Development of a Rockoon Launch Platform and a Sulfur Fuel Pulsed Plasma Thruster CubeSAT

Ian Johnson, Race Roberson, Chad Truitt, Jaime Waldock, Paige Northway, Michael Pfaff, and Robert Winglee
University of Washington
Johnson Hall Rm-070, Box 351310, Seattle, WA 98195-1310; (206) 914-0211
ikj@uw.edu

ABSTRACT

Amateur rocket launches are unable to reach heights much above 30 km due to the high drag of the dense lower atmosphere. Using a balloon to rise to an altitude of 30 km before launching is one means to increase a rockets range. An overview of the concept and a summary of the launch history for the University of Washington rockoon (rocket / balloon) program are given. Such a system will be capable of providing an inexpensive and reduced complexity launch method for student projects. Additionally, the university has recently opened a CubeSAT laboratory to give students hands-on experience with satellite hardware. Once in orbit, CubeSAT missions are limited, in part, due to an inability of low power thrusters to offset atmospheric drag. Recent results show that a coaxial sulfur-fuel Pulsed Plasma Thruster can provide a impulse/energy ratio of 20 mN/kW from a 10 J discharge, double of what a similar geometry Teflon variant is capable of. This increase in performance can provide CubeSATs the propulsion necessary for station-keeping in orbit. With launches planned over the next five years, the University of Washington aims to launch a 3U CubeSAT from a rockoon on a suborbital flight as a student project.

INTRODUCTION

For a university student project to succeed the system must be relatively low-cost, robust, and free of extensive complications. For this reason universities across the country have invested time and money into the development of small, lightweight satellites called CubeSATs Their scientific and technological value has been steadily increasing with each passing year due to the rapid miniaturization of sensors, communication equipment, and electronics. Although the design and fabrication of the satellites are accessible to universities, their launch into orbit remains the largest hurdle in carrying the mission to fruition and the lack of a small size, low power propulsion system prevents extended mission timelines. This paper details two ongoing student projects at the University of Washington: (1) a rockoon launch vehicle to provide low-cost access for higher altitude and velocity flight paths than the traditional amateur rocket launches are capable of and (2) the design and testing of a sulfur-fuel based Pulsed Plasma Thruster (PPT) to provide propulsion for a CubeSAT satellite.

For a satellite to be truly effective, both in terms of control and longevity, a propulsion system is required. Due to the nature of a CubeSAT, the required propulsion system will be severely limited in mass, volume, and power available. These characteristics naturally lead to the use of an electric propulsion thruster. The inherent simplicity and long successful flight history of the PPT make it appropriate for CubeSAT operation. The PPT was first flown in 1964 by the USSR on the Zond-2 Mars mission and has been successfully used on a regular basis ever since.[1] The largest advantage of the PPT is its inherently simple and compact power processing unit (PPU) which includes only one moving component. The thruster uses a solid propellant, negating the need for complex and large fuel tanks. The ablated propellant is accelerated through both electromagnetic and electrothermal forces.

In the 1940s the US government began developing the capability of air-based launches of experimental aircraft.[2] Over the following decades this naturally lead to researching the concept of launching rockets from aircraft at altitude, due to the reduced mass, thrust, and cost requirements of such a system. Further experimentation by James Van Allen and the US Navy lead to rocket launches from balloons, reducing the cost again. [2] The principal advantage of a rocket launch at high altitude is that the rocket is not required to undergo powered flight through the low, dense atmosphere, which imparts a large drag force. This allows the rockoon launch system to conserve a significant amount of mass that would otherwise be needed for propellant, reducing the overall size of the system. The rocket's first stage nozzle can be optimized for low ambient pressure, improving the exhaust velocity and thrust. It is also possible to make use of higher impulse fuels precluded from surface launches, such as those containing beryllium or fluorine, due to their toxicity. Infrastructure and prelaunch costs are reduced due to the nominal requirements of the launch pad and surrounding structure.

LAUNCH CONCEPT OVERVIEW

Balloons are routinely used to lift payloads of more than 200 kg to altitudes above 30 km. These balloons can roughly be placed into two categories: burst and zero-pressure. Burst balloons separate the interior of the balloon from the exterior atmosphere, resulting in the balloon diameter expanding to balance the exterior pressure with increasing altitude. At a given height, the latex will be stretched to a maximum stress limit and break. Zero-pressure balloons can float for extended periods of time once they reach their peak altitude by balancing the interior and exterior pressure. Although requiring a more complicated design, these zero pressure balloons are the obvious choice for the full-scale rockoon, as the ignition of the rocket will not be tied to the unpredictable moment of a balloon burst.

The system to be launched from the ground is shown in Fig. 1. Under normal conditions, the helium filled balloon will lift its payload to an altitude of approximately 30 km. At this height the entire system floats until the ignition command is given from the ground launch control. In the case of an accidental tear of the balloon, its entire payload returns to ground using the parachutes, which are passively deployed. The instrumentation platform and firing control will acquire and send real-time location, status information, and the firing commands, to and from the ground control station.

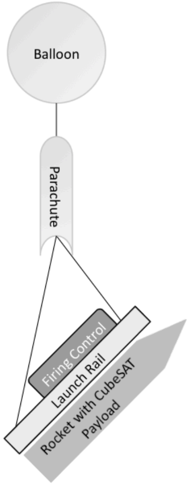

Figure 1: The rockoon launch system.

The typically balloon launch profile can be broken into 5 steps:

1. Balloon Rise: Depending on the amount of Helium placed into the balloon, the system will reach its floating altitude of approximately 30 km 90-120 minutes after launch.
2. Stabilization: Helium will be released from the balloon to create a neutrally buoyant system
3. Ignition: The ignition command will be given from the ground and the rocket will start the powered flight phase at an initial flight angle of ~60 degrees. This inclination is necessary to place the rocket onto a path parallel to Earth without active control, which is restricted to military use.
4. Cutdown: Assuming the balloon is not burst by the rocket launching, the balloon and launch rail will begin to rise after the weight of the rocket is removed. A helium release command from the ground will deflate the balloon, returning the launch rail and firing control box to the ground via passively deployed parachutes.

The balloon based rocket launch requires a mobile launch control, which can be located in a standard SUV. It is estimated that a crew of seven can set up in three hours and complete the launch with orbital insertion in less than six hours. The timeline for the recovery of the instrumentation platform and launch rail will depend on exactly where the payload lands and will vary from launch to launch. This mobility allows launches from virtually any latitude, restricted only by safety range considerations. As with the rockoon programs from the 1950s, the balloon and assembly could be launched from an ocean-based vessel, negating the concern of a rocket ignition over populated areas.

Obviously weather conditions will affect the release of the assembly from the ground and the lower altitude portion of the balloon ascent. Of particular concern is wind speed and direction, which will vary greatly with altitude. However, even low power telemetry systems operating at amateur radio frequencies can communicate over 100+ km distances, and as such, the assembly would reach the floating altitude without drifting out of communication range.

Launching from 30 km provides immense benefit to the simplicity and cost of the rocket, both of which are necessary to allow for the University driven launch. As the first stage fires at 30 km, where atmospheric density and pressure are 2% relative to sea-level, the rocket engine nozzle geometry can be optimized for high efficiency. Furthermore, the value of the maximum dynamic pressure will be extremely low, resulting in a more relaxed structural design. The latter is further supported by lower launch loads (vibrations) compared to conventional large rocket launch.

The solid propellants in O-class motors available for a University launch have a typical specific impulse (Isp) of 212 s, corresponding to an exhaust velocity of 2.08 km/s. The velocity required to place an object into LEO is approximately 7.6 km/s. A total velocity loss of 1.6km/s is assumed, due to thrust-atmospheric loss, drag loss, gravity loss, maneuvering, and launch window allowance. The thrust-atmospheric and drag losses will be much smaller compared to a sea-level launch, due to the high altitude of the entire powered flight. With these assumption the necessary burnout velocity is 9.2 km/s. Assuming a four-stage launch vehicle, with each stage contributing equally to the velocity increment, the burnout velocity after each stage would be 2.3 km/s. This results in a mass ratio per stage of

$$\frac{\Delta m}{m_0} = 1 - \frac{1}{\exp\left(\frac{v_{bo\_stage}}{C_e}\right)} = 0.67 \tag{1}$$

where $\Delta m/m_0$ = mass fraction, v_{bo_stage} = change in velocity at burnout per stage, and C_e = exhaust velocity. Assuming a 10% redundant structure mass, each stage would be able to lift a payload mass 23% of its initial mass, with a final payload mass / initial mass of 0.3%. The table below shows the mass breakdown of the four-stage launch vehicle required to place a 3U (3 kg) CubeSAT into LEO.

Table 1: Mass breakdown of 4-stage rockoon rocket required for CubeSAT LEO insertion.

Stage	Initial Mass (kg)	Fuel Mass (kg)	Structure Mass (kg)	Payload Mass (kg)
1	1072	718.2	107.2	246.6
2	246.6	165.2	24.7	56.7
3	56.7	38	5.7	13
4	13	8.7	1.3	3

Such is a system with this design is theoretically possible, if enough propellant can be efficiently burned. Realistically, as a university student launch, this isn't possible with commercially available motors. As a university project, a rockoon launch system would, at best, be capable of suborbital velocities. The following section details the development work completed to date of the rockoon launch system.

LAUNCH SYSTEM DEVELOPMENT

The University of Washington has a long history of balloon and rocket launches through its ESS205 Access to Space and ESS472 Rockets and Instrumentation courses. Those that are applicable to the Rockoon launch concept, including high-altitude balloon, cluster motor, and multi-stage rocket launches are summarized here. Previous history and future plans for the Rockoon launch are given as well.

Balloon Development

Due to balloon launches being a low-cost means to test student experiments, the department has a long history of high-altitude balloon flights, stretching back to 2004. These have all been flown with 1600 gram latex burst balloons out of Moses Lake, Washington. The altitude profiles for those flights reaching an apogee over 28 km are shown in Figure 2.

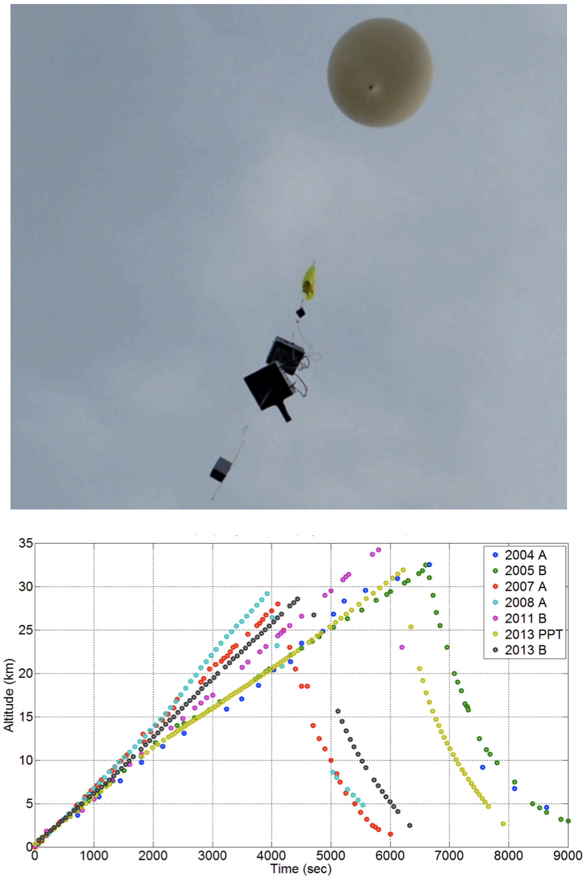

Figure 2: The 2013 PPT atmospheric balloon experiment immediately after launch (top) and altitude profiles for student research flights from the University of Washington that reached apogees over 28 km (bottom).

In addition to the departments burst balloon flights, there is a long history of high-altitude, long duration flights. The professors and research laboratories associated with these launches are still active in the department today. Two of the more notable campaigns are noted here. The INTERBOA campaign in Sweden launched five balloons between 1996 and 1998 to study auroral precipitation from stratospheric balloons in conjunction with scientific satellites. Each flight lasted two days and reached an altitude of 35 km.[3] In 2000 the MAXIS balloon flight around the north-pole was launched from Alaska, ascending to an altitude of 120,000 ft to study electron precipitation into the ionosphere. The balloon traveled east to west around the North Pole over a two-week period.[4]

Rocket Development

The University of Washington first successful cluster motor rocket flights came in 2013 with a 6-motor design. The computer system built for the rockets are designed for wireless ignition and telemetry, transmitting GPS coordinates and acceleration during the flight. The first (flown in Mansfield, Washington) reached a peak acceleration and velocity of 20.9 g's and 1,361 ft/s, respectively, resulting in a maximum altitude of 12,132 ft; while the second launch (flown in Black Rock, Nevada) reached peaks of 20.1 g's and 1,232 ft/s, with a maximum altitude of 14,339 ft.

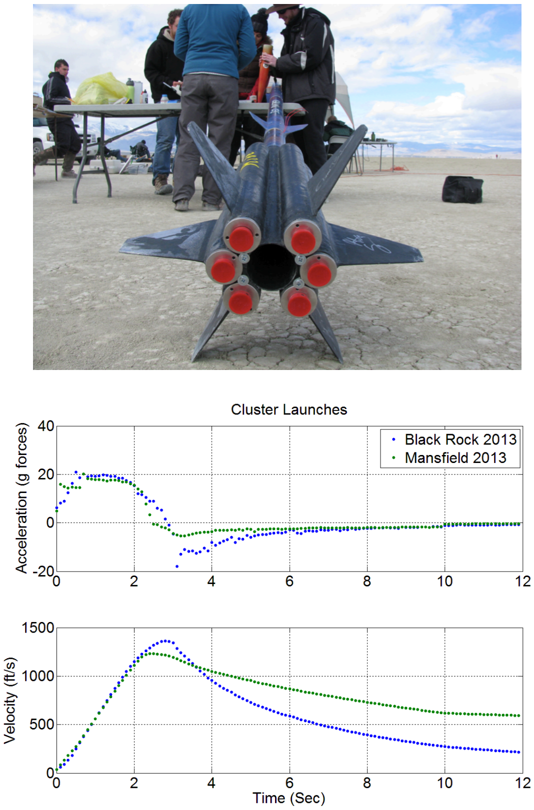

Figure 3: Two 6-motor cluster rockets have been tested (top). The measured acceleration and calculated velocity profiles for the 2013 cluster motor launches are shown (bottom).

In addition to cluster motors, multiple stage rockets will be necessary for a rockoon launch system. To this end, a two-stage rocket was tested. The first stage achieved a maximum acceleration of 9.09 g's and a maximum velocity of 527 ft/s, while the second stage achieved a max acceleration of 3.18 g's and a further increase in velocity to 585 ft/s. The combination of the two stages reached a maximum height of 7,337 ft.

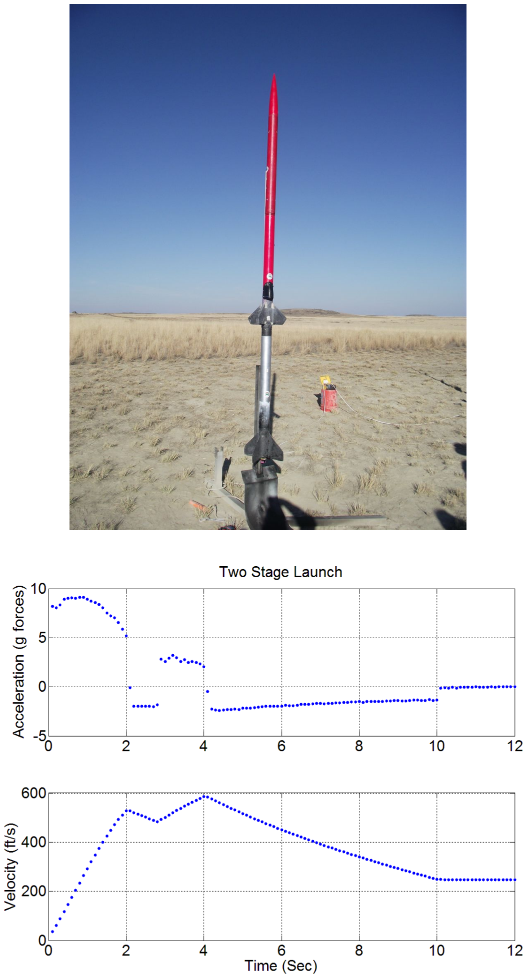

Figure 4: The two-stage rocket on the launch pad (left) and the measured acceleration and calculated velocity profiles (right).

Rockoon Development

To initially determine the feasibility and possibility of a rockoon launch, a tube system suspended off the ground was built (Fig. 5) and tested in 2012. Two single-stage, single-motor rockets were launched from the system. Due to the second rocket catching on the end of the tube while exiting (note acceleration reduction 0.2 s into flight), the launch system was modified to a rail. The rail system was first tested while tethered to the ground for better experimental control and to comply with FAA regulations. In 2013, two 1200 g latex balloons lifted the rail and rocket to an altitude of 1,000 ft. The rocket was successfully launched with apogee at 11,000 ft. The rocket, launch rail, and firing electronics were all recovered undamaged. All three of these launches were single-stage, single motor rockets, reaching peak accelerations between 15 and 30 g's. In 2014, a larger 2-stage rocket was launched from four low-altitude tethered balloons. This rocket was not recovered and the telemetry recorded was inconclusive in regard to it's maximum acceleration, velocity, and altitude.

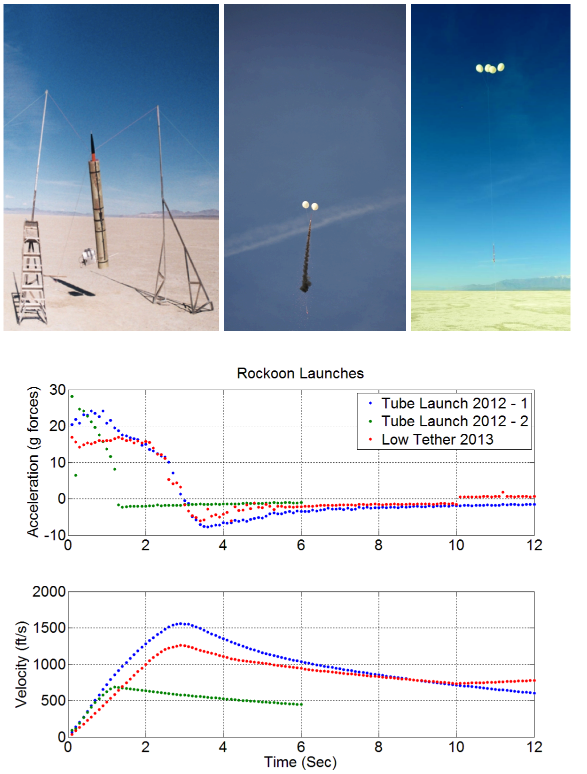

Figure 5: The tube launch rockoon system (top left), 2013 low-altitude tethered single-stage rockoon immediately after ignition (top center), 2014 low-altitude tethered 2-stage rockoon before ignition (top right), and the measured acceleration and calculated velocity flight profiles (bottom).

Currently the laboratory has set a goal of raising a payload to suborbital velocities by the end of the decade. Simulations have shown this can be achieved for a 3U CubeSAT through a three-stage rocket launched from a balloon at a 30 km altitude. The rocket would have an initial mass of 175 kg, launched from a 25 kg rail structure, with the entire system requiring 14.1 m^3 of helium (at STP) to float the system at 30 km. The rockets first stage would be powered from five O-6300 motors, the second stage from three O-6300 motors, and the third from three K-550 motors. This results in a peak vertical force of 30 kN during the first stage burn and a peak acceleration of 400 m/s^2 during the second stage burn. The maximum velocity, 2.5 km/s, is obtained at the end of the third stage and a maximum altitude of 400 km is achieved 280 s into the flight.

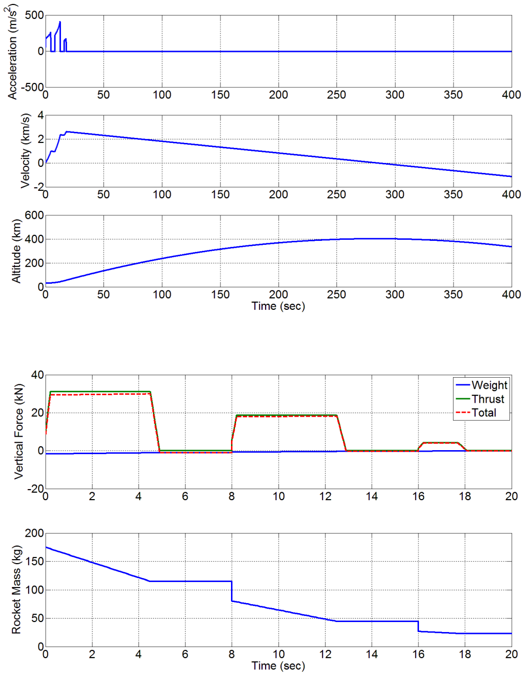

Figure 6: The acceleration, velocity, and vertical position simulations (top) and verical force and mass simulations (bottom) of the proposed 3-stage rockoon rocket.

The rocket motors, acceleration, and velocity values quoted in the previous paragraph are all reasonable for a student built launch vehicle and have been flown before, however the combination of all from a three stage rocket launched from a rockoon has not. At current construction and launch pace, the University of Washington believes a payload launched along a suborbital flight path is achievable by the end of the decade. This launch will be capable of lifting a 3U CubeSAT payload to LEO altitudes; however, larger motors and sustained thrust will be necessary to achieve the horizontal velocity required to stay in orbit.

Table 2: The development timeline proposed for launching a 3U CubeSAT on a suborbital flight by the end of the decade.

Year	Rockoon Launch
2013	Single-stage low-altitude tether
2014	2-stage low-altitude tether
2015	Single-stage from 30 km
2016	Cluster-motor from 30 km
2017	Cluster-motor from 30 km
2018	2-stage cluster from 30 km
2019	2-stage cluster from 30 km
2020	3-stage cluster from 30 km

SULFUR PPT DEVELOPMENT

The PPT is a robust, light-weight, variable power, variable thrust, and inherently simplistic electric propulsion thruster.[1] It is a hybrid electrothermal and electromagnetic device. The use of solid propellant eliminates the complexities of valves, tubing, and pressurized vessels inherent with gas-fed thrusters. The simplistic and increased safety features of the PPT make it ideal for CubeSAT operation. The operation of the PPT consists of four basic steps: (1) Placing a large voltage potential on the cathode and anode with the main discharge capacitor. (2) Completing the cathode/anode circuit with a small amount of seed plasma created from the secondary leads of the igniter transformer. (3) Current from the main discharge capacitor flows across the fuel cell surface, ablating the solid fuel and creating a gas/plasma mixture. (4) The neutral gas and ionized plasma are accelerated out of the thruster.

Figure 9: The coaxial PPT tested in this study.

Teflon has been the historical standard fuel for ablative PPTs due to a high specific impulse, high impulse bit, and little surface charring compared with other propellants. Minor improvements to the efficiency and mass bit have been found with Teflon variants and other plastic fuel sources; however no published research has been found of results from non-plastic fuel sources. Testing at the University of Washington has shown that a PPTs specific thrust can be increased with non-plastic fuels; in particular, fuels which included sulfur. This is believed to be due to sulfurs low melting and boiling point, low enthalpy of sublimation, and low ionization energies.

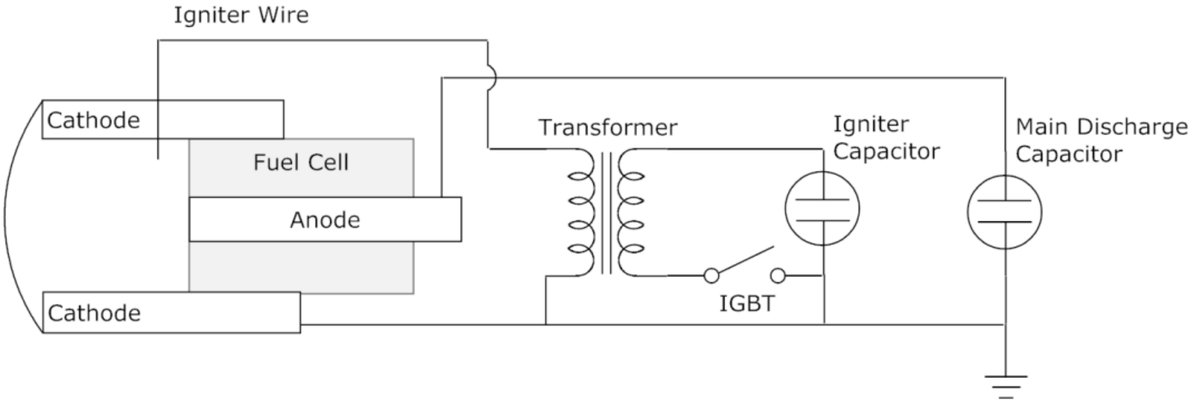

Figure 8: Top-level PPT circuit diagram showing the main and igniter electronic components, electrodes, and fuel cell.

While unpopular due to its corrosive and volatile nature, sulfur and partially sulfur elements are not materials entirely excluded from space flight research. In 1991 sulfur was examined as a possible propellant for a 20,000 s Isp pulsed plasmoid electric thruster.[5] Computer simulations have shown that using sulfur as the working fluid in a high temperature supercritical Brayton cycle power system can produce a 221% efficiency increase over the sodium Rankine cycle.[6]

Theoretically the use of a heavier fuel will increase a thrusters specific thrust at the expense of lower exhaust velocities, as shown by

$$E = \frac{1}{2} m C_e^2 \tag{2}$$

$$T = \dot{m} C_e + \left(P_e - P_0\right) A_e \approx \frac{m C_e}{t} \tag{3}$$

where E = discharge energy, m = fuel mass, C_e = fuel velocity, P_e = nozzle exit pressure, P_0 = ambient pressure, and A_e = nozzle exit area. Assuming the first term of Eq. (3) is >> than the second term, at constant energy a doubling of the propellant mass results in a velocity reduction by a factor of $\sqrt{2}$, resulting in a $\sqrt{2}$ thrust increase.

A comparison of specific thrust for the Teflon, sulfur, and bismuth sulfide thrusters at varying capacitor energies were made at a background pressure of 50 µTorr (Fig. 10). For all fuels, the specific thrust initially rises before leveling off at capacitor energies above 40J. The sulfur PPT leveled off at 18.4 mN/kW, 2.3 times higher than with Teflon and 1.8 times higher than bismuth sulfide. The PPT onboard the Earth Observing One (EO-1) satellite is currently the thruster to which all PPTs today are measured again.[7] A comparison to the specific thrust of the EO-1 PPT is also included in Fig. 3; as with the laboratory thrusters, EO-1 showed an initial increase in specific thrust until leveling off at 15.6 mN/kW, double that of the UW Teflon thruster and 18% lower than the sulfur version. There were numerous design differences between the EO-1 and UW Teflon thruster tested in the APL. The most significant were the increased fuel cell surface area (36%), increase in electrode height (83%), and rectangular design of the EO-1 PPT; all of which may contribute to the performance difference between the Teflon thrusters. However, if the increase in performance with sulfur propellant over an identical Teflon thruster transferred to the EO-1 design, then a sulfur fuel EO-1 PPT could reach specific thrusts of over 35mN/kW.

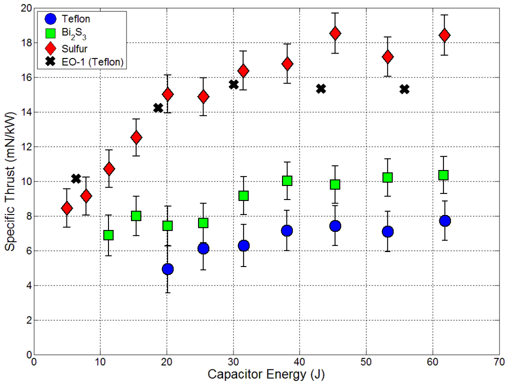

Figure 10: Specific thrust comparison between Teflon, sulfur, bismuth sulfide, and the EO-1 Teflon[5] PPT for varying capacitor energy levels at 1µTorr.

CUEBSAT DEVELOPMENT

A CubeSAT mission is ideal to test and evaluate the performance of a sulfur PPT and mission planners will be initially skeptical to place an untested fuel source onto a larger and more expensive spacecraft. Currently the Advanced Propulsion Laboratory has begun funding and preliminary research into the components required for such a mission. The PPT, housed within the 3D printed CubeSAT, firing in the vacuum chamber at a background pressure of 1uTorr can be seen in Fig. 11.

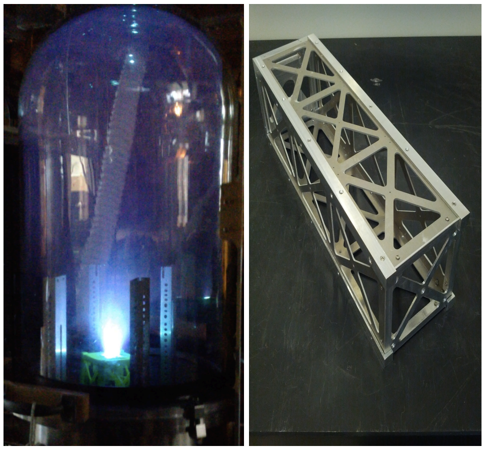

Figure 11: A 10J PPT discharge fired from within the 3D printed plastic CubeSAT (left) and the Al6061 CubeSAT frame (right).

Two 3U structures have been built for testing, one from Al6061 (Fig. 11 right) and the second a 3D printed plastic version (Fig. 11 left). The total mass of the aluminum structure is 490 g and the plastic mass is 325 g. A power processing unit (PPU) consisting of 29.5% efficient solar panels over the four sides of the CubeSAT as well as deployable panels to double the photon collecting area will be used to charge a LiPoly battery pack. This will result in a total solar cell area of 2226 cm^2. Using a generic 52 degree inclination (to equator), 375 km altitude orbit, we can assume that the satellite will have an average of 58.5 minutes of solar illumination per 92 minute orbit. This is calculated to result in 80 W of direct cell irradiation during illumination and an additional 14 W from the Earth's albedo (assumed to be diffuse, 36%). The average efficiency of the array is 29.5%, yielding an average power of 27 W during illumination, or 17 W as an orbital average. Assuming 6 W of power for control and communication, this leaves 11 W for PPT use.

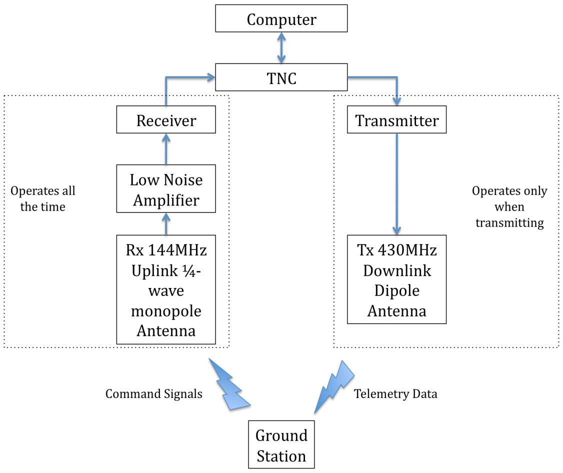

Figure 12: Top-level CubeSAT telemetry schematic

A standard, off the shelf ATMega 1080p Arduino board is being used to control the PPT and CubeSAT satellite. This board was chosen for its low power consumption (<1 W) and extensive documentation. Based on previous CubeSAT flights, two separate antenna systems will be used for telemetry, a 144 MHz monopole antenna for uplink and a 434 MHz dipole antenna for downlink. The receiver will be operational at all times to receive ground communication, while the transmitter will only be powered when in use.

The CubeSAT is designed for full 3-axis attitude control using a redundant system of four small reaction wheels in a tetrahedral geometry. Pointing requirements will be determined by communications requirements and the minimum impulse bit achievable by the PPT, which will be measured as torque using the sensed change in rotation rate of the craft. Additional electromagnets will provide despin upon launch vehicle ejection, as well as provide a means to dump angular momentum from the reaction wheels to prevent saturation. To accommodate the low power availability, power cycling measures will be taken and the control system is designed for <1 W operation.

CONCLUSIONS

A custom launch system for 3U CubeSATs has been proposed and the concept and development to date has been presented. The theoretical capability of this launch system offers an unmatched, unique service for this class of satellites. The intention is not to compete with any current commercial launcher, but rather to fill an unmet need, ultimately complementing existing launch services. In addition to the rockoons theoretical capability to place a payload into LEO, the system offers an inexpensive method for universities to launch student experiments along suborbital flight paths.

The University of Washington has begun to create a CubeSAT laboratory on campus. Initial work has been focused on the creation of a sulfur propellant Pulsed Plasma Thruster to be housed within a 3U CubeSAT.

Acknowledgements

The hundreds of students who have compromised the ESS205 ballooning course and the ESS472 rocket course for their countless hours in furthering our knowledge of this potential launch system.

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