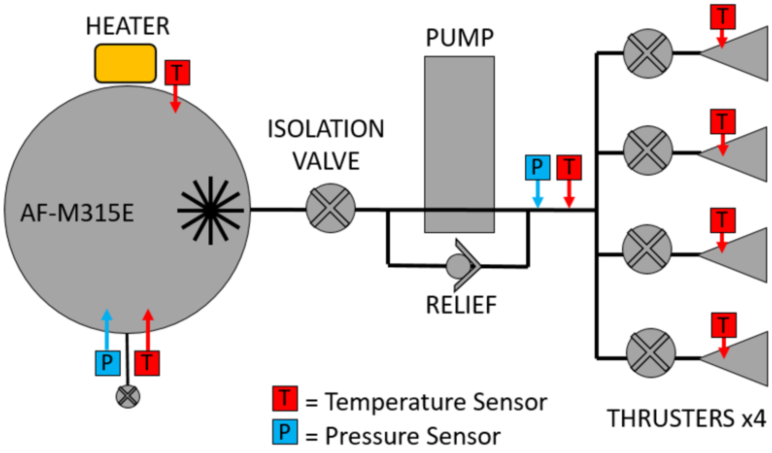

Figure 6: P&ID Schematic for the Lunar Flashlight Propulsion System.

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[1] It is necessary to note that many details of the design have been withheld by discretion, preventing a fully complete story of the development of the Lunar Flashlight Propulsion System design solution. Instead, the discussion will focus on conceptual aspects of the design, leaving the comprehensive design under protection of the project.

The design of the full Lunar Flashlight Propulsion System in its most current revision is represented below in Figure 7. The design solution includes a titanium structure that is split between the tank subassembly and the manifold subassembly. Notably, the manifold structure leverages the use of DMLS additive manufacturing and takes much of its design inspiration from its antecedent cold gas systems mentioned in Section 2.1.

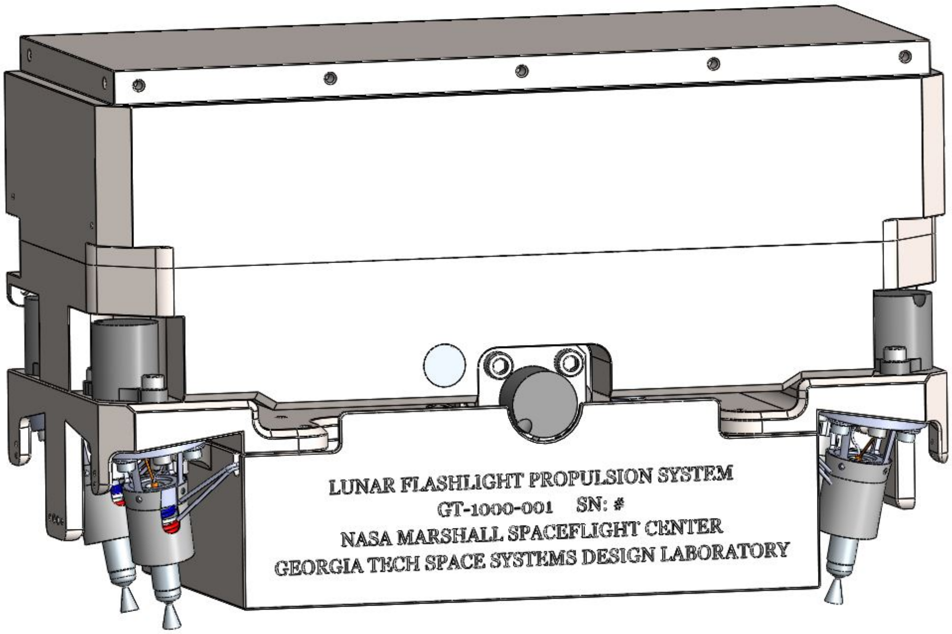

Figure 7: Revision 10 model of the full Lunar Flashlight Propulsion System.

Finally, before the system design is broken down into discussion on its function in propulsion, structure, and avionics, the next page shows the full part tree of components that are included in the design. This also serves as the product breakdown structure of the LFPS assembly.

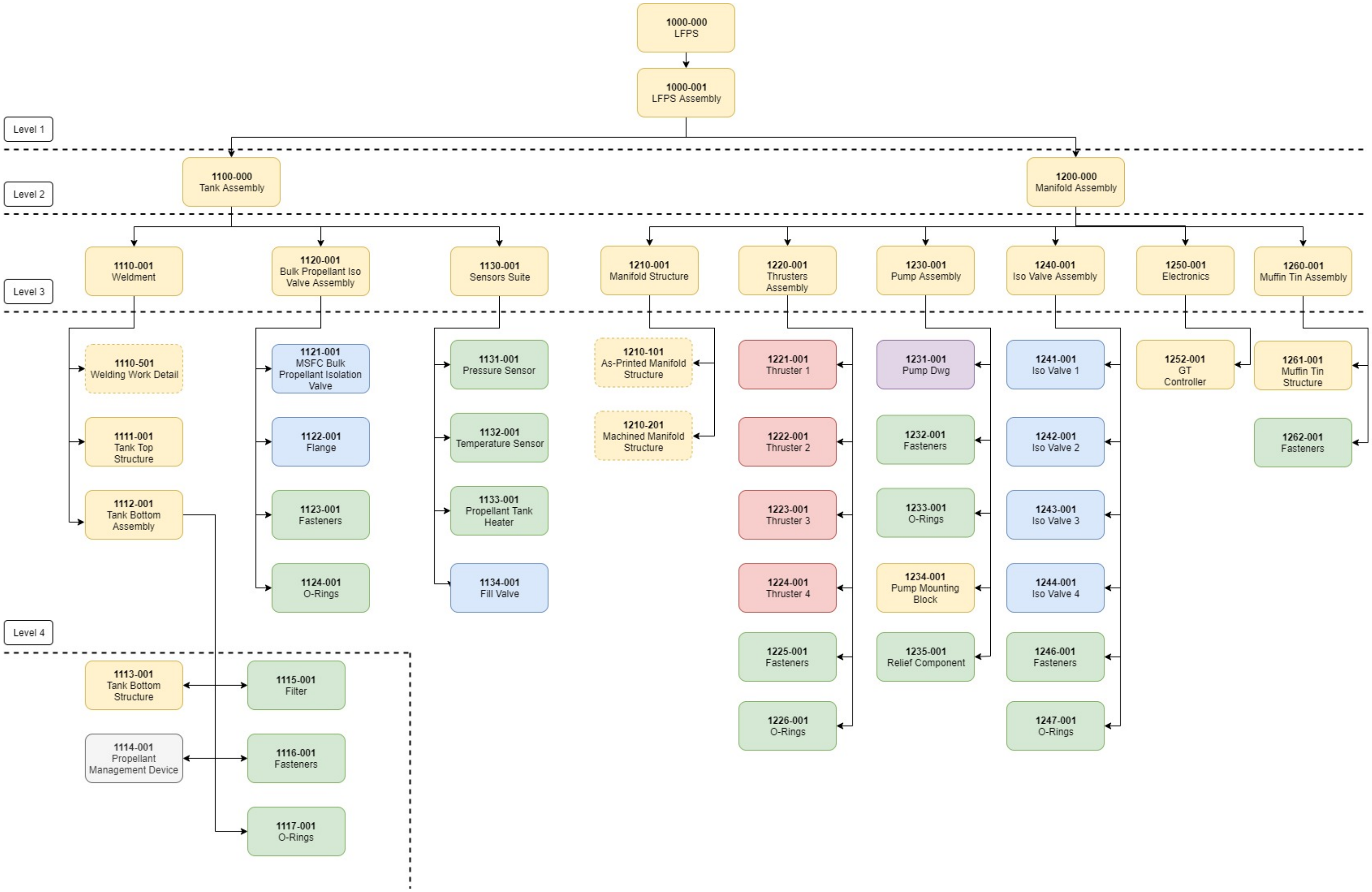

Figure 8: Part tree of drawings included in the LFPS Assembly. Yellow blocks designate Georgia Tech owned components and assemblies, blue blocks designate NASA Marshall ownership, and the remaining colors are grouped by their respective vendors.

4.1 Propulsion

As mentioned already, the LFPS uses a pump-fed monopropellant system. The inclusion of the pump allows the propellant to be stored at low pressures in the tank before being fed into the thruster interface at the much higher required pressures.

Aside from the use of the AF-M315E propellant, the next most critical requirement in the scope of the system's propulsion is the required total impulse. As seen in equation 1 below, the total impulse of the system is directly a function of total propellant mass and the specific impulse of the thruster and propellant.

$$I_{tot} = gI_{sp}m_{prop} \tag{1}$$

For this mission, total impulse was the benchmark for performance. Therefore, wherever room for optimization could be afforded, it was made to raise the total impulse that the system could offer.

4.1.1 System Architecture Trade Study

As discussed earlier, green monopropellants are capable of providing more performance than cold gas propellants. However, as a full system, monopropellant systems require more supporting components and sophisticated system design. This provides challenges at a small scale, and implies that there is a limit to their scalability that must be considered when designing propulsion systems for small satellites.

An early trade study on the Lunar Flashlight Propulsion System ran a comparison between pressure-fed LMP-103S, and pump-fed AF-M315E, and cold gas R236fa, all within the same allotted volume and mass requirements. Each was designed to a rudimentary but fully functional state, with the proposed designs shown in Figure 9 and their associated performance metrics shown in Table 4. All supporting components and their required mass and volume were taken into consideration in these designs, thereby accounting for their differences in complexity from a purely mechanical standpoint.

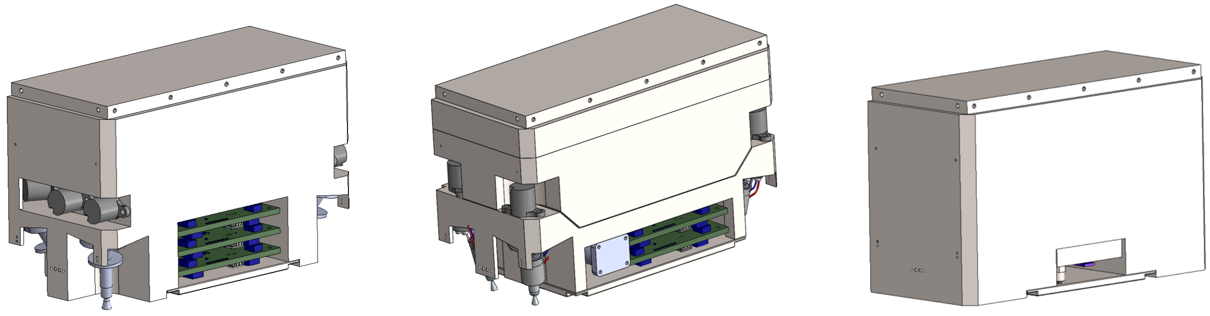

Figure 9: Designs of the three system architectures explored in the trade study. At left is the pressure-fed LMP-103S system, at middle is an early revision (Version 4) of the pump-fed AF-M315E system, and at right is the cold gas R236fa system.

As mentioned briefly in the Project Context, following the presentation of this trade study at the TTR in July of 2019, NASA Marshall led a recommendation to change the system from its original pressure-fed LMP-103S system to the new pump-fed AF-M315E system. This would be a major overhaul in design, requiring considerations for a new propellant, new supporting components, and an entirely different propulsion system architecture. However, as the project progressed under the new design, it became very apparent that this solution indeed had the highest probability of success. Architectural changes trickled down into simplifying safety requirements, required component procurement lead times converged into a favorable schedule, and the design space between various competing requirements was able to close with all positive margins. Furthermore, the trade study also accurately predicted some of the difficulties with this approach, as the project would go on to receive an increase in mass budget in order to meet its performance requirements within the required volume.

	Pressure-Fed LMP-103S	Pump-Fed AF-M315E	Cold Gas R236fa	
Propellant Volume	1463	1562	2500	cc
Pressurant Volume	220	–	–	cc
Dry Mass	2752	3238	1260	g
Propellant Mass	1814	2296	3175	g
Auxiliary Component Mass	900	1360	650	g
Total Wet Mass	5466	6894	4206	g
Total Impulse Estimate	>3000	>3000	1713	g
Most Difficult “Constraint to Beat”	Volume	Mass	Performance	–

Table 4: Comparison of three separate architectures within identical constraints on mass and volume.

4.2 Structure

The primary structure of the Lunar Flashlight Propulsion System consists of two major structural elements: the tank and the manifold. Each will be discussed for their separate design requirements, as they have very different responsibilities within the overall system.

4.2.1 Tank Subassembly

The primary responsibility of the LFPS tank is to store the propellant through launch and during operation of the spacecraft. It will contain the AF-M315E propellant and a Nitrogen ullage, as well as all components related to propellant filling, monitoring, and control. Its design was largely driven by strength and deformation requirements under static pressure loading.

The current design is a Titanium 6Al-4V (Grade 5) machined piece, joined by a 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 zero-gravity fluid management. On its exterior are mounting locations for the tank to manifold joint, as well as for the spacecraft to the propulsion system. Figure 10 shows the current revision of the design.

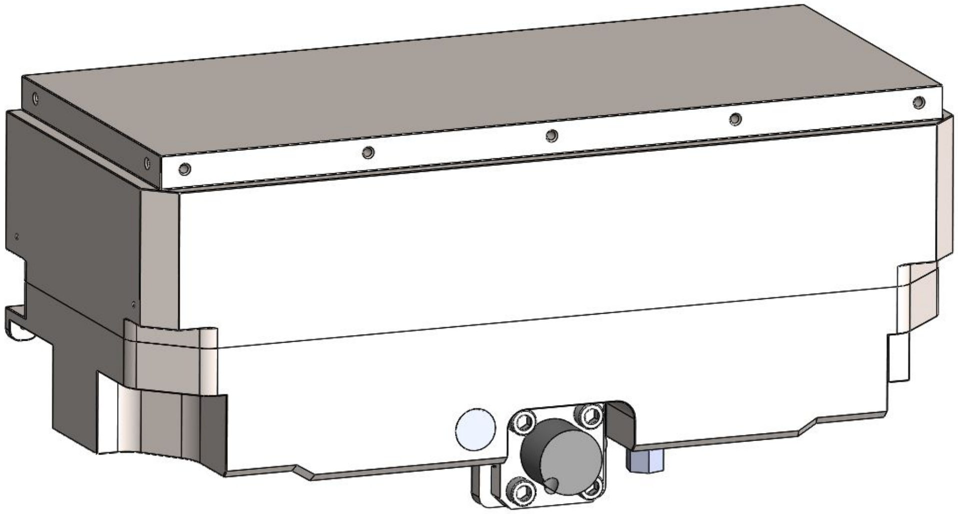

Figure 10: Current revision of the tank subassembly.

One unique aspect of the tank is its shape. Very rarely are propellant tanks designed to such a prismatic shape, since cylindrical and spherical tanks offer significantly better better volume efficiency and strength when loaded with internal pressures. However, the CubeSat platform uses a very boxy unit-wise design, and its strictest constraint is often volume. Thus, to maximize our performance and meet our requirements, it was most appropriate to utilize a rectangular volume allotment for our propellant tanks, despite it being an unconventional decision. As a design solution, the tanks include arched structural reinforcements, similar to the style of beams on a vaulted ceiling or supports on a barrel. These take over the majority of pressure stress loading, distributing it along the curvature of the ribs in ways that the concave corners of the structure would otherwise concentrate and fail. They also provide stiffness against deformation from pressure loads by dividing up large unsupported faces. The analysis below shows a simplified model of the tank passing its Maximum Design Pressure (MDP) case for deformation:

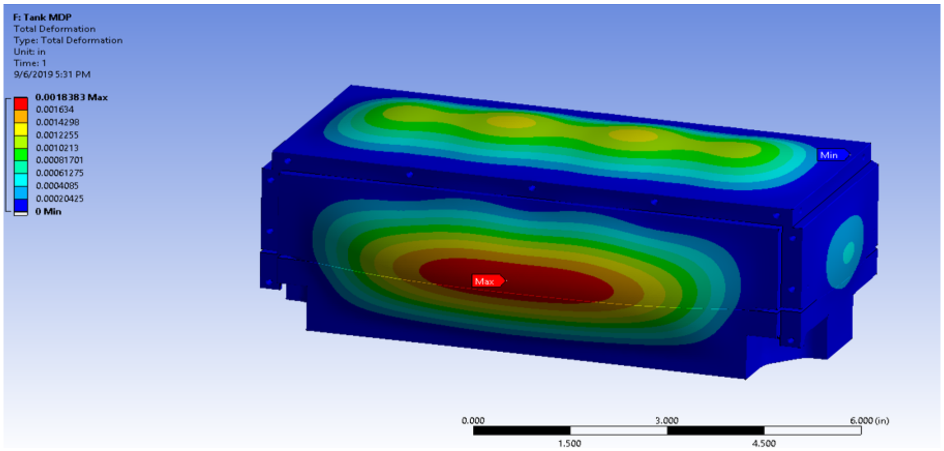

Figure 11: Deformation results from the FEA analysis of the tank, loaded to MDP values.

4.2.2 Manifold Subassembly

In addition to the tanks, the LFPS includes a manifold structure that houses all of the valves and fluid passages that one might typically associate with a monopropellant engine. The manifold is responsible for all fluid handling downstream of the tank and its isolation valve. It incorporates interfaces to the tank, all four thrusters, the four thruster valves, and the pump and relief circuitry. Internally, it contains all fluid passages that route between these components. In addition, it structurally supports the avionics stack as well as the system's cover and radiation shield (nicknamed the "Muffin Tin").

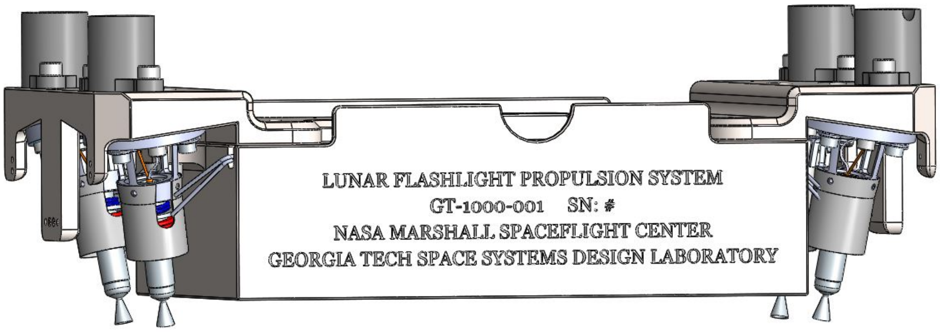

Figure 12: Current revision of the manifold subassembly.

For a functionally equivalent system, a design for traditional machining would require significant craftsmanship, as special equipment would be needed to plunge the minuscule flow passages and several welding steps would be required. Alternatively, using tubing and connectors would require upwards of 40 separate non-standard components, vastly increasing mass and complexity. DMLS allows the structure to include structural supports and fluid passages that would otherwise be impossible to machine, while simultaneously simplifying part count and avoiding welds altogether. The design effort itself is simplified by organically routing fluid channels without machining limitations and giving total flexibility to the placement of components. It also provides the most efficient packaging of the fluid system in terns of mass and volume.

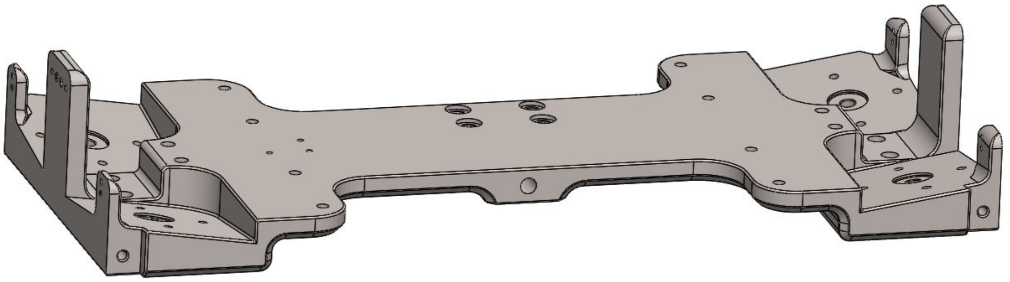

Figure 13: Manifold structure shown alone without any interfacing components (orientation rotated 180° from Figure 12 above).

As stated before, the manifold's primary function is fluid control. So, despite the complexity of the part and all of its components, the manifold design can be simplified into two essential design criteria. Both regard the internal fluid passages, as they enable the most critical responsibilities within the structure.

Firstly, the fluid passages should be analyzed to characterize the pressure losses that it incurs. For small satellite propulsion systems, tube diameters are often on the order of millimeters if not smaller, though they also only require a very small flow rate. Thus, Poiseuille's law for pressure losses of an incompressible laminar flow in a pipe is shown as follows [14]:

$$P_1 - P_2 = \frac{f \rho L V^2}{2D} \tag{2}$$

using variables as defined below:

$$\begin{aligned} f &= \frac{64}{Re} \\ Re &= \frac{\rho V D}{\mu} \\ V &= \frac{Q}{A} \\ A &= \frac{\pi D^2}{4} \end{aligned} \tag{3}$$

which leads to

$$P_1 - P_2 = \frac{128 \mu L Q}{\pi D^4} \tag{4}$$

In these equations, f is the Darcy-Weisbach friction factor for laminar flow in a circular cross-section pipe, Re is the Reynolds number, Q is the volumetric flow rate, ρ is the density, μ is the dynamic viscosity, and finally L, D, and A are the length, diameter, and area respectively of the circular pipe. With these equations estimating the fluid flow, it was possible to ensure that the manifold satisfied its requirement for feed pressure and flow rate into the thrusters.

Secondly, and similar to the tank, the manifold must be able to survive loading from internal static pressure under worst-case environmental conditions. The internal passages were designed to satisfy pressure loading according to the thick-walled pressure vessel circumferential stress equations:

$$\sigma_c = \frac{(p_i r_i^2 - p_o r_o^2)}{(r_o^2 - r_i^2)} - \frac{r_i^2 r_o^2 (p_o - p_i)}{(r_2(r_o^2 - r_i^2))} \tag{5}$$

where σ_c is the circumferential stress, p indicates pressure, r indicates radius, and the o and i designate outer and inner faces of the vessel respectively. With this providing a minimum bound on the wall thickness of the tubing, the fluid passages could otherwise be placed freely within the manifold structure with assurance that the strength requirements would be met under pressure loads. Note that this equation does not take into account any stress due to constrained thermal expansion of the fluid – comments on design for thermal considerations will be covered in the next section. In practice, safety factors were applied to cover for unaccounted loading scenarios.

Following the completion of the design of the manifold, a Finite Element Analysis (FEA) did in fact show positive margins for stress and deformation through the part when subjected to its MDP:

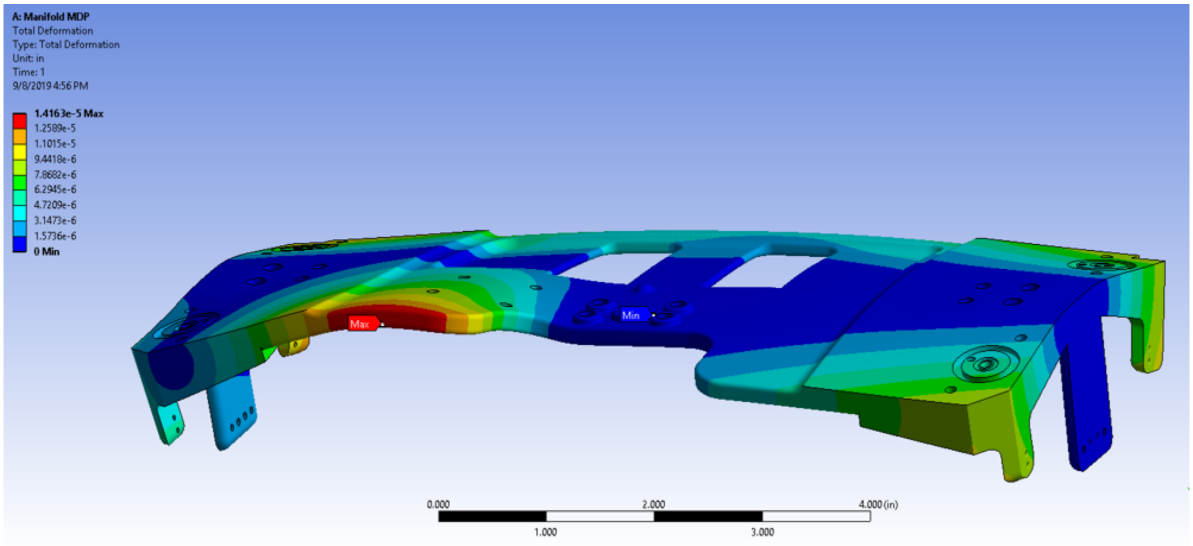

Figure 14: Deformation results from the FEA analysis of the manifold, loaded to MDP values.

Finally, the manifold's various interfaces and complex geometry led to several other design considerations, ranging from self-induced thermal loads, additively manufactured material properties, and control over pressure mechanisms on a closed system. These will be addressed more generally in the next section covering some of the more advanced topics within the LFPS design.

4.3 Avionics

The Lunar Flashlight Propulsion System includes a custom designed controller that is responsible for monitoring system sensors, controlling valves, pumps, and thrusters, and handling all communication to and from the spacecraft. As on previous cold gas thrusters, the intention of this controller is to allow the propulsion unit to function as a fully independent subsystem within the spacecraft.

When the project was passed from its previous contractor to Georgia Tech in June 2019, the controller responsibility was considered a dual-path effort, with Georgia Tech and NASA Marshall each independently working on systems that could interchangeably "drop in" with the rest of the system. Georgia Tech would custom design a system from the ground up, and NASA Marshall would adapt the former system's electronics to be compatible with the new system. However, changes to the schematic and revisions on the design ultimately prompted the Lunar Flashlight project to favor the custom electronics by Georgia Tech, which was officially decided in September of 2019.

Similar to the design of the structure, the electronics are being designed within strict interfacing requirements because of the evolution of the project. They must emulate many aspects of the design (such as connector hardware and telecommand formats) while adapting to requirements of a very different system (such as driving the pump and having a new microcontroller). The current design allots volume for approximately two standard CubeSat boards (10 x 10 cm), and will be included in the manifold subassembly where it is shielded from radiation under the "Muffin Tin" cover. Ultimately, the design of the controller is considered to be an entire project in and of itself, and is well beyond the scope of the design of the propulsion and structure.

5 Methodology

Through the design of the Lunar Flashlight Propulsion System, several challenges were faced that were unique to this type of system and the technologies that it includes. As a result, new design considerations were learned as part of the LFPS project that were noteworthy advancements beyond previous experience in cold gas propulsion.

5.1 Design for AF-M315E

Firstly, and perhaps obviously, the design of a monopropellant system must accommodate all requirements for the successful storage and control of the propellant.

Material choices for compatibility with AF-M315E involves consideration to both metals and soft goods. As a acidic ionic liquid, it is mildly corrosive. Also, it may experience decomposition following "prolonged contact with certain metals (iron, nickel, copper, and other transition metals)." [8] This drove the design of the LFPS towards a titanium structure with stainless steel for all wetted components, since both these metals were known to be compatible in long-term storage and considering the integrity of both the metal and the propellant.

The viscosity of AF-M315E is heavily dependent on its temperature, though the its exact properties are export controlled. In essence, it requires the propulsion system to include careful thermal monitoring and active control. The viscosity of the fluid is of particular importance for the design of the manifold passages and the control of the pump. However, at its lower bounds, the propellant does not run the risk of freezing, instead experiencing 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.

5.2 Design for Thermal Environments

To continue discussing the importance of thermal control on this system, the thermal loads and self-induced heating within monopropellant systems are very important design considerations. The thermal requirements on this system gave standard bounds on environmental and operational temperature ranges. Additionally, the system includes heaters that provide active thermal control.

Unlike cold gas, the exothermic extraction of chemical energy from the propellant causes extreme temperatures to be experienced in the decomposition chambers of the thrusters. This causes significant conductive heat transfer into the structure that interfaces with the thrusters, as well as radiative heating on nearby exposed faces. Another location of self-heating comes the operational case of running the pump and simultaneously relieving fluid pressure from downstream to upstream of the pump. A purely adiabatic model would show infinite runaway temperatures over time because the energy being input into the fluid has no method of heat loss or work output. Therefore the model must add considerations for heat transfer in order to correctly model the pump.

Additionally, since monopropellant systems require metal components throughout, the structure itself requires analysis for its conductive and radiative heat transfer. Thermal gradients across mechanical joints

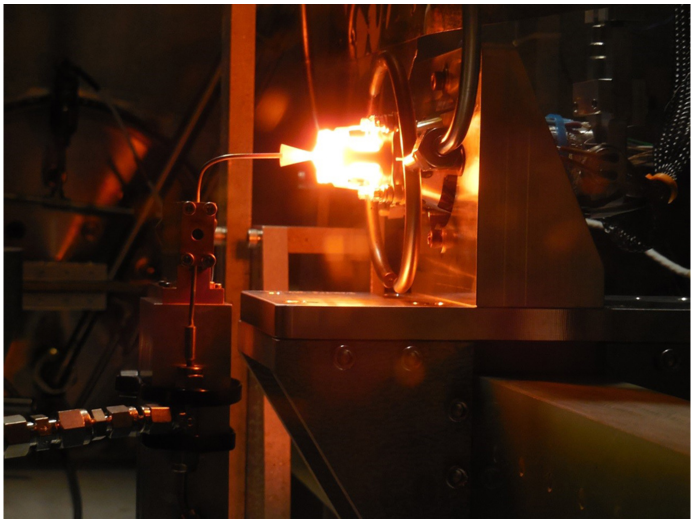

Figure 15: Test fire of an AF-M315E thruster for the GPIM mission, demonstrating significant self-induced thermal loads. [15]

can compromise structural integrity and fluid seals. And, as mentioned in the previous section, conductive heat transfer from the structure to the propellant has a considerable impact on the fluid's viscosity.

In summary, the major thermal loads considered in the design of the LFPS included:

- Environmental thermal loading
- Controlled heating of the fluid
- Conductivity from the thrusters when firing
- Radiation from the thrusters when firing
- Work input on the fluid by the pump

Conductive heat transfer, as in the case of the thruster's heat input to the manifold and the heater's heat input to the tank fluid, can be simplified to Fourier's Law, which states that:

$$q = \frac{kAdT}{t} \tag{6}$$

In Fourier's Law, q is the heat transfer, k is the thermal conductivity of the material, t is the material thickness, A is the area, and dT is the temperature difference across the piece. For radiative heat transfer, the conservative assumption treats any surrounding structure as a black body and uses the Stefan-Boltzmann Law where:

$$q = \sigma T^4 A \tag{7}$$

Here, q is again heat transfer, σ is the Stefan-Boltzmann constant, T is the absolute temperature, and A is the emitting area. Finally, for a simple estimate of the thermal impact of the pump, the fluid was treated as steady flow through an adiabatic closed volume with a work input, finding fluid temperature solely through enthalpy. A transitive thermal simulation that fully models heat transfer through these components is still in work for the project, but the fundamental theory can be further simplified using worst case operational values to remove the time dependence. For example, the thruster radiation estimate was made by assuming constant firing for the longest estimated maneuver, which allows maximum expected temperature of surrounding parts to be solved directly from the total heat flux.

Thermal inputs to the fluid are important to track because in certain operational cases, the fluid may experience thermal expansion while constrained to a fixed volume. Similar to an engine experiencing hydraulic lock, this can be an extremely destructive failure scenario since liquids give very little to compressibility and instead dump all their pressure onto their container. Therefore, thermal loading is a critically important case when analyzing the manifold for stress. As mentioned in Section 4.2.2, the structural strength of the manifold must be designed to consider these thermal inputs in order to ensure that it survives all operational scenarios. Additionally, thermal analysis is necessary because the system is capable of incorporating passive strategies for cooling. Since the manifold is additively manufactured, it is relatively simple to provide additional lengths of tubing run-out between components. This increases surface area so that excessive heat may be conducted back into cooler parts of the structure.

5.3 Design for Fluid Control

On previous projects with cold-gas systems, the use of a two-phase fluid simplified several of the challenges when desigining in-space propulsion systems. In contrast, since AF-M315E exists as a liquid with very little vapor pressure at normal operating temperatures, it becomes necessary to consider zero-gravity fluid management and ullage pressurization mediums. [8]

In the tanks, the inclusion of a propellant management device was necessary to handle the liquid propellant once in zero-gravity. Common methods for positive expulsion include piston, elastomeric diaphragm, or balloon designs, though these require soft goods and actuated components that can be difficult to resolve with AF-M315E material compatibility requirements. [16] Instead, a passive method leverages capillary action through the addition of veins, screens, and/or sponge structures inside the tank. The Lunar Flashlight Propulsion system used this style of PMD, which was provided for the project after being custom designed to the properties of AF-M315E by a specialist in this field.

An analysis was performed early in the design process to determine acceptable fill percentages of ullage and propellant. System requirements included constraints on volume, mass, performance, and feed pressure to components, all of which directly compete with each other for determining the tank fill.

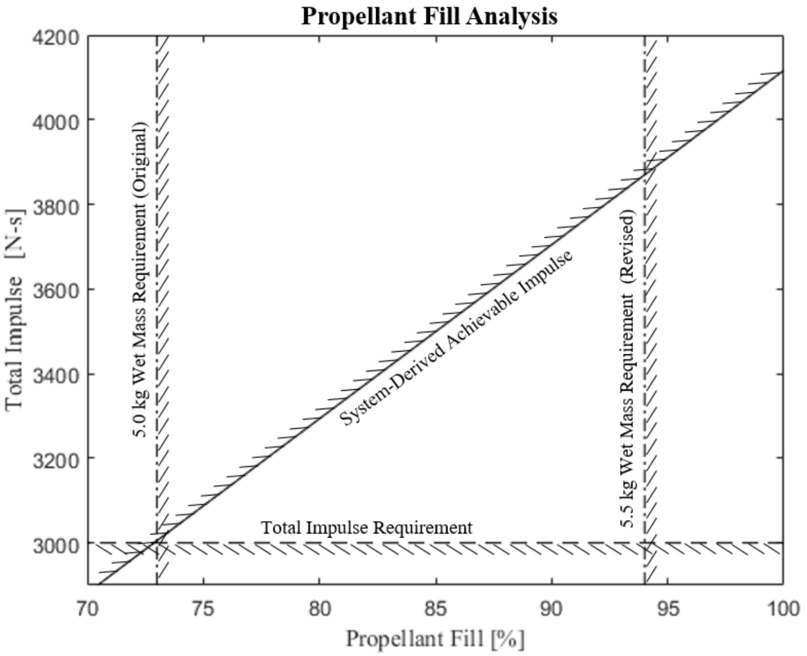

Figure 16: Analysis of propellant fill as a trade between mass and performance requirements constrained by the achievable impulse. Contour lines are shown with hashmarks indicating no-go regions.

The initial results of the study are shown in Figure 16. This study conservatively assumed worst case environmental conditions, and required that ullage pressurization never exceed the 100psi limit to become classified 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 a series of ideal gas law calculations. Under the original requirements, the analysis found the acceptable range of propellant fill to require a precision of .1%, or approximately 100mL. The competing constraints were the minimum total impulse performance requirement, which increases linearly with propellant mass, versus the maximum wet mass of the system, which prefers ullage for its lesser density. After presenting this at the PDR, and with support of the NASA Marshall team, the LFPS wet mass budget was increased by 0.5 kilograms. This resolved any potential issue with the results of the ullage trade study, and provided significant margin for the rest of the design of the system.

5.4 Design for Additive Manufacturing

Direct metal laser sintering is a form of additively 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. DMLS prints have a minimum feature size of .006", and are most commonly seen for Stainless Steel, Nickel alloys, Aluminum, and Titanium material choices[17]. To create a model that can be successfully additively manufactured, there are a few rules of thumb that should be considered.

1. Firstly, the laser sintering process creates thermal gradients during printing. Over sharp concave corners, these 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 17 below.
2. Secondly, internal cavities must have a clear route for removing any remaining 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. In similar comment to the thermal gradients, any powder left in contact with surface areas retaining significant heat may partially fuse into the main structure. 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.

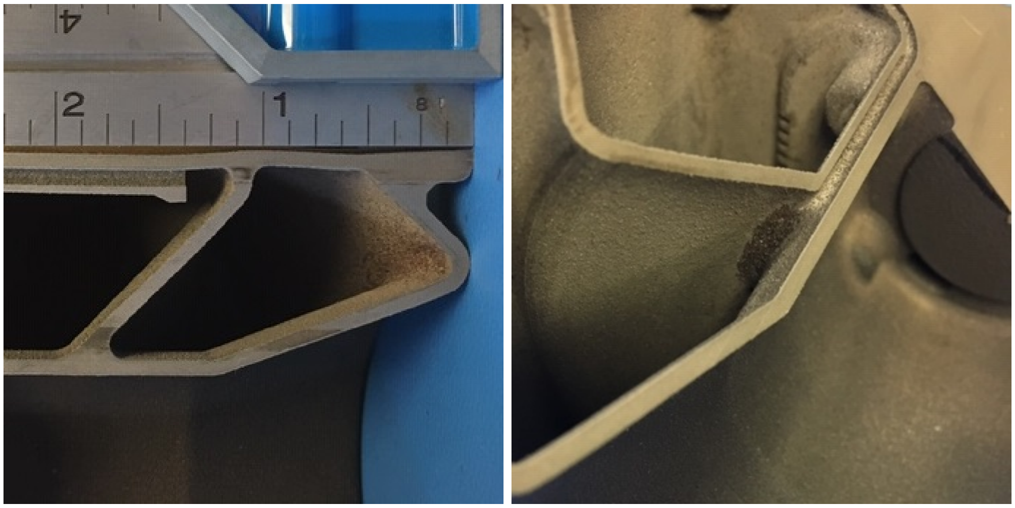

Figure 17: Examples of part abnormalities during DMLS printing. At left is an example of warping through a wall intended to be completely flat. At right is an example of residual powder fused into thick convex features, where the dark coloring and increased surface roughness in the corner indicates this phenomenon.

3. 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.

4. Fourth, the material properties of DMLS 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 on can give the designer control over how the material strength axes align with the major axes of the part. One may wish to take this into account if designing a piece that is particularly sensitive to strength. The layer-based macroscopic material properties also impact surface finish, and so it may be desirable to bias certain features "with" versus "against" the grain of the layer-by-layer build. As a mitigation, and as performed on the LFPS project, it is often recommended to include material testing samples on the print bed while manufacturing the part. This allows analyses to be reinforced with experimentally validated material properties, and can help identify any abnormalities that may have occurred during the print.

While this is not an exhaustive list, these are several of the major considerations to be made when designing a DMLS part. All four of these considerations were leveraged on the Lunar Flashlight Project, and would be recommended as guidelines to have in mind when creating additively manufactured metal parts.

5.5 Design for Safety Control

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. Early on in the project, the tank design raised concerns about fracture criticality, especially 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 effort to clear it by fracture control. However, when the design matured to a pump-fed system, the need for stored pressure was thereby eliminated and the pressure vessel designation no longer applied.

One key take away from these initial concerns about fracture control was that the use of additive manufacturing would be extremely disadvantageous in fracture control. This is due to the naturally striated macro-structure of layer-by-layer printed materials, which may be considered microfractures and would require extensive material testing to receive approval from the 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 now necessary 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 and concentric o-rings on all seals to protect from breaches. However, the LFPS project used several strategies to buy down these risks and reduce this complexity related to leakage. Firstly, the propellant's own high viscosity at its designed low storage pressure decreased its likelihood to leak through small gaps. It also has practically no vapor pressure, and thus "[would] not self-pressurize or evaporate through small fissures."[18] Also, with the tank and its auxiliary components as the only wetted parts during launch, it was possible to isolate these requirements to only the tank subassembly. This allowed the redundancy and sealing requirements in the manifold to be driven only by mission needs as opposed to launch vehicle safety boards.

It is important to note that the rigor placed on the safety control for the LFPS system was a direct derivative of having SLS as the launch provider. For example, the Lunar Flashlight system made efforts to treat the AF-M315E propellant as a catastrophically hazardous fluid. In comparison, the GPIM mission mentioned in Section 2.2.2 successfully claimed that "leakage of AF-M315E is rated as a critical rather than catastrophic failure," allowing it significant advantages in requirements of fault tolerance and fracture control. [7] However, the more conservative posture was decided to be the best way to manage risk as a secondary payload to the SLS rocket's first launch.

6 Continued Development on Monopropellant Systems

6.1 On Lunar Flashlight

To continue progress towards the flight hardware delivery to the Lunar Flashlight Mission, the LFPS design will progress through manufacturing, integration, and testing in spring of 2020. Since successful completion of the MRR in November 2019, the Lunar Flashlight project has begun acquisition of the Pathfinder, an initial unit meant to validate the manufacturing process. Subsequent units will be manufactured for the Flight Unit, the Spare Unit, and the destructive test unit, all of which will be identical in design, process, and quality standard.

The project calls for various testing steps on the system's hardware. Throughout the manufacturing process, non-destructive evaluation (NDE) will be required after each machining step, as well as after the weld. Material coupons will be included in the print of the additively manufactured part, and will be used to verify material properties used in analysis. The system hardware test plan includes leak testing, pressure testing, and inspections. Finally, the test plan includes destructive burst testing, where the system will be pressurized until failure. Remaining environmental testing, thruster firing, and all performance characterization will be under the responsibility of NASA Marshall following the project's hardware delivery.

6.2 On Future Missions

On future missions, if the mission's launch provider allows for additively manufactured materials, it would be suggested to manufacture the entire structure out of one continuous piece. This would save on mass, manufacturing timeline, test campaign, and integration effort since the primary structure would be simplified into a single piece. This could also provide more flexibility to improve the layout of the structure, for example, allowing for more unconventional arrangements that could improve heat transfer paths. Another possible improvement would be to include an extrude honing step during manufacturing to refine the manifold's passageways. Extrude honing improves the surface finish on interior features, which would guarantee that additively manufactured cavities were completely clear of any structural support or residual powder. While not deemed necessary on the Lunar Flashlight system, this could improve system efficiency by reducing friction pressure losses.

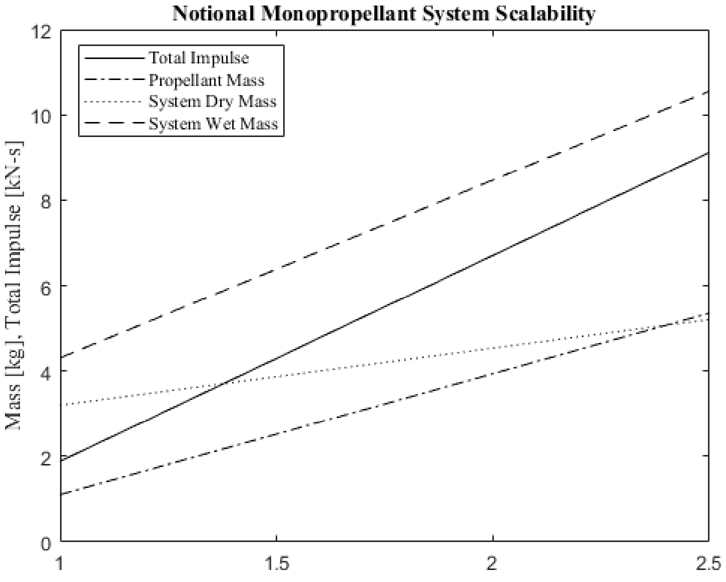

Figure 18: Plot approximating relationship between performance and major system metrics when matched with standardized CubeSat allocations. This assumes that one face of the system is 2U x 1U in order to mate with the existing LFPS manifold subassembly, with tank heights adjusted to fill any remaining volume.

Finally, the design of the Lunar Flashlight Propulsion System has been designed to allow some amount of adaptability for future missions. The manifold sub-assembly contains all necessary components downstream of the tank and fits within a standard 1x2U span. Minor changes to the thruster placement can be handled as small revisions to the manifold piece as well; since it is additively manufactured, is a relatively simple part to revise. Using an identical manifold sub-assembly, future systems could have a fully functionally propulsion unit with total freedom to adjust the tank volume to their mission's volume and performance needs. In Figure 18 , performance metrics are given of identical systems with tanks scaled to meet different standard CubeSat volume allocations. These values were found by adjusting dimensions on the LFPS design, and the performance metrics were calculated identically to what was shown in Section 4.1. Key assumptions include a 90% propellant fill of the tank, with 90% of that amount considered usable propellant for the performance estimate.

At the current state of the technology's maturity, it would not be recommended to attempt a green monopropellant propulsion system any smaller than 1U in allocated height, or 2U in total volume. This is because the manifold stands around 6cm in height, nearly two-thirds the height of 1U. Also, it spans an area of 2U by 1U, which is necessary to contain four thrusters and all supporting components. It is limited from any further miniaturization by the height of the components that it must include, namely the thrusters and the micropump.

7 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 an achievement for the world of small satellites. In addition to enabling such accomplishments as helping Lunar Flashlight become he 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. The design of the system has been discussed at length with support of the NASA Marshall team, and iterations on the system architecture and design have culminated into the solution presented in Section 4. Along the way, design considerations advanced beyond what was required of former cold gas systems produced by the Glenn Lightsey Research Group, and were compiled for the development of a small satellite monopropellant propulsion system design methodology. This system indicates growing possibilities in the realm of green monopropellant propulsion, and ultimately exemplifies a massive increase in capability for small satellite missions.

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