Design and Development of a CubeSat De-Orbit Device
Final Report MAE 435

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Abstract

There is a large accumulation of debris in lower earth orbit from defunct satellites and associated debris. The United Nations Inter-Agency Debris Coordination Committee (IDAC) has pressed NASA, ESA, and private groups to de-orbit satellites orbiting below 2000 km within 25 years of mission completion. This has the potential to limit the altitudes available to CubeSat satellites, limiting their ability to piggyback on more-expensive, primary spacecraft launches to higher altitudes; thus restricting low-cost access to space. The objective of this project is to design and test a de-orbit system for CubeSats that, when placed in higher orbital altitudes, can reduce their orbital lifetime in low earth orbit to less than 25 years. In addition, the de-orbit unit can have the potential to lower CubeSat orbits from higher orbital altitudes to lower orbital altitudes in a shorter period of time.

A sounding rocket test flight is currently being pursued by the team for experimental proof-of-concept testing and validation of a CubeSat de-orbit prototype device. Sounding rocket flights can enable students and researchers to perform experiments in the low earth orbital environment at modest cost in a relatively short period of time. The current team has performed research experimentation and associated laboratory work for the deployment device, aerodynamic brake, and telemetry for a planned flight test article, forming the basis for a flight-qualified demonstration unit that is expected to follow.
Introduction

Since the beginning of the Space Age, thousands of defunct satellites, components, and associated debris have accumulated in Earth’s immediate orbital neighborhood. Orbiting at high altitudes, their lifetimes can span a thousand years or more, and during that time will remain a hazard to all satellites with similar orbits. The hazard of space debris was made apparent when the windshield of the Space Shuttle was damaged significantly in a collision with a tiny flake of paint that had a relative velocity of between 2 km/s and 8 km/s.\[^1\] More recently, a dead Soviet communication satellite collided with and destroyed a functioning Iridium communication satellite.\[^2\] Collectively, this group of orbital refuse is known as space debris, or “space junk”.

Though no formal treaty exists for the mitigation of space debris, the United Nations has formed an eleven-nation study to address the issue, and the United Nations Office for Outer Space Affairs has set up a group of mandates meant to stop the growing space debris problem\[^3\]. The Inter-Agency Debris Coordination Committee (IDAC) has pressed NASA, ESA, and private groups to de-orbit satellites orbiting below 2000 km within 25 years of mission completion.

CubeSats are picosatellites utilized by colleges and research institutions to perform valuable research in low earth orbit. CubeSats are popular mainly because of their relatively low cost in providing a platform to conduct research in low earth orbit. CubeSat sizes range from 1U (single unit), 2U (double unit), and 3U (triple unit) which are 10 x 10 x 10cm, 20x 10 x 10cm and 30 x 10 x 10cm respectively. The low-cost is due both to the small sizes of CubeSats and the
ability to add these small systems to the overall payload of a bigger, more-costly spacecraft launch. That opportunity occurs because launch vehicle systems are designed to deliver specific overall payloads to specific orbits and the overall mass of the primary customer payload is rarely equal to the maximum delivery mass for a particular launch vehicle stack, necessitating the addition of ballast to the payload in order to achieve the desired orbit. CubeSats can be substituted for ballast mass, but the resulting CubeSat orbits are tied directly to the specifications of the primary customer. Current orbiting CubeSats are flying at altitudes as high is 900 km, where their expected orbital lifetimes exceed 1,000 years. An international treaty limiting the time satellites can remain in orbit upon mission completion will restrict the use of CubeSats to altitudes below 500 km without some mechanism to de-orbit them within a specified time frame. At a 900 km altitude, an orbiting CubeSat can be a lethal hazard to other satellites for centuries.

The objective of this project is to design and test a de-orbit system for CubeSats that can reduce orbital lifetime in low earth orbit to less than 25 years. The de-orbit device must prove to be a robust and viable system having commercial viability at a minimum cost. In order to achieve that goal, the design team has determined that it will be necessary to build a prototype deployment device that can be flown into space to demonstrate overall system performance and justify final development of a commercially-competitive unit that can be integrated into scientific CubeSat payloads, enabling them either to de-orbit within less than ten years or achieve lower orbital altitudes in a shorter period of
time. Recently, a competing system has been advertised as being available for purchase\(^1\).

Three current options for performing the experimental demonstration tests necessary to accomplish the current objectives have been considered: (1) a high altitude balloon test; (2) an orbital demonstrator, and (3) a suborbital sounding rocket deployment demonstration. A suborbital sounding rocket flight was selected as the best overall choice in terms of time until demonstration and cost. That option is being pursued currently.

Our goal is to develop an aerodynamic brake component small enough to be installed in standard CubeSat units, using only a minimum of available volume and mass, as constrained by the CubeSat design. We used a single-unit (1U) CubeSat as our mission template.

The goal of the current design team is to utilize sublimating benzoic acid to inflate a 1.22 m diameter balloon during the microgravity portion of a sounding rocket flight. At altitudes above 90 km, the ambient pressure is low enough to cause benzoic acid to sublimate from a powder phase to a gaseous phase at moderate temperatures. The inflated balloon would present a large enough surface area for significant increases in drag to occur. An alternative option under investigation was to employ Shape Memory Alloy (SMA) to deploy a similar balloon-shaped structure. Shape memory alloy is manipulated and heat treated to form a desired shape. At low temperatures SMA can be folded into a

compact shape for stowage and, after heating to a critical temperature, be made subsequently to unfold into a desired shape. Nitinol wire is the shape memory alloy that is currently available to the team and may represent a feasible option. Using benzoic acid sublimation for balloon inflation, along with deployment of an integrated Nitinol wire frame to reinforce the structure of the aerodynamic brake, although not yet tested by the current team, may be the best method.

Methods

1. Sounding Rocket Test Flight

The current platform for the planned experimental demonstration test of our CubeSat with an installed de-orbit device that is being pursued currently is through a sounding rocket test flight. Sounding rockets provide a relatively simple and inexpensive way for students and researchers to perform research in a low earth orbit environment. Sounding rockets are divided into two parts: the payload and the launch vehicle stack[2]. When the sounding rocket is launched it follows a parabolic trajectory. When the last stage of the launch vehicle stack exhausts its propellant, it separates from the payload following a different trajectory from the payload due to its higher drag. The experiments placed on the payload are then exposed to a low earth orbit environment. Once the payload descends to low altitude, it is gently brought down to earth by a parachute.

The launch opportunity the team is currently pursuing for a sounding rocket test flight is NASA’s RockSat-X program at Wallops Flight Facility. The RockSat-X program utilizes the Terrier-Improved Malamute suborbital sounding rocket that nominally achieves an apogee of approximately 160 km altitude.[4]
The sounding rocket’s skin and nose cone are ejected after second stage burn-out. The RockSat-X payload canister utilizes decks, as shown in Figure 1, on which customers mount their payloads as opposed to the canisters used in its predecessor RockSat-C. The RockSat-X decks are in a stacked configuration interconnected by longerons spanning the entire length of the RockSat-X payload as shown in Figure 2. The decks are designed to provide customers direct access to the environment of space and allow payloads to deploy booms and other mechanical devices once the skin is ejected.
NASA Wallops Flight Facility still provides sounding rocket flights through the predecessor of RockSat-X; the aforementioned RockSat-C program. The team considered both options—due particularly to the difference in cost. The RockSat-C is the cheapest option at $12,000 for a canister compared to $24,000 for a RockSat-X deck plate. However, the access that RockSat-X provides to the low earth orbital space environment that will allow for the ejection of a CubeSat test article, along with the superior power and telemetry provided compared to RockSat-C are the primary reasons that it was determined by the team to be the best sounding rocket option for our experiment. The team recommends submission of an Intent to Fly form, along with the necessary $2000 deposit to the RockSat-X sounding rocket program office, requesting a launch in 2014.
2. Electronics

The current design will utilize one (1) Arduino Uno board, a 3M SD card reader, and one (1) Xbee Wifi transmitter/receiver incorporated as part of the sounding rocket host payload rack, while the remaining Arduino, Xbee, and other components will be part of the deployed CubeSat demonstrator unit. For experiment command and control, the primary sounding rocket payload can provide up to four (4) timed control events utilizing a time-of-launch reference time that can be user defined. The anticipated nominal events are defined in the following table (resetting reference time to zero at payload separation):

<table>
<thead>
<tr>
<th>Signal</th>
<th>Time(seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power up &amp; release CubeSat</td>
<td>0</td>
</tr>
<tr>
<td>Start Taking Pictures</td>
<td>1.5</td>
</tr>
<tr>
<td>Release Brake</td>
<td>5</td>
</tr>
<tr>
<td>Turn off Experiment</td>
<td>330</td>
</tr>
</tbody>
</table>

Once transmitted, pictures will be stored on an SD card mounted on the host payload rack. Utilizing the primary payload rack will enable our experiment to account for different data rates associated with the onboard payload telemetry and the Xbee transmitter. Once the experimental data has been completely stored, it will be transmitted down to the ground station at the baud telemetry interface data rate of 15360 bits per second.
3. O-Pod Deployment Device

3.1 CubeSat Exit Velocity Test

In order to validate the performance of the inflatable airbrake, the planned free-flying test article design must separate from the sounding rocket payload host. Since our benzoic acid sublimation analysis has determined that inflation should be initiated at an altitude above 90 km, it will be necessary for the free-flying test element to be far enough from the host so that inflation can occur in a space environment that is not affected by the host. Furthermore, due to the low mass and power that will be available on board the free flyer, the distance between the free flyer and the host must be less than approximately 100 m to permit reliable communication. Hence, free flyer deployment specifications, based on a detailed analysis, is a critical element. The O-POD deployment device that was fabricated by the 2011-12 capstone design team was employed in tests conducted this semester to investigate the frictional resistance between the aluminum launch rails and the aluminum surface (as would be encountered in the CubeSat deployment experiment prototype). Frictional losses will have a significant influence on the exit velocity produced by the compressed-spring launch system. Prior tests had used a cardboard mock-up and experiments indicated a release velocity of about 1.6 m/s. However, those prior tests were not documented sufficiently, and further testing was required.

In order to test the O-POD deployment device, a test mock-up (MockSat) of a CubeSat was fabricated from structural two by fours, screwed together to produce a wooden 10 cm cube, and then covered with aluminum foil. The overall
dimensions were just under 4x4x4 in\(^3\) (a CubeSat is 10x10x10 cm\(^3\)). The Aluminum foil was bonded to the surfaces of the MockSat using superglue.

Time and funding constraints prevented using a pair of photo detectors and an accurate clock to measure “trap speed” at the point of separation. However, because of the low anticipated release velocities, aerodynamic losses would be very small, and it was decided that measuring the horizontal distance traversed by MockSat when it was launched horizontally from an elevated platform of known height would permit estimation of the launch velocity to reasonable accuracy. The acceleration of gravity can be taken as constant over small distances above the Earth’s surface. Therefore, the distance the object falls can be utilized with the gravitational constant to estimate accurately the time it took to hit the floor. Neglecting drag losses, the horizontal distance travelled during free fall can be measured and used to estimate the release velocity as follows:

\[ Dy = \frac{1}{2} g t^2, \ g = 9.81 \text{ m/s} \]
\[ Dx = Vx t \]

The O-Pod launcher was positioned on a table in our ODU dorm. The table height was measured to be 0.575 m, as measured from the lower rails on the O-POD to increase the accuracy of the results. Each test was conducted with the lip of the O-POD just over the edge of the table, and back-braced with textbooks. Pictures of the test set-up are included in Appendix Figure A1.1. In
order to obtain consistent results, the O-POD was pushed to full spring compression each time, using a pusher (ballpoint pen) centered on the front face of the MockSat. The MockSat was “armed” and released 10 times, and the distance it traveled was marked on the floor in front of the O-POD with tape after each trial (see Appendix A1.2).

3.2 Finite Elemental Analysis

The team was unable to retrieve the PATRAN files modeling the O-pod launcher produced by the 2011-12 design team. Consequently, a new model was built. The new model has incorporated a supporting ring-plate on the front opening of the deployment system. Unlike the previous model (based on the 2011-12 final design report), dimensions and properties are in millimeters, and the model utilized a finite element mesh consisting of tetrahedral elements instead of quadrilateral elements. Stress and vibration analyses were performed with this new model, matching some of the results from the previous team.

Two PATRAN models were utilized in this study: (1) a linear static model for estimating the inertial loads; and (2) a normal mode model for vibration analysis. For the linear static simulation, the model was constrained at the bottom of the O-POD geometry, along the lengthwise inner face plate. A displacement constraint vector <0,0,0> on the nodes of this face plate created the boundary condition for the static solution. An inertial acceleration loading of 25g (245.2 m/s²) was then applied to the entire model, mimicking the peak thrust produced during the sounding rocket ascent.
4. Inflatable Aerodynamic Brake

Based upon the inflation tests performed by the previous ODU CubeSat design team, benzoic acid powder is considered currently to be the best gas source for inflation of the 1U CubeSat deployable aerodynamic brake experiment. The next goal of the inflation tests was to determine the temperature at which the benzoic acid will sublime and inflate the aerodynamic brake, along with estimating the subsequent inflation time. To help determine the sublimation temperature of benzoic acid, the air brake team used the web-based Emerald Kalama Chemical, LLC data sheet.

(http://www.emeraldmaterials.com/epm/kalama/mioms_doc_admin.display?p_customer=FISKALAMA&p_name=PRODBULL-BENZOICACID.PDF). The data sheet provided an equation for estimating the vapor pressures of benzoic acid at various temperatures using the Antoine based equation.

- Benzoic acid empirical sublimation formula based on Antoine equation

\[ \log(P) = A - \left[ \frac{B}{(t + C)} \right] \]

- Log is the logarithm based of 10
- P = pressure (mmHg)
- t= temperature (°C)
- A, B, C are substance-specific coefficients (Antoine constants)
- A=8.57134
- B=2726.2
- C=230
Using the US Standard Atmosphere chart provided by Thermal Protection Systems Expert and Material Properties Database (http://tpsx.arc.nasa.gov/cgi-perl/alt.pl), the air brake team was able to develop a table of ambient pressure and associated benzoic acid sublimation temperature versus altitude (Table 2) to enable refinement of the sounding rocket prototype aerodynamic brake deployment experiment design.

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Ambient Pressure(mmHg)</th>
<th>Sublimation Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.013E+05</td>
<td>249.08</td>
</tr>
<tr>
<td>10</td>
<td>1.99E+02</td>
<td>204.59</td>
</tr>
<tr>
<td>20</td>
<td>4.15E+01</td>
<td>162.06</td>
</tr>
<tr>
<td>30</td>
<td>8.98E+00</td>
<td>127.85</td>
</tr>
<tr>
<td>40</td>
<td>2.15E+00</td>
<td>100.92</td>
</tr>
<tr>
<td>50</td>
<td>0.598</td>
<td>79.99</td>
</tr>
<tr>
<td>60</td>
<td>0.160</td>
<td>61.01</td>
</tr>
<tr>
<td>70</td>
<td>0.039</td>
<td>43.20</td>
</tr>
<tr>
<td>80</td>
<td>7.894E-03</td>
<td>25.40</td>
</tr>
<tr>
<td>90</td>
<td>1.360E-03</td>
<td>8.35</td>
</tr>
<tr>
<td>100</td>
<td>2.415E-04</td>
<td>-6.33</td>
</tr>
<tr>
<td>110</td>
<td>5.393E-05</td>
<td>-17.67</td>
</tr>
<tr>
<td>120</td>
<td>1.913E-05</td>
<td>-24.86</td>
</tr>
<tr>
<td>130</td>
<td>9.405E-06</td>
<td>-29.51</td>
</tr>
<tr>
<td>140</td>
<td>5.408E-06</td>
<td>-33.00</td>
</tr>
<tr>
<td>150</td>
<td>3.410E-06</td>
<td>-35.81</td>
</tr>
<tr>
<td>160</td>
<td>1.420E-06</td>
<td>-40.93</td>
</tr>
</tbody>
</table>

**Table 2 Altitude and Pressure vs. Benzoic Acid Sublimation Temperature**

Assuming that less than 300 seconds will be available during the sounding rocket flight trajectory to inflate the Mylar balloon, active heating to effect inflation in a short time requires substantial amounts of energy (translating to a high-capacity battery). As an alternative, the air brake team has been investigating the feasibility of inflating the Mylar balloon using thermal energy stored in the aluminum prototype free flyer rather than using an onboard battery, thus reducing
the overall payload mass and cost of the CubeSat deployment prototype. At 90 km, the nominal ambient pressure corresponds to a benzoic acid sublimation temperature of 8.35 °C. That sublimation temperature would be low enough that a deflated balloon encased in a sealed, membrane-covered cavity could be maintained at one atmosphere and the nominal ambient launch temperature (25 °C) by the aluminum housing so that when the membrane seal is broken, adequate energy is available to sublimate benzoic acid powder contained within the deflated balloon, inflating the balloon while the test article is ejected by the O-Pod launcher.

Another goal of the inflation tests is to verify the amount of benzoic acid to inflate an 18 inch (45.7 cm) diameter Mylar balloon, which is considered to be the largest size that can be tested in an available vacuum chamber. The required benzoic acid powder mass must be verified experimentally while techniques are being developed to distribute the powder uniformly within the deflated balloon. The even distribution of benzoic acid will assist in the unraveling of the tightly folded balloon.

Aside from testing the Mylar balloons for sublimation and inflation, the air brake team also tried to efficiently fold and fit the Mylar balloon inside a nominal prototype aluminum base plate housing cavity. Several approaches were examined and the best technique identified thus far was to have a square fold pattern as shown in Figure 3.
This simple folding technique can allow the deflated Mylar balloon to fit within the 9 cm x 9 cm x 1 cm aluminum base plate cavity. The original diameter of the spherical Mylar balloons purchased at a grocery store, was 1.22 m and the folding technique reduced the largest dimension by half after each fold. After the fifth fold, the diameter was 7.625 cm; small enough and thin enough to fit within the 9 cm x 9 cm x 1 cm cavity.

Results

1. Deployment Device

1.1 CubeSat Exit Velocity Test

To determine if an aluminum-aluminum surface interaction would lead to reduced exit velocity from an O-POD deployment device, a number of tests using
a CubeSat mock-up (MockSat) were carried out. The MockSat consisted of two pieces of 2x4 lumber cut down and screwed together, then covered with aluminum foil. The fall time from a known height was used to determine the exit velocity of the MockSat as it left the O-POD in order to determine if aluminum on aluminum friction makes a difference.

**CubeSat Exit Velocity Test**

Ten ejection velocity tests were conducted. The results of those tests are listed in Table 3. While there were small variations in the height of the ejection release point, the estimated time-of-flight for each test was assumed to be t=0.03429 sec. The results were tabulated and calculated using Microsoft Excel Spreadsheet software as shown in Table 3. The maximum ejection velocity imparted to a 1U CubeSat mock-up was 1.46 m/s. The results were tabulated and calculated using Microsoft Excel Spreadsheet software. The average velocity is about 1.280 m/s with a standard deviation of +/-0.122. These results are considered to be conservative because the aluminum foil skin covering the MockSat was so thin that the shear stresses produced by sliding friction caused the foil to wrinkle and tear occasionally while sliding along the O-pod guide rails. The test results are therefore conservative and fall within a predictable range. Future tests using a more realistic prototype should be conducted to establish an upper bound on the ejection velocity in order to estimate more accurately the distance over which radio communication between the free flyer and the host must be maintained. The MockSat design can be improved by incorporating rigid
rails along the wooden prototype edges, rather than utilizing the current aluminum foil skin.

**Table 3 Summary of Ejection Velocity Test Results**

<table>
<thead>
<tr>
<th>Test</th>
<th>Distance (in)</th>
<th>Distance (m)</th>
<th>Launch Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19</td>
<td>0.483</td>
<td>1.407</td>
</tr>
<tr>
<td>2</td>
<td>18.625</td>
<td>0.473</td>
<td>1.379</td>
</tr>
<tr>
<td>3</td>
<td>14.75</td>
<td>0.375</td>
<td>1.093</td>
</tr>
<tr>
<td>4</td>
<td>15.25</td>
<td>0.387</td>
<td>1.129</td>
</tr>
<tr>
<td>5</td>
<td>16.75</td>
<td>0.425</td>
<td>1.241</td>
</tr>
<tr>
<td>6</td>
<td>16.375</td>
<td>0.416</td>
<td>1.213</td>
</tr>
<tr>
<td>7</td>
<td>16</td>
<td>0.406</td>
<td>1.185</td>
</tr>
<tr>
<td>8</td>
<td>17.25</td>
<td>0.438</td>
<td>1.278</td>
</tr>
<tr>
<td>9</td>
<td>19.75</td>
<td>0.502</td>
<td>1.463</td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>0.483</td>
<td>1.407</td>
</tr>
</tbody>
</table>

**1.2 Finite Elementa l Analysis**

Figure 3 shows the stress distribution and displacements, along with the color scales required to interpret the stress levels in the model. The PATRAN simulation indicated that the maximum deflection would be 0.972 millimeters, and the maximum stress encountered would be 55.7 MPa.

In the normal mode simulation, all loads and boundary conditions from the static solution were subtracted to obtain free vibration the model. Figure 5 represents Mode 7, which shows significant deflection at 44.5Hz. Figure 6 represents Mode 10, which has a frequency of 148Hz--outside the nominal range encountered during the anticipated sounding rocket flight. Even though deflection is exhibited by this mode, it will not be encountered during ascent. It is clear that the ring-plate on the front of the O-POD has helped control potential
vibration problems, and with the addition of the mass of the CubeSat and other components in the design, the natural frequencies will increase further.

Figure 4

Figure 5
2. Inflatable Aerodynamic Brake

When testing of benzoic acid sublimation inflation was initiated utilizing the vacuum chamber that had been available previously by the Physics Department, an unexpected obstacle was encountered. After several weeks of tedious examination, it was finally determined that there was a tiny leak in the baseplate but the leak could not be located. As a result, a miniature vacuum chamber was made available to us by Dr. Charles Sukenik, chairman of the Physics Department. That system was so small that it was only possible to fit a six-inch (15.2 cm) diameter Mylar balloon experiment inside the chamber. The amount of benzoic acid was so minuscule that the air brake team could only use 2 grains of powder for preliminary sublimation and inflation experiments. A total of 5 tests were conducted, to determine benzoic acid inflation and sublimation and the
recorded time is tabulate in Table 4. Unfortunately, it was not possible to monitor the temperatures inside the vacuum chamber, nor was the volumetric pumping capacity of the miniature vacuum pump known, resulting in the inconclusive test results contained in the table.

<table>
<thead>
<tr>
<th>Balloons (6&quot;)</th>
<th>time</th>
<th>temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balloon 1</td>
<td>15+ mins.</td>
<td>ambient</td>
</tr>
<tr>
<td>Balloon 2</td>
<td>15+ mins.</td>
<td>ambient</td>
</tr>
<tr>
<td>Balloon 3</td>
<td>15+ mins.</td>
<td>ambient</td>
</tr>
<tr>
<td>Balloon 4</td>
<td>12+ mins.</td>
<td>33~35°C</td>
</tr>
<tr>
<td>Balloon 5</td>
<td>12+ mins.</td>
<td>33~35°C</td>
</tr>
</tbody>
</table>

Discussion

1. Inflatable Aerodynamic Brake

The goal of the de-orbit device is to successfully deploy a tethered spherical balloon from a 1U CubeSat housed initially in a 9 cm x 9 cm x1 cm storage space. When the spherical balloon is fully inflated, the resulting drag will act like an aerodynamic brake that will greatly reduce the 1U CubeSat orbital lifetime. The main concerns of the de-orbiting device after deployment are the ability to withstand ultraviolet radiation, atomic oxygen, changes in temperature, and micro meteor impact.

Weight and volume are critical constraints for the de-orbiting system due to the mass and volume restrictions for the CubeSat. In order to achieve low-cost CubeSat payload orbits, it is necessary to find secondary payload launch opportunities, where most of the launch costs are borne by the primary customer.
A 1U CubeSat occupies a 10 cm x 10 cm x 10 cm volume with an upper mass limit of 1kg (a 3U P-pod launcher unit is somewhat more than a factor of three larger). Therefore, the CubeSat de-orbit unit must be small in volume and mass. Since the CubeSat provides low-budget access to space, the de-orbit device must also be economical. Overall, if the CubeSat de-orbit mechanism is intended to be used commercially; it must be small, affordable, and able to withstand the conditions of space for approximately ten years.

The starting point of the CubeSat project was to research and design a suitable membrane for the inflatable unit. The study focused on the membrane portion of the de-orbiting mechanism through the lifetime of a 1U CubeSat. A goal of the present study was to design, fabricate and build a prototype inflatable unit that could be flown on a demonstration sounding rocket flight.

The ideal polymer for constructing the membrane must withstand ultraviolet radiation and atomic oxygen bombardment; and the best available material was Upilex® brand polyimide film produced by UBE industries. Upilex® is commonly used to protect against ultraviolet radiation and can also withstand atomic oxygen reactions when enhanced with a silicon oxide coating.

Another key aspect of the aerodynamic brake mechanism is the shape and size of the inflatable membrane. The inflated membrane shape must produce a controlled cross-sectional area to produce the desired drag. Since the drag force produced by the inflatable will be substantially larger than the drag force produced by the 1U CubeSat, the inflated membrane cross-section will always be facing perpendicular to the direction of travel. However, during initial
deployment, it is possible that the CubeSat will rotate, turn, and tumble. As long as the tether doesn’t tangle with the CubeSat of the membrane, the drag device will eventually be aligned behind the CubeSat. A spherical membrane shape has been selected as the baseline since it is completely insensitive to flow direction.

Previous groups also conducted research using ODU’s virtual lab Satellite Tool Kit (STK) simulation and concluded it would take the 1U CubeSat at least 480 years to return back into Earth from an altitude of 800 km under unassisted conditions (Figure 7). Through European Space Agency (ESA), all satellites upon completing its mission are recommended to be de-orbit down to Earth or into Low Earth Orbit (LEO) region within 25 years. Through the STK simulation, it was determined that a 1U CubeSat satellite could be made to return to Earth within 126 months if a drag device with a minimum cross-sectional area of 0.5625 square meters was deployed (Figure 8). This would allow the 1UCubeSat to comply with the pending National Space Treaty.
In 1960, NASA deployed a 100-foot diameter inflatable satellite fitted within a 67 cm spherical container. The original idea was to use compressed gas with regulators to inflate the aluminized balloon. The weight limitation shifted NASA into finding a better option. NASA used benzoic acid and anthraquinone to reduce the need of compressed gas, thus reducing the need of regulators and storage device. The benzoic acid was evenly distributed within the membrane of the satellite. When mixed with anthraquinone, the benzoic acid turned from a fine solid powder into a paste, allowing the compound to speed up the sublimation process and inflate the satellite. The sublimation process of benzoic acid
required minimum solar heat to inflate, but problems arise as the satellite passes through the shadow of Earth.\textsuperscript{2}

Exploiting the successful launch of NASA’s Echo 1 Satellite, the 2011-2012 capstone design team attempted to utilize the same deployment method for the CubeSat de-orbit mechanism. Though NASA used benzoic acid and anthraquinone, the team was restricted from using anthraquinone due to proper containment and financial limitations. Even without anthraquinone, benzoic acid alone at 900 km altitude with solar heat will produce a vapor pressure of between 3 to 5 torr (400~650 Pa). This estimation of pressure will be used to inflate the de-orbit mechanism as the exterior pressure at 900 km altitude is minimal.

In order to carry out benzoic acid inflations, the former team used store bought Mylar balloons. The sizes of the Mylar balloons were 18 inches in diameter; one balloon was filled with 10 grams and the other with 15 grams or acid. Air was removed from the balloons and sealed with space grade epoxy to ensure sealant in a space-like environment. The balloons were then folded tightly and tested within a vacuum chamber under ambient room temperature. The test inflations were successful; however no record of Mylar balloon fully inflated within the 300 second limits.

Through the simulation of 90 km altitude using the vacuum chamber, the air brake team has determined few flaws to why benzoic acid did not inflate. The major factor that benzoic acid did not fully sublimate is not enough energy or

\textsuperscript{2} Clemmons, Dewey L. Jr. (1964.)"The Echo 1 Inflation System." NASA Technical Note. NASA Langley Research Center, [Print]( accessed on Nov. 30, 2012).
latent heat from the aluminum base plate. In order to prove benzoic acid inflation as a practical choice, further tests must be done within the vacuum chamber with heating element to show benzoic acid can sublimate less than 300 seconds. When testing benzoic inflation, the team must also have a quick and easier way to remove air to simulate a sealed Mylar balloon of bigger size. Using a small syringe with needle consumes time and not being very effective.

2. O-Pod Deployment Device

2.1 CubeSat Exit Velocity

Based upon the results obtained, it appears that the aluminum-aluminum interaction does not play a significant role on the exit velocity. As the design constraints limit the velocity to less than about 3.3 m/s, these results are well below maximum tolerance. In respect to the previously obtained velocity of about 1.6 m/s, the results demonstrate that this is feasible. However, even though the obtained velocities are conservative and consistent, the results do raise more questions. Further testing will be required to determine the actual friction of Cardboard on the rails to validate the results obtained here. Any inconsistencies may be due to the limitations of the test.

Limitations to the test can be broadly broken down into three problems: design, mass, and prior test inconsistencies. As stated previously, more testing is needed to definitively prove if the aluminum-aluminum surface contact has a detrimental frictional interaction. In respect to mass, the MockSat was massed at about 500 grams (using a conventional desktop digital postage scale). Although
a 1U CubeSat can have a maximum mass of 1kg, and the goal mass for this CubeSat has not yet been determined, the mass factor does need to be taken into account, even if it did not potentially contribute as much to error as the other factors.

Design was the largest limitation. The Aluminum foil had to be patched-up every test or so due to ablation from the rails, thus leading to potential inconsistencies. In addition, unlike aluminum plate, the foil was a bit wrinkly which would present a different coefficient of friction. Alternative designs for the MockSat were considered and pursued, but due to unforeseen complications were not carried to completion. A design utilizing aluminum plate will yield more accurate results.

Even taking the limitations into account, the conservative nature of the results obtained suggest that the test was still very accurate and at least demonstrated that the surface interaction does not contribute greatly to launch velocity losses. Future testing will need to be conducted to fully appreciate the validity of these results, but the original goal was met to some degree.

2.2 Finite Elemental Analysis

The previous CubeSat team machined a prototype of the O-POD, complete with a supporting ring-plate and a functional spring. Using a mockup CubeSat, the same group managed to perform velocity tests on the O-POD’s spring. Results were encouraging, but it was discovered that the mockup, constructed of cardboard and tape, had an inconsistent coefficient of friction,
which varied by humidity. Nevertheless, results showed that the O-POD spring was sufficient to eject a CubeSat of 1kg mass or less.

A desirable velocity of 1.6 m/s was mentioned by the previous CubeSat team based upon the exit velocities reported from Cal Poly’s P-Pod deployment device. The desired exit velocity has since been called into question, but nevertheless velocity tests showed the spring inside the O-POD prototype is sufficient. ASTM-A228 "Music Wire" spring was chosen with the following properties: 7.625" long, wire diameter of 0.095", outer diameter (OD) of 3.25", with 7 active coils. The spring rate which decided these properties was 6.78 N/m. The previous team found that, due to the 1Hz rotation of the sounding rocket, angular momentum would also aid in launching the CubeSat, possibly importing more velocity. It was determined that the bottom guide rails would need lubrication to mitigate friction between the CubeSat and O-POD.

During the design phase of the O-POD, a computer model was created to map out potential stresses experienced aboard the sounding rocket. The O-POD model was designed within MSC PATRAN/NASTRAN (Santa Ana, California) and was subjected to both inertial loading and vibrations analysis. Five versions of the model were created, each successively more detailed than the other. The peak thrust was determined to be 25g (245.2 m/s^2), and the areas of highest stress were on the bottom plate, near assumed bolt hole connections. All dimensions and associated properties were based on centimeters.

After recovering material, two main tasks were addressed- finishing the PATRAN model, and performing velocity tests on an improved mockup of the
CubeSat. While the previous mockup and O-POD prototype were available from the start, the PATRAN models were decidedly inaccessible, and remain on a former student's account.

Possible errors in the current simulations likely stem from the location of the constraint nodes, which were located on a loop edge of the bottom plate. In a real design, bolts would be located farther from those edges to prevent failure. The nodes on the face plate were chosen because all other nodes were irregularly placed due to the nature of Tetrahedral meshing elements. The spring and the loading due to the CubeSat and the plate that will restrain it within the O-POD are not accounted for which will create error in the vibrations analysis.

3. Electronics

An important aspect of the CubeSat aero brake project will be the successful implementation of various sensors and communication systems into a demonstration test article that can be flown on a sounding rocket payload. Old Dominion University was provided with a US Air Force CubeSat development kit, including a 30x10x10 cm 3U CubeSat breadboard, wireless antenna router, multiple microprocessors, and a laptop computer with radio communication interfaces. Access and use of the laptop and the associated hardware and software is restricted to US citizens. It is expected that the USAF Plug and Play system will be used for communications with Wallops Flight Facility (WFF) and will be the most extensively used item in this kit. The electrical team has recruited Mr. Jason Harris (currently a student at TCC, with a Ham Radio license and
planning to transfer to ODU in the fall) to help with overall performance specifications and design of the electrical system. With his recommendations, most of the hardware required for a prototype flight article have been identified and purchased. These components include two (2) Atmega microprocessors (Atmel, San Jose, California), two (2) Xbee WiFi transmitters/receivers (Digi International, Minnetonka, Minnesota), Linksprite JPEG camera (Sparkfun), SD card reader (3M electronics, St. Paul, Minnesota), and various capacitors and connectors necessary to complete the system. The electrical team’s budget can be found in the Appendices Table A1.1. The electrical team has the responsibility of properly integrating and installing these components on to the CubeSat demonstration platform. It is vital that these devices function properly in the flight experiment. In order assure overall system performance, data acquisition, command and control systems will be developed for testing inside the large vacuum chamber that has been made available to this project by the Physics Department. After the base plate has been replaced, data gathered from space environment simulations employing the vacuum chamber will provide valuable performance and reliability data that can be used directly in the design of the free-flying aero brake test article.

The Arduino Uno board was selected for its intuitive and relatively simple graphical user interface (GUI), as compared to the interface used in the previous microprocessor systems. A benefit of using this platform is the vast amount of code already developed by the Arduino user base. This can reduce significantly the time required to develop all of the code; instead relying on the incorporation
of the existing code that best suits our needs. The Xbee transmitter/receivers provide an excellent range of up to 1 km with plentiful data transmission bandwidth of 38400 bits per second while consuming low amounts of power. The Linksprite camera can take pictures with a 160x120 pixel resolution. Since it will be placed within close proximity of the inflating balloon, this is satisfactory resolution. Exact placement of the electrical components during vacuum chamber testing can begin once the components are received. Complications in shipping have resulted in a package being lost.³

Conclusion

1. Deployment Device

Although certain files could not be recovered from the previous team, the new PATRAN model was sufficient for performing analysis of the stress, deflection, and vibrations encountered in flight. With a completed prototype and a steadily improving CubeSat mockup, work can continue on designing and implementing a quick release mechanism. Possible future velocity tests might be done using a spinning 1Hz platform, although it would be advised such a test might be difficult or too complex.

Future work on the PATRAN model should reduce failure modes. In possible later analysis, including the mass values of the CubeSat and other attached components may shift the natural frequency up further, which is desired.

³ The initial order for a majority of our components was lost. The vendor’s records indicate they were delivered, however nothing was received.
One of the two competing quick release mechanism designs must eventually be chosen, and be designed to interface with the sounding rocket timer signals to release the CubeSat at the right time. In addition, the deployment system must be properly centered within 2” along the axis of thrust of the sounding rocket, and this could be done easily after finding the center of mass of the loaded O-POD system. A "docking plate" considered by the previous team was deemed not worth the effort, as the O-POD can be directly bolted to the RockSat-X deck.

2. Electronics

As a result of extensive research and specification of the electrical needs of the project, the components necessary to construct a viable power and telemetry system for the CubeSat were purchased. Coding for these components has begun and is nearing completion. The physical configuration of the components is in discussion and with further experimentation can be achieved in the near future.

Future teams should focus their efforts on implementing the system into CubeSat itself and integrating that into the sounding rocket payload through the provided, onboard power and telemetry system. One of the biggest tasks going into the future for this team will be the placement of the camera in relation to the expanding balloon. It will be necessary to position and angle the camera such that pictures taken can be analyzed and prove the full inflation of the balloon. As
testing progresses, it may become necessary to purchase other components that can measure pressure and temperature inside of the balloon.

3. Inflatable Aerodynamic Brake

Through the simulation of 90 km altitude using the vacuum chamber, the air brake team has identified a number of possible explanations as to why benzoic acid sublimation did not inflate the balloon. The major factor was probably insufficient thermal energy or latent heat from the aluminum base plate to effect sublimation. In order to demonstrate that benzoic acid inflation is the preferred inflation choice, further tests must be done within the vacuum chamber, probably incorporating a heating element, but certainly measuring the temperature of the balloon envelope in order to determine how benzoic acid sublimation can effect inflation of the sounding rocket test article in less than 300 seconds. When testing benzoic inflation, the team must also have a quick and easier way to remove residual air from inside the deflated membrane to better-simulate a sealed Mylar balloon of larger size. Using a small syringe to extract air consumes a great deal of time and was not very effective.

The future work for the team is to repair the original 18 inch diameter vacuum chamber made available by the Physics Department to improve benzoic acid inflation and sublimation simulations. The repair would also help the future team to incorporate Mylar balloon folding techniques with benzoic acid inflation tests. Another important benefit from repairing the larger vacuum chamber is the
ability to add temperature sensors and heating element(s) within the vacuum chamber for better-controlled benzoic acid inflation tests.

A critical element is the development of the necessary instrumentation and system elements in a vacuum chamber based prototype that can be used to simulate command, control and data acquisition of an accurately controlled and instrumented deflated balloon containing the appropriate mass of benzoic acid powder\(^4\) that sublimates to inflate the aluminized Mylar balloon under simulated Rock Sat-X flight conditions. The testing of benzoic acid inflation in the miniature vacuum chamber did not yield useful results and therefore did not confirm the Mylar balloon performance predictions.

Overall, this project has been moving along toward development of the necessary prototypes that can justify a sounding rocket demonstration flight and ultimately the development of a commercially viable de-orbit system. The future team must validate the theoretical performance predictions with more tests so that a viable commercial design can be evolved.

\(^4\) Upon calculation using the US Standard Atmosphere and ideal gas law (PV=nRT), the required amount of benzoic acid should be 1.39 grams.
Appendices

Figure A1.1

Figure A1.2
Table A1.1

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
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<tr>
<td>Xbee Wifi (2x)($35.00 ea)</td>
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<tr>
<td>Linksprite JPEG camera</td>
<td>$49.95</td>
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<tr>
<td>UltraLife 9V lithium battery (2x)($5.15 ea)</td>
<td>$10.30</td>
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<td>100 Resistor Assortment</td>
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<td>Insulated 9V Battery Snap connectors($2.19 ea)</td>
<td>$4.38</td>
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<tr>
<td>Wiring</td>
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Total: 149.81

Figure A1.3 Current Gantt Chart
References