SPECTRE: DESIGN OF A DUAL-MODE GREEN MONOPROPELLANT PROPULSION SYSTEM

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Miniaturization of propulsion systems has pushed the capabilities of small satellites by allowing them to perform more complex tasks such as orbital maneuvers and formation flying. Georgia Institute of Technology's Space Systems Design Lab (SSDL) is designing a dual-mode propulsion system referred to as Spectre which will utilize AF-M315E (ASCENT) monopropellant to feed both modes. The propulsion system is capable of performing high thrust maneuvers via a chemical thruster that provides 1 N of thrust force and high efficiency maneuvers with 4 groups of electrospray thrusters. Spectre provides a total ΔV of 1097 m/s for a 12U CubeSat and has a dry mass estimate of 5.2 kg. This design accounts for approximately 8U (229mm x 238mm x 146 mm) of the CubeSat volume. The internal volume allocates 4.78 L for propellant, a pressurant gas and a propellant management device. Development efforts for this system are performed in collaboration with Massachusetts Institute of Technology (MIT) and NASA Marshall Space Flight Center (MSFC). This report presents the design efforts of the additively manufactured tank, the mechanical integration of Spectre, and future work.

INTRODUCTION

The advancement of propulsion systems for small spacecraft in recent years has allowed this class of vehicles to evolve from relatively simple Earth orbiting platforms to interplanetary spacecraft with ambitious yet achievable scientific goals. Chemical and electrical propulsion systems are key enabling technologies in this endeavor for small spacecraft [1,2]. A system with both propulsion technologies is attractive since it allows for high thrust impulsive maneuvers and more efficient smaller ones. Traditionally, these system types have used different propellants, requiring integrated systems to have complex multiple propellant tanks [1,2]. However, the recent maturation of the AF-M315E (ASCENT) green monopropellant has made it possible to integrate these systems using a single propellant supply tank[3].

BACKGROUND

The Glenn Lightsey Research Group (GLRG) in the Georgia Tech Space Systems Design Lab (SSDL) has been leading work in the design and development of CubeSats propulsion systems, many of which have used additive manufacturing (AM) techniques. These systems have been traditionally cold gas systems but have recently expanded to include liquid monopropellant. A summary of these systems is presented in Table 1.

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Table 1: Summary of propulsion systems developed by GLRG in chronological order [4]

Mission	Dry Mass	Total Impulse	Propellant Type	Material	AM Process
PROX-1	6.000 kg	999 N-s	Cold Gas	Accura Bluestone	SLA
BioSentinel	1.265 kg	36 N-s	Cold Gas	Accura Bluestone	SLA
ASCENT	3.660 kg	549 N-s	Cold Gas	Perform	SLA
LFPS	5.550 kg	1800 N-s	Monopropellant	Ti-6AI-4V	L-PBF
SunRISE	1.27 kg	135 N-s	Cold Gas	SOMOS PerFORM	SLA
SWARM-EX	0.475 kg	82 N-s	Cold Gas	SOMOS PerFORM	SLA
VISORS	1.031 – 1.117kg	117 – 197 N-s	Cold Gas	SOMOS PerFORM	SLA

Georgia Institute of Technology's (GT's) Space Systems Design Lab (SSDL) is designing a dual-mode propulsion system, referred to as Spectre, in collaboration with Massachusetts Institute of Technology (MIT) and NASA Marshall Space Flight Center (MSFC). The integrated system design, presented here, is led by GT. The electrospray system is developed by MIT's Space Propulsion Lab (SPL) and overall project guidance has been provided by MSFC. Emphasis was placed on minimizing component development efforts and focusing on the integration task required for such a system. Many of the selected components for Spectre are drawn from the Lunar Flashlight Propulsion System (LFPS) which was previously developed jointly by GT's SSDL, and NASA's MSFC and the Jet Propulsion Lab (JPL) for the Lunar Flashlight CubeSat mission. By doing so, the development time and cost of these components are expected to be relatively low while delivering a product with a high Technology Readiness Level (TRL). For Spectre, these components include the valves, pump, heaters, and sensors. Design efforts thus far have been focused on the tank and mechanical integration of the system which are presented in this paper.

Propulsion Modes

Recent developments in the small satellite community have focused on developing propulsive technologies that can provide adequate performance in the given design space. The main propulsion concepts discussed in this paper are cold gas, chemical monopropellant, and electric propulsion technologies. Each of these are covered in more detail in the following sections.

In order to characterize and compare different systems propulsion systems, several key performance parameters are used in this paper: thrust, delta – V and specific impulse (I_{sp}). Thrust is the mechanical force produced by the propulsion system, allowing the spacecraft to change its orientation and velocity. The concept is based on applying Newton's third law, in which accelerating a propellant out of the system, a force that is equal and opposite in direction is imparted onto the spacecraft. Delta – V is the change in velocity required to perform orbital maneuvers and is a function of the amount of fuel and specific impulse of the system. Meanwhile, the I_{sp} is the thrust per unit flow rate and is used to assess the efficiency of the system [5]. The Tsiolkovsky rocket equation, equation 1, relates the I_{sp} and delta – V, where g_0 is the gravitational constant of Earth, m_0 / m_f is the ratio of initial to final mass of the spacecraft [5]. Figure 1 shows a general thrust vs specific impulse plot of these different technologies.

$$\Delta V = g_0 I_{sp} \ln \left({}^{m_0}/_{m_f} \right) \qquad (1)$$

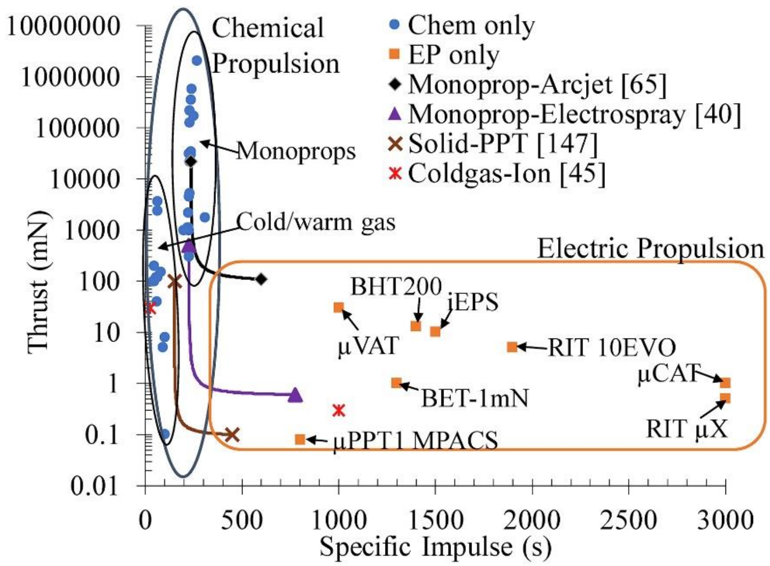

Figure 1: Thrust – Specific Impulse map for various propulsion technologies. [6]

Cold Gas Propulsion

Several cold gas propulsion systems have been developed by GLRG such as the BioSentinel flight system shown in Figure 2. In order to meet launch vehicle safety requirements, these systems provide thrust via the expansion of a propellant that has been stored at pressures below 100 PSI. Traditional architectures for cold gas systems are relatively simple. These require a main tank that holds the bulk of the propellant, a plenum to provide a controlled expansion space, a set of converging-diverging nozzles and flow control valves. The tank is typically additively manufactured to fill the available volume on the vehicle. This approach allows cold gas systems to be developed relatively quickly at a low cost. Because there is no combustion processes occurring, propellant selection is not limited to those for traditional combustion processes. Typical propellants for cold gas systems include refrigerants like R-236fa and inert gases such as Ar, Ne, and He [6,7]. Specific impulse for these systems ranges between 40-300 s [1,2,4] These lower values constrain cold gas systems to be used for attitude control and lower delta-V maneuvers.

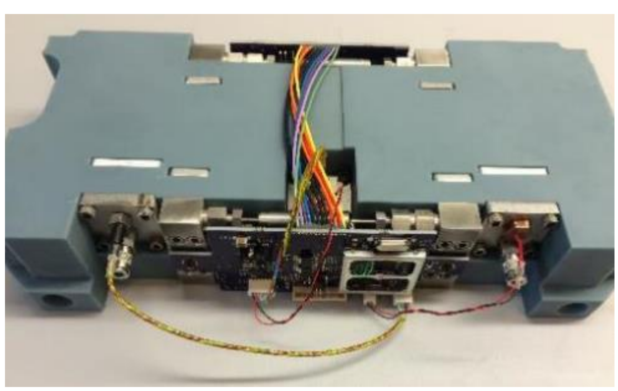

Figure 2: BioSentinel propulsion system developed by GLRG. [7]

Monopropellant Chemical Propulsion

Chemical propulsion systems provide thrust by accessing the chemical energy stored in the molecular bonds of the propellant. This requires the temperature of the propellant to raise and initiate the reaction process. Once raised to the necessary temperatures, the propellant flows through a catalyst bed which starts the decomposition process. The exothermic reaction provides the energy required to accelerate the chemical byproducts and produce thrust. Overall, monopropellant system architectures are more complex than the previously discussed cold gas systems. This fact is due to the more advanced controller schemes that are needed to monitor and maintain thermostatic control of the propellant's condition and thruster firing. Figure 3 shows the LFPS system developed by GLRG for the Lunar Flashlight spacecraft that makes use of monopropellant chemical propulsion. Performance of these systems can be expected to deliver I_{sp} and thrust values range between 200-260 s and 0.1-75 N respectively [1,2,9]. These higher performance values are what allow monopropellant systems to be used for more significant maneuvers that require larger amounts of delta – V such as orbital insertions. However, this increase in performance typically comes at the cost of safety complications due to greater potential energy stored in the propellant and the use of ignition devices [1].

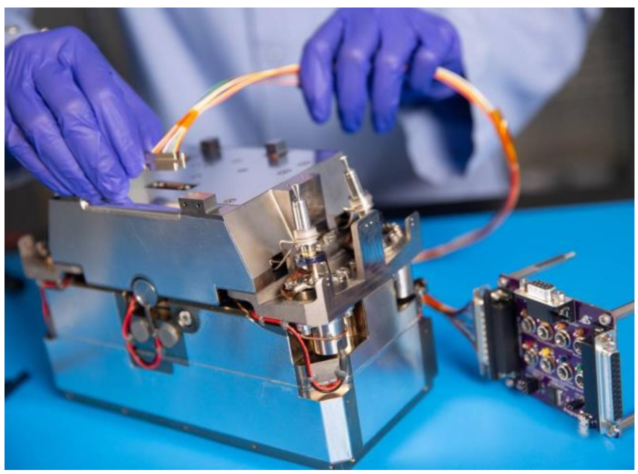

Figure 3: Lunar Flashlight Propulsion System (LFPS) developed by GLRG

Electrical Propulsion

Electric propulsion systems can be divided into three main categories: electrothermal, electromagnetic, and electrostatic. For the purposes of this research, the focus is on the electrostatic systems that make use of electrospray thrusters such as the one shown in Figure 4. At a high level, thrust is produced by having charged particles accelerated by an electric field. This requires the propellant to be an ionic liquid such as AF-M315E or EMI-BF. I_{sp} values ranges between 1000-3000 s, providing thrust on the order of 5 to 20 μN [3]. These performance values make electrospray systems an attractive option for low thrust maneuvers with high propulsive efficiency.

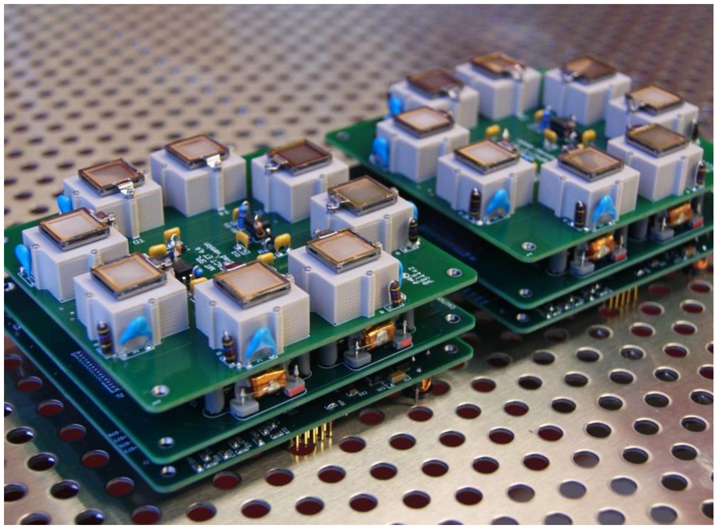

Figure 4: iEPS electric propulsion system developed by MIT SPL. Image courtesy of Amelia Bruno

Bimodal Propulsion

Bimodal propulsion systems are those that share the same propellant for two different propulsion technologies. Based on the pros and cons listed for each of the systems, a bimodal system can select technologies that complement each other's deficiencies. This allows a spacecraft to have access to separate performance regions: high thrust, and high efficiency maneuvers. Figure 5 shows some example bimodal propulsion systems [6].

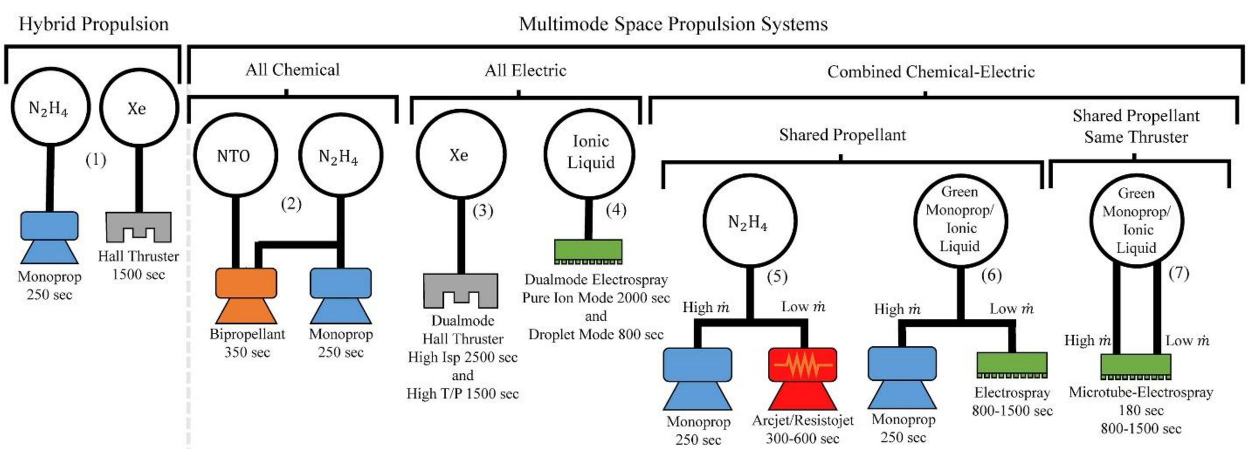

Figure 5: Examples of bimodal propulsion systems [6]

SPECTRE SYSTEM DESIGN

While prior research has been done in propulsion systems [1,2,3,6], a major difficulty in multimode architectures has been the compatibility between the different thruster types and a shared propellant [6]. The Spectre propulsion system builds on separately developed technologies and integrates them together to make use of the same propellant source. Spectre uses a pump-fed architecture to drive a chemical thruster and four electrospray thruster groups. The former provides relatively high thrust for a CubeSat in the 100 mN to 1 N range while the latter allows for more propulsively efficient maneuvers at smaller force values. The Spectre propulsion system was constrained to fit inside a 12U CubeSat volume with an overall mechanical envelope of 229 mm x 238 mm x 146 mm (approximately 8U).

Small satellites are typically constrained by volume rather than by mass. The use of additive manufacturing (AM) techniques allows for the design of components which are not typically possible with traditional manufacturing (TM) techniques, leading to more efficient packaging. This design approach allows for additional propellant volume and a more compact layout of the propellant routing passages and nozzles, leading to more efficient use of the available volume. The integrated design approach can also reduce weight, cost, and risk, and extend mission lifetime. Spectre will make use of a fully additively manufactured tank which will have all of the required mechanical interfaces and propellant passages directly printed into the structure.

System Specifications & Concept of Operations

The design presented in the following sections was developed such that any interface changes required for a specific spacecraft can be achieved with relative ease. Based on guidance from MSFC, the driving requirements were established as shown in Table 2 and Table 3. A notional future technology demonstration mission concept of operations is provided in Table 4. Finally, mission success criteria proposed by the chemical and electrospray design teams are presented in Table 5.

Table 2: Mass allocation for a 12U system

Spacecraft Initial Mass (kg)	20
Prop Sys Total Mass (%S/C)	40%
Prop System Dry Mass (%S/C)	20%
Spacecraft Final Mass (kg)	15.04
Propellant Load (kg)	4.96

Table 3: Specifications for both thruster configurations

	Chemical	**Electrical**	**Total**
I_{SP} (s)	250	1500	---
Allocated Propellant (kg)	4.464	0.496	---
Delta V (m/s)	619	477	1097
Thruster Class (N)	1	2.00E-05	---
Prop Flow Rate (g/s)	0.55	5.00E-07	---
Number of Thrusters	1	16	---

Table 4: Potential Concept of Operations

#	Operation/Sequence	Mission Time
0	Launch & Deployment	Day 0
1	Spacecraft Commissioning	Day 0
2	Prop System Commissioning	Day 1
3	Chemical Thruster Checkout	Day 1
4	Electrospray Fill Operation	Day 1
5	Electrospray Thruster Checkout	Day 1
6	Chemical Thruster Endurance Burn #1	Day 2 -3
7	Electrospray Thruster Endurance Test #1	Day 4 – 29
8	Chemical Thruster Endurance Burn #2	Day 30 -31
9	Electrospray Thruster Endurance Test #2	Day 32 – 59
10	Chemical Thruster Endurance Burn #3	Day 60 -61
11	Electrospray Thruster Endurance Burn #3	Day 62-89
12	Disposal Burn (Chemical & Electrospray Thrusters)	Day 90
13	End of Mission	Day 90

Table 5: Success Criteria – Established by Chemical and Electrospray Design Teams

##	Success Criteria
C1	Chemical thruster accumulated 1 hour of firing time
C2	One successful firing of the chemical thruster during electrospray firing
C3	Propellant operating pressure and temperatures verified
C4	Successful thruster conditioning after first thruster firing
E1	Initial electrospray thruster reservoir fill-up successful
E2	Electrical isolation of all electrospray thrusters verified
E3	One successful refill operation achieved for each electrospray thruster reservoir
E4	Electrical isolation verified on all electrospray thruster's after first refill operation
E5	Each electrospray thruster accumulates 500 hrs. of operation
E6	>50% of all electrospray thrusters accumulate > 1000 hours of operation

System Schematic

Traditional liquid monopropellant systems use either pressure-fed or pump-fed architectures. Pressure-fed systems store propellant in the tank at high pressure for the entire duration of the mission. This requires structurally strong tanks, which are typically spherical or cylindrical, to avoid any possible stress-related deformations and failure. These types of tanks require a large amount of volume and use space less efficiently in tightly packed rectangular prism CubeSats. For these reasons, pump-fed architectures are attractive alternatives for CubeSat propulsion systems that require high pressure propellants. A pump-fed system utilizes a pump to raise the pressure of the propellant to the required operating pressure. This approach also leads to additional valves, heaters, sensors, electronics, and software that are needed to control the system. Following the needs of a pump-fed system and the previously established requirements, a system level schematic was developed as shown in Figure 6. This schematic accounts for the general layout of the system, main components, and required sensors such as thermocouples and pressure sensors.

Each electrospray group contains a separate tank capable of holding 5 mL of propellant in an unpressurized tank. Before injection from the main tank into the secondary tanks, the propellant must be conditioned for use in the electrospray thrusters. A Compact Pressure Regulating System (CPRS) component was designed to condition the propellant and fill the secondary tanks. Details of the system are presented in the following sections.

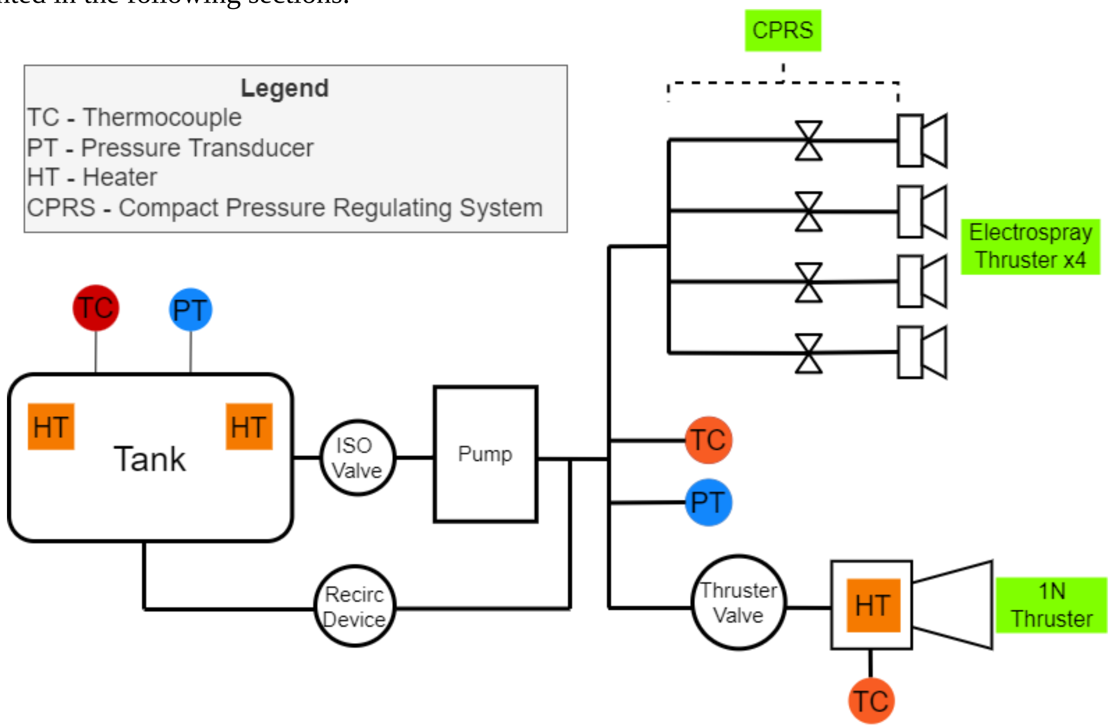

Figure 6: Spectre system schematic diagram.

Firing Modes

Each of Spectre's two propulsion modes has a distinct set of steps to prepare the system and fire. The chemical thruster requires relatively high temperatures and pressures while the electrosprays operate over longer durations.

When executing a high thrust maneuver, the controller commands the isolation valve to open, allowing the propellant to pass through a filter and enter the pump. The pump is then commanded to raise the propellant pressure to the operating range and the thruster is heated via a thermostatic control scheme. Once the desired pressure and temperature levels are achieved, the thruster valve is opened and the thruster fires.

The electrosprays do not need a continuous propellant supply when firing due to their extremely low mass flow rates; their tanks only need to be replenished as their fuel depletes (after every ~150 hours of firing). In this mode, the pump and Compact Pressure Regulating System (CPRS) are only used during fill and refill procedures. The electrosprays are then fired by their power processing unit (PPU).

MECHANICAL DESIGN

The main components outlined in the system schematic have been modeled and assembled into a preliminary CAD model. The necessary mechanical interfaces for integration with a 12U CubeSat are based on guidance from MSFC. The CAD assembly has been used to account for the volume of each component, its location and required interfaces for assembly.

Figure 7 shows several key components: all of the thrusters, CPRS valves and a thermal protection cone. The chemical thruster has been placed in the center in order to provide the high thrust through the center of mass of the system. The four groups of electrospray thrusters are placed in each corner and canted to provide three-axis attitude control. Volume has been allocated for the controllers on the sides of the propulsion system. A single group of electrospray thrusters is shown in further detail in Figure 8. Figure 9 shows the micro pump, isolation valve and GT controller on one side which will be shielded with a cover plate. The PPU will be placed on the opposite side with a similar cover plate. The top of the system will house a variety of pressure transducers (PT) and thermocouples (TC) to monitor the system. These components along with the chemical thruster valve are shown in Figure 10. Due to the placement of the electrical components and controllers on different planes of the system, a bridge like feature has been added for cable management.

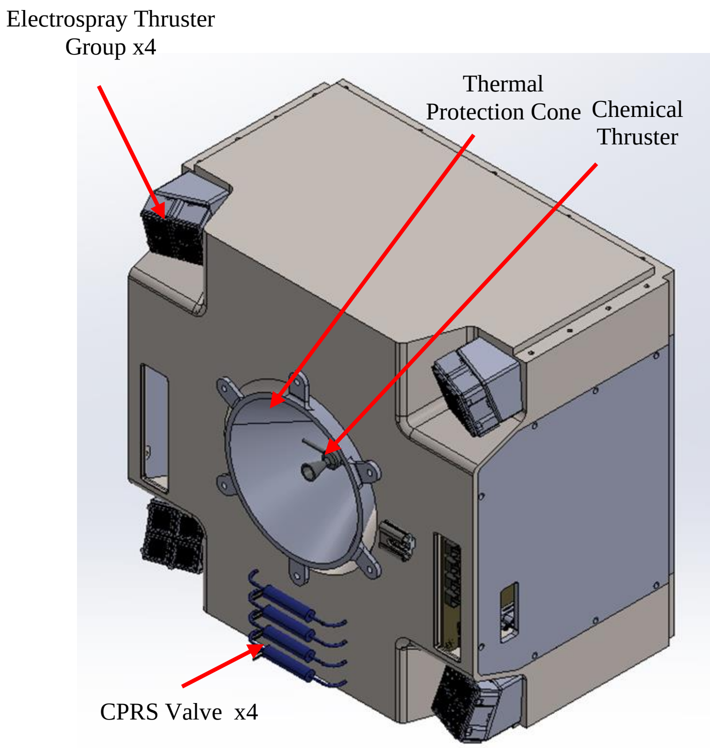

Figure 7: Isometric view exposing bottom face.

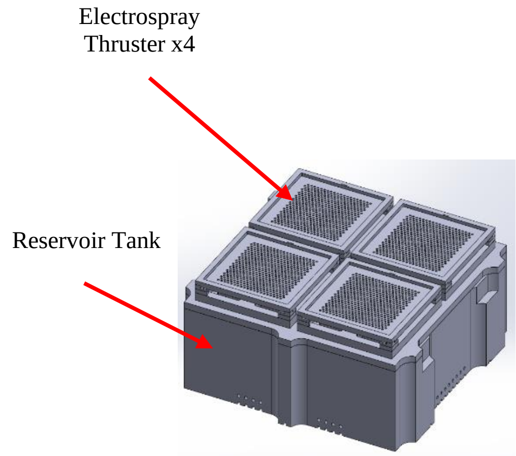

Figure 8: Electrospray group with a single tank and four thruster heads.

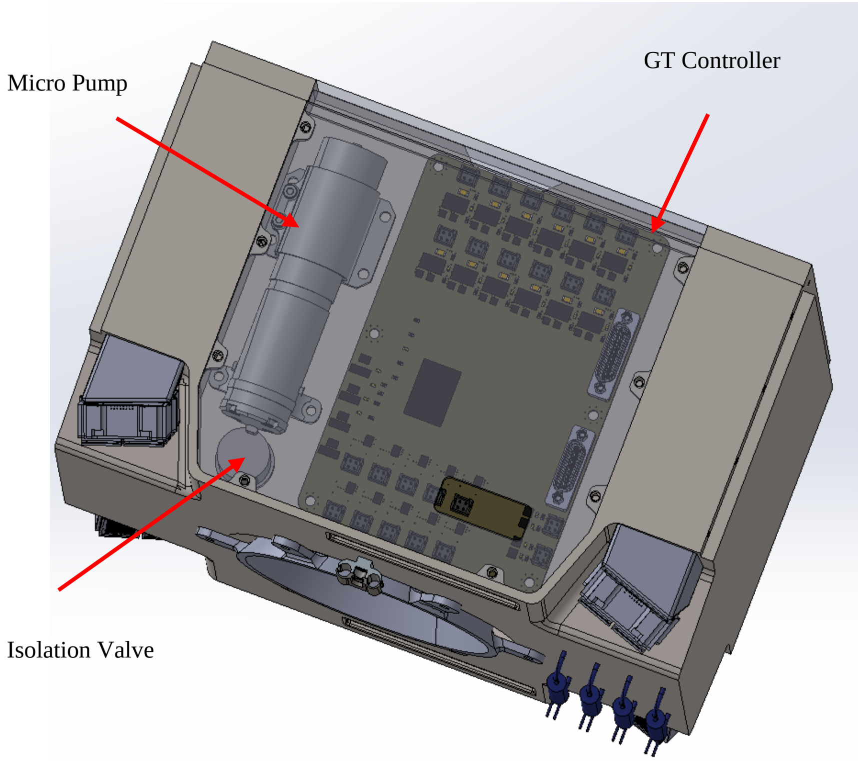

Figure 9: Isometric view exposing the side where the isolation valve, pump and controller are mounted.

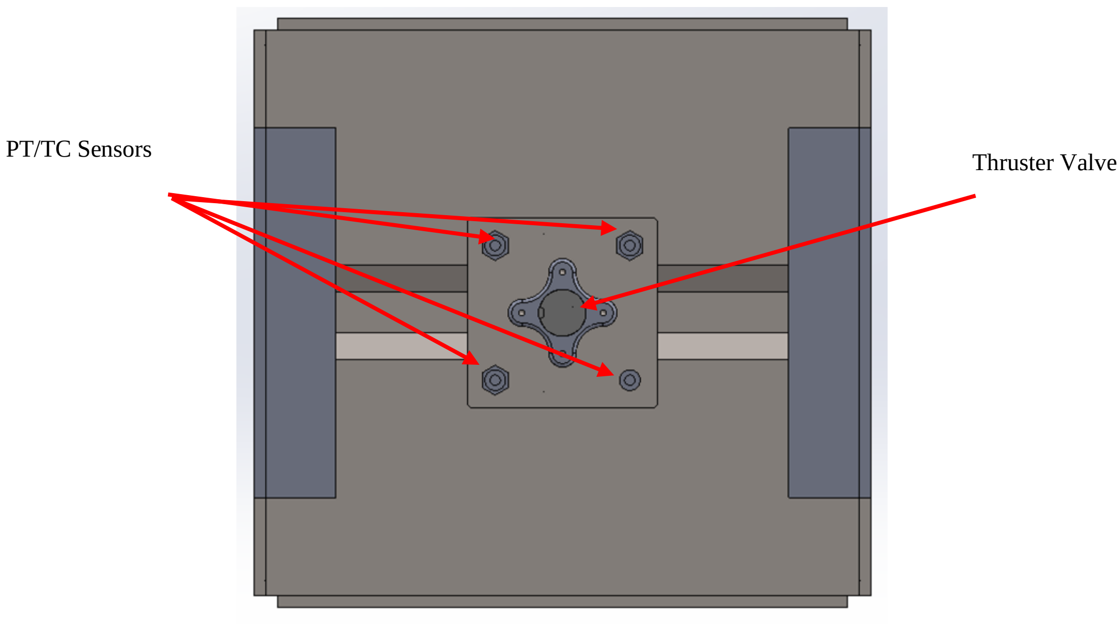

Figure 10: Top view.

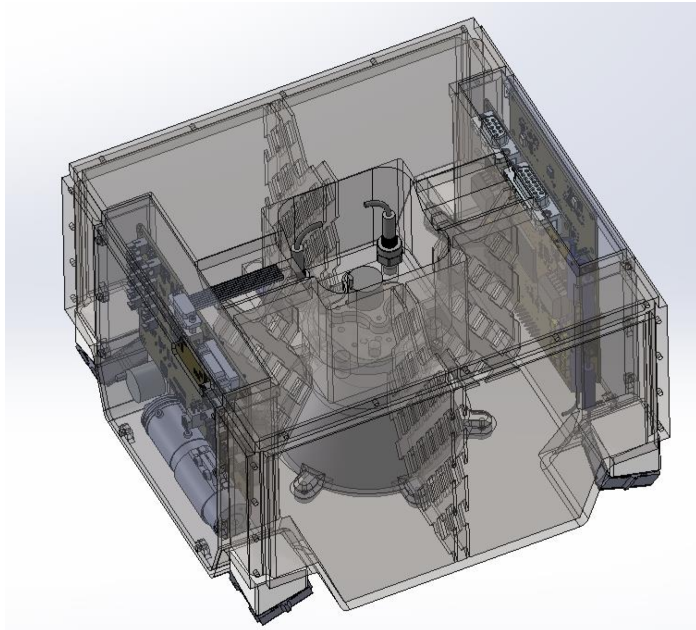

Figure 11: Isometric view with tank transparent tank.

Tank

A key driver in designing the tank is the need for high structural integrity and compatibility with the ASCENT (AF-M315E) propellant. Ti-6AI-4V (Grade 5 Titanium) has been selected as the material due to its successful flight heritage with similar monopropellant systems such as the Green Propellant Infusion Mission (GPIM) [10,11]. The tank will house a propellant management device (PMD) to mitigate the effects of microgravity environments during the mission. This device will ensure that the propellant throughout the tank is moved via surface tension to the tank's exit port. Additionally, a 10-micron filter will be used to prevent any larger debris from entering the other components. The preliminary tank design has an internal volume of 4.78 L. This value is expected to decrease as additional structural features are added and internal components such as the PMD, filter and necessary fasteners are included.

Previous propulsion systems developed by GLRG have made use of AM to design volumetrically efficient systems. Most recently, the LFPS design uses an additively manufactured manifold made of Ti-6Al-4V [3,9]. Expanding on the lessons lear **Figure 11:** Isometric view with tank transparent tank. printed with direct metal laser sintering (DMLS) techniques. AM enables various design features that were previously not possible with traditional manufacturing methods. The most impactful of these are printing the PMD device directly into the tank and printing the necessary internal passages to route the propellant. Figure 12 shows a proposed layout of this concept, where the red arrows indicate the propellant passages and the orange features show the radially symmetric location of the PMD. Due to the need for support structures throughout the printing process, design efforts have focused on making use of necessary features to double as structural support. For example, the PMD will be placed beneath the cable management bridge to act as the support. The tank will be printed along the Z direction, ending in a top open face. This design will allow for access into the internal structure for post printing processes such as surface finishes and any required geometry modifications. Once these elements have been assembled, a top cover plate will be placed and welded to the tank.

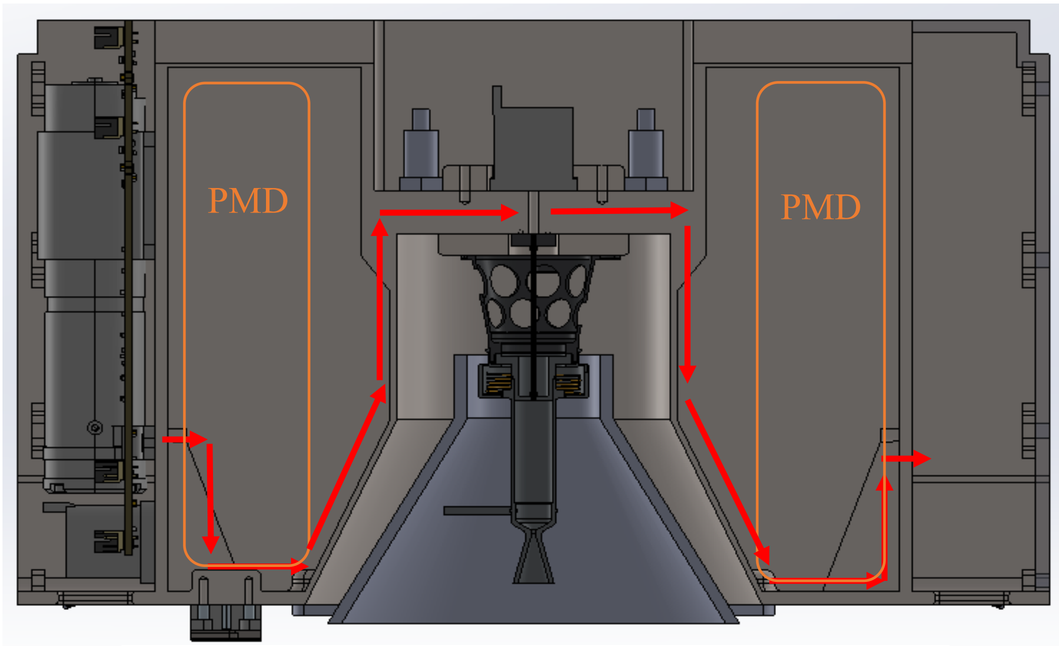

Figure 12: Cross section view of the tank with proposed layout of internal

The central pocket, shown in Figure 12, was designed to efficiently package the chemical thruster, thruster valve, PT's and TC's. Figure 13 shows a transparent view of the central pocket, with each of the mechanical interfaces labeled 1 through 4. One set of PT's and TC's will make use of interface 1 to monitor the conditions of the propellant directly from the tank. The second set of sensors will be placed on interface 2. By leveraging the capabilities of AM, interface 2 has passages strategically printed such that the sensors can monitor the propellant downstream of the pump. This allows the system to check the condition of the propellant before firing the chemical thruster or electrospray refill operations. Finally, the thruster valve and chemical thruster are placed on interfaces 3 and 4 respectively.

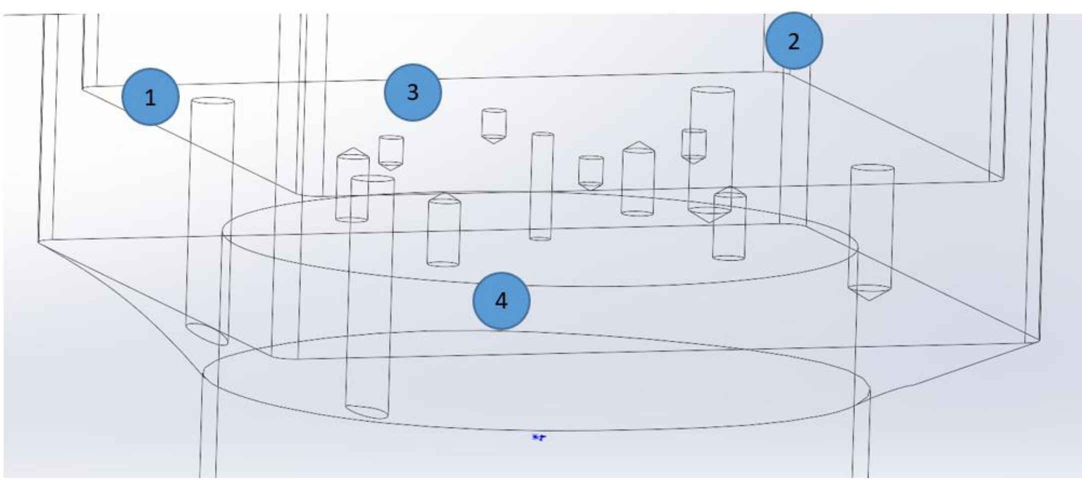

Figure 13: Transparent view of center pocket with mechanical interfaces labeled.

The PMD will consist of thin fins, radiating out from the center of the tank in pairs to each interior wall as shown in Figure 14. By positioning the fins touching each wall, and the exit port of the tank close to one set of fins, the PMD will help to move the fluid from each face towards the exit, and not allow it to get stuck along edges of faces or in corners. Each fin will have a pattern of diamond shapes cut out of it as seen in Figure 15, sized to lower the overall mass of the PMD while still preserving its function and allowing for it to be printed without additional supports. The fins will be rounded to the surfaces they contact, and because they are printed into the structure, can be modified to fit around the geometry of any other features inside the tank. Additionally, the PMD vanes will provide a structure along which propellent passages can be easily routed through the center without need of additional supports during printing.

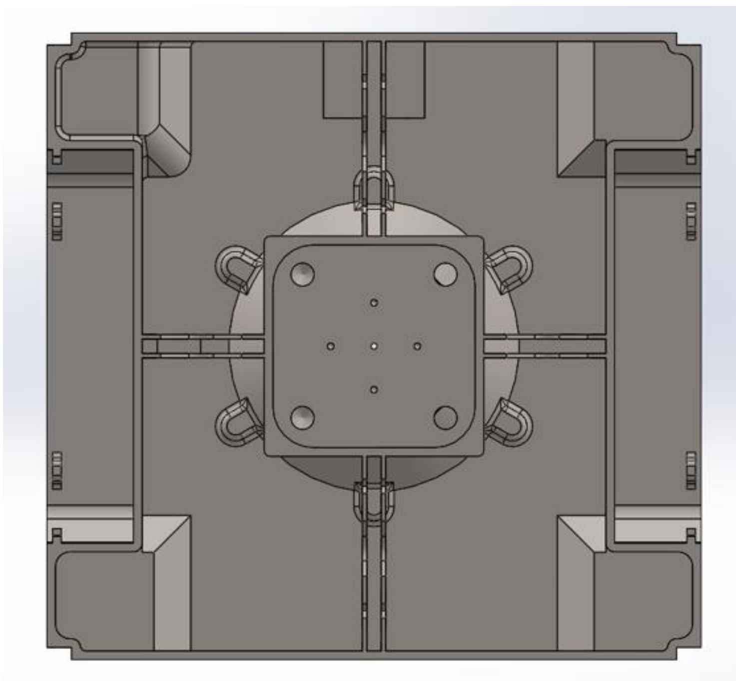

Figure 14: View of the tank interior from above with PMD vanes

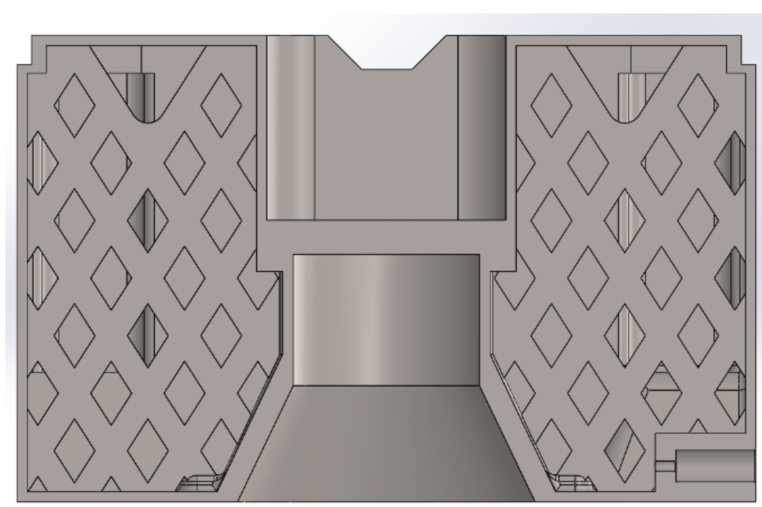

Figure 15: Cross section view of the tank exposing the PMD

Valves

Three types of valves are placed throughout the system to ensure the propellent does not flow in or out of components when it is not needed. The first is the fill/drain valve, shown in Figure 16, which allows propellant to flow into and out of the tank during the filling operations for testing and final integration. The second is a micro-solenoid isolation valve, shown in Figure 17, which was developed by MSFC for CubeSat propulsion systems. One is placed between the tank and the pump interface to prevent propellant leaving the tank before use. Another isolation valve is placed before the thruster to prevent any propellant from entering the thruster when it is not being fired. Finally, the CPRS makes use of four commercial solenoid valves from The Lee Company, seen in Figure 18.

Figure 16: Fill/drain valve. [12]

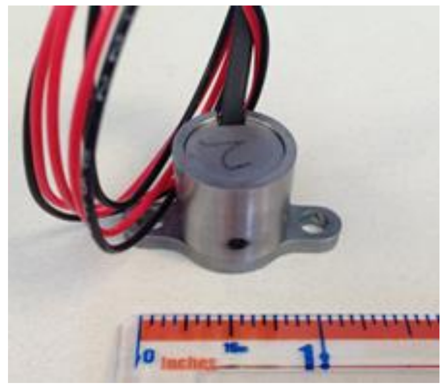

Figure 17: Micro-solenoid valve. [12]

Figure 18: Solenoid valve for CPRS.

Pump

A pump is used to prime the propellant from storage pressure (approximately 70 psi) up to the chemical thruster operating pressure of 350 psi. The miniaturized pump, currently available at TRL 6, was originally developed by Flight Works Inc (FWI) for the LFPS project. It is capable of delivering flowrates up to 45 mL/min. A sample pump is shown in Figure 19.

Figure 19: FWI micro-pump. [12]

Recirculation Block

Prior to firing the chemical thruster, the propellant must be raised to the operating pressure and temperature. Once this state is achieved, the valves open and allow the propellant to flow from the tank to the thrusters for firing or refilling operations. After the system fires for the first time, a small amount of propellant will be left over in the routing lines. For the following thruster conditioning portions, the propellant in these lines must be routed through a recirculation loop that adds resistance to the flow, allowing it to flow once the propellant pressure or flow rate reaches target levels. Currently, the placement and implementation of this feature is an open trade. The recirculation block shown in Figure 20 and Figure 21 was developed by GLRG for LFPS and would require only a mounting interface on the current Spectre design. A second option is to build in the device during the AM process.

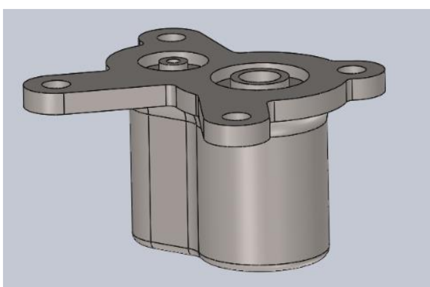

Figure 20: Recirculation Block.

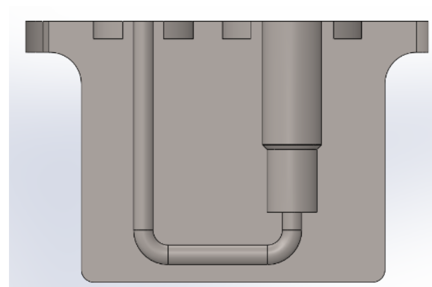

Figure 21: Cross section of the Recirculation Block.

Thruster

The chemical propulsion mode of Spectre makes use of a 1 N thruster provided by Plasma Processes Inc (PPI). It provides 250 s of specific impulse in steady state operations and 236 s in pulse mode. A built-in heater requires 15 W to operate and is used to condition the propellant for firing. A thermocouple is used to monitor the temperature near the catalyst bed heater. This allows the controller to use a feedback loop to maintain thermostatic control when priming and firing the thruster. The overall mass is estimated to range between 140 g and 150 g. Figure 22and Figure 23 show the thruster in preparation for testing and during testing respectively.

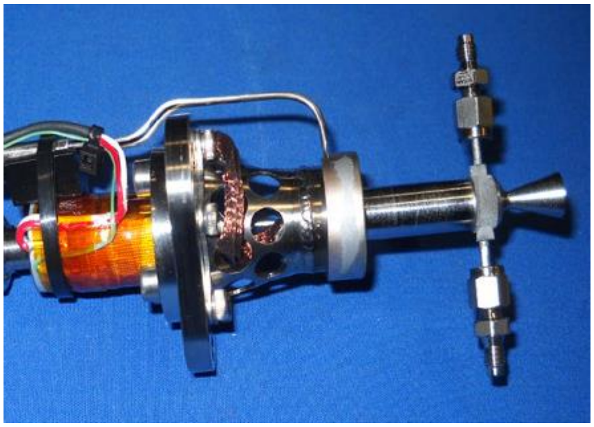

Figure 22: 1 N thruster in preparation for testing. Image courtesy of Tomas Hasanof.

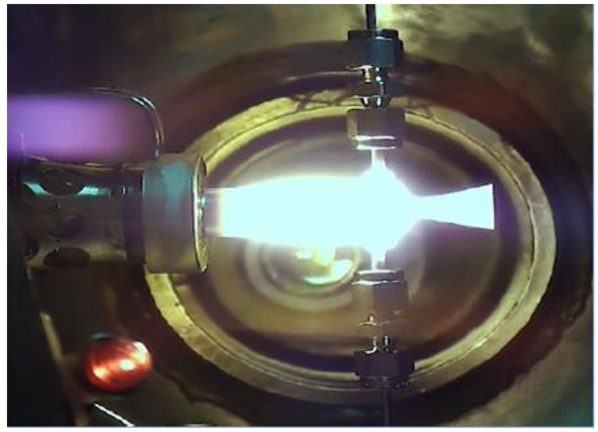

Figure 23: 1 N thruster undergoing hot fire testing. Image courtesy of Tomas Hasanof.

Heat Shield Cone

During nominal operation, the thruster is expected to reach over 1600 °C, which can be harmful to any sensitive components that are in close proximity. For this reason, a heat shield is employed to help shield the tank as seen in Figure 24 The preliminary design focuses on a cone shaped geometry which will allow for ease of integration. An ongoing trade study is being done to determine potential coatings on the inner walls of the heat shield. PPI has previously worked on a similar application for the Parker Solar Probe. Based on this heritage system, the cone's material will be Inconel and various spray coatings will be applied on the surface. The first layer would be a bonding layer, followed by a thermally insulating layer made of zirconium oxide and finally a thermally reflective layer made of AMB (aluminum, magnesium, boron) nitride.

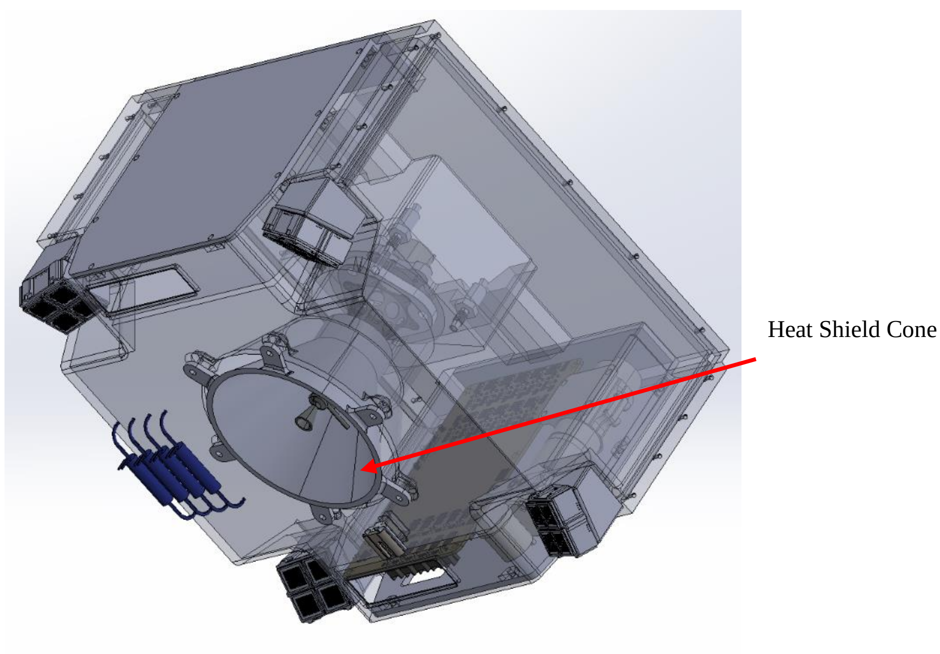

Figure 24: Thruster cone.

Compact Pressure Regulating System (CPRS)

The CPRS was developed by NASA and MIT for Spectre. The design consists of a set of solenoid valves for flow control, internal passages with specific geometry for pressure regulation, and insulting plastic tubing for electrical isolation [3]. The Spectre electronics can control the timing of the CPRS valves in order to deliver known volumes of propellant to the electrospray tanks, and refill as required over the duration of the mission. To achieve the specific geometry, a prototype AM model was printed using the same DMLS techniques and characterized during FlatSat testing. The implementation into the tank is an open trade at this time.

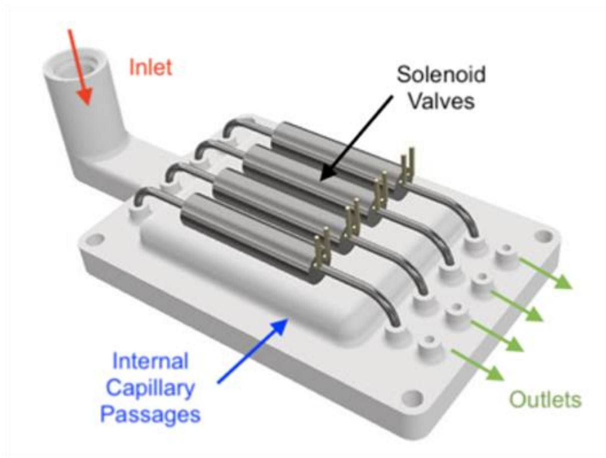

Figure 25: CPRS subassembly. Image courtesy of Amelia Bruno.

Electrospray Thrusters

The electrospray system in Spectre is currently being developed by MIT's Space Propulsion Lab. Each thruster head consists of an array of micromachined emitter tips aligned with an extractor grid. The propellant is passively fed through from the reservoir beneath thruster head [3]. Performance characteristics are tabulated in Table 6. These thrusters have successfully demonstrated 500-hour operation with ASCENT propellant [13]. Spectre will have 4 modules with 4 thruster heads each, for a total of 16, such as the one shown in Figure 26.

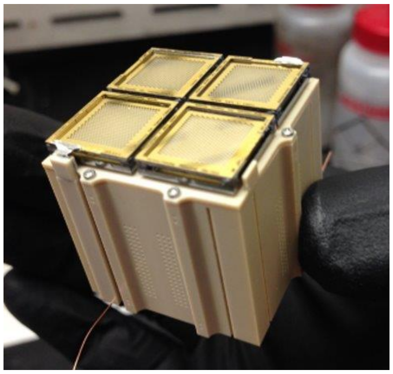

Figure 26: Single module with 4 thruster heads. Image courtesy of Amelia Bruno.

Table 6: Electrospray performance characteristics. Courtesy of Amelia Bruno.

	Per Individual. Thruster Head	Per 4-Thruster Tank/Unit
Thrust	20 μN	80 μN
Flow Rate	0.5 μg/s	2 μg/s
Specific Impulse	1800 s	1800 s
Dry Mass	-	15 g
Propellant Volume	-	5 mL

CONTROLLER & ELECTRONICS

Spectre makes use of an electronic control system that manages the sensors and device drivers. The system has a set of two controller boards that employ a Leader-Follower configuration. Each controller board is designed by a different design team based on its purpose. In this paper, the leader controller board is referred to as the GT controller and the follower board as the PPU. The system's controller firmware utilizes the F Prime flight software framework developed by JPL [14].

The GT controller, seen in Figure 27 is being developed by the Georgia Tech team and is based on the LFPS controller design which utilizes an ATMEGA128 microcontroller [15]. The integrated circuit board is responsible for communicating with the spacecraft, passing commands to the PPU, monitoring the system via the various sensors as well as driving the valves, heaters, and a pump. The controller has the built-in capability to perform thermostatic control of the chemical thruster heaters and tank heaters. Figure 28 shows the heritage design LFPS controller for comparison. Finally, the PPU shown in Figure 29 is responsible for firing the electrospray thrusters and reporting back telemetry to the GT controller.

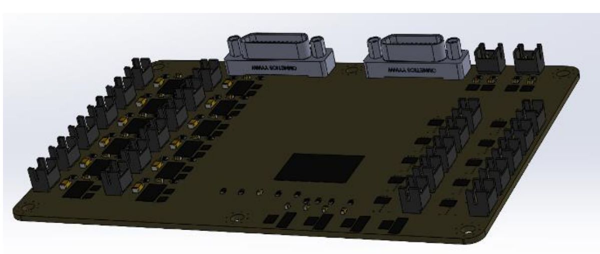

Figure 27: Proposed Spectre controller board making use of a single board.

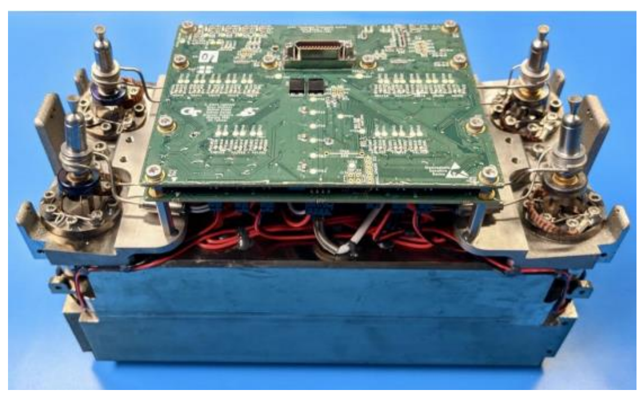

Figure 28: LFPS controller comprised of 3 individual boards [15].

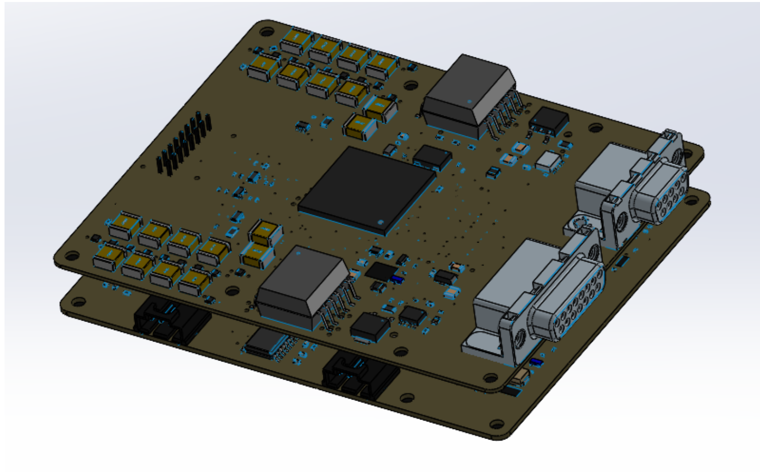

Figure 29: PPU CAD model.

PRELIMINARY STRUCTURAL ASSESSMENT

A preliminary structural analysis was performed at the following three pressure values: 100 PSIA (Maximum Design Pressure or MDP), 150 PSIA (MDP times 1.5) and 200 PSIA (MDP times 2). The SolidWorks Finite Element Analysis (FEA) toolbox was utilized for this analysis due to the ease of integration with the existing CAD model developed in the same software package.

Ti-6Al-4V is commonly used in TM methods, with material properties widely studied and available for FEA analysis. However, AM applications can alter the material properties depending on the specific printing process. Effects such as thermal cycling, cooling rates, power absorption and more during the solidification process play a significant role in the material's final microstructure [16]. This causes variability in the material property selection and therefore requires more stringent attention to the selected values when compared to material properties for TM applications. For this analysis, material properties were provided from MSFC due to their experience and leadership with AM processes[16]. The printing process selected was Direct Metal Laser Sintering (DMLS) which resulted in values for yield strength and ultimate tensile strength of 768 MPa and 810 MPA respectively.

Results for each test case are shown below in Table 7. The 200 PSIA case resulted in a safety factor of 0.8, which indicates a need to strengthen the design. All three test cases have the maximum stress occurring near the electrospray mounting interface, seen in Figure 30. A cross section of the tank, shown in Figure 31, reveals the high stress location is on the inside, where the geometry curves and thins the wall. Furthermore, the maximum deflections occur on the +/- Y faces of the tank, requiring additional design work to minimize the effects, as seen in Figure 32.

Table 7: Structural analysis results

Test Case	Von Misses Stress [Pa]	Deformation [mm]	Safety Factor
MDP – 100 PSIA	5.187e8	1.658	1.6
MDP*1.5 – 150 PSIA	7.781e8	2.487	1.1
MDP*2 – 200 PSIA	1.037e9	3.316	0.8

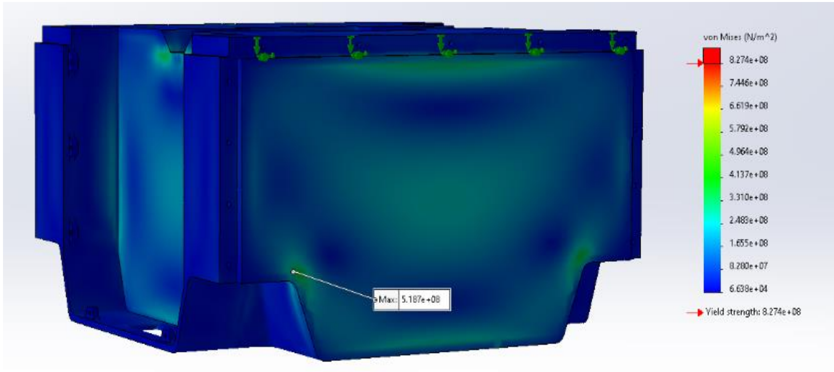

Figure 30: Stress Plot - 100 PSIA

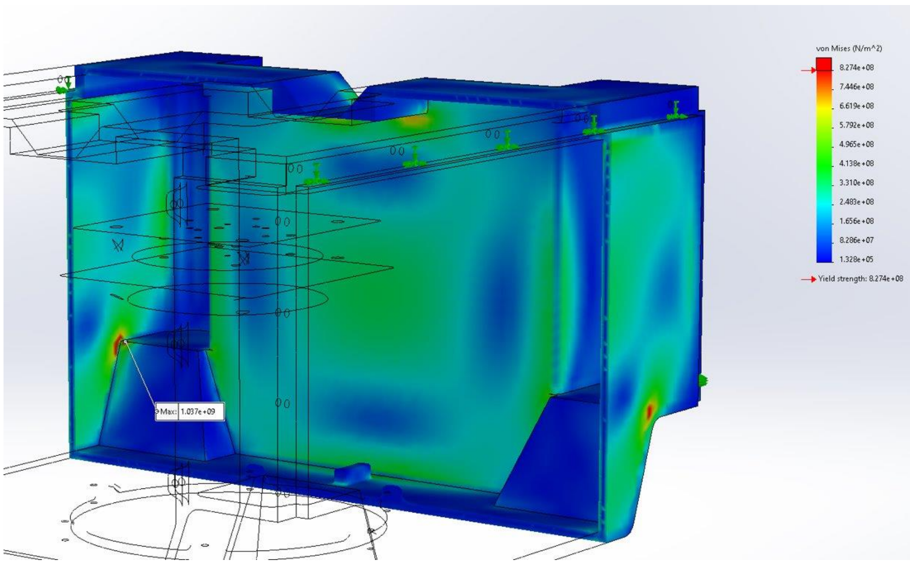

Figure 31: Cross section for 100 PSIA – Stress Plot

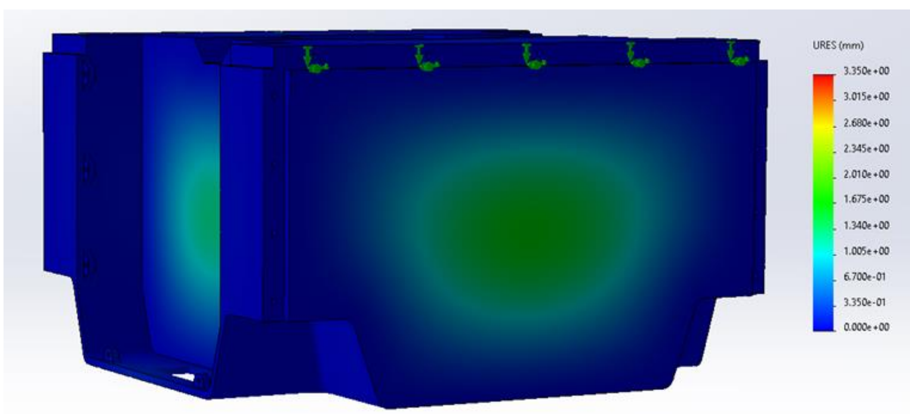

Figure 32: Deflections Plot – 100 PSIA

Redesign work is currently in process to address these findings. The PMD structure will be designed such that it acts as a structural element on the +/- Y faces to aid in reducing the deflection of these. Experience from LFPS suggests this low safety factor at burst may be the result of model meshing, rather than a physical low value. The LFPS propellant tank analytical failure pressure was approximately 300 PSIA, with testing failure occurring at 2200 psia [17]. While the LFPS tank was fabricated using TM methods, the manifold was AM in the same way the Spectre tank is being proposed. Both of these cases suggest that analysis approach is fairly conservative. A more detailed structural analysis will be performed as part of future work and development for this project.

PRELIMINARY HEATING ASSESSMENT

A preliminary heating assessment was performed in order to size surface-mount Kapton heaters for the system. The propellent must be heated to at least 10 °C before being pulled from the tank into the lines to achieve the necessary viscosity to run the pump. Some proportion of the fuel must be heated from its steady state temperature to 10 °C before running the pump to fire the thrusters. The thermal analysis done for LFPS was used as a baseline for system requirements and thermal environment. It was assumed that the tank would heat much faster than the propellent, and 10% of the propellent must be heated to run the system, so the heaters must be capable of heating 10% of the propellent, plus the mass of the tank from their steady state temperature (assumed to be -15 °C) to 10 °C.

The first estimate was made based solely on the thermal mass of the system with no losses assumed, and it was found that to heat that thermal mass in one hour, it would take 20.12 watts of heat input. Next, different wattages of heaters were used to calculate time to heat propellent (using an energy balance and Fourier's law) in 3 different cases: a case with no heat loss due to radiation and no solar heating, the case with heat lost to black body radiation, and the case with black body radiation and full solar heating. These times were calculated for a variety of heater wattages and are shown in table 8. An example output graph of heating in the case with heat loss due to radiation for a heater that produces 18.4W when provided with 12V shown in Figure 33.

Table 8. Sample heating times for heater wattage in each of 3 heating environments

Total Heater Wattage (W)	Time with no radiation, no heating (Min)	Time With Radiation (Min)	Time With Radiation and Solar Heating (Min)
11	120	380	19
14	92	185	18
18.4	73	121	17
29.4	45	60	15

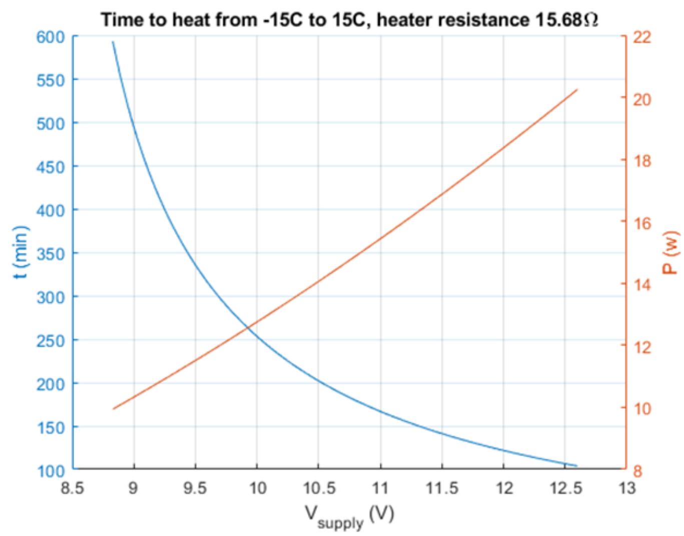

Figure 33: Heating Plot for a heater with resistance of 15.68 Ohms in the case with heat loss due to radiation

This data was compared to the heating times accepted on the LFPS flight system. Based on the data that was accepted for heating on LFPS, it was decided that in total 18.4 W of heating would be sufficient to heat the system in a reasonable time. This was confirmed by running a steady state temperature analysis on the worst-case heating for a system with 18.4W in, where black body radiation was calculated for heat loss. The steady state temperature for this case was around 40 °C, providing significant margin above the required propellent temperature, and proving that these heaters would be sufficient to heat the system in a reasonable time.

FUTURE WORK

Design efforts for Spectre are continuing on multiple fronts at the time of this writing. The design team continues to work on both the mechanical and electrical components. Current efforts with the electrical team are focused on selecting adequate PT's, TC's and tank heaters to ensure proper performance and meeting the necessary mechanical interfaces. Mechanical design work on the detailed design of the PMD and placement of the fill/drain valves is currently underway. The next steps will focus on the layout for the internal propellant passages and the top plate. Several key analyses will further refine the design, including a detailed structural, vibrational, and thermal analysis. Finally, a printability assessment will highlight any potential features that may be prone to failure during the printing process, providing invaluable insight.

CONCLUSION

A bimodal propulsion system, referred to as Spectre, is currently being designed to make use of the AF-M315 green monopropellant, providing the ability to perform both high thrust and high efficiency maneuvers. The current design accounts for all necessary components and their mechanical interfaces for a 12U CubeSat. Making use of additive manufacturing, Spectre has an internal volume of 4.7 L, a dry mass of 5.2 kg and provides a ΔV of 1097 m/s. Preliminary structural analyses show safety factors greater than one for the MDP and MDP times 1.5 cases. Further structural reinforcement is required for the MDP times 2 case. Finally, future work will focus on detailed design of the PMD and propellant passages along with detailed structural, thermal and printability analyses.

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