DESIGN, ANALYSIS, TESTING, AND FLIGHT ACTIVITIES FOR A GREEN PROPULSION DUAL MODE (GPDM) TECHNOLOGY DEMONSTRATION MISSION

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ABSTRACT

NASA's Strategic Plan (2022) outlines specific technology development objectives which direct the Agency to "innovate and advance transformational space technologies." An example of these potentially high-impact space technologies is the low-toxicity or "green" rocket propellant known as ASCENT (or Advanced Spacecraft Energetic Non-Toxic Propellant). Developed in the 2010's by the Air Force Research Lab (AFRL), ASCENT (formerly AF-315E) has shown improved specific impulse density (50% higher) vs. hydrazine in addition to its favorable in-space storability and ease of handling capability. The chemical propulsion capability of ASCENT has been demonstrated on several missions including the Green Propulsion Infusion Mission (GPIM) in 2019 and most recently, the Lunar Flashlight mission. ASCENT is an ionic liquid, which lends itself as both a chemical and an electrospray propellant. The capability to use the same propellants in multiple modes using the same propellant tank and feed system has yet to be demonstrated in orbit. This capability, if proven successful has the potential to reduce system weight and complexity, while taking advantage of both high thrust and high propellant efficiency in electrospray mode. The GPDM Project, managed by the Marshall Space Flight Center is seeking to develop a dual-mode propulsion system as the payload on a small spacecraft (6U CubeSat) and subsequent in-space demonstration. This paper will summarize the concept, ground testing as well as mission operations plan for demonstrating green "dual-mode" propulsion.

INTRODUCTION

Low-toxicity or "Green" rocket propellants offer tantalizing ground handlining, long-term on-orbit storage, and overall performance alternatives to traditionally used hypergolic propellants for in-space transportation. While several low-toxicity alternatives to hypergols exist, few have achieved a technology readiness state such that they are considered low risk for a variety of mission architectures and mission use cases. Furthermore, inconstancies exist within the industry as to what is considered "green". The Green Prop Road Map (2018) focused on ionic liquid monopropellants (e.g., Advanced Spacecraft Energetic Non-toxic Propellant ASCENT and High-Performance Green Propellant (HPGP)) as leading candidates for further thruster development leading to flight qualification and use on specific NASA and industry missions. The AFRL developed ASCENT has been used on several missions including GPIM (2019) and the JPL-led CubeSat science mission, Lunar Flashlight in 2022. The recent ASCENT based propulsion system for Lunar Flashlight's CubeSat mission used four 0.1 N thrusters to demonstrate limited successful performance, including producing a mission averaged Isp's of 210 seconds and a net delta V of 16 m/s while battling fuel-line debris due to AM 3D printed powder restrictions in the manifold.

ASCENT has an ionic liquid makeup; as such, it has the propensity for use in a bi-modal fashion, both as a chemical monopropellant when reacted with a catalytic material and as an electrospray thruster propellant when it interacts with an electromagnetic field. Consequently, a major benefit of ASCENT in dual-mode usage is the mass savings benefit of using a common propellant/feed system while operating in a high thrust chemical and high efficiency electrospray modes.

Furthermore, given ASCENT's low vapor pressure and relatively safe handling for ground loading operations there is strong interest in expanding the use of ASCENT for more complex propulsion systems for future exploration missions. NASA's strategic plan calls for strategic thrusts which include - developing advanced in-space transportation as well as commercialization of technology investments.

NASA's Marshall Spaceflight Center in collaboration with MIT (via the NSTRGO Program) has developed a dual-mode ground test facility known as the 'Flat-Sat' in its Green Propulsion laboratory. Initial dual-mode testing was demonstrated in 2021 showing promise for using ASCENT in both chemical and electrospray modes. The Green Propulsion Dual Mode (GPDM) mission seeks to expand this capability from the initial ground test into an in-space demonstration, on a 6U CubeSat form factor, for a CLSI funded mission, slated for a NET launch date of Summer 2025. Financed by STMD/SST- GPDM is addressing specific Agency/gaps including "Gap" Advanced Propulsion for Small Spacecraft and those in the Green Prop Roadmap to close technical gaps related to growing the capability of reliably flying green propellants for in-space transportation. This paper will summarize the initial dual-mode design concept, ground testing, propulsion system development, and planned mission operation of GPDM.

DESIGN AND DEVELOPMENT

GPDM developed as a successor to the Lunar Flashlight Propulsion System's (LFPS) technology developments and as an evolution of the Specter propulsion system. [1] Design changes including moving from a fully NASA-developed chemical propulsion system to Rubicon Space System's developed Sprite propulsion module and a significantly updated Compact Pressure Reduction System (CPRS) compared to the proposed additively manufactured (AM) CPRS design as presented in Reference [1]. The scope of GPDM also increased when GPDM increased from a 6U propulsion system to the entire 6U CubeSat.

BREAKDOWN OF GPDM DESIGN

GPDM's payload is its propulsion system, referred to as the Dual-Mode Propulsion System (DMPS). It comprises of three major mechanical systems, the Sprite propulsion module, the electrospray thrusters, and the Compact Pressure Reduction System, and two electrical boards, the Foxglove controller, and the Power Processing Unit. DMPS was designed to be spacecraft agnostic. The DMPS is shown below in Figure 1.

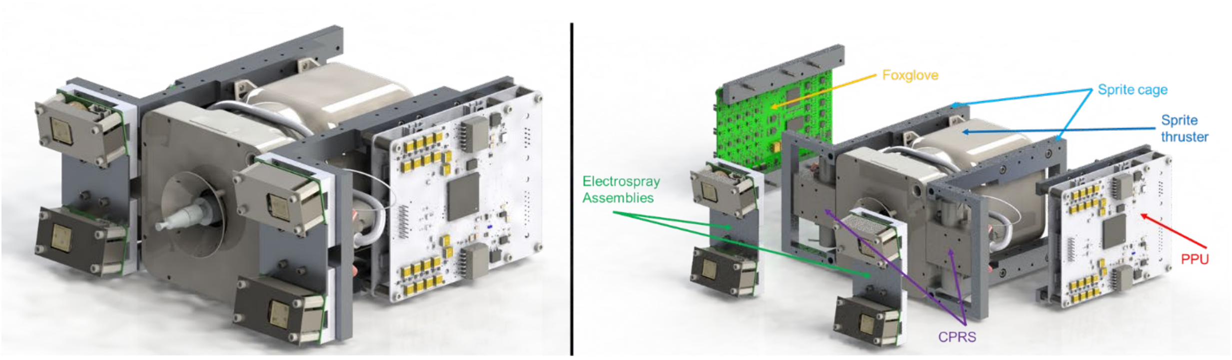

Figure 1. GPDM’s Dual-Mode Propulsion System.

Sprite serves as the “core” of DMPS. Sprite is a self-contained chemical propulsion system provided by Rubicon Space Systems (a subsidiary of Plasma Processes LLC). Sprite is an additively manufactured, titanium pressure vessel with a single integrated 0.1 N (100 mN) ASCENT thruster. These thrusters’ design was qualified for Lunar Flashlight. Sprite is a blowdown system operating from 275 psi to 60 psi. The development of the Sprite propulsion system is detailed in Reference [2].

DMPS contains 4 ASCENT electrospray thrusters in the ion Electrospray Propulsion System (iEPS) provided by MIT SPL under an STTR agreement. The electrospray thrusters consist of an emitter array aligned with extractor electrode that can extract ions directly from the ASCENT propellant. The emitter is passively fed propellant via a reservoir that rids ASCENT of its water content and other volatiles. [3] The Power Processing Unit (PPU) was designed by Espace and supplies the electrospray thrusters their required high voltage power.

The electrospray thrusters have a maximum inlet pressure of <10 psi. With the Sprite module operating at pressures up to 275 psi, there is a need for a system to step down the tank pressure to a pressure acceptable for the electrospray thrusters. The Compact Pressure Reduction System (CPRS) serves this purpose and as the manifold to distribute the propellant from one outlet line to four electrospray thrusters. CPRS is managed, designed, and tested by MSFC with collaboration with GT.

The Foxglove controller was designed by GT and commercially manufactured. It is a slightly modified version of the Foxglove controller used on the Lunar Flashlight Propulsion System. The Foxglove controller serves as the flight controller for the GPDM spacecraft, commanding the DMPS components.

The rest of the spacecraft (referred to as “the bus”) is relies mostly upon COTS components and flight heritage hardware. The COTS components include the XACT-50 attitude control system by Blue Canyon Technologies, the 112W SADA solar array by MMA Design, the antenna suite by Haigh-Farr, the RDMS receiver and TIMTER transmitter by Quasonix, and the Q7 flight computer by Xiphos.

The electrical power system (EPS) is designed and built by GT. It includes of 15 18650 Li-Ion distributed across the spacecraft in packages of 3. The EPS is largely based on the system used on Lunar Flashlight, with minor updates, namely cell balancing between battery packs, an in-house hardware-based watchdog circuit, and output voltage changes.

COMPACT PRESSURE REDUCTION SYSTEM

The CPRS underwent a significant number of design changes from Specter to GPDM. The initial development was conducted by MIT in support of their iEPS as discussed in Reference [4] [4]. An AM version of the CPRS was proposed as part of the design development for the Specter propulsion system. [1] An AM design was proposed to meet volume constraints. Furthermore, the design was developed to take advantage of COTS micro solenoid valves. Furthermore, the AM design took advantage of AM designs to allow for longer channel lengths in a more compact volume. Furthermore, the surface finish of the AM channels allowed for additional pressure drops. This in turn allowed for larger cross-sectional areas compared to capillary tubes from the MIT design. As shown in Figure 2, a unit was designed, printed, and tested in support of the Specter Flat Sat testing in 2021.

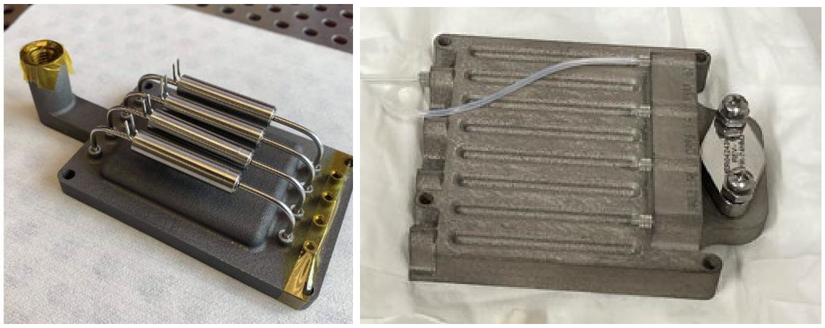

Figure 2. A) Specter AM Brazed CPRS Design. B) AM Fitting-joint CPRS Design.

Testing for the AM design resulted in successful demonstration of dual-mode operations. However, limitations with the AM CPRS design were identified. The brazed valves to the CPRS made removing a valve and qualifying the joint challenging. In addition, concerns with removing powder from the complicated channels resulted in re-evaluating the AM design. Further, the change of the GPDM mission from purely a propulsion system to the entire spacecraft, allowed for additional volume for a larger CPRS as needed. Concerns about the controllability of the passive AM CPRS along with FOD concerns from an AM CPRS resulted in the desire to redesign the CPRS.

The redesign of the CPRS ultimately incorporated more robust, proven components with the additional volume available and was able to deliver propellant reliably to the electrospray thrusters. Instead of being a single module, CPRS evolved into a pair of traditionally machined blocks that allowed the thruster valves to be close coupled to the electrospray thrusters. This limited the line length between the electrospray thrusters which mitigated risk by decreasing the length of polymer tubing required for electrical isolation. Instead of using tortuous AM pathways for pressure reduction, COTS viscojet flow restrictions were installed upstream of each thruster valve. The COTS micro-solenoid valves were replaced with Lunar Flashlight Propulsion System Heritage Solenoid Valves due to their excellent performance on that spacecraft. The interfaces to the electrospray thrusters were redesigned as part of the CPRS development, to use COTS fittings designed to work with polymer tubing, but compatible with metal ports. The flight version of CPRS can be operated in two modes: vapor pressure and direct transfer. Both methods of transfer have been tested at MSFC using the COTS viscojet as the flow restriction. The completed CPRS design is shown in Figure 3.

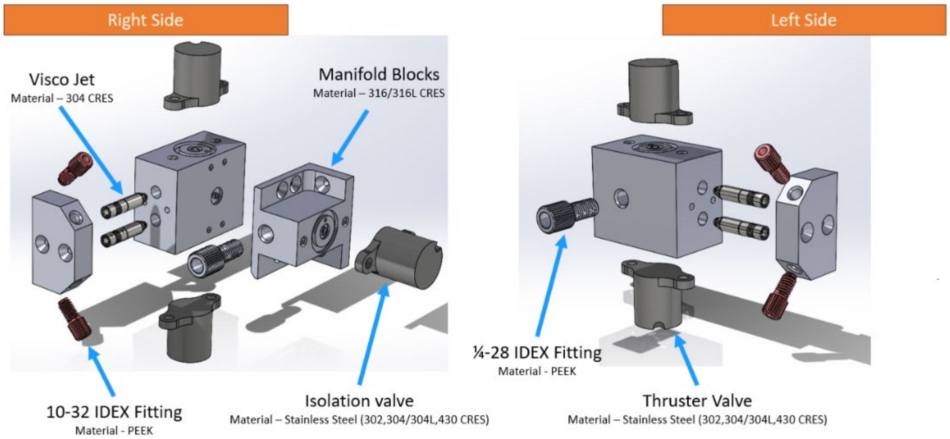

Figure 3. Detailed breakdown of updated CPRS design.

The vapor pressure method relies on the properties of ASCENT itself and the porous teflon reservoir of the electrospray thrusters. Since gasses can move freely out of the reservoirs, the vacuum environment allows the water in ASCENT to vaporize and escape. In practice, this means that propellant lines not isolated from the thruster reservoirs will form gas bubbles over time, and those bubbles will travel the length of the propellant line to the reservoir, pushing liquid ASCENT along for the ride. Although this method is slow, it results in an extremely low-pressure transfer of an exact fluid quantity. Operationally, the procedure is as follows:

1. During spacecraft initialization, open thruster isolation valve to allow any nitrogen between the propellant isolation valve and thruster valve to escape.
2. Close thruster valve.
3. Open propellant isolation valve, allowing the line between the valves to fill with propellant. This is a known volume.
4. Close the propellant isolation valve and open the thruster valve. As the water in ASCENT vaporizes due to its vapor pressure, gas pockets form in the propellant line and the whole volume travels slowly into the electrospray reservoir. This process may take significant durations of time dependent upon the line length it needs to travel.
5. Once all propellant has transferred, close the thruster valve. The line volume between the valves is now in the electrospray reservoir, and the line volume has been vacated and is ready for another transfer.
6. Repeat this process until the desired volume is transferred to the reservoir.

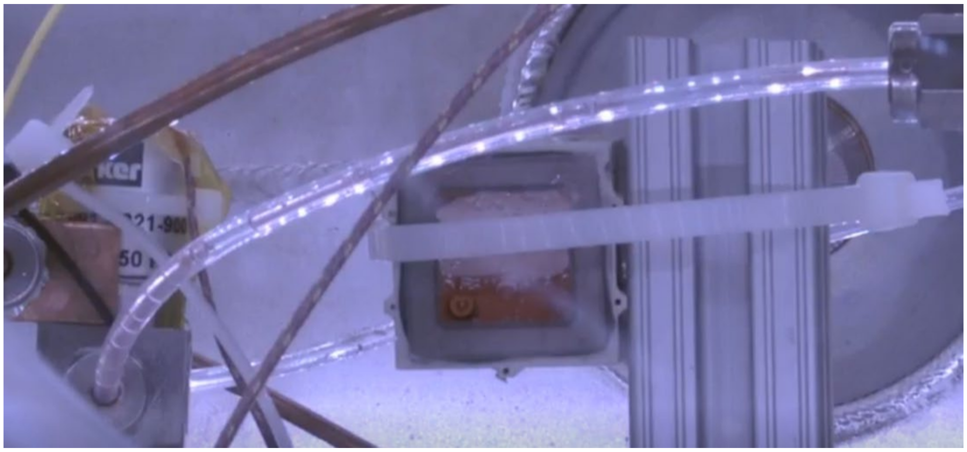

Figure 4. Vapor transfer testing was completed as a proof of concept using a facsimile electrospray reservoir and a pair of COTS mini-solenoid valves. The clear polymer tubing used allowed for visualization of the water vaporization.

The direct transfer method is simply opening both the thruster and propellant isolation valves and allowing ASCENT to flow directly into the reservoir. The COTS viscojet device provides a significant pressure drop whose exact value is dependent on the pressure of the SPRITE tank, since it is a blow-down system. Testing is ongoing at MSFC to determine the flowrates and pressure drops of the CPRS system as a function of SPRITE pressure. The transfer initially will be completed in a series of pulses at the higher SPRITE pressures and can be completed in a single transfer of the total volume at lower SPRITE pressures. This transfer method has the benefit of the being fast but is a higher-pressure transfer that must be monitored for the safety of the electrospray thrusters.

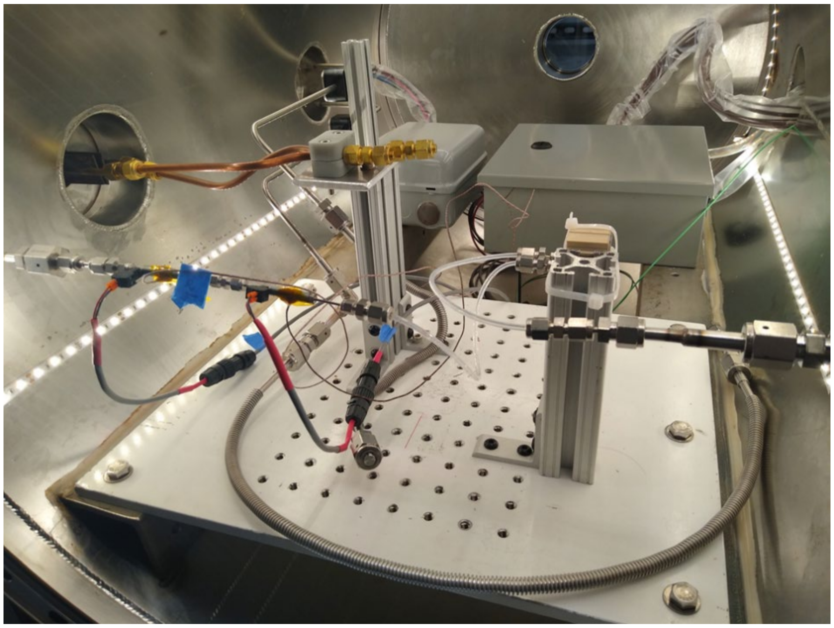

Figure 5. Initial direct transfer testing using the viscojet was completed with COTS micro-solenoid valves and a facsimile electrospray tank reservoir in a 2 ft vacuum chamber as a proof of concept. Testing using flight-equivalent components is ongoing at MSFC.

ADDITIVELY MANUFACTURED PRESSURE VESSEL

The SPRITE pressure vessel represents one of the first additively manufactured pressure vessels to be incorporated on a spacecraft. Typical pressure vessel standards still apply to prevent loss of craft or mission; however, most of these standards are not formulated with additive manufacturing in mind and the unique qualities of the final product. This presented a challenge to follow both NASA-STD-6030 (for additive manufacturing) as well as S-080 for metallic pressure vessels. A tailored approach to both standards due to the size of the tank and its contents allowed for successful completion of the design.

The initial analysis of the pressure vessel showed significant margins on static (pressurized) strength as well as inertial loading due to launch loads. These static margins were verified through pressurized testing where the MEOP of the tank was exceeded by more than a factor of 5. The analytical strain measurements were experimentally verified as well with a Digital Image Correlation software suite showing good agreement between the predicted and actual deformations.

However, for spaceflight the pressure vessel must also be accepted by range safety. One of the challenges with additive manufacturing is that the part is challenging to inspect, and minimal fatigue and fracture properties are available which are required for compliance to S-080 and NASA-STD-6030. Work across Marshall developed fatigue and fracture properties of the material from printed specimens, which allowed for point certification of this specific tank set. While the NASA standards for additive manufacturing require substantial sample sets to certify both the machine and process for general usage, this was tailored to the specific flight hardware by developing test samples obtained from the build plate utilized for the flight hardware. Existing tensile test data compared well with tensile tests performed and Marshall while fracture specimens and fatigue specimens were fabricated and tested successfully to develop properties to be used in the analysis.

LESSONS LEARNED FROM LUNAR FLASHLIGHT

Anomaly Summary

The Lunar Flashlight mission commenced in December 2022 after a successfully demonstrated and safe loading of ASCENT at Marshall Spaceflight Center. The propulsion system was designed to perform a series of trajectory correction maneuvers using the 4, 0.1 N thrusters on its journey through cis-lunar space and on its way to the NRHO orbit. The thrusters were also planned for use during LFs insertion burns to NRHO. After a successful deployment from the dispenser, Lunar Flashlight performed a nominally planned propulsion system checkout [5]. Ground based telemetry revealed a difference between the vehicles expected momentum rate and the actual rate which pointed to a reduction in thruster performance of the system. Initially, there was indication that Thruster 1 was producing less thrust than the 0.1N which each thruster was qualified for during the ground qualification testing. Eventually, anomalous performance was seen in Thrusters 2 and then 3, leaving Thruster 4 as the only nominally operating means of chemical propulsion. After about a month of troubleshooting, Thruster 4 also saw sub-nominal and anomalous performance. The joint JPL-MSFC-GT team began to work through a fault tree to investigate the anomalous thruster behavior across the system. The apparent anomalies did not seem to impact other propulsion system components including thruster valves and the pumps or controllers. The team was able to use telemetry to observe that the manifold was able to hold nominal pressure as well. Pump reversal activities allowed the team to temporarily but intermittently recover performance from the thrusters, pointing to potential obstructions of the flow passages in the manifolds and to the thrusters. Overall, the thrusters did produce a combined 16 m/s of delta V, but this was not enough to achieve lunar orbit insertion into the planned NRHO. The Lunar Flashlight CubeSat never reached NRHO; after months of operations in cis-lunar space, the mission effectively ended in May 2023 when LF did its final flyby of Earth prior to entering heliocentric space.

Lessons Learned Summary

A NASA internal "lessons learned" summary was led by the NASA Engineering & Safety Council (NESC) to further understand "what happened with Lunar Flashlight" [5]. Like GPDM, Lunar Flashlight was a NASA Procedural Requirements (NPR) 7120.8 "Research & Technology" project. NPR 7120.8 projects are highly tailorable projects in which the risk posture is drastically different than NPR 7120.5 projects (which include human spaceflight mission activities in which safety of crew is the highest priority). As such, system development for LFPS (and GPDM) emphasizes a "higher risk acceptance, least restrictive, but high impact posture" per the Small Spacecraft Technology program. Furthermore, LFPS was not subject to the same quality control and safety & mission assurance pedigree that would be expected for a 7120.5 style NASA project/mission.

The Lunar Flashlight Propulsion System's manifold was made as a single structural component (including the propellant fuel lines) from 3D printed additively manufactured Ti64, in which the Laser Powder Bed Fusion (LPBF) approach was implemented. From the NESC study, it is suggested that either during manufacturing, post-processing, integration, or even launch due to high vibration loads, foreign object debris (FOD) in the form of un-sintered Ti64 powder may have contaminated the extremely small fluid lines which were routed from the propellant tank through the four thrusters. A specific culprit for this FOD is that after the LPBF process during the manifold's build, open spaces in the fuel channels within the manifold block, powered which didn't fully adhere to the manifold walls remained loose. While heat treatment had been performed for the LFPS manifold, it’s possible that this process didn't cause all of the powder to adhere to the walls; thus, remaining powder which was partially sintered may become loose later in the integration process and subsequently become contaminants/FOD withing the fuel lines. Given the short schedule and overall risk posture, the LFPS Project did not implement rigid contamination and control, nor did it perform CT scans or a subsequent hotfire test of the flight system although the propulsion system individual components (thrusters, pumps, and valves) did undergo extensive ground qualification test campaigns. Specific NESC recommendations from the study for 3D printed/AM small spacecraft propulsion systems included implementation of more rigorous contamination and control plans, implementation of CT scanning of 3D printed passages, and using filtration between specific fluid components (e.g., between thruster and propellant tank) to behave as a physical barrier or last line of defense against future contaminants.

GPDM Implementation

The 3D printed parts for the GPDM propulsion system are specific to the Sprite chemical propulsion subsystem - specifically, the Sprite propellant tank, propellant management device (PMD) and manifold which is welded to the tank and houses the Foxglove controller, thruster and fill/drain valve and mates to the chemical thruster itself. Sprite's 3D printed components will use the LPBF approach as was used to machine the LFPS manifold block but with several modifications and with additional post machining procedures to ensure proper fluid delivery to the rest of the propulsion system. First, after machining, the Sprite manifold internal passages will be treated with an adverse flow machining (or slurry honing) agent which has shown promise in clearing out loose powder in 3D printed passageways in other applications including automotive design. This approach has been and will be applied to both the Sprite engineering development units and the actual GPDM Sprite flight unit. Second, the GPDM project and Rubicon Space Systems has implemented CT scanning of the Sprite 3D printed manifolds. Initial scans of the engineering development units show no visible signs of passages. This approach will be duplicated for the flight unit which is planned for completion in Summer 2024. Third, filter elements are planned for implementation into the flight unit for Sprite and within the CPRS system. Specific locations of filters include downstream of the Sprite propellant tank and upstream of the thruster inlets as well as the thruster valve and fill-drain valves. Fourth, Rubicon Space Systems conducted an initial ground hotfire test in October 2023, in which it demonstrated successful propellant flow through of the 3D printed manifold. During Rubicon's initial Sprite hotfire test, the manifold in a flight-like configuration experienced propellant conditions which simulated the full range of pressures that the blowdown system will experience from beginning of life (BOL) pressure of 275 psi all the way down to the end-of-life (EOL) condition of around 75 psi. During this test campaign, there was no sign of propellant restrictions in the Sprite 3D printed manifold, nor was there indication of thruster performance degradation. The 0.1N thruster reached steady state conditions of over 100% nominal thruster in some cases. The GPDM Project plans to repeat these tests on a protoflight unit at MSFC prior to GPDM vehicle integration which is planned to start in the Fall 2024 timeframe.

ANALYSIS

THERMAL ANALYSIS FINDINGS

GPDM faces the typical thermal concerns that are associated with low Earth orbit spaceflight, which are maintaining components within their specified temperature ranges in environments that include the dichotomy of solar heating and the coldness of space. In addition, GPDM must be able to survive any self-induced heating from components. While this is true for all spacecraft, in particular the heat generated by the preheat and decomposition process for the chemical propulsion system could cause issues if not properly managed. A thermal model was created with the current baselined configuration to assess the worthiness of the design, as well as to make recommendations to the design to increase likelihood of success and reduce risks. Due to a recent increase in scope, the Bus components are in a very early phase of modeling, and thermal results are not available. However, DMPS is further along in its modeling, and can provide preliminary thermal analysis findings. Ansys Thermal Desktop is the program of choice due to its speed, accuracy, and capability of modeling orbital environments.

When creating thermal models for spacecraft, simplifications are often made avoid undesirable run times. If a simplified region yields results that are not within design constraints, design changes are suggested, and modeling fidelity is increase within that region. In addition, models are often bounded between a worst-case hot and worst-case cold case to help ensure a viable design. These are the approaches being taken for GPDM.

As mentioned, DMPS modeling is only providing preliminary findings at this point. However, these findings are still able to help inform design changes, stir discussion, and uncover where current modeling fidelity need to be increased. One of the most important design changes that has come from thermal modeling is the addition of thermal tape on the sun-facing surfaces. The optical properties of bare metal often have a higher value of solar absorptivity (α) compared to infrared emissivity (ε). When this ratio, α/ε, is greater than 1, it often results in high temperatures for sun-facing surfaces. This often results in more heat propagation deeper into the spacecraft, where more temperature sensitive components typically are. By taping surfaces low α/ε properties, spacecrafts can reject more energy. This has benefited GPDM in that the DMPS does contains such temperature sensitive components, and thus, taping the sun-facing surfaces has helped reduced the thermal environment that these components are experiencing.

An example of one of these components is the Foxglove electrical board that is contained within the Sprite module. Even with design changes, the thermal environment, in addition to its self-induced heating, was causing this board to exceed its current temperature limits. However, these current temperature limits were results of testing that were limited in their maximum temperature range. After discussion with the team, it was determined that the board could likely survive these higher temperatures, but new qualification tests were warranted. Another discussion that was stirred from the thermal modeling was about the low end of the AF-M15E temperature limit. During the worst-case cold case, thermal modeling was showing that the lower limit of the propellant inside the tank was being exceeded. However, similarly to the Foxglove electrical board, it was determined that tests would be conducted at a lower temperature limit to requalify components.

As mentioned, modeling fidelity is increased in regions where components are exceeding their temperature limits. This situation occurred with the GPDM electrospray thrusters, as they were exceeding their temperature limits. However, after discussion with MIT and gaining a better understanding of the electrospray configuration, it is believed they will not exceed limits after modeling fidelity is increased, which is currently in work.

Thermal modeling has provided valuable insight for GPDM resulting in design changes and stirring conversations. The preliminary results have also helped uncover where modeling fidelity needs to be increased to capture temperature gradients more accurately. The model will continue to be used this manner and will soon include Bus components to help better inform the GPDM mission. There are currently no components that do not have a path forward to ensure requirements will be met.

STRESS ANALYSIS FINDINGS

The stress analysis of the additively manufactured test specimen found that the design is suitable for flight usage. Significant margins were predicted via finite element analysis, which for a cutting edge additively manufactured design reduce risks. Additive manufacturing material properties can have significant scatter in the data which for an initial design can present uncertainty in acceptability until enough data is collected.

After significant static margin was established, the fatigue and fracture material properties developed were used for Nasgro analysis. Because this is a blowdown tank utilized for only one mission, only very large through flaws are significant enough to reduce the fatigue life below the minimum number of cycles required. These large flaws can be easily detected either through inspection or measuring the leak rate during acceptance.

To verify the static strength predictions, MEOP and burst tests were performed on the test article Sprite tank. The predicted burst pressure was approximately 2,300 PSI based on the minimum tested material properties, so as predicted, the tank survived 1700 PSI of pressure, a factor of safety of approximately 5 on the MEOP. Digital Image Correlation using the ARAMIS system was then utilized for a MEOP pressurization of 275 PSI. Both the shape and measured strains compared favorably with predictions as shown in Figure 6.

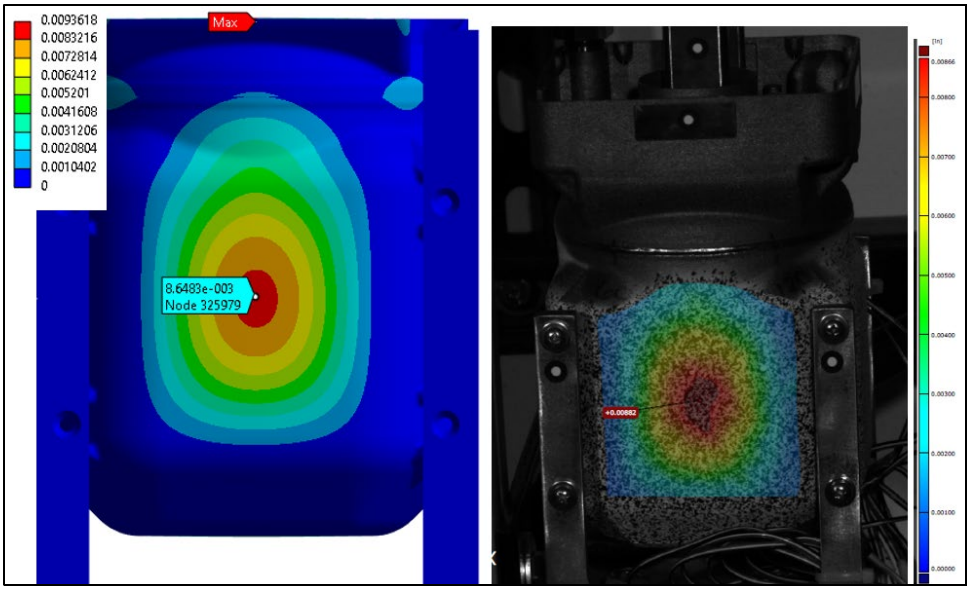

Figure 6. Predicted vs actual Sprite burst testing.

DIGITAL IMAGE CORRELATION FOR PROOF TEST VALIDATION

Digital Image Correlation (DIC) is a contactless deformation measurement technique that has become a powerful tool in experimental mechanics. The method works by using one or more calibrated digital cameras to measure a randomly speckled surface as it undergoes deformation. The cameras are calibrated with a known reference object to determine the lens distortion, focal length, and relative position and orientation of the cameras with respect to the measurement body and to each other. A random speckle pattern is applied to the structure, with a desired speckle diameter that is typically between 3-7 camera pixels and a speckle density of approximately 50%. With the recorded image data, this speckled surface is discretized into small regions of at least 2 pixels each called subsets or facets. These subsets are then tracked through the test for each camera and then triangulated to provide both in and out of plane displacement data. A few of the key advantages of DIC are the measurement of displacement and strain over entire surfaces, displacement resolutions as low as 1/100th of a pixel, and through choice of cameras and field of view the ability to make measurements at virtually any framerate and length scale.

In this test, a two-camera ARAMIS DIC setup was used to measure the surface deformations of the SPRITE article. The article was first painted a matte white, after which a black speckle pattern was applied to the surface. In addition to the speckled surface, single point tracking dots were applied to the thrust mount and mounting frame of the article to provide. These provided measurements of both the thrust mount displacement and a correction for possible rigid body motion between the article and cameras. Two, 1.3 MP Photron high speed cameras were stereo calibrated and collected images at 125 Hz during the test after being manually triggered. A total of 106 seconds of DIC data was captured over the pressure ramp during testing.

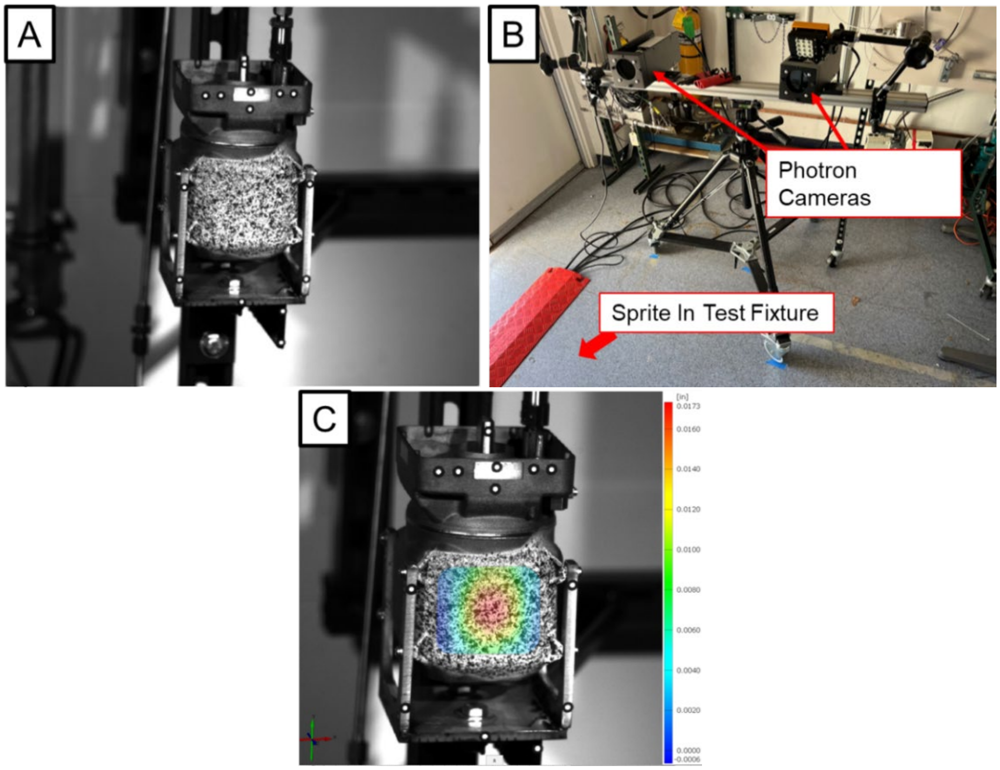

Figure 7. A) Speckled SPRITE article in test figure, as seen by cameras. B) Stereo camera setup. C) Processed surface normal displacement field.

The test data was down sampled and processed at a framerate of 5 Hz, and the resulting deformation data was temporally aligned with the pressure time history. After discretization of the surface image data 418 subsets were identified and tracked, each providing a time history measurement of displacement and strain. The test results indicated a linear relationship between the surface strains on the article and the internal pressure. A maximum von Mises strain of 0.34% was observed at the maximum captured gage pressure of 517 psig. Good correlation was found between the measured strains over the surface from DIC and those predicted by FEA analysis, and there were no concerning deformations measured from DIC up to the maximum pressure recorded. The use of DIC for this test demonstrated its ability to measure full field deformations quickly and easily on pressurized hardware.

GROUND BASED TESTING

GPDM has undergone ground-based testing campaigns concurrent with mission design and development activities. These campaigns have informed CPRS design and development (as mentioned above) along with DMPS development. With GPDM and DMPS designs more mature, Flat-Sat testing campaigns are ongoing to qualify and confirm different designs' success in the completed integrated system.

Each of the campaigns are designed to incorporate flight-like hardware, software, and procedures in a systematic method. The culmination of the effort is a complete propulsion module with flight-like components and features that reaches the 'test-as-you-fly' philosophy as closely as possible. The original sequence of testing as planned would have completed the campaigns in sequential order. Development doesn't always follow a linear path, and each of the campaigns could build on others or focus on specific areas while development continued in other areas.

Table 1. GPDM Flat Sat Testing Campaign

Campaign	Description	Status
1A	Chemical feed system builds and limited thruster testing	Complete
1B	CPRS and electrospray filling demonstration	Bench Level
2A	Performance data in LF typical profiles	Completed
2B	Performance data in GPDM typical profiles	Completed
3	Performance data in GPDM expected profiles (durations and pulse rates)	Partial
4	Electrospray reservoir, CPRS integration/modifications	Upcoming
5	Combined chemical thruster testing and electrospray reservoir filling	Upcoming
6	Combined chemical and electrospray thruster operations	Upcoming

Figure 8. Chemical thruster test stand.

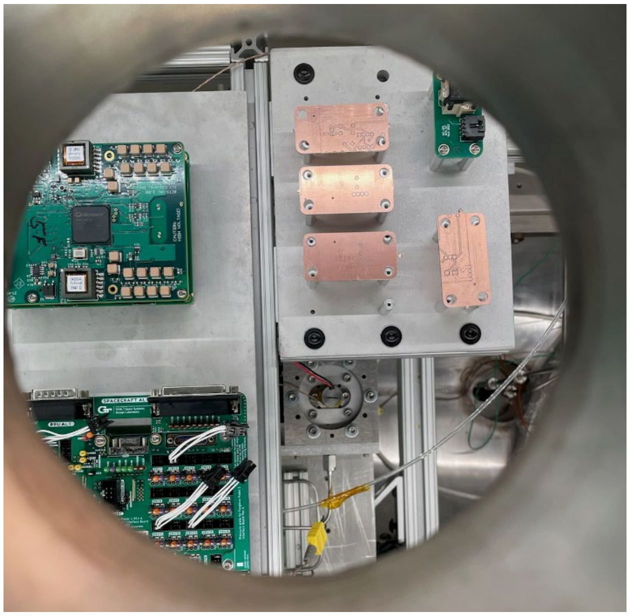

Figure 9. Electrospray thruster test stand.

Campaign 1A focuses on chemical thruster feed system development and integration. Previous lessons from the LF mission and how the team tested the hardware form a big part of the current efforts. Developing the feed system and supporting structure for the GPDM FlatSat testing during this part of the testing was iterative. Accurate flow measurement at the 100 mN thrust range (approximately 45 mg/sec) ASCENT flow rates are challenging, both for steady-state and pulsing flows. The original system used a propellant supply tank internal to the FlatSat system that resided in the altitude chamber. The flow measurement system was located outside of the chamber, which led to long propellant lines out of and then back into the chamber. To shorten the propellant lines, the propellant supply was moved outside of the altitude chamber. This resulted in easier operations and higher fidelity specific impulse measurements. Hot fire testing of the 100 mN ASCENT chemical thruster proved the hardware and feed system ability to provide propellant accurately to the FlatSat test article.

Campaign 1B focuses on the electrospray reservoir filling hardware and the CPRS developments. The GPDM mission requirement to fill and refill each of the electrosprays drives introduces complexities in pressure reduction and flowrate control to protect the electrospray thrusters from over-pressurization.

Campaign 2A and 2B return focus to the chemical thruster operations. Because of the lessons learned from LF, modifications to the test stand hardware/feed systems, and the potentially different operating environment for the chemical thruster, a basis for comparison to previous data was needed. Campaign 2A replicated operational profiles from LF. Campaign 2B focused on GPDM anticipated sequences.

Campaign 3 is like campaign 2B but expands into inlet pressure variation mapping. LF was a pump driven propulsion system that provided a constant thruster inlet pressure regardless of the propellant tank supply pressure. GPDM's requirements and mission goals didn't require the pump capabilities, therefore the 100 mN thruster will operate in blowdown mode. The data set available at various inlet conditions is less complete at lower inlet pressures, therefore this campaign focuses on thruster performance at lower inlet pressures. Thruster inlet pressures between 75 psia and 275 psia are used with the same pulse sequences to gather specific impulse, thrust, and thermal data to support mission design and thermal models.

Campaign 4 begins integrating chemical and electrospray reservoir hardware together. The CPRS design continued to evolve during the early phases of the FlatSat development. As the design matured, parts were added to the FlatSat system or tested on the bench to verify operation. Because the development hardware isn't flight-like, the system is controller with the lab data and control systems.

Campaign 5 is the first opportunity to test loading electrospray reservoirs using the GPDM flight-like controllers and software. The timing for loading operations, and fluid flow characteristics are the primary data from this campaign.

Campaign 6 is a full demonstration of chemical and electrospray operations. The previous 5 campaigns demonstrate all the features of the system separately, but this test sequence will be the first demonstration combined into one sequence. Reaching this test campaign requires extensive verification that the facility, personnel, and FlatSat are ready for operations. Once the electrosprays are wetted with propellant the altitude chamber will not be repressurized until the completion of testing.

Data reduction and video analysis of the test campaigns continues. Preliminary reviews show excellent performance of to meet the GPDM needs. Data matching the LF performance agrees at the tested conditions. Figure 10 shows a single 10 second steady-state pulse at 275 inlet pressure. At this condition, the expected thrust is approximately 120 mN.

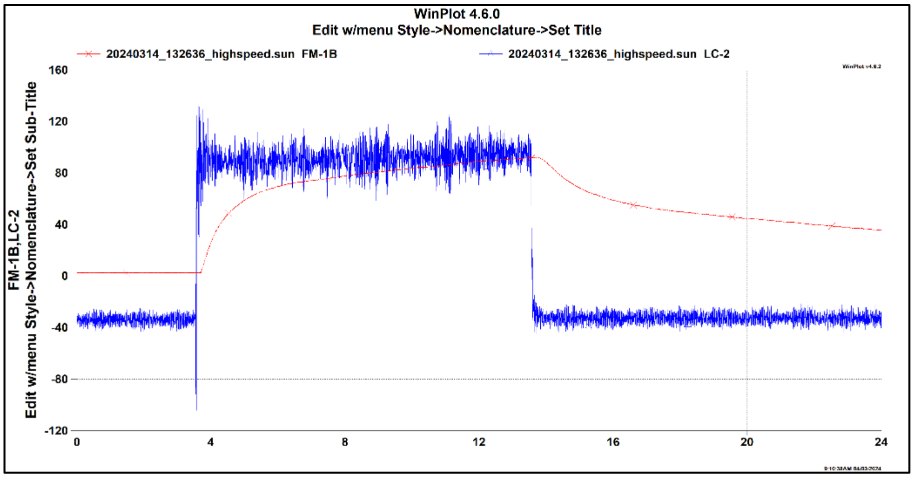

Figure 10. 10 second single pulse.

MISSION OPERATIONS PLAN

The GPDM satellite mission is a 9-month endeavor aimed at showcasing a new propulsion capability utilizing ASCENT propellant, testing the refueling capabilities of electrospray thrusters, and testing electrospray thruster effectivity through altitude change maneuver. The mission's operational plan involves deploying the satellite as a secondary payload at an altitude of 520km, then performing frequently altitude change maneuvers with both the electrospray and chemical thrusters between a perigee of 520km and an apogee of 525km to demonstrate its propulsion capabilities.

The Mission Operations Center (MOC) for the GPDM satellite is situated at the Georgia Institute of Technology (GT), with propulsion experts stationed at NASA/MSFC in Huntsville, AL. The mission comprises multiple phases of increasing complexity building on each successful burn duration until mission duration is complete or fuel reserves required for decommissioning are reached.

During the launch, the GT team will be on-console to monitor the satellite's deployment from the launch at 520km – approximately 1 hour after liftoff. At the pre-determined timing sequence from deployment, the spacecraft will initiate automated bootup, perform detumbling processes to stabilize itself, and establishing communication with the MOC. Once ground communications are established, the Mission Ops team will assess the spacecraft's health, ensuring all systems are operating nominally. In the subsequent weeks we will incrementally increase thruster burn durations to assess performance as part of commissioning the propulsion system (electrospray and chemical thrusters) for full-scale operations. Upon the successful completion of the commissioning phase approximately 22 days into the mission, a Mission Readiness Review (MRR) will be conducted to review the commissioning results with Project and Program management and obtain approval to move into operations.

The operational phases entail executing longer duration iterations of the propulsion system, using the Electrospray thrusters and/or chemical thrusters to adjust the satellite's orbit either upward or downward. The distinction between operational phases lies in the duration of each burn. At the culmination of the 9-month mission, the satellite will be maneuvered into a de-orbit attitude of 480km or below, marking the conclusion of the mission.

SUMMARY, CONCLUSIONS, AND FUTURE WORK

This paper summarizes design, analysis, testing, and planned flight activities of a Green Propulsion Dual Mode (GPDM) spacecraft for a research and technology demonstration mission on a 6U CubeSat. This project is building on lessons learned and prior experience with using the low-toxicity, ionic liquid known as ASCENT for small spacecraft (e.g., Lunar Flashlight's Propulsion System). GPDM is demonstrating the use of ASCENT as both a chemical and electrospray propellant in a common feed system to achieve high thrust and high efficiency translation and rotation in LEO. Thus far, the GPDM project has demonstrated successful design, development and testing of dual-mode system components, including the 0.1 N chemical thruster, the compact pressure reduction system (CPRS), and the 3D printed additively manufactured propellant tank and manifold in the Sprite chemical propulsion subsystem. GPDM is actively working to move into several major project milestones and subsequently prepare for a launch through the CubeSat Launch Initiative (CSLI) rideshare activity as a secondary payload nominally planned for the Fall 2025 timeframe.

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