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Pressurized 1U CubeSat Propulsion Unit

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ABSTRACT

Since the advent of CubeSats, the demand to push mission capabilities of the form-factor has steadily increased. Propulsion systems are one of the driving factors pushing CubeSats towards increasingly complex missions. One propulsion device, an electrothermal plasma thruster known as Pocket Rocket strikes a balance between performance and cost efficiency, in line with the spirit of the CubeSat standard. The thruster has previously been integrated and tested within a 1U CubeSat form factor. However, while functional, the design lacked sufficient propellant storage capability for most missions. To increase propellant storage capability, a 1U CubeSat form factor where the structure itself is a pressure vessel is developed. The Pocket Rocket thruster is embedded into the structure, with batteries, power processing unit (PPU), and propellant regulation and delivery system contained within the pressure vessel. Containing electronic components inside the pressure vessel assists with radiation and thermal protection systems. When used as part of a generic 3U CubeSat mission, the pressurized 1U form factor is capable of producing between 5 and 50 m/s of Δv.

INTRODUCTION

The modular 10 cm cubic CubeSat form factor is an efficient, low-cost space exploration technology. To date, hundreds of CubeSats have been launched [1,2] for missions including technology demonstration, [3,4], scientific studies [5,6], and even as the first national satellite for emerging space nations [7,8]. Advanced CubeSat mission require micro-propulsion systems for orbit adjustments, extended mission lifetimes, and end-of-life requirements [9].

One micro-propulsion system that is under development for CubeSat applications is an electrothermal plasma micro-thruster known as Pocket Rocket [10]. The Pocket Rocket thruster was first conceived of and investigated by the Australian National University [11,12]. Radiofrequency (RF) power of a few Watts ionizes a fraction of an inert neutral propellant creating a weakly ionized plasma. Charge exchange collisions in the plasma heat the remaining neutral propellant [13,14], increasing thrust and specific impulse produced compared to a cold gas thruster of similar size [10].

In preparation for flight demonstration, a self-contained 1U CubeSat form factor containing two Pocket Rocket thrusters has been developed [15]. This design used two cylindrical canisters containing argon gas at approximately 30 psi, to suit the current CubeSat Specifications (revision 13) [16]. The canisters were bought commercial-off-the-shelf (COTS), and as such had to be placed across the diagonal dimension of the 1U structure to fit. This layout is inefficient in regard to tank placement and size, and limits the amount of propellant that can be carried on board. To increase propellant storage capability, a 1U CubeSat form factor where the structure itself is a pressure vessel is developed. The Pocket Rocket thruster is embedded into the structure, with batteries, power processing unit (PPU), and propellant regulation and delivery system contained within the pressure vessel. The components used for the pressurized 1U system are outlined in the Subsystems section, with the integrated design described in the Integration section. The 1U propulsion module is designed to be manufactured with means currently available at Cal Poly, and hence it is expected other Universities.

Containing the electronics and power distribution elements inside the pressure vessel assist with radiation and thermal protection systems. Results of a thermal study and other environmental considerations are included in the Environmental Analysis section. Finally, estimated performance values for the pressurized 1U CubeSat propulsion system are given in the Performance Estimate section.

SUBSYSTEMS

The required subsystems for a self-contained propulsion system are propellant delivery, power delivery and the thruster itself. It is assumed here that the main satellite bus will contain the system board, communications system, payload interface board (PIB), and other mission specific components, hence they are not included here. Figure 1 is a schematic of the interfaces for the required subsystems both internal and external to the pressure vessel.

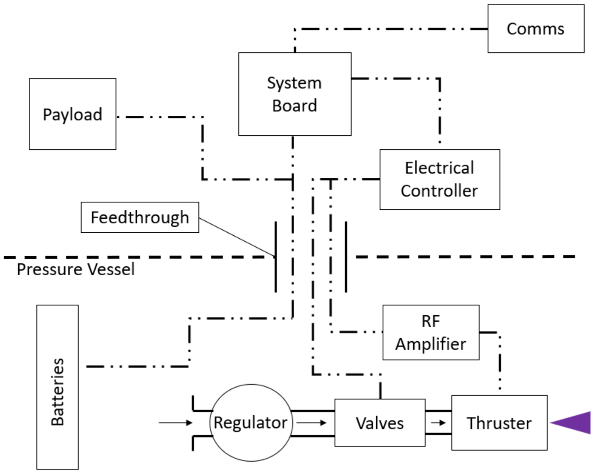

Figure 1: Propulsion module system schematic. Double dashed lines denote electrical connections, arrows denote fluid piping.

All subsystems are designed to work together and to conform to the current CubeSat Specification (revision 13) for 1U systems [16]. The complete pressurized module including all subsystems is shown in Figure 2. The batteries (1), thruster (2), regulator (3), and thruster control valve (4) are mounted within the pressure vessel. Vent (5) and fill valves (6) are mounted to through the pressure vessel for easy access. The DC-RF converter board (7) and electrical feedthrough (8) mount to the lid of the pressure vessel.

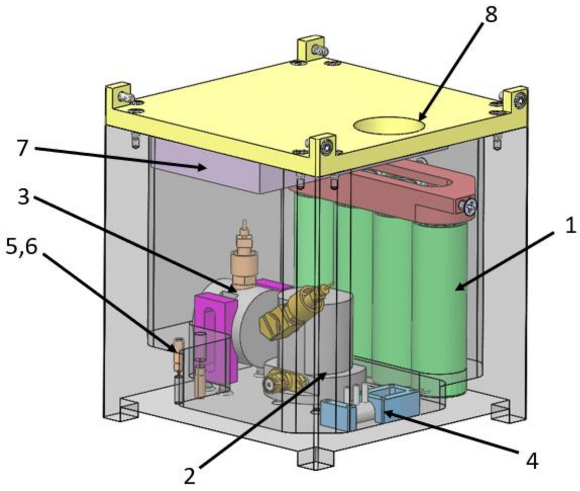

Figure 2: Full Module Assembly

The Pocket Rocket thruster itself has a mass of 60 g, is 35 mm long and cylindrical in shape with an outer radius of 25 mm. A cross-section view outlining the internal thruster geometry is given in Figure 3. The thruster operates with plenum pressures ranging from 2 to 5 Torr. RF power is supplied at 13.56 MHz with the thruster capable of running from 2 to upwards of 10 Watts. A full description of the operation principles of the thruster can be found in reference [10].

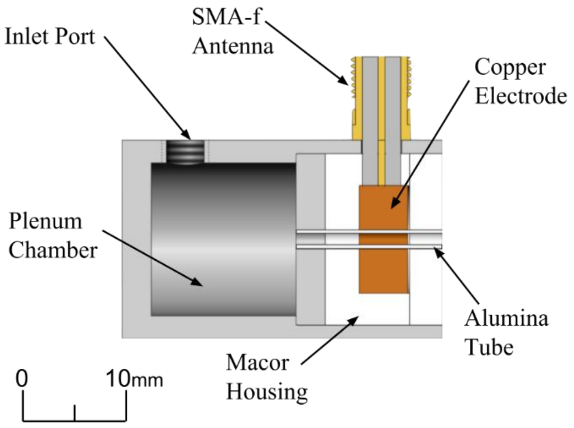

Figure 3: Cross-section of Pocket Rocket thruster

Gas Storage, Regulation and Delivery

Although primarily used with argon as the propellant, Pocket Rocket can operate on other gases such as nitrogen or carbon dioxide [17]. However, the thruster operates with the highest efficiency using argon due to higher operational temperatures [10]. The gas storage and delivery system is designed to easily integrate any propellant into the system by utilizing a common adapter to fill the pressure vessel.

The ability to easily fill and vent the chamber is one of the key design considerations approached. The system incorporates the use of O'Keefe Controls ZC-20 threaded insert check valves (Figure 4) to fill the pressure vessel and prevent backflow into the pressure vessel from the vent valve. The valves have a maximum operational pressure of 1000 psi [18].

Figure 4: O'Keefe Controls threaded fill valve [18]

The operational pressure range for Pocket Rocket is 0.04-0.09 psi (2-5 Torr). In previous studies [15], a Beswick Engineering PRD3 pressure regulator (Figure 5) successfully reduced pressure from storage pressures of 200 psi to operational pressures of 0.04 to 0.09 psi. The same regulator is incorporated here. However, the inflow port of the regulator opens directly into the pressure vessel, rather than being connected through a manifold and piping system to separate gas storage canisters.

Figure 5: Beswick Engineering PRD3 regulator [19]

Connections between gas delivery subsystem components is achieved through flexible tubing. Flexible tubing is implemented instead of fixed piping due to its flexibility in routing and its lower mass. The pressurized gas can be vented directly through the thruster tube. However, this process is inefficient as the pressure of the gas input into the thrusters is significantly lowered from the storage pressure by the regulator. To aid in depressurization, a dedicated vent valve is incorporated into the pressure vessel wall.

Power Storage and Delivery System

Power for the propulsion module, satellite bus, and payload is supplied by 4 commercial Tenergy 18650 lithium ion batteries mounted within the pressure vessel. While the batteries provide power to the entire satellite, they have been mounted within the propulsion module for thermal considerations, expanded on further in the Environmental Analysis section. To enable power transfer from the batteries to components outside the pressure vessel an electrical feedthrough is needed, as noted in the system schematic in Figure 1. Additionally, the feedthrough provides the connections between the satellite system board and propulsion components for command and control purposes.

ExoCube, a previous 3U mission flown by the Cal Poly CubeSat Laboratory [20] used a pressurized environmental chamber to encase a mass spectrometer. The ExoCube design incorporated a custom face-sealing hermetic electrical feedthrough for electrical connections between the mass spectrometer and system bus. This feedthrough permits integration with a wide variety of CubeSat buses with up 20 electrical connections in and out of the pressure vessel, hence is used here as well. Figure 6 is an example of a similar feed-through, but is not specifically the one implemented in this design. While the feedthrough itself is not modeled within the assembly analyzed here, a mount sized for the feedthrough has been included in the top lid of the chamber.

Figure 6: Face-seal hermetic feedthrough [21]

The batteries used to power the spacecraft provide DC power at 3.7 V. Therefore, a DC to RF converter is required to supply the correct frequency and voltage to the thruster. A working prototype of a DC-RF converter for Pocket Rocket was previously designed and tested by Stanford University in conjunction with the Australian National University [22]. The board converts standard 3.7 V DC power supplied from batteries into 13.56 MHz RF at a few hundred Volts as required by the thruster. A new design of the board is currently under development at Cal Poly which integrates better with the pressurized module. The RF power is delivered to the thruster through a standard SMA-f antenna connector.

Pressure Vessel and Structure

The pressure vessel structure is designed to maximize available volume and operational pressure while minimizing mass. Spherical or cylindrical pressure vessels are commonly used to minimize stress concentrations from internal pressures. However, to fit within the CubeSat specification [16], an external rail chassis would need to be added, increasing mass. To maximize propellant storage volume and permit the pressure vessel structure to also act as the rails required for CubeSat deployment, a cubic shape is used instead. Additionally, it is easier to manufacture internal mounting structures within a cubic shape.

For installation of and access to internal components, the pressure vessel is designed as a five sided base component, known as the chamber, with a separated single side or lid, as depicted in Figure 7. The chamber is and lid are both constructed from 7075 aluminum. As any joins contribute to potential failure points, the chamber is designed to be machined out of a single piece of aluminum. In a perfectly cube shaped pressure vessel, sharp corners are inherent stress concentrators. As such, the design of the chamber incorporates filleted surfaces on the internal sides to reduce stress concentrations.

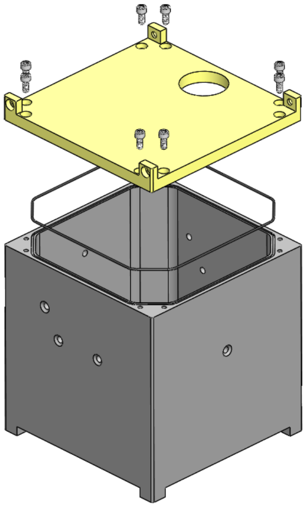

Figure 7: Pressure vessel assembly showing the five sided base chamber and the singe side lid

CUBESAT INTEGRATION

Adhering to the CubeSat Design Specification [16], two main factors are addressed in the design of the module; internal pressure and mass. Currently, the maximum allowable pressure for a CubeSat is 2 atm. However, this yields a mass of propellant capable of producing only 0.05 m/s of Δv for a 4 kg 3U CubeSat using Pocket Rocket. Therefore, higher internal pressures are required for meaningful performance with the system. As deviations from the CubeSat standard are possible on a case-by-case basis, and the potential for the standard to change in future revisions as technology matures, this is deemed an acceptable approach.

The mass of the propulsion module is driven primarily by the thickness of the pressure vessel walls, which in turn is driven by the storage pressure of the propellant. A wall thickness of 4 mm gives a total dry mass of the pressurized 1U module including all subsystems outlined above of 1.37 kg.

A wall thickness of 4 mm for the pressure vessel permits a maximum internal pressure of 68 atm (~1000 psi), confirmed using SolidWords. However, a safety factor of 3.7 should be included reducing the recommended propellant storage pressure to 13.6 atm (~200 psi). At 13.6 atm of internal pressure, the module yields 8 g of argon giving a 1.38 kg wet mass. While this is slightly higher than the 1.33 kg standard for a single 1U CubeSat, this module will form part of a larger CubeSat with higher total mass available.

A combination of screws tapped from the external faces of the chamber and rubber O-rings are used to mount components within the module and prevent leakage. The thruster is mounted in the center of the bottom face of the chamber using four tapped holes from the outside of the chamber that do not fully pass through the thruster housing as shown in Figure 8. A circular O-ring surrounds all four screws to create a seal between the pressure vessel and external environment while exposing the thruster nozzle to the ambient environment for thrust.

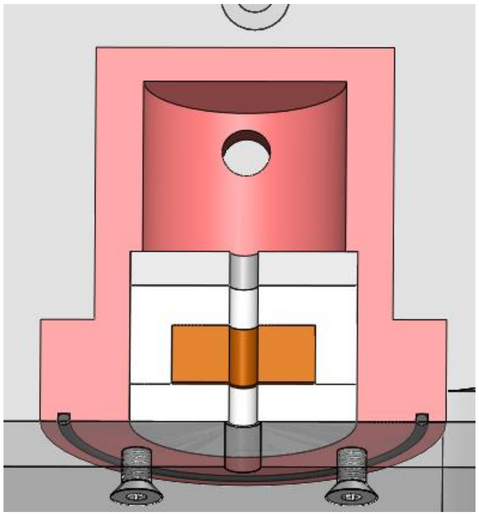

Figure 8: Cross-sectional view of thruster mount

The batteries are constrained to a side face of the chamber using screws inserted from the outside of the chamber to constrain a mounting. This specific mount uses flathead screws integrated with rubber O-rings as depicted in Figure 9. The screws are rated to 10,000 psi, far exceeding the capabilities of the pressure vessel itself.

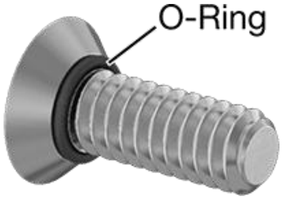

Figure 9: Sealing flathead screw [23]

Although still undergoing assembly and test at Cal Poly, approximate dimensions for the DC-RF board are used for mounting considerations. The DC-RF converter is mounted to the bottom surface of the lid using standard socket head screws to blind tapped holes on the internal face of the lid. The lid is used for mounting due to its proximity to the electrical feedthrough. As the holes do not fully pass through the chamber, sealing is not necessary here.

The irregular shape of the regulator adds additional challenges to mounting. Cutout rectangular struts interface with the railed segments on the regulator to mount it to the bottom surface of the chamber. The mounting brackets are fastened using the same sealing flathead screws used in the battery mounting bracket. The solenoid thruster control valve is constrained by a pair of brackets to the bottom face of the chamber. As for the DC-RF converter, the mount utilizes standard socket head screws in blind tapped holes and do not require sealing.

Static pressure analysis using Solidworks, shown in Figure 10, indicates notable stress concentrations around the screw holes on the lid and feedthrough connector. The increased stress points at the screw holes and feedthrough mount can be explained by simplified boundary conditions used in the simulation. The physical feedthrough and screws are not included in the model, so the support provided by the physical presence of the inserted components is not considered.

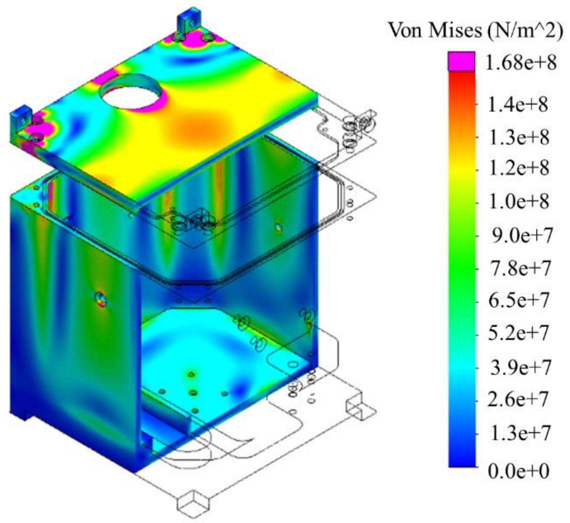

Figure 10: Static pressure analysis of pressure vessel at 200 psi. Pink sections denote stress above a safety factor of 3.7 but are overestimated due to simplified boundary conditions in the model.

ENVIRONMENTAL ANALYSIS

The Pocket Rocket thruster is embedded into the structure, with batteries, power processing unit (PPU), and propellant regulation and delivery system contained within the pressure vessel. Containing electrical components inside the pressure vessel assists with radiation and thermal protection for the spacecraft. Photon and charged particle radiation travelling through the high pressure propellant will lose some energy prior to impacting the embedded electronics, somewhat reducing effects from single event upsets and total ionizing dose. To further understand the effect the propellant storage has on radiation effects, a complete radiation study should be performed for the particular mission in question.

The sealed pressure vessel provides some protection against contamination and outgassing of internally located components. The high pressure argon will prevent outgassing of any components stored within the pressure vessel until towards the end of the mission when the argon propellant has depleted to low pressures. Contamination from on-orbit sources is not a consideration for the internally mounted components as the pressure vessel is completely sealed. Additionally, the thicker walls of the pressure vessel provide increased protection against micro-meteoroid impacts.

The heat storage capacity of the propellant will assist in creating a more stable thermal environment for the enclosed components. Simplified worst case scenarios for both hot and cold were run to ensure that all components, especially the batteries, remain within operational limits for a generic Low Earth Orbit (LEO) mission.

For the hot case, it is assumed the side of the CubeSat where the batteries are mounted, called the B-face for this analysis, is facing the Sun. This produces the highest heat load and therefore temperatures for the batteries. A solar heat flux of 1366 W/m^2 is applied to B-face, with the other five faces radiating to space (3 K). While the spacecraft may be tumbling throughout the orbit, one side continuously facing the Sun will give the most extreme temperatures.

The thruster is on to ensure highest heat loads from internal components, being the thruster itself and the DC-RF converter. The temperature of the outer housing of the thruster is assumed to be 315 K from previous thermal studies [24]. The DC-RF converter is assumed to output 1 W of heat power, based on 90 % efficiency at 10 W thruster operation [22]. Results for the hot case are given in Figure 11. The B-face is the left side with the cylinders representing the batteries along its internal face. The temperature of the batteries is approximately 315 K, well below the upper operational temperature of 333 K [25]. This simulation assumes minimal propellant remaining in the pressure vessel to maintain the worst case scenario. The additional of pressurized propellant will lower the slight thermal gradient across the module and provide more thermal stability.

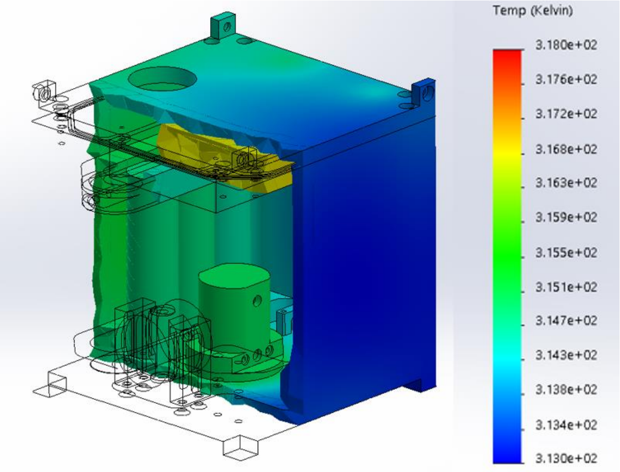

Figure 11: Hot case thermal analysis for thruster operation and battery mounted face continuously facing the Sun.

For the cold case scenario, it is assumed the spacecraft is in full eclipse, so the only environmental heat load comes from infra-red from the Earth at 240 W/m^2 [26]. It is assumed the spacecraft is tumbling, so no particular face receives a higher heat load. The thruster is assumed to non-operational for the cold case, with the only internal heat source being power generation by the batteries for a spacecraft in non-transmitting standby mode. At 90% efficiency [25], the batteries will output approximately 0.03 W of heat power to provide the 0.3 W required power for standby operation of a standard Cal Poly CubeSat bus.

Results for the cold case are given in Figure 12. As for Figure 11, the B-face is the left side with the cylinders representing the batteries along its internal face. The temperature of the batteries is approximately 264 K, above the stated lower operational temperature bound of 253 K for discharging [25].

For both the worst case hot and cold thermal models, the temperature of the batteries remained within operational ranges. Other components within the system have broader operational temperature ranges, therefore will also meet thermal requirements. As for radiation, a full thermal analysis should be performed for any mission using the pressurized module to fully understand the thermal environment.

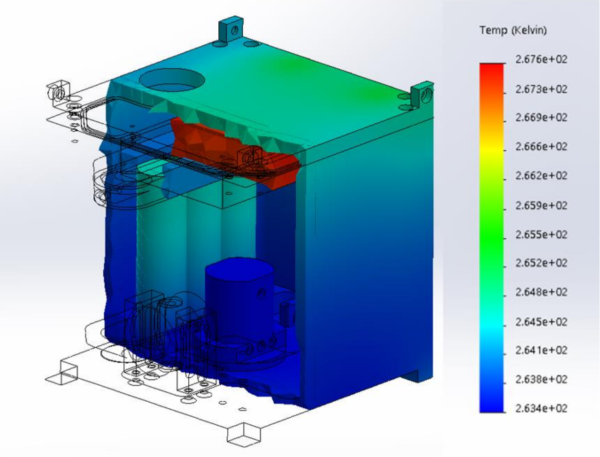

Figure 12: Cold case thermal analysis for satellite under standby mode in eclipse.

PERFORMANCE ESTIMATES

Expected delta-v (Δv) of the pressurized Pocket Rocket propulsion module is estimated using the ideal rocket equation, shown in Equation 1.

$$\Delta v = I_{sp} g \ln\left(\frac{m_{wet}}{m_{dry}}\right) \tag{1}$$

The spacecraft dry mass (m_{dry}) includes all component except the propellant and is 1.37 kg, with the spacecraft wet mass (m_{wet}) including all components and the maximum propellant amount based on pressure. The specific impulse (I_{sp}) is taken to be 100 s [10], and the standard gravitational acceleration constant (g) is 9.81 m/s^2.

The available propellant mass (m_p) is found for various storage pressures using the ideal gas law, shown in Equation 2 where p is storage pressure, V is storage volume, R is the Universal gas constant, M is the molar mass of argon, and T is the storage temperature, taken to be 295 K here.

$$pV = \frac{m_p RT}{M} \tag{2}$$

The calculated Δv available with gas storage pressures is shown in Figure 13 for varying additional spacecraft mass capacities in a 3U form factor. The additional mass includes all other on-board components and payload above the 1.37 kg from the dry propulsion module and propellant mass.

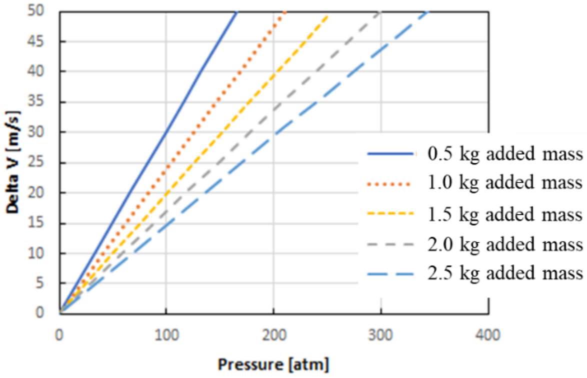

Figure 13: Available delta-V with propellant storage pressure for various additional spacecraft masses above that of the pressurized propellant module.

CONCLUSIONS

To maximize propellant storage capabilities, a 1U CubeSat form factor where the structure itself is a pressure vessel was developed. The Pocket Rocket thruster is embedded into the structure, with batteries, power processing unit (PPU), and propellant regulation and delivery system contained within the pressure vessel. All manufacturing is capable of being performed within a standard University workshop.

Using a cubic pressure vessel design to maximize propellant storage volume, the maximum propellant storage pressure is 200 psi using a safety factor of 3.7. A simple thermal analysis showed all critical components remain within operational envelopes in the worst case scenario of full sun with thruster operation, and full eclipse with no thruster operation and the spacecraft in standby mode.

When used as part of a 3U CubeSat mission, the pressurized 1U form factor is capable of producing between 5 and 50 m/s of Δv for different payload masses. This design shows the feasibility of using a pressurized CubeSat form factor for increased propellant storage and therefore increased mission capabilities. The next steps in the project will be to create a physical prototype for laboratory testing.

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