Integration and Testing of a 2U Cold-Gas Propulsion System for the SunRISE Mission

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The Georgia Tech (GT) Space Systems Design Laboratory (SSDL) is building six identical cold-gas propulsion systems to provide the necessary maneuvering capabilities required by the SunRISE mission. The mission plans to observe low frequency emissions from the Sun by utilizing an array of CubeSats that will formation fly to create a large radio telescope in space. The cold-gas system design is based on the lab's heritage design used for previous missions, namely BioSentinel, which leverages additive manufacturing to create a highly optimized propulsion system for the CubeSat form factor. The unique system consists of mainly a singular printed multifunctional structure encompassing tanks, plumbing, and nozzles, and utilizes a two-phase propellant to maximize the amount of propellant stored in the restricted volume and hence the total impulse provided by the system. This report provides a brief overview of the system design and its purpose in the SunRISE mission, while detailing the integration process and extensive testing campaign each flight unit goes through before they are delivered for integration with the spacecraft.

Nomenclature

Abbreviations

AM	=	Additive manufacturing
COTS	=	Commercial Off-The-Shelf
EDU	=	Engineering development unit
ESD	=	Electrostatic discharge
FEA	=	Finite element analysis

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FHL = Flight Hardware Lab

GEO = Geosynchronous Earth orbit

GSE = Ground Support Equipment

GT = Georgia Tech

I_{sp} = Specific Impulse

JPL = Jet Propulsion Laboratory

MEOP = Maximum expected operation pressure

PCB = Printed circuit board

QCD = Quick disconnect

SDL = Space Dynamics Lab

SLA = Stereolithography

SPS = SunRISE Propulsion System

SSDL = Space Systems Design Lab

TVAC = Thermal vacuum

I. Introduction

Over the past two decades, humanity has witnessed a paradigm shift in the way the space community produces satellites. Instead of only designing and building big, complex, and expensive satellites that have numerous capabilities, the space community is leveraging the relatively recent miniaturization of electronics and advancements in manufacturing techniques to create smaller and cheaper satellites, capable of performing more simple functions than traditional satellites, or work in a formation to perform more complex and never done before tasks. One of the most popular platforms for small satellites is the CubeSat. With the availability of high performance and cheap commercial off-the-shelf (COTS) technology, CubeSats provide a low-cost and modular solution to building and launching a variety of missions for the entire space community, from space agencies to universities. CubeSat mission objectives have ranged from technology demonstration and science proof-of-concept validation to providing high resolution day to day imagery of Earth. However, CubeSats are mainly restricted in their capability by their small form factor, providing a very tight mass and volume budget to work with. Therefore, the development and supply of highly integrated and miniaturized subsystems is necessary for the CubeSat market to continue to flourish.

One of the more challenging subsystems to miniaturize is the propulsion subsystem. As more CubeSats get launched with an attempt to perform more advanced tasks for longer periods of time, the necessity of miniaturized and efficient in-space propulsions systems becomes more apparent. Such systems provide mobility capabilities for station keeping to extend mission life time, orbit insertion for conducting new science, collision avoidance, attitude control, faster deorbit, and many more. A variety of both chemical and electric in-space propulsion systems have already been used onboard a variety of CubeSat missions with each type targeting a different type of mobility profile. Chemical systems are required for more energetic burns and quick impulsive maneuvers whereas electric systems are typically used for very efficient but low thrust maneuvers, such as deep-space maneuvering. Furthermore, electrical systems are very power intensive and therefore are usually not feasible for many smaller CubeSat missions that have limited onboard power.

Cold-gas systems offer the simplest, safest, and most cost-effective chemical propulsion solution but exhibit a low specific impulse (I_{sp}), which is the measure of how efficiently the engine uses its propellant to create thrust. While such systems utilize neither heating nor chemical reactions to extract more work from the propellant in the way that monopropellant and bipropellant propulsion systems do, they are still very capable and reliable. However, most of the cold-gas systems on the current market are not as optimized for the CubeSat form factor, mainly due to manufacturing limitations. The cold-gas system still requires many individual components, such as the thruster, valves, plumbing, and propellant tanks, that need to interface together, the assembly of which requires tooling access. This directly limits the amount of available volume that can be used for storing propellant, which in turn limits the total impulse or delta-v capability of the system.

For the past few years, the Georgia Tech (GT) Space Systems Design Laboratory (SSDL) has taken advantage of the recent advancements in additive manufacturing (AM), or 3D printing, to develop a more optimized and efficient cold-gas system for the CubeSat form factor. Using additive manufacturing as the primary means of building propulsion systems provides many advantages, including reduction of components, interfaces, and consequently less leak pathways, easier and quicker assembly, and design of irregular tank geometries. This has allowed SSDL to develop a modular propulsion system design standard where the bulk of the system is a singular printed part, shaped to best maximize the volume available. Furthermore, the use of a two-phase commercial refrigerant increases the performance of such system. To date, SSDL has developed and built two of such cold-gas systems, namely the BioSentinel propulsion system which serves as the design standard for the Lab and the ASCENT propulsion system which has been successfully operating in space for months [1]. Building from this heritage, the lab is currently working on the integration and testing of the SunRISE Propulsion System (SPS) that will provide delta-v and attitude control maneuvering capabilities for the NASA SunRISE formation flying mission, planned to launch no earlier than July 1, 2023 [2].

This report will outline the development of the SunRISE cold-gas propulsion system, with an emphasis on the integration and testing phase of the mission. The first section will provide a brief overview of the SunRISE mission as well as the role of the propulsion system in the context of the mission. The second section will dive into the design and working principle of the SPS. Next, an in-depth overview of the integration and testing of the propulsion system necessary to qualify it for flight will be provided. Lastly, the current status and future work of the project will be elaborated on.

II. SunRISE Mission

The Sun Radio Interferometer Space Experiment, SunRISE, is a formation flying mission, managed by NASA's Jet Propulsion Laboratory (JPL), to use an array of six identical toaster-size (6U) CubeSats to study solar activity. Each spacecraft, which is built by Space Dynamics Lab (SDL), will orbit within about 10km of one another in a supersynchronous geosynchronous Earth orbit (GEO) to create a giant single-aperture radio telescope as shown in Fig. 1 [2]. This is done through a method known as interferometry, in which many smaller radio telescopes can be combined to mimic a single, much larger observatory with a very high resolving power. This radio telescope will be used to observe low frequency emissions from the Sun and create 3D maps of where energetic radio emissions occur in the Sun's magnetic atmosphere, which signify the locations of extremely powerful bursts of radiation [2]. These maps will then be utilized to better understand what triggers them, how the particles are accelerated, and the ways in which particle storms evolve. These solar particle storms are hazardous to both spacecraft and astronauts. Therefore, increasing the community's knowledge of them will directly help develop solutions that can best protect future missions at risk of such storms. Furthermore, for the first time ever, SunRISE will map the magnetic field lines that originate from the Sun's interior and extend throughout interplanetary space [3]. Ultimately, the SunRISE mission will provide crucial data that will directly help scientists forecast space weather and improve humanity's understanding of how the Sun functions.

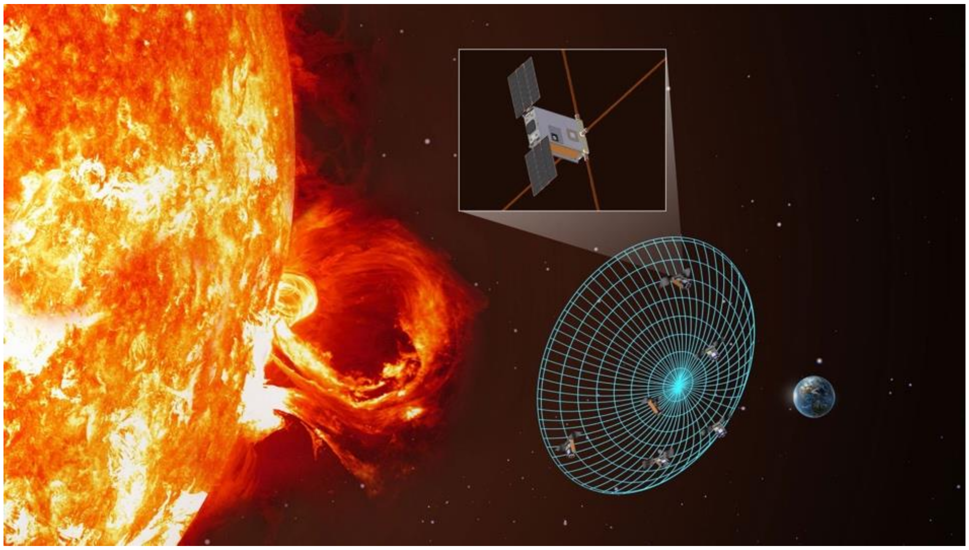

Fig. 1 Artist's concept of the SunRISE mission architecture [3].

For the constellation of spacecraft to precisely control their position and attitude relative to each other, each spacecraft will use an identical cold-gas propulsion system designed and built by GT SSDL. The SPS will be responsible for providing delta-v burns to insert each spacecraft into its designated location in orbit, maintain its location relative to other spacecraft, as well as provide attitude control maneuvers required for momentum dumping and science experiments. The propulsion system occupies about a third of the total 6U spacecraft volume and is located at one end of each spacecraft as shown in the Fig. 2.

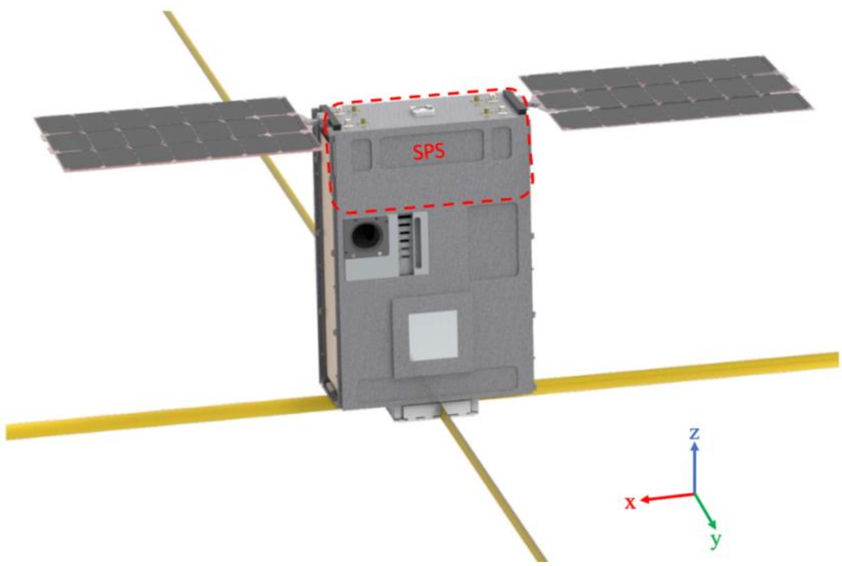

Fig. 2 Location of SPS in the SunRISE spacecraft [2].

III. System Design

A. Working Principle

Cold-gas propulsion systems typically rely on the ejection of a pressurized gas through a converging diverging nozzle to create thrust. The propellant is typically regulated to operate at a designed pressure and a control valve is used to provide the desired impulse. A simple schematic of a typical cold-gas system is shown in Fig. 3. A single-phase, usually gaseous, propellant is typically stored at very high pressures, on the order of 1000 psi or more, in thick pressure vessels to provide sufficient total impulse to meet the mission requirements. Working with such high pressures could be unsafe for handling, hazardous to the spacecraft and the launch vehicle, and therefore requires more extensive testing to ensure that the risk of any anomalies occurring is very low.

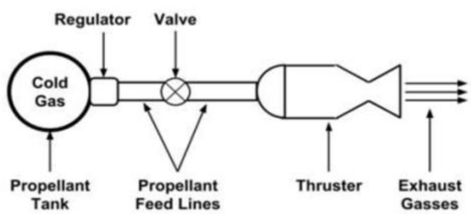

Fig. 3 Schematic of a typical cold-gas propulsion system [4].

To reduce the high pressures of typical cold-gas systems, the SPS uses a two-phase propellant. Two-phase propellants exist in both the liquid and vapor phase of the fluid stored at a constant saturation pressure for a given temperature. As the temperature of the fluid increases, the saturation pressure goes up and vice versa. There are two main advantages of using such a propellant. Thinner tank walls with irregular geometries can be designed as the propellent can be stored at much lower pressures than traditional systems allowing for more volume to be devoted to the propellant. Additionally, the propellant can be stored as a liquid which has a much higher density and therefore increasing the amount of propellant that can be stored for a given volume. The SPS uses R-236fa, which is a non-toxic and nonflammable, commercial refrigerant. Compared to other two-phase propellants available for this application, such as Butane or Ammonia, this propellant was chosen due to its high volumetric I_{sp}, handling safety, and its relatively low saturation pressure [1]. For reference, this propellant, at the maximum system operating temperature of 50°C, has a saturation pressure of 84.73 psia. This represents the maximum expected operating pressure (MEOP) of the system. Since the MEOP is under 100 psia, the system is considered as a “sealed container” rather than a “pressure vessel” and therefore is waived for stringent fracture control requirements that require more extensive testing [5]. Furthermore, this propellant is a relatively large molecule, reducing the potential for high leak rates.

While these two-phase propellants provide the advantage of being stored as liquids, the ingestion of liquid through the nozzles can cause rapid density changes that will significantly degrade the performance of the system, mainly its specific impulse [6]. The SPS uses a simple and power-effective solution to this problem by utilizing a two-tank approach. This method uses a main tank which holds the saturated liquid-vapor mixture, and a secondary smaller tank, called the plenum, that only contains the propellent in the vapor state. The nozzles are then only fed vapor from the plenum. As the system pulses, the propellant is consumed and the pressure in the plenum decreases. Once the pressure drops below a user-defined fraction of the main tank pressure, a refill valve is opened, and the plenum is repressurized from the main tank. The pressure in the main tank is lowered when this occurs, and some of the liquid propellant boils to replace the vapor. The SPS is designed such that both tanks, along with the plumbing and nozzles, are all a part of singular additively manufactured part as discussed in the next section.

B. Propulsion System Design

The SPS utilizes the two-tank approach explained above with six nozzles to provide the necessary maneuvering capabilities required by the SunRISE mission. The system architecture is shown in Fig. 4. To best utilize the available volume at hand, AM has been leveraged to convert this system architecture to a highly optimized system. In fact, the largest component of the SPS is a singular additively manufactured multi-functional structure. This part encompasses both the main and plenum tank, propellant feed plumbing, nozzles, and the control valve and spacecraft mounting interfaces. The CAD model of the printed structure is shown in Fig. 5, along with a transparent view of it displaying the internal tanks and plumbing. The section highlighted in green is the plenum tank which has a volume of 64cc, and the section colored in blue is the main tank that has a volume of 274cc. Furthermore, two of the six nozzles are straight and are considered as the delta-v nozzles, and the rest are canted 30 degrees from the body z-axis and are used for attitude control. The structure was designed to withstand 2.5 times the MEOP and was verified via finite element analysis (FEA) [6].

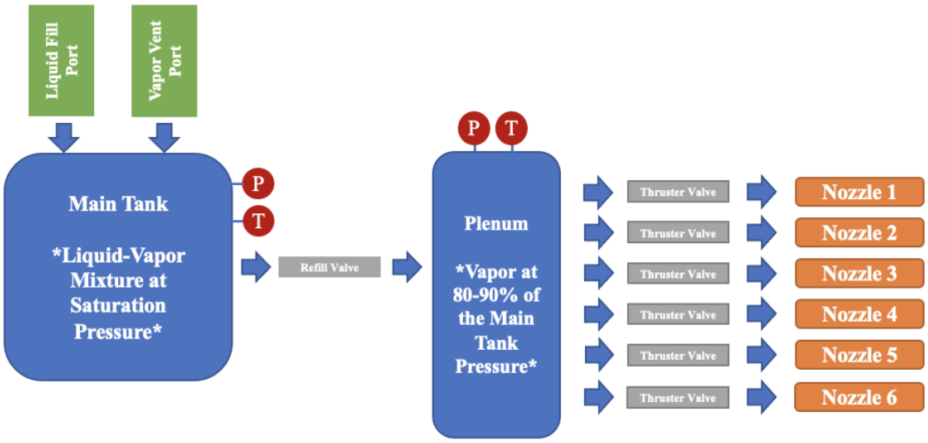

Fig. 4 Schematic of the SPS system architecture.

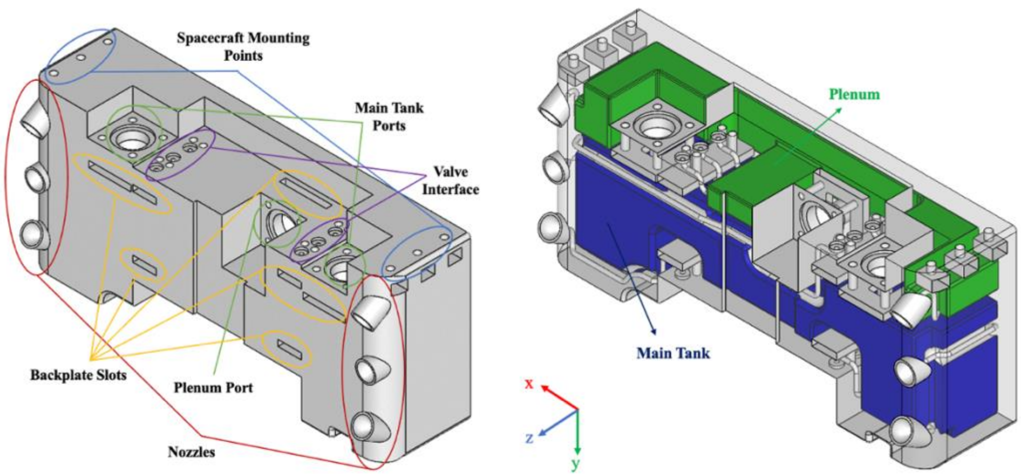

Fig. 5 CAD model of SPS printed structure.

The specific AM technique used to produce the SPS structure is called stereolithography (SLA). SLA printers use an ultra-violet laser to cure a liquid resin into a hardened plastic in a process called photopolymerization. Compared to Fused Deposition Modeling (FDM), SLA can produce highly accurate and isotropic parts in a range of advanced materials with fine features and smooth surface finishes [5]. This method allows for better control of the internal structure and reduction of fluid interfaces. However, SLA does come with certain drawbacks, notably the addition of support structure both internal and external to the designed part during the printing process. Since they cannot be removed, it is critical that no internal support structure was printed as that would not only reduce the effective tank volume but more importantly provide a risk of creating debris and clogging fluid channels. While external printed support was not as big of a concern, it was important that it not damage critical interfaces when removed. To avoid printing any internal support, the part was printed in a unique tilted orientation. The structure is printed out of Somos

PerFORM, which is a strong, stiff, and high-temperature resistant composite that can be printed with high feature resolution. After it is printed, the part goes through a thermal post-cure that provides it with higher tensile strength as compared to a typical UV post-cure. Furthermore, the external surfaces are usually glass bead blasted to create a final smooth surface finish, but due to risks of glass beads entering and getting stuck in the tank, this step was skipped for this specific part. Additionally, when handling the part, charges can build up very easily on the chosen material without direct discharging pathways, increasing the risk of electrostatic discharge (ESD) events. To avoid such an event, ionizers are always used when handling the printed structure.

To complete the system, a series of COTS parts were utilized. Propellant flow is controlled by seven miniature solenoid valves, one for each nozzle and another for the refilling of the plenum. These valves are two-way axial-flow solenoid-operated valves, installed in two manifolds that interface with the printed structure. A 5-micron sintered filter is used upstream of every valve to ensure that no debris can contaminate or damage the valves as well as cause blockage of the downstream plumbing or nozzle throat. These valves were selected primarily due to their small form factor, relatively high flow rate, good vibration and temperature ratings, and ease of operation [1]. Furthermore, both the main tank and plenum are equipped with temperature and pressure sensors so that the state of the propellant is always known through operation. Additionally, two miniature quick disconnects (QDC) are used for filling and draining of the main tank. The sensors and QDCs are installed onto manifold plates that interface with the printed structure. All manifolds are traditionally manufactured via CNC machining out of 304 stainless steel and are sealed against the printed structure by EPDM O-rings. EPDM O-rings were chosen due to their compatibility with the propellant. Finally, the system is controlled by two printed circuit boards (PCB) fastened to the valve manifolds with the valve stems soldered onto the boards. A CAD model of the fully assembled system is shown in Fig. 6.

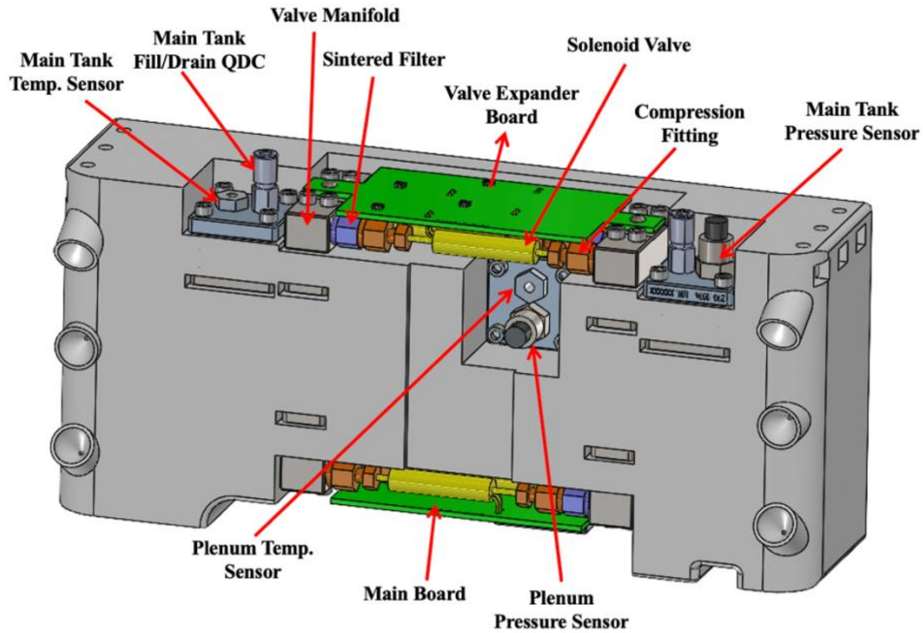

Fig. 6 CAD model of the SPS assembly.

IV. System Integration

All propulsion units are integrated at SSDL's Flight Hardware Lab (FHL). The FHL has a 400 ft^2 class 100,000 clean room and provides access to all the tooling necessary for inspection, documentation, and integration of the system. SDL and JPL have provided support throughout the integration phase where GT does not have the appropriate personnel, such as a quality assurance engineer, or facility, such as a precision cleaning lab. Before the system can be integrated, all custom manufactured and COTS parts are inspected and cleaned with certain parts going through post-processing to achieve the as-designed system. The main integration process is relatively simple and quick due to the central role of AM in the system design. Lastly, the integrated system is filled with the required amount of propellant. The pre-integration, main integration, and filling processes of the system are detailed in the sections below.

A. Part Inspection and Printed Structure Post-Processing

As mentioned in Section III, the SPS is a combination of a single printed structure, COTS components, and traditionally manufactured manifolds and structural plates that provide the interface between the two previous items. Before the system can be integrated, all the components are inspected to ensure they do not visually exhibit any flaws, such as nicks, burs, or signs of corrosion, and are manufactured per the drawings. Additionally, a dry fit check is done to confirm that all parts function and interface as intended. This inspection is vital in catching defects before moving forward with the integration process, saving the project from a more difficult and costly problem that may result down the road. Once all the parts have been inspected, the printed structure is post processed to achieve desired interfaces and features, whose critical designs cannot be guaranteed by the printing process alone. Due to the complex internal geometry of the part, which required it to be printed in a tilted orientation, and the material used, critical features are printed with rougher surfaces and slight imperfections, such as the nozzle throats having slightly different shape and size across different units. Such flaws were observed on an initial engineering development unit (EDU) printed structure, which lead to the decision to post-process it.

For the SPS design, two features were deemed critical to the performance of the system and were therefore post processed to achieve not only the desired feature as it was designed but ensure repeatability across the units. One of the features were the O-ring grooves. The geometry, dimensions, and surface roughness of an O-ring groove are critical to the O-ring's performance in keeping the system sealed and reduce propellant leakage to space over the course of the mission. Smooth surfaces, on the order of 16-32 microinches, and round edges ensure that no damage is done to the O-ring while the correct dimensioning of the groove ensures proper compression and sitting of the O-ring. Therefore, the printed structure was printed with no O-ring grooves and instead a multi-axis CNC mill was used to create those grooves as designed. The other critical features are the throat and diverging section of the nozzles. The throat size determines the choked mass flow rate downstream of the valves and establishes the right nozzle expansion ratio, both of which are critical to achieving the designed performance. Furthermore, the diverging section allows for the supersonic expansion of the flow to create the desired thrust and its smooth bell-shaped contour and exit area are critical to reducing nozzle losses. Therefore, a multi-axis CNC mill was used to remove deliberately added extra printed material to the inner walls of the diverging section of the nozzle by following its contour to create a smooth surface, reducing the risk of forming shocks or expansion fans in the nozzle, while maintaining the original optimized geometry. Finally, the nozzle throats were typically undersized, so they were reamed out with a drill bit size equal to the diameter of the designed throat diameter. Pictures of the pre- and post-machined of the mentioned features is shown in Fig. 7.

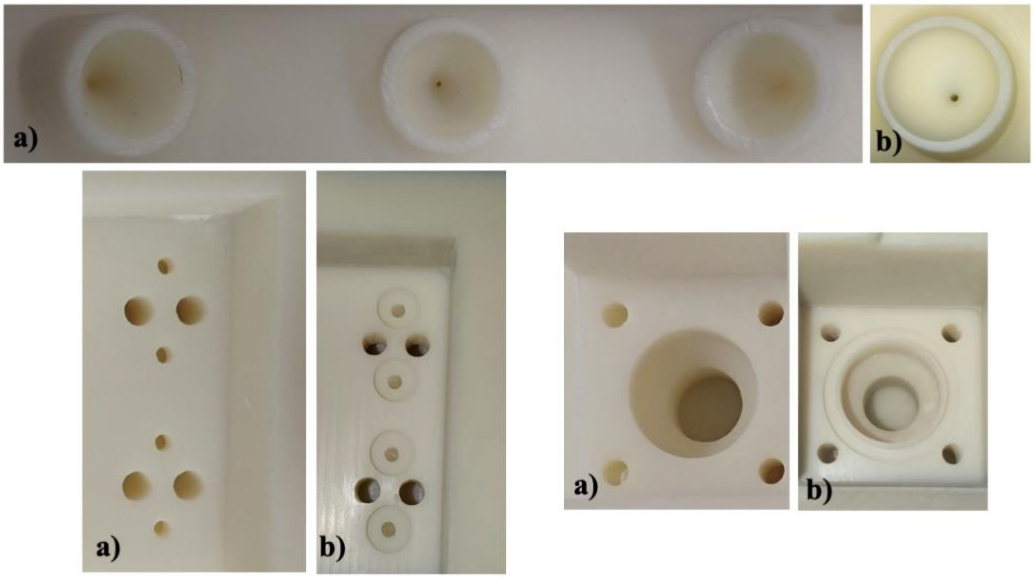

Fig. 7 Printed structure a) pre- and b) post-machined nozzles and O-ring grooves.

B. Hardware Precision Cleaning and Bake Out

Once critical interfaces of the printed structure have been machined, it goes through an extensive precision cleaning process at SDL along with all other wetted components, such as the manifolds and valves. For context, a wetted component is one that comes into contact with the propellant in the integrated system and therefore provides the risk of contaminating the system. All wetted parts were precision cleaned to a specification of PCL 100 to achieve a very low total particulate count. Through testing, it was observed that at this cleanliness level, none of the in-line sintered filters could get obstructed enough, given the total flow load they will experience, to cause appreciable reduction in mass flow. Additionally, it ensured that any unwanted residue left from the printing process was removed from the internal tanks and plumbing. While it was relatively easy to achieve such a cleanliness specification on the metallic components and COTS parts, it was much harder to reach that specification for the printed structure due to its material and complex internal geometry. It required an extensive cleaning campaign, utilizing various cleaning methodologies, to achieve the cleaning specification mentioned. The components' cleanliness were verified via particulate counts. All other non-wetted components were also cleaned with a standard IPA soak and rinse as their cleanliness posed less risk to the overall system. Furthermore, all non-metallic parts were baked out in a thermal-vacuum (TVAC) chamber to remove all volatiles that could contaminate and consequently damage other components in the propulsion system or spacecraft at future vacuum-level testing.

C. Main System Integration

By leveraging additive manufacturing for much of the design, the integration process is relatively straight forward. There are two major sets of subassemblies that are assembled first. The first set consists of three manifold plates that allow for filling and draining of the system, as well as monitoring the pressure and temperature of both tanks. Each plate interfaces with a combination of two of the mentioned components. Two of three plates interface with main tank ports and therefore each have a QDC and either a pressure transducer or thermistor as shown in Fig. 8 below. The other plate interfaces with the plenum port and hosts only sensors. These COTS components are threaded into the designated manifold plates and torqued to a designed value. The sensor wirings were then striped, crimped, and attached to designated connectors. The second subassembly is the valve manifold subassembly as shown in the Fig 9. Each unit has two of such subassemblies, one with four valves and the other with three. To assist in the assembly, a stencil ground support equipment (GSE) was made to imitate the printed structure interface and ensure that the solenoid valves were integrated in the correct orientation and position such that they could be soldered on to the PCBs at the designated spots. The 5-micron filters and 1/16" tube compression fitting bodies were first torqued onto the manifold blocks and the valves were placed on the stencil with their corresponding fitting nut and ferrules. The manifold blocks were then lined up on the stencil such that the valve tubes could be sealed against, or swaged to, the fitting body using the corresponding fitting nut. Kapton-tape was placed on each fitting nut to track how much the fitting nut was rotated past finger-tight to ensure proper compression and consequent seal.

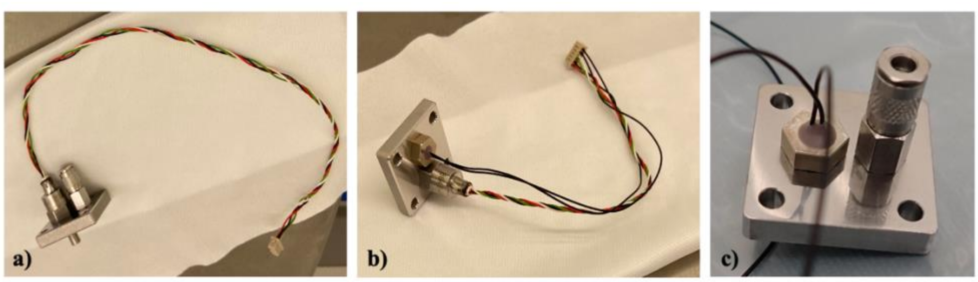

Fig. 8 Assembled a) main tank fill-pressure plate, b) plenum pressure-temp plate, and c) main tank fill-temp plate.

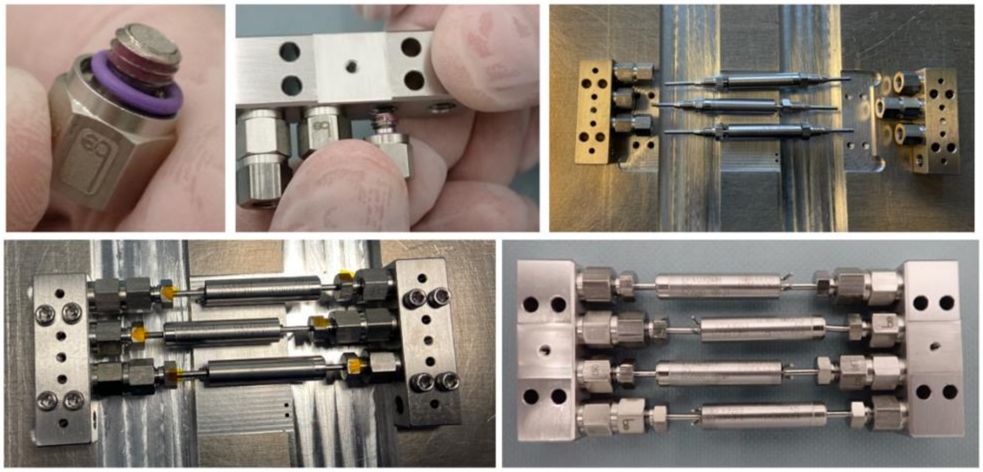

Fig. 9 Integration process of a valve manifold subassembly.

The subassemblies are then integrated onto the printed structure. All the subassemblies are secured to the printed structure via a simple bolt-nut clamp design. Fasteners are torqued to stainless steel backplates placed in designated slots in the printed structure to provide the designed clamp load. The PCBs are then placed on top of their respective valve manifold assembly and are mounted to the manifold blocks via fasteners. This process is displayed in Fig. 10. The valve stems and the main board to valve expander board interconnecting wires are then soldered on to the boards. All the sensor wiring is then routed uniquely and connected to the boards with an appropriate amount of slack. Finally, all the wires are staked to the structure, manifolds, or the PCBs to ensure they are not exceeding past the spacecraft bounding envelope requirement, as well as make sure there is no risk of damage to them when experiencing intense vibrations during launch by getting caught on sharp edges. All the fastener heads are also torque stripped. The assembled unit is then allowed to rest in the clean room to allow for all the staking and thread-locking epoxy to fully cure before filling or testing the system. A picture of the completely integrated SPS is shown in the Fig. 11.

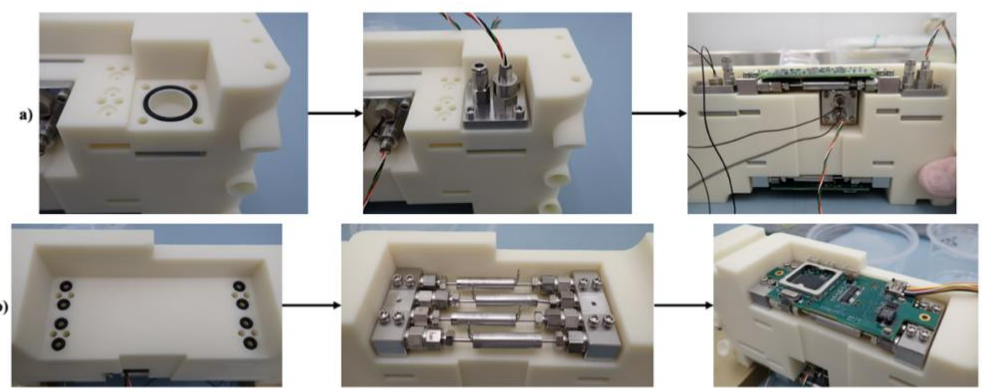

Fig. 10 Integration of a) fill-sensor manifold plate and b) valve manifold subassemblies onto the printed structure.

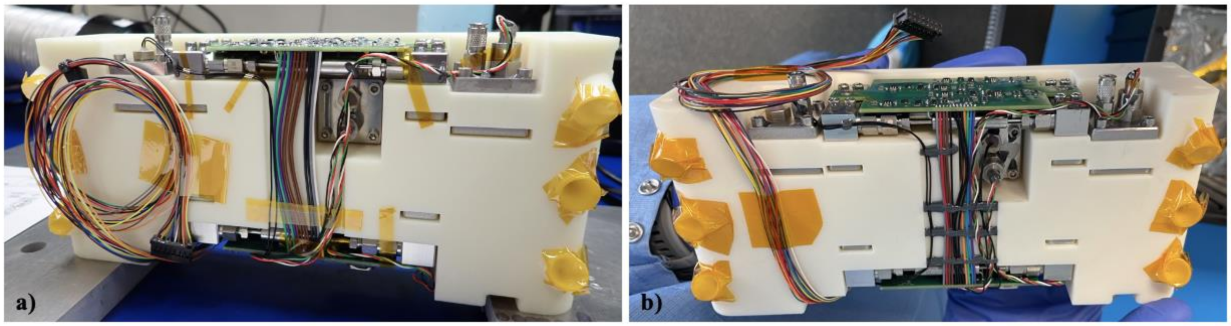

Fig. 11 Integrated SPS a) pre- and b) post-staking.

It is important to note that a space-safe thread-locking epoxy was applied to all fastener or component male threads before they were torqued. This is done per the recommendation of NASA-STD-5020A of using at least one secondary thread locking feature for all threaded parts used in a preloaded joint with preloading via torquing providing the primary locking mechanism. Furthermore, the thread-locking epoxy has the additional advantage of providing some lubrication to the joint which improves torque control and reduces the risk of galling when using very clean and dry threads. Additionally, all components and manifolds use O-rings to provide a seal. The O-rings are lubricated with a silicone-based grease, Molykote 55, to enhance their sealing performance by slightly swelling them and help protect them from damage by pinching, abrasion, or cutting, as well as assist in keeping them seated in their designated groove. Testing was done to verify that the chosen grease was compatible with the propellant.

D. Propellant Loading

The last ingredient needed to complete the assembled SPS and prepare it for testing is loading it with propellant. Given the simple design of the system, there's no sensor to detect the amount of propellant in the tank at a given time. Instead, the system is filled by measuring its total mass as it is being filled. The precise mass of the propellant needed is calculated based on the amount required to fill the main tank 95% volumetrically with liquid, the remainder being the ullage. This amount will provide enough fuel to achieve the total delta-v required by the mission and some margin. Since the saturated liquid expands as its temperature rises, its density drops and therefore requires more volume for the same amount of mass. If the liquid volume expands beyond the available tank volume, it will cause a rapid increase in internal pressure due to its incompressible nature and put the tank at the risk of hydro locking and severely damaging the structure. To avoid this, the required mass of propellent needed is calculated using the propellant density at 50°C, the maximum mission operating temperature, where the propellant is the least dense. Since the filling process occurs at room temperature, less than 95% of the main tank volume will be filled but it guarantees that at the hottest operational temperature, 5% of the main tank volume will be ullage.

The loading of the propulsion system is a two-step process. First, a main fill harness that contains a sample cylinder, called a fill bottle, is filled with R-236fa from a much bigger propellant dewar. Once filled, the harness is then attached to one of the QDC ports on the SPS with a vent harness attached to the other QDC port, while the SPS is sitting on a high-precision scale. All the harnessing is securely attached to a plumbing support structure to ensure that little to no weight loads are placed on the SPS as well as avoid any fill hardware from falling on the SPS. The set-up is shown in Fig 12. Once the harnesses are connected to the system, a venturi pump is first used to suck all the ambient air from the main tank via the vent harness and provide a rough vacuum that will create the differential pressure needed to initiate the fill process. After a vacuum is achieved, manual miniature ball valves on the fill harness are opened to allow for the loading process to start. As the propellant is loaded into the tank, it will boil and slowly reach saturation pressure and at that point, the fill rate becomes only gravity driven. This makes the loading process much slower, so the vent harness is used to frequently vent out the vapor, increasing the differential pressure and fill rate again. The fill set-up is placed in a steady environment and little contact is made with any of the hardware to avoid drifting of the scale reading. The system is slightly overfilled so that precise manual venting can then be used to achieve the required mass of propellant with a precision of 1g.

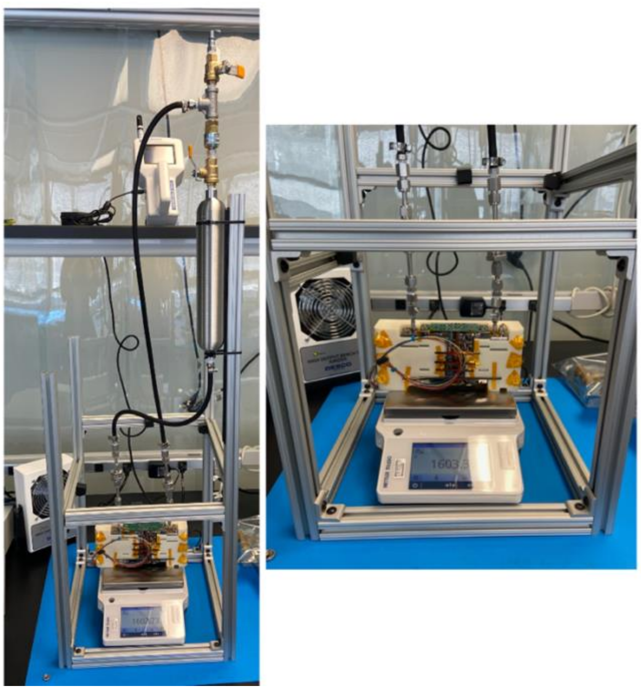

Fig. 12 SPS propellant loading set-up.

V. System Testing

Each SPS unit is qualified and characterized through an extensive testing campaign. The system first goes through environmental testing to verify the system's ability to survive the chaotic launch environment as well as the vacuum, pressure, and temperatures profiles it will experience in its orbit. The unit is then characterized through a performance testing that will provide impulse measurements from each nozzle and the specific impulse of the system, as well as how these values are impacted by changes in propellant temperature. Functional tests and visual inspections are done before, after, and in-between tests to verify the health of the system throughout the testing campaign. A flow diagram of the overall test campaign in the executed order is displayed in Fig 13.

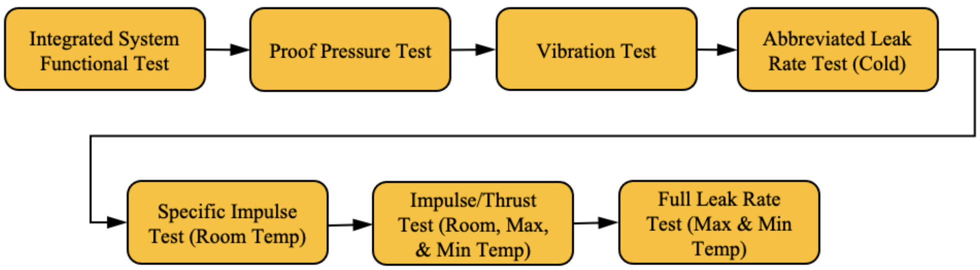

Fig. 13 SPS qualification and characterization testing campaign.

A. Proof Pressure Test

Before the system can be filled with propellant for testing, it goes through a proof pressure test. This test is done to validate the structural integrity of the printed structure by pressurizing its internal tanks to 1.5 times the MEOP, equating to 141.75 psia. Even though the printed structure was designed and analyzed with a factor of safety of 2.5, such a test confirms that no un-inspectable printing defects exist inside the tank that may provide a risk of damage due to over-pressurization. Furthermore, since this is the first test after the integration of the propulsion system, it also serves as workmanship check confirming that everything was assembled as intended and no audible leaks exist.

The test was conducted by pressurizing the SPS with nitrogen gas using a plumbing GSE set-up, the schematic of which is displayed in Fig. 14. Nitrogen gas was chosen due to ease of access and its inert nature. The proof pressure plumbing connects a nitrogen k-bottle to one of the QDCs on the propulsion system. A regulator is used to increase the pressure inside the system in increments of 20 psi until the maximum test pressure is achieved. Once the system is fully pressurized, it is slowly vented to the ambient environment via a drain valve. In addition, to avoid over-pressurization of the system, a relief valve and burst disc will be triggered at a pressure just above the maximum test pressure. Since this test involves dealing with high pressures, an ESD-safe containment chamber is utilized to avoid harm to test personnel and clean room equipment in case of a burst. At the time of this writing, multiple EDUs and flight units have successfully passed the proof pressure test.

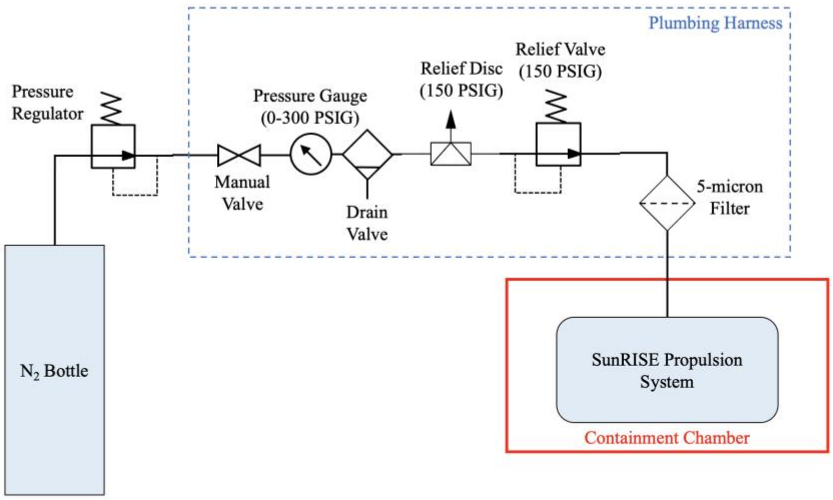

Fig. 14 Proof pressure test plumbing GSE schematic.

B. Vibration Test

After the unit is proof tested, it goes through an environmental vibrational test at a subsystem level. The main objective of this test is to verify that the system can withstand, and function as intended after exposure to, cyclic loading associated with the chaotic launch vibrations. Overall, it establishes confidence that the system will maintain general structural integrity with no flight harnesses being damaged through launch.

To conduct testing in all three axes, a slip table configuration was used for two axes and a head expander was used for the third axis. An aluminum fixture was made to allow for the propulsion system to interface with the shaker table bolt pattern. Furthermore, the plate was designed such that the same thread engagement is made with the propulsion system as it would once it is integrated into the satellite. The propulsion system was also tested while fully loaded with propellant to simulate the launch configuration. Two tri-axis accelerometers were placed on the system to measure its response during testing, the location of which was selected based on high transmissibility locations on the printed structure determined through modal analysis. The vibration testing set-up is shown in Fig. 15.

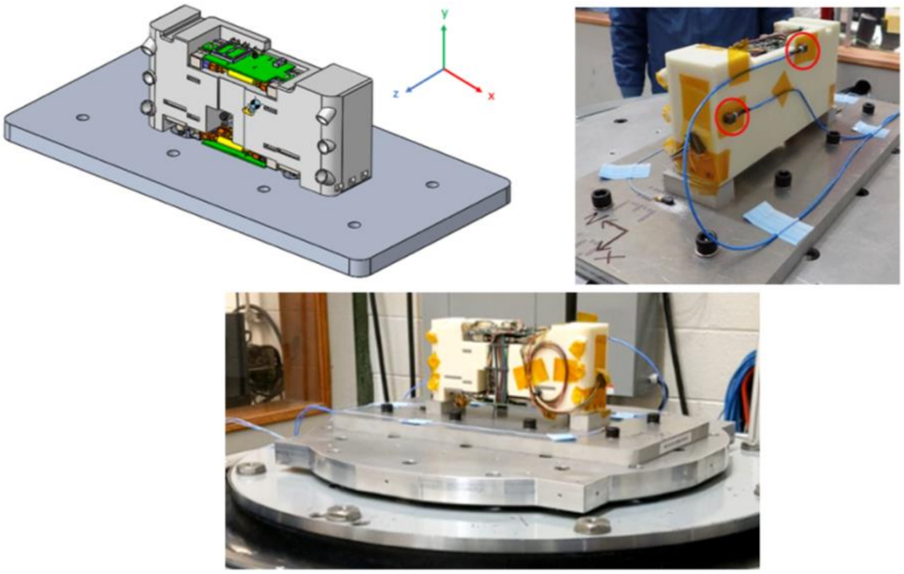

Fig. 15 Vibration test set-up.

To conduct the test efficiently, a test flow was made prior to any testing to facilitate the coordination between the engineers operating the shaker table and the GT engineers to minimize wasted shaker table time while conducting appropriate functional tests in between test runs. Inadvertently skipping a performance test would inhibit the team from determining which exposure drove performance deviations or failures. Furthermore, the axis test sequence is chosen with the axis that has the highest potential of causing a failure mode to be conducted first. This will allow for identification of any damage earlier in the testing, providing more time to find an adequate solution towards it and restart the testing campaign.

Each unit goes through a pre- and post-modal sine survey and random vibration test profile for each axis. A low-level modal sine survey profile is conducted to acquire data that will provide useful information regarding the systems modes of vibration, primarily natural frequencies but also damping and mode shapes. This test is conducted at low acceleration levels to make sure that the system is not stressed or fatigued. The low-level model survey test is conducted before all proto-flight level exposure tests to establish a baseline response plot that can be used to assess the health of the system after the tests have been conducted. If no major damage has been caused to the system, the pre- and post-response plots should perfectly lay-over each other with acceptable deviations. For the exposure tests, a random vibration profile for each axis was provided by SDL. This profile was generated based on the dynamic and acoustic flight launch environment and accounts for the damping provided by the deployment canister. Test tolerances were employed during testing to provide alarm and abort points during testing and ensure that the system is tested to the levels intended by the test profiles. Finally, a clear list of pre-defined pass/fail criteria are used to assess whether the system successfully met the test objectives. Such a verification method can allow for a justifiable decision to be made regarding whether the test conducted, and subsequent results obtained, is sufficient in establishing confidence in the subsystem surviving the launch environment or if another test campaign is required for such verification. At the time of this writing, an EDU has successfully passed the vibration test.

C. Leak Rate Test

Leak rate testing is done to verify that the assembled SPS does not significantly leak to the vacuum environment of space. Since no system is perfectly sealed, the test's purpose is to measure the rate at which propellant leaks out of the system and ensure that it meets the leak rate requirement. The requirement is driven by the minimum amount of fuel needed to conduct all the necessary burns to achieve a successful mission during the designed mission length as well as accounting for shelf-time before launch. Excessive leakage could hinder the capability and lifetime of the mission. During the testing campaign, each unit is leak rate tested twice. An abbreviated test is done after vibrational testing at the minimum operational temperature to quickly validate that the system was correctly integrated and no excessive leaking exists. Then, a full leak rate test is done after performance testing at both the maximum and minimum operational temperature to verify that the system is still properly sealed after completeing many burn and plenum refills.

The test is conducted via a system mass loss technique. The fully loaded SPS is first baked out in a TVAC chamber for 24 hours to ensure that all volatiles, mainly water vapor, are removed from the structure. Skipping this step can significantly affect the recorded differential mass of the system pre and post-test. After it has been baked out, its mass is measured using a digital scale. The system is placed back in the TVAC chamber and sits at 1×10^{-6} torr for 72 hours at 50°C and another 72 hours for -15°C. Due to extreme operational temperatures, different materials on the spacecraft expand and contract at different rates, causing variations in critical interfaces that may lead to leaking. After being in the TVAC chamber for 144 hours, the mass of the unit is measured again. The difference in the mass of the system is then divided by the total amount of time the system was in vacuum to obtain a leak rate. Observing a value that meets the leak rate requirements ensures a robust leak-tight system. Furthermore, through this test, the system's functionally after experiencing thermal cycling is verified.

D. Performance Test

The most critical part of the entire testing campaign is characterizing the performance of the system and verifying it against the expected performance calculated using Quasi-1D assumptions. Two key performance parameters are measured during this testing phase: impulse exerted by each nozzle and the specific impulse of the system. Additionally, the impulse is measured at the maximum and minimum mission operational temperatures to measure the impact of temperature on the performance of the system.

Due to the low thrust level and short firing times generated by the system, a torsional pendulum thrust stand was used to measure the mentioned parameters of interest. This low cost and relatively simple thrust stand was designed to fit in the GT SSDL TVAC chamber since a vacuum environment is necessary for testing because the exit velocity of the fluid is dependent on the pressure ratio of the plenum to the ambient pressure, which for strictly in-space missions is vacuum. The thrust stand with the SPS attached to it inside the TVAC chamber is shown in Fig. 16. The thrust stand consists of a fixed frame that supports a horizontal rotating arm with the SPS attached to one end of it using a mounting plate. Impulse exerted by the propulsions system causes the arm to rotate and a restoring force, caused by nearly frictionless flexure pivots, produces an oscillation in the arm. The amplitude of the oscillation is measured by a Linear Variable Differential Transformer (LVDT) sensor which is then used to calculate the impulse imparted by the system. The sensor measures the displacement of a metallic core fixed to the rotating arm against the sensor housing that is fixed to the stationary frame. Counterweight wheels are used to balance the SPS and keep the center of mass of the rotating segment near the axle. The hub of each wheel is threaded, allowing them to be precisely positioned. Furthermore, leveling feet are used to set the zero point of the stand. The specific design details, dynamics of the thrust stand, and data processing utilized to convert deflection measurements to impulse values is detailed by Stevenson [5].

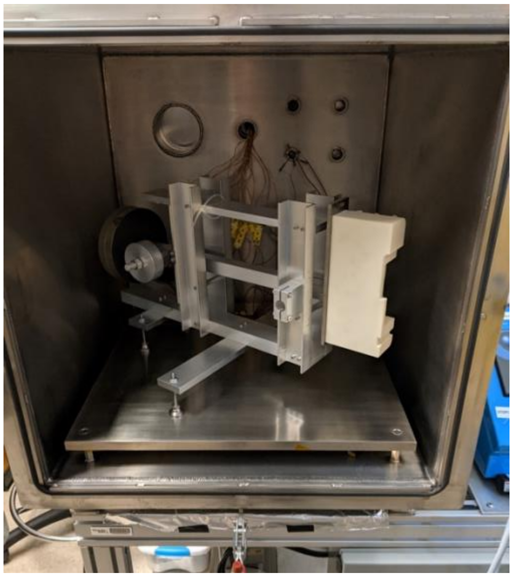

Fig. 16 Thrust stand set-up in GT SSDL TVAC chamber.

1. Impulse Testing

The first parameter investigated is the impulse produced by each of the six nozzles for a given firing, or valve opening, time. In this test, each valve corresponding to a certain nozzle is pulsed slightly over 200 times, with the first 10 pulses ranging from 3ms to 150ms long and the rest being 150ms long. The upper limit of the pulse length tested is set at 150ms as any pulse length larger than that produces a large enough impulse to cause the thrust stand to saturate, or cause the LVDT sensor to max out, and therefore cannot be measured properly. The impulse test results, conducted at room temperature, for an EDU are displayed in the Fig. 17. The plot on the left shows the impulse measured by the thrust stand for all six nozzles for a given pulse length. As expected, a roughly linear trend can be observed between the impulse and pulse width. The impulse is then divided by the commanded pulse duration to obtain an average thrust value, shown in Fig. 17b. The plotted data does not show a constant thrust for all pulse lengths, but rather much higher average thrust values for pulse lengths shorter than 50 milliseconds. This a result of the opening and closing delays of the solenoid control valves after a command is sent. The solenoid valves take a finite amount of time to move so when the valve is commanded to open for a certain amount of time, it requires some time to open and some time to close. While the valve armature is moving, the cross-sectional area of the valve is changing, and so the mass flow rate, and hence the thrust, will be reduced roughly proportional to how far the armature has moved. If the closing time is longer than the opening time, each pulse will gain some extra impulse, as the valve is technically open for longer than the commanded time. For short pulses, this "extra" impulse will cause a significant overestimate of the average thrust but becomes nearly negligible for longer pulses as illustrated by Fig. 18. Because of this phenomenon, it was decided that SPS's minimum impulse bit should be 1mN-s corresponding to a pulse width of 25ms, even though the system could realistically provide a smaller impulse. Furthermore, it can be observed from Fig. 18 that different nozzles produced slightly different impulses for a given pulse length. This can be contributed to the variation in pressure drop occurring upstream of each nozzle caused by different upstream plumbing length and inconsistent surface roughness.

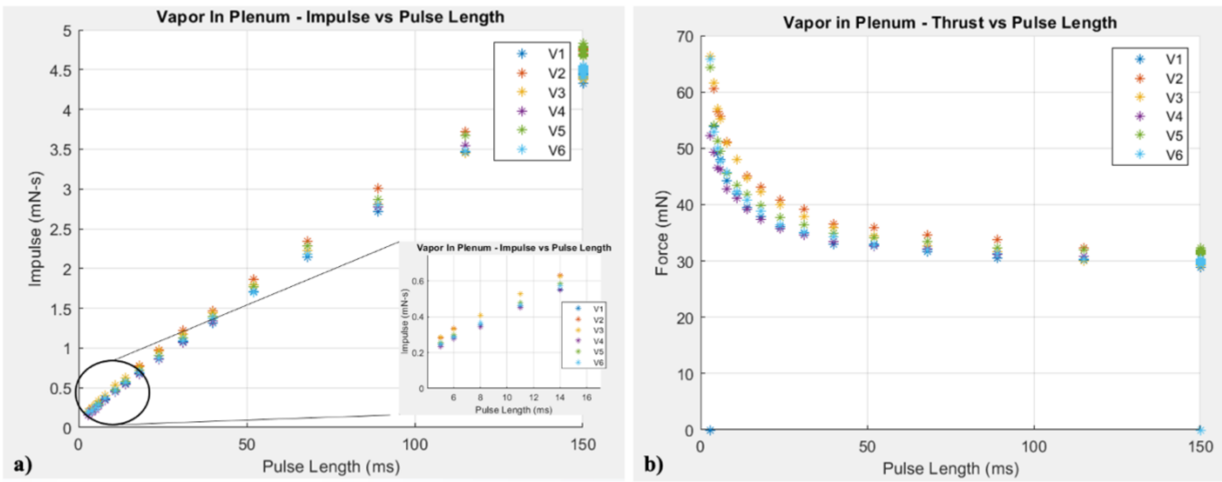

Fig. 17 SPS EDU a) impulse and b) average thrust performance data.

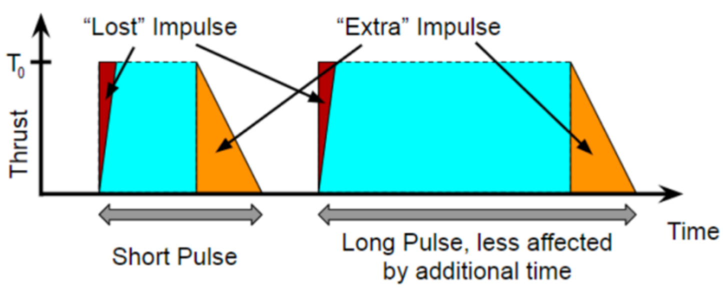

Fig. 18 Solenoid valve opening and closing time impact on calculated average thrust [5].

Since the saturation pressure of the propellant is a function of temperature, impulse test of the SPS is done at both the maximum and minimum mission operational temperature extremes. Data collected at such temperatures will allow for interpolation of the test data to identify the performance expected in flight for a given system temperature.

2.   Burn-Refill Testing

During the impulse testing, the plenum was refilled to the same pressure after each pulse to ensure the impulse would be as consistent across testing as possible. However, the SPS is designed to operate in an autonomous closed loop burn-refill cycle, with the pressure sensors on the plenum and the main tank guiding this cycle. The plenum is first filled such that it is at 90% of the pressure of the main tank (high refill threshold) and once the pressure drops to 80% of the main tank pressure (low refill threshold), the closed-loop refill valve is automatically triggered to open until the pressure in the plenum has reached the high threshold pressure again. The high threshold is set at 90% to ensure that only vapor exists in the plenum. However, during testing of an EDU, it was observed that after the plenum pressure had hit the high refill threshold value and the refill valve was closed, the pressure in the plenum kept on increasing for a few seconds and ultimately reached a value close to the main tank pressure. This suggested that the plenum was at saturation pressure and therefore some amount of liquid existed in the plenum. This is attributed to the low evaporation rate of the propellant. Essentially, once the refill valve is opened, liquid can flow from the main tank into the plenum, slowly boiling off to reach saturation pressure. However, since the liquid does not evaporate immediately, by the time the plenum pressure has reached the high refill threshold, more liquid than wanted is released into the plenum.

To better understand this phenomenon, more testing was done on an EDU. Specifically, the EDU was set up in different orientations to examine how the refill process is impacted by the location of the liquid propellant in the main tank relative to the refill valve inlet. Specifically, three set of burn-refill profiles were executed for each system orientation. The first set was a simulation of delta-v burns where a fixed time was commended for each burn and subsequent refill. The second and third set incorporated the autonomous closed-loop refill cycle but investigated the difference in only executing short and long burns, respectively. Before each burn-refill profile was executed, the plenum was emptied to vacuum to provide a consistent initial plenum status. The test results for two orientations, -Z and +X side of the system on the ground, are shown in Fig 19. When the -Z side of the system is on the ground, liquid is resting at the inlet of the refill valve while for the +X case, only vapor is resting at the refill valve inlet due to gravity. The first, second, and third burn-refill profiles are circled in green, black, and yellow, respectively. In the -Z case, for the second and third set of burns, the pressure in the plenum would exceed past the high refill threshold and settle near the main tank pressure, showing that liquid indeed existed in the plenum. It is unclear if there was liquid in the plenum for the first set of burns as the pressure in the plenum was never allowed to settle. On the other hand, for the +X case, the pressure in the plenum is maintained within the high and low refill threshold bounds for all sets of burns. These results indicated that if only vapor is sucked out of the main tank to refill the plenum, the autonomous closed-loop refill cycle works consistently. However, in the case of microgravity, the location of the liquid in the tank is governed by surface tension instead of gravity and therefore, there’s a high probability that the tank walls near the refill valve inlet will be mostly covered with liquid during most the mission. This implies that more than likely, the designed closed-loop refill cycle would cause inconsistent refilling of the plenum with a high chance of unwanted liquid being introduced into the plenum.

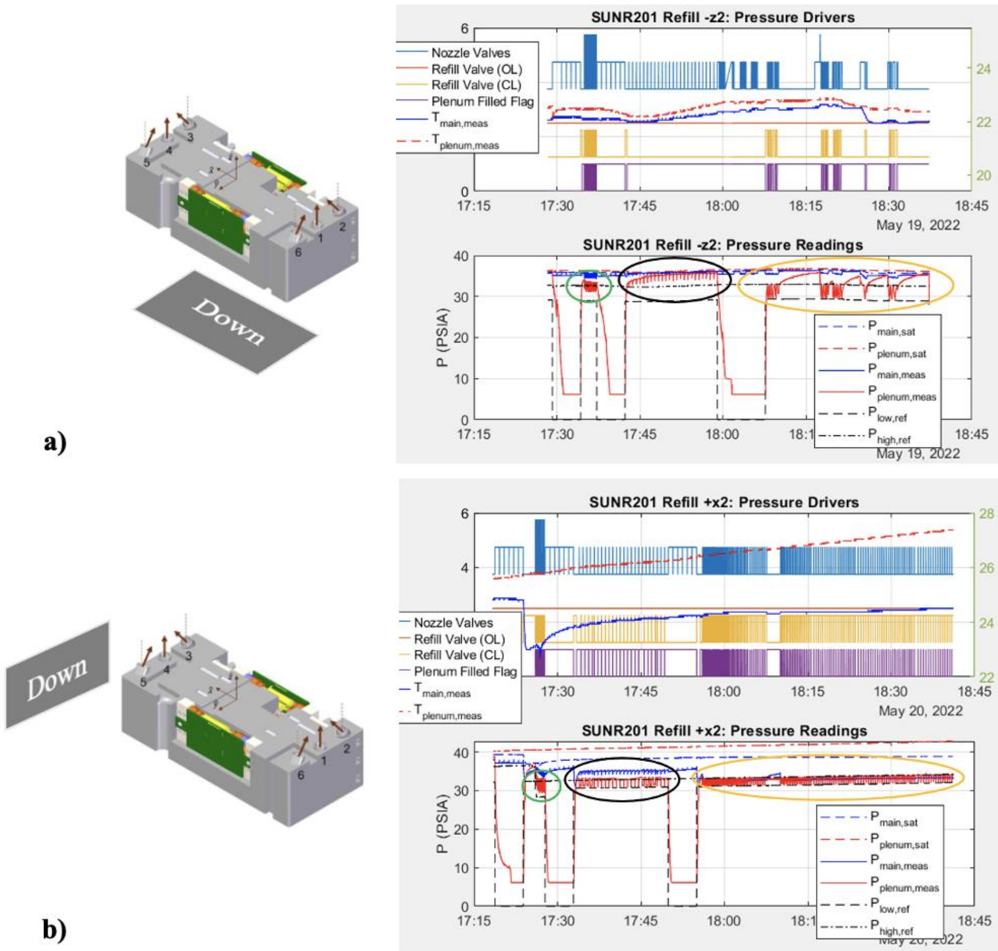

Fig. 19 SPS burn-refill testing with the a) -Z side and b) +X side set on the ground.

Further testing was conducted to evaluate the impact of liquid existing in the plenum on the performance of the system. This was done by commanding long refill valve opening times and making sure plenty of liquid existed in the plenum. It was identified that depending on the orientation of the system, various amounts of liquid-vapor mixture can exit the plenum, but all vaporize before going through the nozzle. This was witnessed as large inconsistent impulses for short pulse lengths but a similar I_{sp} being measured as compared to the measurement with only vapor in the plenum. It is worth noting that only 10ms long pulses could be tested as the thrust stand would saturate very easily due to the higher inconsistent impulses imparted by the system. This suggests that if longer pulses could be fired and measured properly, there's a good probability that the liquid-vapor mixture could not all evaporate and therefore liquid could be injected by the nozzles and a very low I_{sp} would be measured.

To combat getting liquid in the plenum and mitigate the risk of inconsistent and poor system performance, a refill logic was devised to ensure that only vapor existed in the plenum after a closed-loop refill cycle command. Instead of continuously having the refill valve open until the high refill threshold had been reached, the refill valve would open for 50ms and wait 3s for any liquid that may have reached the plenum to vaporize. This would then be repeated automatically until the high refill threshold has been reached. The disadvantage of such a refill technique is that the refill takes a much longer time than the previous strategy causing actual flight burns to take sustainably longer. At the time of this writing, SDL and GT are working to further optimize this method such that the refill time can be decreased as well as investigate its feasibility for the required mission burns.

3. Specific Impulse Test

Another important characteristic of the propulsion system is its specific impulse. Since the exact thrust profile and mass flow rate across each nozzle is not directly measured, the specific impulse is measured by the total mass of propellant lost for an applied total impulse by the system. The SPS has a low mass flow rate and requires a relatively long valve opening time to experience a measurable mass loss. To optimize testing time, the I_{sp} test is done while the impulse test is occurring. The testing sequence has most pulses being 150ms long such that a measurable mass can be lost in the quickest time possible. The total mass loss and cumulative impulse measured from the system are used to determine the average specific impulse of the system. Since the mass of the systems is critical to this test, the system is kept in vacuum for at least 24 hours to allow for all volatiles to outgas, ensuring an accurate differential mass is measured before and after the test. All nozzle valves are fired the same number of times to keep the valve cycling and filter duty consistent across all nozzles. Furthermore, using the leak rate observed earlier in the testing campaign, mass lost to leakage is reduced from the total mass lost. Initial testing of the EDU has shown an I_{sp} measurement of around 42 seconds at 25°C. At the time of this writing, more I_{sp} testing is being conducted to generate more data points and increase confidence in the achieved value.

VI. Conclusion

This report outlined a low-cost, efficient, and capable cold-gas propulsion system designed to provide both transitional and rotational maneuvering capabilities for the SunRISE array of toaster-sized CubeSats. The design was based on a heritage system designed in GT SSDL, that leveraged the advancement in additive manufacturing to reduce the overall part count of a traditional cold-gas system by merging propellant tanks, plumbing, valve interface, and nozzles into a single piece of printed material, optimized to use most of the allocated volume on the spacecraft. Such a design has allowed for a relatively simple integration process as detailed in Section IV. Additionally, all units go through an extensive testing process to ensure that they can survive the launch and perform as intended. Six of these systems are currently being built and tested at the GT SSDL, with the support of SDL and JPL.

At the time of this writing, three EDUs have been built and have gone through various testing to better understand the flight integration and testing processes as well as obtain initial measurements of the system performance. Additionally, two flight units are fully integrated and are headed to environmental testing, while the rest of the units are being built. In parallel, the EDUs are still frequently tested to better understand and characterize the system at hand to ensure that a reliable and robust system is delivered. Finally, other propulsion systems utilizing a similar design are being built and tested for two future missions, SWARM-EX and VISORS, at GT SSDL.

Acknowledgements

While this report provides an overview of my graduate research work, many of my experiences would have not been possible without the help of many individuals I was lucky to work with. First, I would like to thank Dr. Lightsey for being the best advisor I could ask for and providing me with many enriching opportunities that directly aligned with my interests, having ultimately shaped me into the person I am today. Furthermore, the SunRISE project would not have gotten to where it is today without the great leadership of Nathan Daniel and the exceptional work done by Mackenzie Glaser, Sam Hart, and Mark Hartigan. You all have made working in the lab everyday a pleasure and I am grateful for all the memories we have made. Finally, I want to thank everyone at GT SSDL for making the past three years a surreal experience, from seeing GT-1 get launched into space to working on small spacecraft propulsion systems, and I cannot wait to see the amazing things that you all will do in the near future.

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