Consumable Spacecraft Structure with 3-D Printed Acrylonitrile Butadiene Styrene (ABS) Hybrid Rocket Thrusters

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ABSTRACT

An additively manufactured hybrid rocket thruster system has been developed to provide CubeSats with safe and efficient in-space maneuverability. To date, over 650 CubeSats have been launched via rideshare to varying degrees of operational success, and the numbers are increasing yearly. No system is currently available that can support large, impulsive maneuvers that would expand CubeSat mission capabilities and mitigate the space debris generated by the small spacecraft. To provide a solution, hybrid rocket technology developed at Utah State University has been reworked into four Acrylonitrile Butadiene Styrene thrusters 3D printed into a 2U CubeSat form factor consumable structure. The system has restart capabilities, non-hazardous propellants, and a simple configuration. The ABS/GOX thruster system is expected to have a vacuum specific impulse greater than 280 seconds and be capable of producing over 90 m/s of ΔV for a 4 kg, 3U CubeSat. The provided amount of ΔV is estimated to be sufficient to deorbit the 3U CubeSat in less than 25 years from a maximum initial altitude of 700 km. Hydrostatic testing has been successfully completed on the additively manufactured motor case, and hot-fire testing is expected to confirm performance estimates.

INTRODUCTION

Since the launch of Sputnik in 1957, thousands of objects have been sent into space. While many have since returned to Earth or decomposed upon atmospheric reentry, others are still in orbit. The sentiment for many years was that space is "big", and any number of satellites could be launched to orbit with no chance of accidental interaction; that assumption has since proven false. The first confirmed collision in space occurred in 1996 when French satellite Cerise was struck by a catalogued piece of debris[1]. Space debris is any man-made object in space that is not under precise control including inoperable satellites, spent and jettisoned rocket stages, and even paint chips. More collisions have occurred since the Cerise incident, damaging satellites and generating even more debris. Avoiding collisions in space is costly, and for satellites as large as the International Space Station (ISS), it can be dangerous. The ISS has had to complete several debris-avoidance maneuvers to avoid endangering the Station and crew's lives[2,3]. With more satellites being launched every year and new initiatives to advance the state of the art of human space travel, the problems associated with space debris will continue to grow. A type of small satellite called a CubeSat is of particular interest for this paper.

The CubeSat concept, introduced in 1999, drastically increased the ease of getting a small satellite project launched to orbit through standardization. A 1 unit (U) CubeSat has a nominal mass of 1.33 kg and volume of 10 cm X 10 cm X 10 cm, and several U's can be combined to make larger spacecraft. Many CubeSat components are now available for commercial-off-the-shelf (COTS) purchase online, and as long as the spacecraft adheres to California Polytechnic State University's CubeSat Standard, it can easily find a ride to space via rideshare with a larger launch vehicle[4]. As of June 2017, over 650 CubeSats have been launched to varying degrees of operational success[5]. Because they are relatively inexpensive to build and have regulations to help direct the design process, entities of varying experience levels have launched CubeSats with missions to provide communication, gather scientific data, test new technologies, and teach students a range of hands-on skills. Affordability was achieved through the size constraints, weight restrictions, cube form factor, and pressure vessel limits that allow CubeSats to launch on rideshares. Unfortunately, the same standards have limited the capability of these small spacecraft. This is increasingly important as the number of CubeSats being launched to orbit has exhibited an upward trend, as shown in Figure 1, and will likely continue to grow[5].

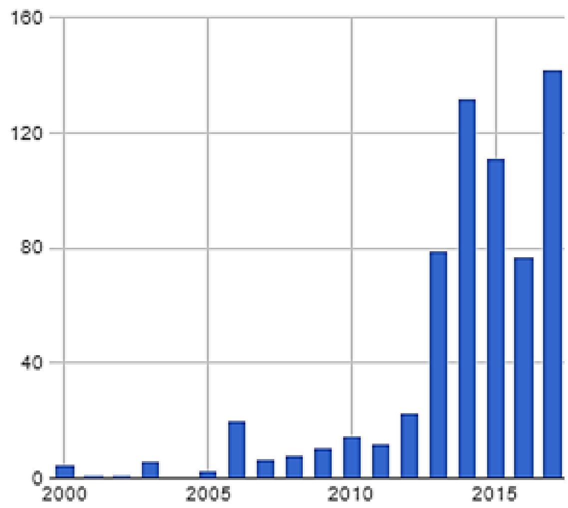

Figure 1. CubeSats launched yearly since 2000

As auxiliary payloads, CubeSats have little control over their destination orbit parameters. The majority of CubeSats have thus far been launched into low earth orbit (LEO), many of which were launched from the International Space Station (ISS). Multiple studies of CubeSat orbital decay have determined that CubeSats orbiting in LEO at or above 600 km may have lifetimes exceeding the internationally recognized 25 year lifetime limit, and the space debris hazard is becoming significant[6,7,8]. LEO is heavily populated with satellites, and a satellite must pass through LEO to reach higher orbits. Considering the added CubeSat obstacles, some of which are not operational, the likelihood of collisions in LEO is high.

Collisions in space are predicted by considering conjunctions, which are probabilities that two space objects will be in close proximity to each other. A study by Lewis and the University of Southampton determined that "Over their orbital lifetime, two-thirds of all CubeSats in the database have experienced one conjunction per day, one-third have experienced three conjunctions per day and one-tenth have experienced five conjunctions per day"[9]. This study was for CubeSats in orbit between June 2003 and December 2013, and Lewis predicts that by 2023 one in every 10 on-orbit conjunctions will involve a CubeSat, and collisions involving CubeSats could generate up to one fragment of debris for every 4.4 CubeSats on-orbit. Based on the increase in launches in the years since 2013, the estimates would likely now be even higher. The longer a CubeSat is in orbit, the more chances for conjunction it will create. Currently no feasible options exist for CubeSats to maneuver to avoid conjunctions, so larger and arguably more important satellites must use valuable propellant to maneuver around CubeSats. With an efficient on-board propulsion system, CubeSats would be able to complete in-space maneuvering and end-of-life deorbiting.

While many variations on CubeSat propulsion systems are available as concepts, few have been flown on a CubeSat mission. Most commercially-available propulsion systems are electric, cold gas, or use toxic monopropellants like hydrazine. Nearly all systems have low overall thrust and are non-impulsive; most thrusters for small satellites are rated in milli- or micro-N. Several high ΔV systems have recently been tested with success, but obstacles remain to installing these systems in CubeSats. The Aerospace Corporation, for example, designed and tested two small solid rocket propulsion systems that can provide up to 1400 m/s of ΔV with thrust vector control, but restartability was an unresolved issue[10]. A liquid bi-propellant system from Hyperion Technologies has been experimentally shown to provide up to 231 m/s of ΔV with restart capability, but further testing is required before it's ready for flight[11]. Hybrid rockets, while less common, are safer than solid rockets and require a simpler configuration than liquid rockets. The following discussion investigates using a hybrid rocket propulsion system to deorbit small satellites.

ABS/GOX HYBRID ROCKET TECHNOLOGY

Hybrid rockets possess several qualities that make them a viable option for a CubeSat propulsion system. Researchers at Utah State University (USU) have developed and extensively tested a reliably restartable hybrid propulsion system that uses an additively-manufactured acrylonitrile butadiene styrene (ABS) fuel grain along with gaseous oxygen (GOX) to create thrust. Both the ABS and GOX are safe to handle and present no vapor hazard. Compared to the ever-popular hydrazine, which requires a self-contained atmospheric protective ensemble (SCAPE) suit to handle, managing the hybrid propellants is significantly safer and more affordable. ABS can be stored nearly indefinitely with little to no deterioration, which is ideal for an unknown launch schedule. The GOX must be pressurized, but the safety precautions are not as extensive as with most other oxidizers. Unlike solids, which are live as soon as they have been mixed and cured, hybrids are inert until the ignition event occurs while coupled with oxidizer flow.

Through additive manufacturing, the ABS fuel grain can be printed into any shape with the ignition system built-in. The motors have primarily been printed at USU with a Stratasys Dimension® 1200es 3-D fused deposition modeling (FDM) printer using their standard density (0.975 g/cm3) ABS stock material. Nearly any

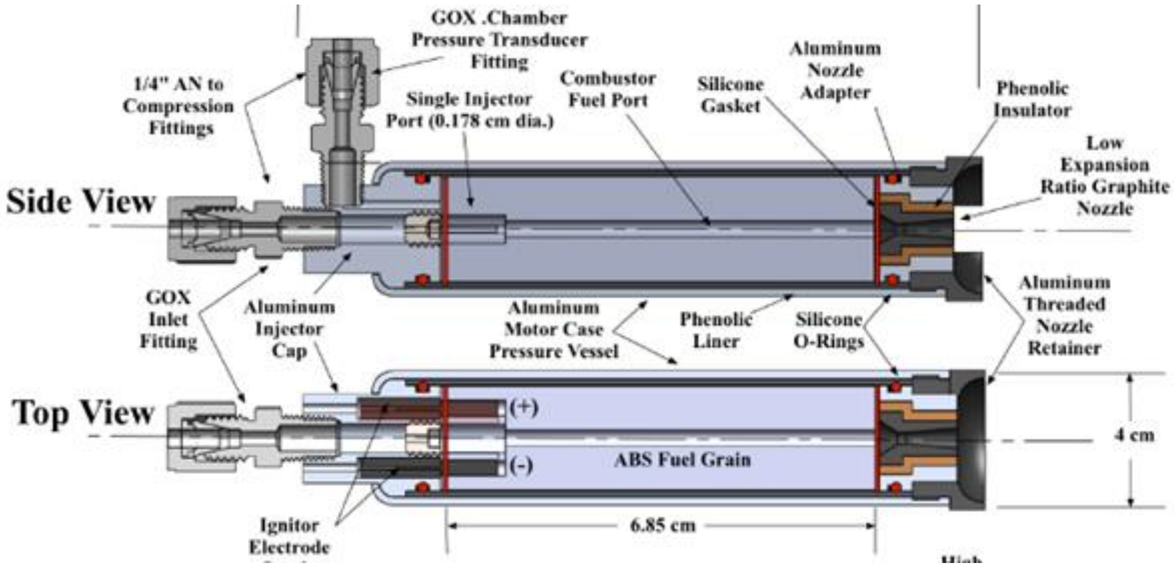

Figure 2. Configuration of USU's experimentally tested ABS/GOX hybrid rocket

printer capable of printing ABS can print the motors, which makes manufacturing extremely accessible.

The ABS/GOX arc-ignition system requires power as little as 6 W to initiate and provides nearly instantaneous restartability[12]. When an electrostatic potential is placed across the electrodes, electricity flows through a pre-existing surface arc-track, resulting in localized pyrolysis and ignition as soon as oxidizer flow is initiated. After the initial ignition, combustion is self-sustaining. The arc-ignition capability replaces the more traditional one-time-use igniters, and coupling it with hybrid rocket technology results in a reliably restartable system. Several sizes of motors have been tested at USU, one of which is sized similarly to the consumable structure motors presented in the following sections. Under ambient conditions with an optimized expansion ratio nozzle, the experimentally tested ABS/GOX system achieves specific impulse (I_{sp}) values of 215 s and near 25 N of thrust [13]. Tests completed on the same configuration but under vacuum conditions with a high expansion ratio nozzle at NASA Marshall Space Flight Center (MSFC) showed that the system is capable of delivering an I_{sp} of at least 280 s and near 30 N of thrust. This configuration of this system is shown in Figure 2.

These I_{sp} values surpass hydrazine-based systems, yet the hybrid configuration is inherently simpler and safer. Hydrazine is highly flammable and presents a vapor hazard, and so must be handled with extreme safety precautions. In stark contrast, many household products including toys are made out of ABS mixed with burn retardants. Of course, pressurized oxidizer must be handled with some care, but it represents a nearly insignificant hazard compared to hydrazine. Since the oxidizer is stored separately from the fuel in hybrid rocket systems, the chance of accidental ignition is greatly reduced. Furthermore, the arc-ignition system is inert until the signal to introduce a voltage is sent. The safety and sustainability provided by this ABS hybrid propulsion system makes it an ideal candidate for SmallSat applications.

CONSUMABLE CUBESAT STRUCTURE

An innovative four-motor thruster system has been developed in a 2U CubeSat form factor by applying the mature ABS/GOX hybrid rocket technology previously developed at USU. The integrated fuel grains will provide structural support, thereby decreasing overall mass and launch costs with a partially-consumable structure. When it's time to deorbit at the end of the CubeSat mission, structural support is no longer required, so the fuel grains can be burned to their limit, consuming the structure for added thrust to place the CubeSat in as low of a disposal altitude as the remaining propellant allows. The lower the final disposal altitude, the quicker the CubeSat will reenter the atmosphere. The system was designed to support at least a 1U volume payload for an expected total satellite mass of approximately 5 kg, which is the maximum reported 3U CubeSat mass[14].

ΔV Requirements

While it is desired that the system be able to support a range of in-space maneuvers, the ability to deorbit the 3U CubeSat from low Earth orbit (LEO) is a good preliminary benchmark for determining the minimum required ΔV that needs to be available. Deorbiting involves moving the CubeSat to an orbital altitude at which atmospheric drag will quickly cause the satellite to lose altitude and disintegrate upon atmospheric reentry in order to avoid potential collisions with other spacecraft or debris. A 5 kg, 3U CubeSat orbiting above approximately 500 km altitude is at risk of not meeting the international 25-year lifetime limitation guideline without any active deorbiting[15]. This orbital altitude (or below) will be referred to as the disposal orbit.

Moving the CubeSat to a circular disposal orbit can be achieved with a Hohmann transfer, which requires two, impulsive thruster burns. The amount of ΔV required to complete such a maneuver from a range of initial orbit altitudes to a range of deorbit altitudes was calculated by Summing ΔV_1 and ΔV_2 from eqs.(1).

$$\Delta V_1 = \sqrt{(2\,\mu)/r_i - \mu/a_H} - \sqrt{\mu/r_i}$$

$$\Delta V_2 = \sqrt{\mu/r_f} - \sqrt{(2\,\mu)/r_f - \mu/a_H} \qquad (1)$$

Based on the final orbital altitude after the rocket motor ceases firing, the CubeSat will reenter the Earth's atmosphere after a period of time. Several models for predicting this deorbit time are available, so a comparison was performed between a model that requires numerical integration of the equations of motion and an analytical model as presented in eqs.(2), where e_0 and a_0 are the initial orbital eccentricity and semi-major axis respectively, n is the mean motion, and I_1 is the Bessel function of the first kind and order[16].

The average cross-sectional area of a 3U CubeSat is estimated to be 350 cm^2 and was used to calculate β, the ballistic coefficient[14]. Atmospheric density, ρ, and scale height, H, were obtained from the 1976 Standard Atmosphere data.

$$\tau = \frac{{e_0}^2}{2B}\left(1 - \frac{11}{6}e_0 + \frac{29}{16}{e_0}^2 + \frac{7}{8}\frac{H}{a_0}\right)$$

$$B = n\beta\rho_0 a_0 e_0 I_1 \exp\left(-e_0\left[1 + \frac{a_0}{H}\right]\right) \qquad (2)$$

Both models were programmed in MATLAB, and the time required for a 5 kg, 3U CubeSat to reenter the atmosphere due to atmospheric drag from a range of disposal altitudes was calculated. This length of time, τ, was plotted against the ΔV required to conduct a Hohmann transfer from an initial orbital altitude of 400 km (approximately that of the ISS) to the same range of disposal altitudes. The comparison is shown in Figure 3.

While the numerical model produces a smoother curve, it took several minutes to compute. In contrast, the analytical model computed nearly instantly. The analytical lifetime estimate was selected as the best compromise between computation time and predicted accuracy.

Calculated from the analytical model, the disposal time, τ, was again plotted against the ΔV required to conduct a Hohmann transfer from a range of insertion altitudes

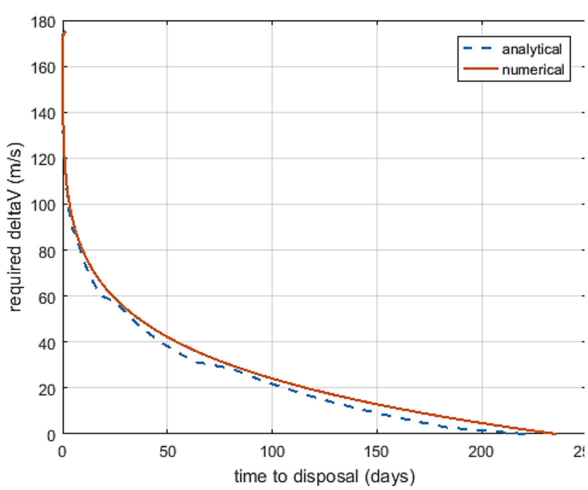

Figure 3. Comparison of analytical and numerical deorbit model accuracies: *plot of ΔV required to achieve disposal of a 5 kg, 3U CubeSat in a given amount of time after a Hohmann transfer from an initial altitude of 400 km*

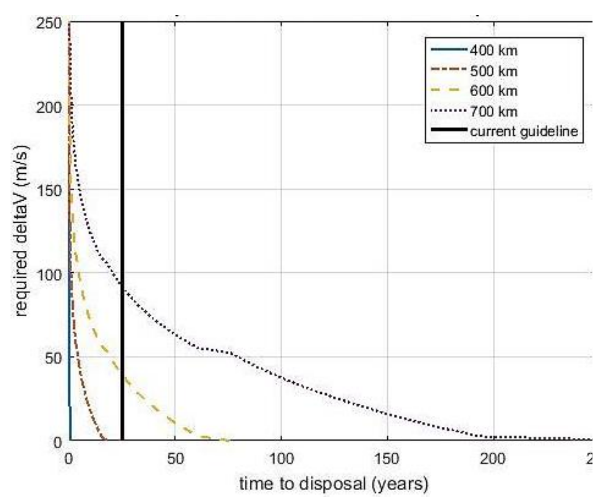

Figure 4. Comparison of initial altitudes: *plot of ΔV required to achieve disposal of a 5 kg, 3U CubeSat in a given amount of time after a Hohmann transfer from initial altitudes of 400, 500, 600, and 700 km*

to the same range of disposal altitudes as shown in Figure 4. The distribution of CubeSats in LEO are primarily in circular orbits between 600 and 1000 km, so this altitudes in this range were assumed for the initial insertion orbital altitude, or rather the altitude at ejection from the rideshare [6]. Zero ΔV represents the time it would take the CubeSat to reenter the atmosphere due to atmospheric drag if no Hohmann transfer were completed to bring the spacecraft to a lower disposal altitude. As confirmed by Figure 4, if the initial altitude is much above 500 km, the CubeSat will be in up to an orbit of magnitude greater than the 25 year lifetime limit. A value of τ approaching zero represents a Hohmann transfer to a very low altitude where reentry is nearly instantaneous.

At minimum, the hybrid propulsion system needs to be able to produce approximately 50 m/s to be useful in deorbiting CubeSats that would currently exceed the lifetime guideline. Any lesser amount of available ΔV would, however, still be useful for deorbiting in less time than is possible from atmospheric drag alone in addition to providing other maneuvering capabilities.

Propellant Sizing

The maximum wet mass is largely limited by the regulated mass and volume of the CubeSat standard, and the amount of useable ABS and GOX that can fit in a 2U CubeSat volume dictates the amount of ΔV that the propulsion system will be able to provide. Sizing is dependent on several parameters. Total allowable wet mass was estimated as the maximum 3U mass of 5 kg. It was assumed that the estimated I_{sp} and optimal O/F of 1.5 for this system is approximately equivalent to the values produced by the previously described USU motors. The design of the integrated ABS fuel grain structure is significantly driven by the available oxidizer tank. A lightweight composite tank was procured from HyPerComp Engineering Inc. that can sustain up to 31,026.41 kPa of pressure and has an internal volume of approximately 192.5 cm^2. The volume of ABS fuel that could be burned was calculated based on the available GOX volume and optimal O/F. The outer diameter of the fuel grain was iterated until the required grain length was less than a maximum of 15 cm, and the ratio of length to diameter was acceptable. The final dimensions of the cylindrical ABS motor are given in Table 1. The total mass of useable fuel is 52 g. A model of the prototype system with a triangular cross section is shown assembled with the oxidizer tank in Figure 5. Using a triangular or semi-angular cross section will maximize the available space for fuel storage.

Table 1. Final dimensions of burnable, cylindrical portion of ABS fuel grain

Parameter	Value
Bore diameter	0.5 cm
Burnable outer diameter	1.4 cm
Length	9.55 cm

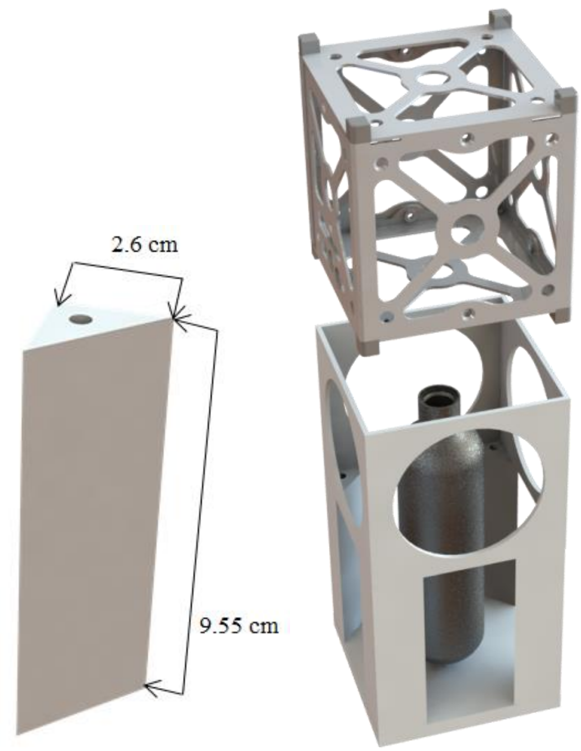

Figure 5. CAD model of single fuel grain (left) and prototype consumable structure shown with example 1U payload (right)

Ignition System

While the basic technology for the arc-ignition igniter had been developed previously at USU, the preferred implementation using bullet connectors was designed for use in larger, cylindrical motors. An alternative implementation with wires glued into the ABS grain had been used with success in other motor configurations; however, the triangular geometry of the consumable structure fuel grains required a modified design. A 3D-printed ABS igniter section with grooves was designed to hold the wires, which are glued and held in place with small ABS chips. A pre-combustion chamber will allow the ablated ABS created by the generated electrical spark to better mix with the injected gaseous oxygen (GOX). The igniter section is shown in Figure 6 as a CAD model on the left and 3D printed out of black ABS with black wires on the right. In order to test the effectiveness of the igniter, the wire leads were connected to a power source and a voltage was applied. An electrical arc developed along the pre-combustion chamber shelf between the wire endpoints as expected. The spark test was successfully repeated several times, which ensures that this igniter design supports a restartable thruster capability.

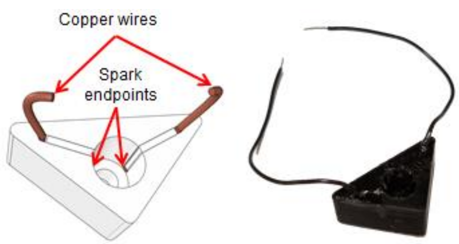

Figure 6. CAD model (left) and 3D printed ABS test article (right) of the igniter

Injector

Sizing the injector orifice diameter required the optimization of several parameters. The driving value was the oxidizer injector mass flow rate, which was desired to be a constant 2 g/s per motor for a total of 8 g/s supplied by the GOX tank for the four thrusters. The initial total mass flow rate of GOX and ABS must be initialized in the consumable structure hybrid thruster performance model used for the optimization, and it is directly affected by the injector mass flow rate. Varying the injector pressure affects both the chamber pressure and mass flow rate, so the predicted chamber pressure was monitored to ensure it remained greater than approximately 100 psi. Injector orifice diameter, total initial mass flow rate, and injector pressure were iterated until the optimal choked oxidizer mass flow rate was obtained with a minimum chamber pressure greater than 100 psi. The final values of the parameters after iterating are given in Table 2.

Table 2. Final injector design parameters

Parameter	Value
Initial total mass flow rate	5.0 g/s
Injector pressure	265 psi
Injector orifice diameter	0.0292 in

Nozzles

The nozzle interface is designed to accommodate interchangeable high and low expansion ratio conical nozzles made from graphite. In both cases, the convergent section is conical at a 45 degree angle. The expansion ratio for the ambient nozzle was designed for testing at USU in Logan, Utah and is approximately 1.9:1; the exact ratio will be measured on the final machined nozzle. The expansion ratio for the vacuum condition nozzle will be 15:1. The throat diameter for both nozzles is 0.114”.

Predicted Performance

A hybrid rocket performance model was developed to estimate the expected performance of the system. The model simulates the four, integrated thrusters burning until all available GOX in the tank is depleted. Given the optimized injector parameters and injector pressure of 265 psi, the approximate expected performance at ambient and vacuum conditions of a single thruster is described in Table 3. The total burn time is predicted to be over 10 s.

Experimental testing is required to verify the performance. Ambient testing will be completed at the testing facilities at USU in Logan, UT. Further testing under vacuum conditions will be completed at NASA MSFC.

Table 3. Estimated thruster performance in ambient and vacuum conditions

Parameter	Ambient Value	Vacuum Value	Units
Mean thrust	1.6	2.3	lbf
Mean specific impulse	212	302	s
Burn time	10.7	10.7	s
Mean chamber pressure	128	128	psi
Average O/F	1.43	1.42	

For a 5 kg, 3U CubeSat, the system should provide at least 70 m/s of ΔV as calculated from eq.(3). For a 4 kg CubeSat, the ΔV increases to over 90 m/s. This is greater than the 50 m/s minimum obtained from the deorbit analysis, so the hybrid propulsion system has the potential to be effectively used to mitigate space debris from future CubeSats and be applied to other orbital maneuvers or station keeping. The GOX tank used for this design was COTS, so it was necessarily smaller than optimal for the 2U CubeSat volume. If an optimally sized GOX tank could be procured, the available ΔV would be much higher.

$$\Delta V = I_{sp} g_0 \ln\left(\frac{m_{wet}}{m_{dry}}\right) \quad (3)$$

MOTOR CASE DEVELOPMENT AND TESTING

While ABS has strong material properties, the additive manufacturing process makes the material porous, and a case is required to withstand the chamber pressures generated by the hybrid thruster during operation. Based on a maximum expected pressure of 265 psi and a safety factor of 1.5, the case needs to support approximately 400 psi or greater. Two options for the case configuration, nickel plating and a 3D-printed Vero shell were analyzed.

Nickel Plating

Applying nickel plating directly to the additively manufactured ABS creates a custom motor case for the non-traditional geometry of the consumable structure. Ultimately, the entire four-motor consumable structure could be plated together, rendering it as a strong, modular propulsion unit.

The feasibility of the method was tested previously at USU and NASA MSFC on a series of simplified, cylindrical, prototype ABS/GOX hybrid motors. The prototype 3D-printed ABS fuel grains were electroplated with nickel and subjected to hydro-burst tests; the prototypes withstood pressures as high as 2000 psia before failure[17]. The prototype configuration is shown in Figure 7 with nickel plating applied after fittings were installed in the 3D-printed ABS.

Hot-fire tests on the nickel-plated prototypes were comparable to USU's typical ABS/GOX motor tests using a conventional motor case. Based on USU's successful prior testing, the nickel-plating motor case method was accepted for further investigation in conjunction with the consumable structure.

In order to maintain affordability while nickel-plating many iterations of the consumable structure, an in-house method for nickel-plating was attempted. The first step was creating a conductive layer onto which the nickel can be plated. Copper Conductive Paint supplied by Caswell Inc. Caswell's paint was tested by diluting it 5:1 with water according to manufacturer's recommendations. This was painted with a high-volume low-pressure (HVLP) spray gun onto ABS samples of varying geometry and size, but the coating was uneven due to the uneven surface of the ABS created by the deposition nature of the 3D printer. The paint was unfortunately easily removed when tape was applied to the surface and peeled off.

Two plating solutions were tested for use with the Caswell Paint: a homemade solution of water and copper sulfate pentahydrate from ZEP Root Kill and a ready-made solution from Caswell. Plating with either solution was not possible on the first sample due to breaks in the conductivity from the uneven paint surface. The resistivity of the Caswell solution was found to be much lower, however, which is preferred for plating, so it was used in the rest of the testing.

In an effort to make the paint coating more even to

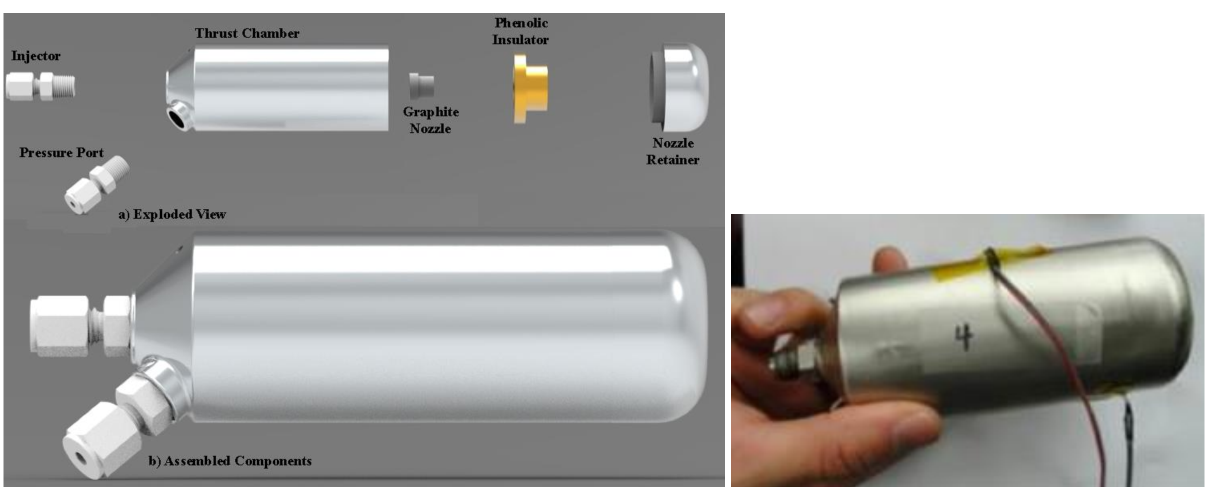

Figure 7. Nickel-Plated ABS Thrust Chamber Design

increase conductivity for plating, the surface was sanded smooth with 120-grit sandpaper, sprayed with compressed air, and rinsed with isopropyl alcohol (IPA). This resulted in a much more even coat of paint. Small amounts of paint were still removed, however, with the tape test. The substrate plated more evenly than before, but was still not uniform, likely because parts of the surface were not evenly sanded due to difficult sample geometries. After plating, rinsing with water and gently wiping with a paper towel removed the plated and painted material. In a final attempt, fine-particle sandblasting was used before painting, but this method resulted in poorer plating performance than the hand-sanded samples.

The poor bonding of the copper paint to the ABS is likely due to the hydrophobic property of ABS combined with the water-based conductive paint. In order to overcome this, a piranha solution (98% sulfuric acid and 30% hydrogen peroxide) will be tested for etching the surface to make it hydrophilic and more likely to bond with the paint.

3D-Printed VeroClear Shell

Due to the limited success with the in-house nickel plating methods and other time constraints, an alternative 3D-printed Vero plastic case configuration was investigated. The Vero family of materials is rigid, polycarbonate-based photopolymers featuring proven dimensional stability for general-purpose rapid prototyping. This widely-available material can be printed by a number of commercially available PolyJet® printers. Opaque varieties, like VeroBlue and VeroOrange were considered, but the final design employed VeroClear since translucency makes for richer test observations. A preliminary study at USU employed shells of VeroClear as motor cases for small ABS/GOX rockets with success; the VeroClear case withstood the chamber pressures and temperatures typical of the USU motors, and mild deformation was only observed near the nozzle and injector after the burn was through. With these promising results, the technology was adapted for use with the consumable structure motors.

A triangular VeroClear case was created with the same outer dimensions as the consumable structure motor shown in Figure 5. A chamber within the case was designed to accommodate the equivalent cylindrical motor described in Table 1. The case is approximately 4 mm thick at the thinnest side and accommodates a single, cylindrical consumable structure ABS motor with nozzle, igniter, and injector as described previously. Models of the motor and Vero case are shown in Figure 8.

The case was printed with the nozzle port sealed in order to conduct hydro-static testing. The hole on the injector end of the case was tapped, and the GOX feedline fitting (used for water in the hydro-static tests) was installed. Super glue was used to secure the wires on top that would be used for the ignition system and a stainless steel tube fitted for the pressure transducer on the side. Strain gauges aligned parallel to the axial and longitudinal axes were mounted near the center of the test article on one side and the hypotenuse in order to capture the deformations during testing.

Water was pumped into the assembly until it failed while pressure and strain were logged via National Instruments data acquisition devices and LabView Virtual Instrument. A photograph of the assembly post-test is shown in Figure 9.

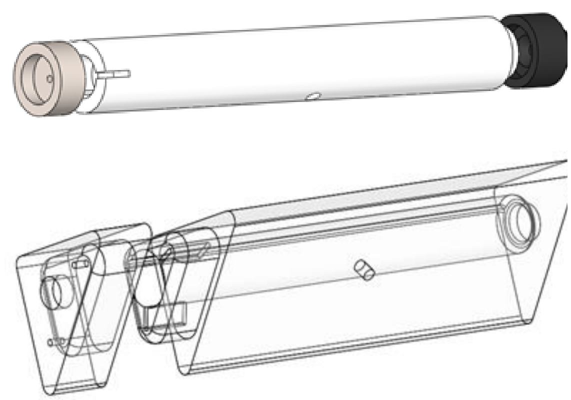

Figure 8. Exploded view of injector, ABS fuel grain, and nozzle (top) and VeroClear case (bottom)

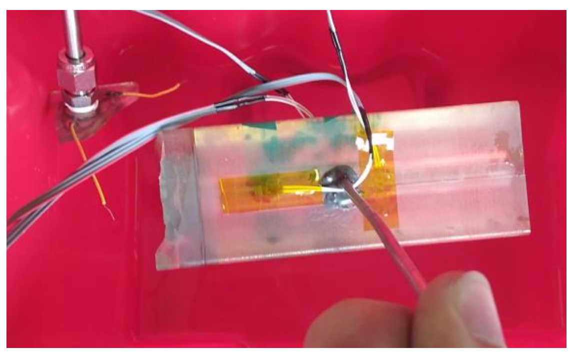

Figure 9. VeroClear Case after hydro-static testing. *Shown with GOX feed line, igniter lead wires, strain gauges, and pressure transducer tube installed*

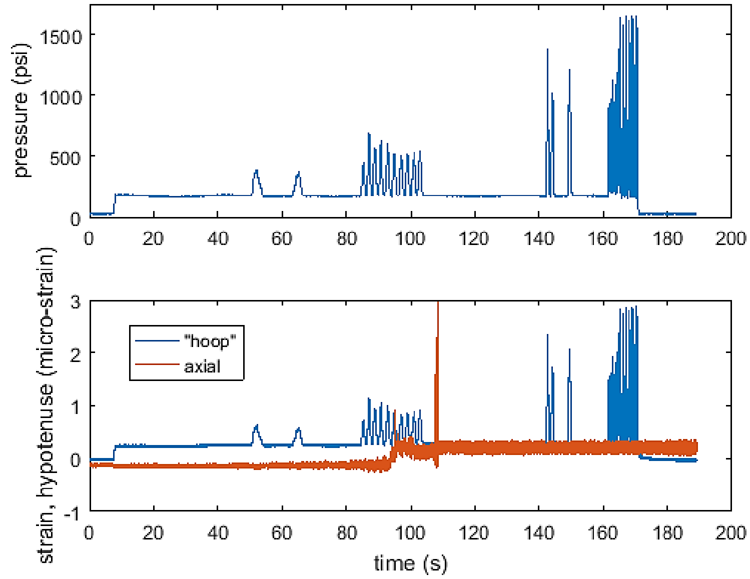

Figure 10. Results of hydro-static test on VeroClear motor Case

Time histories of the data are shown in Figure 10. From the plots, failure of the assembly occurred between 80 and 100 seconds (the earlier peaks are from some cycling of the pressure, which was increased by hand). The case was able to withstand nearly 800 psi before failing, which is close to double the minimum requirement. A pressure gauge on the pump read approximately 825 psi before a visual failure was observed. Deformation on the side was minimal, but the hypotenuse strains follow the changes in pressure.

Based on these results and the previous USU prototype results, the VeroClear case may feasibly be used with hot-fire tests of the consumable structure motor.

CONCLUSION

The ABS/GOX hybrid rocket consumable structure propulsion system has the design potential to provide efficient, safe, and reliable impulsive ΔV for quick control over a spacecraft. By 3D printing the ABS fuel into a portion of the structure that would otherwise be added as necessary supportive dry mass, the overall mass is reduced, which can lead to increased payloads or decreased launch costs.

Promising progress has been made toward developing a simple in-house nickel plating process that will allow for a quick and affordable thruster assembly. Further work on the in-house plating process and research into out-of-house plating will enable testing of the plated consumable structure configuration in the future. Research into using an additively manufactured VeroClear shell as the motor case has shown potential, and hot-fire tests using this casing method will be completed on both a single thruster and the four-thruster system to verify the actual system performance.

Using a propulsion system to deorbit a CubeSat provides an advantage over other existing space debris mitigation methods in that the system can also be used during the mission to initiate other maneuvers. The consumable structure hybrid rocket propulsion system will allow CubeSats to perform more complex missions while remaining non-hazardous to developers and safe for ride shares. This will help ensure that CubeSat missions continue having the opportunity to launch for many years to come without impacting the success of other missions.

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