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High Power Rocket Design Report

Laura E. Calcara
Loyola Marymount University, lauracalcara@gmail.com

Monica Fernandez
Loyola Marymount University

Chris Green
Loyola Marymount University

Trent Hosokawa
Loyola Marymount University

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High Power Rocket Design Report

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by

Laura Calcara

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Loyola Marymount University
Frank R. Seaver College of Science and Engineering

Team Narwhal: Laura Calcara, Monica Fernandez, Chris Green, & Trent Hosokawa
Mentor: Dan Larson

April 28, 2016

Abstract

High-power rockets are extremely sensitive systems that require precise planning, testing, and analysis in order to yield accurate results. Under the guidance of project advisor, Dan Larson, a high-power rocket was designed and built to reach an apogee of 3000 feet. Additionally, means of dual deployment was used in order to aid in the safe descent and recovery of the rocket. In order to meet this expectation, two parachutes were used in conjunction with black powder ejection charges. Compliance with the safety standards of NAR and NFPA was met for the ejection system used in dual deployment. To ensure that the rocket would perform safely and successfully, various analytical methods were utilized. These methods included, but were not limited to, computational analysis, simulations, experimental testing, and failure modes and effects analysis (FMEA). As a result of these design and testing processes, the rocket achieved an apogee of 2769 feet with successful dual deployment on the first launch and an apogee of 2778 feet without successful dual deployment on the second launch.

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Design

Objective

Utilizing skills and knowledge of key mechanical engineering concepts, Team Narwhal was required to conceptualize, fabricate, launch, and recover a high-power rocket under the requirements and expectations provided by project advisor Dan Larson. The rocket was to reach an apogee of 3000 feet while using dual deployment methods to eject the drogue and main parachutes. To verify the achieved apogee, an altimeter attached to the rocket recorded its altitude during flight. Furthermore, the rocket had to be completely reusable after flight, meaning that the body and its components were to be completely intact upon recovery. Compliance with the National Fire Protection Association (NFPA) code 1127 for high-power rockets was necessary, and preventative measures were to be taken in order to safely and legally acquire sensitive materials.

Background

The first documented use of rockets were Chinese fire-arrows, created in 1232, and used in warfare against the Mongols. These simple, solid-propellant rockets attached to arrow shafts were used for centuries of warfare. It was not until the 17th century that the scientific foundations for modern rocketry were set in place by Sir Isaac Newton with his three laws of motion. Jumping forward, countries involved in WWII tasked their military scientists to push the boundaries of rocketry. Germany, in particular, made many advancements that contributed to the design of infamous rockets, such as the V-2, as seen in Figure 1. However with the completion of the war, the utilization of rockets for exploration and scientific discovery became a worthwhile proposition. This new pursuit led to an emphasis on efficiency, power density, and reusability with advancement of rocket propellants, aerodynamics, and overall performance. [1]

Rocket clubs and societies flourished immediately following WWII, with initial models being low powered, and only reaching heights of around 500 meters. It was not until the mid-1980's that the field of high powered rocketry (HPR) was within reach for the general public. Specifically, HPR deals with motors that have greater than an "H" class, being of more than 160 Newton-seconds of impulse, 125 grams of propellant, having a hybrid motor, weighing more than 1.5 kilograms, or including any airframe parts of ductile metal. [2]

Figure 1. V-2 Rocket Launch

Prior Work

The members of Team Narwhal had no prior experience in rocketry before undertaking this project. However, each member completed background research on the field of high powered and reusable rockets before beginning the design process. Though the team lacked direct experience in rocket design, each member had experience in basic design processes and engineering principles. These fundamental skills allowed for an effective research and concept selection process that resulted in a preliminary design of a rocket that met the requirements and specifications of the project. This two-semester long project gave the team the opportunity to gather a large base of rocketry knowledge. Each individual on the team took it upon themselves to attempt their Level 1 high-power certification, commemorative pin shown in Figure 2. The experience of building and launching kit rockets for each certification allowed for a better understanding of the build and launch phase for this project. Though the team had no prior experience with rocketry before undertaking this project, each member became skillful in the model rocket design process over the course of the project.

Figure 2. NAR L1 Certification Pin

Design Specifications

Team Narwhal was given the major requirements, as seen in Table 1 below, at the beginning of the project where brainstorming and preliminary designs were undertaken. The main aspects of the requirements set forth by Dan Larson were that the rocket must hit an apogee of 3000 feet while also exemplifying reusability and successful dual deployment.

Table 1. Major requirements set forth by project advisor, Dan Larson.

#	**Requirement**
1	Design goal shall be to build a high-power rocket targeting 3,000'
4	Body diameter must be >2.61"
5	Rocket must demonstrate full reusability
8	"I" motors are the highest impulse class motor allowed for this design project
14	Avoid damage to rocket and zippering
15	Black powder use is acceptable for dual deployment if receiving training on March 12, 2016

Reusability was defined as being able to launch the same rocket twice on launch day. Dual deployment has been used for high powered rocketry where the deployment of two parachutes functions to reduce the rocket's horizontal drift. In dual deployment, a drogue parachute should be deployed at apogee and the main chute between 500 and 800 feet, as seen in Figure 3. Utilizing this technique would reduce the horizontal distance that the rocket drifted upon descent, reducing the retrieval distance by a few miles [3]. These requirements were complied with during the brainstorming and design phase of the high-power rocket. A table of the full requirements can be found in Appendix A.

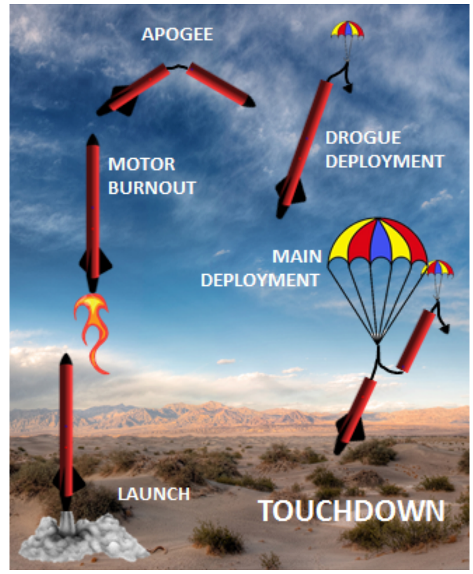

Figure 3. Dual Deployment Rendering

The National Fire Protection Agency (NFPA) codes and National Association of Rocketry (NAR) standards were followed when designing, manufacturing, assembling, transporting, and launching the model rocket and its components. They were set for the general safety of the team as well as the public to avoid explosions, fire, and danger to human life. An example of the guidelines from NFPA 1125 and NFPA 1127 can be reviewed in the Safety section. The recovery system was one example of a system influenced by NAR requirements. Number 10 of the NAR Rocket Safety code states, "I will use a recovery system such as a streamer or parachute in my rocket so that it returns safely and undamaged and can be flown again, and I will use only flame-resistant or fireproof recovery system wadding in my rocket" [2]. Thus, a ripstop nylon parachute was incorporated into the rocket design. Also, testing before launch was required for the rocket in order to determine the success of the dual deployment system as well as the structural integrity of the fins. These NFPA and NAR requirements can be found in the references [2][3].

The requirements added by Team Narwhal were requirements 14 and 15, as seen in Table 1. Requirement 14 was set in place to ensure that the rocket maintained its reusability. It was discerned that major zippering would inhibit a second launch because the rocket would be in a state of disrepair. Additionally, fins were considered a major risk because of their potential to fracture on impact. Thus, the designing of a removable fin mount system became a priority so that fins could be swapped out in minimal time in the event of a break. Requirement 15 relates to a few NFPA and NAR codes, as well as a general safety concern. Dual deployment commonly uses black powder to create enough pressure to break the shear pins and separate the rocket to allow parachutes to deploy [5]. In order to learn how to safely use black powder and affirm that the dual deployment system was working properly, Team Narwhal participated in the Dual Deployment Test on March 12, 2016 at Lucerne Dry Lake, CA. Black powder testing can be read about more in-depth in the Testing section.

Conceptual Development and Selection Methods

To satisfy the requirements above, various design concepts were considered and compared against each other. To determine the ideal design, Pugh's Concept Selection Technique was used and a concept scoring matrix was developed [6]. A detailed analysis of preliminary concepts can be found in Appendix B .

The categories used to determine a well-designed rocket were the rocket's accuracy in achieving target apogee, stability, robustness of the design, reusability, safety of the design, overall cost, ease of manufacturing, weight, portability, and aesthetics.The aesthetics for each iteration were rated zero due to the finishes, rocket motor smoke color, etc. were not a part of the initial designs. In terms of accuracy, the rocket was rated on how close it reached 3000 feet without a margin of error. The stability rating was determined by how many calibres the center of gravity and center of pressure were apart from each other. Reusability was rated on how efficiently the rocket could be prepped for re-launch. The final ratings for each rocket were within a tenth of each other. It was because of this that the most innovative and unique aspects of each rocket design, such as trapezoidal fins and a haack series nose cone, should be incorporated into the final rocket design.

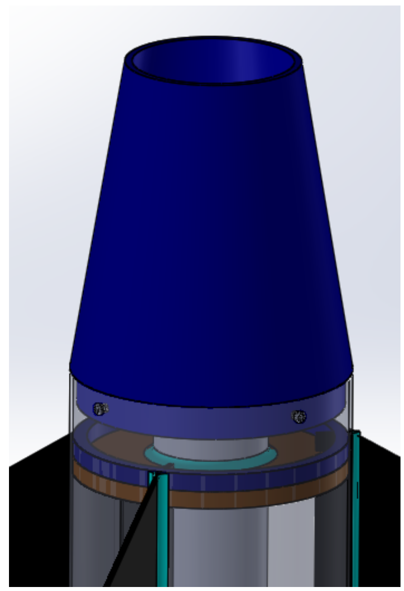

Figure 4. Boat Tail Concept Design

Innovation

Certain design features of the Narwhal rocket were created in order to serve a more functional and aesthetically-pleasing purpose. For example, the nose cone was 3D printed using the MakerBot Replicator 2 printer with PLA plastic filament that would ensure rigidness and durability. It featured a haack series design which was intended to aid in minimizing the overall drag on the rocket during subsonic speeds. To combat the issue of surface roughness that accompanies 3D printing, wood filler was applied to the nose cone to fill in divots and wet-sanded in order to achieve a smooth finish. Having the exposed length of the nose cone be the same as the diameter was implemented in order to decrease the amount of drag it would experience.

In addition to the nose cone, the boat tail was also 3D printed with PLA plastic. The addition of the boat tail was implemented to aid in the overall stability of the rocket and improve aerodynamic efficiency. The boat tail ensured relatively low drag at subsonic speeds and the reduction of turbulent drag effects on the exhaust. Additionally, the overall flight velocity of the rocket was also maintained more accurately because of this addition to the design. Similar to the nose cone, the boat tail was wood filled and sanded to achieve a smooth finish. There were concerns about the boat tail deforming due to the heated motor exhaust. However, Sandi White, Senior Research Technician at Aerotech, confirmed that the burn temperature of the motor would be about 100°C, whereas the melting point of PLA plastic lies around 110°C [7]. Due to the fact that motor burn time was only one second, it was less likely that the boat tail would deform from heat exposure. However, in order to adequately address the potentiality of deformation, the boat tail was oriented in such a way that engine retainer sat past the end of the boat tail. This was done by extending the length of the inner blue tube past the end of the outer body tube, which would divert the engine exhaust directly out of the end rather than contacting the inside of the inner engine tube.

Figure 5. PLA Boat Tail

A material called Blue Tube was used for the creation of the rocket body. Blue tube has "far more resistance to abrasion and has no cracking or brittleness" [8]. Although fiberglass was considered as an option for the Narwhal rocket, its weight in comparison to blue tube was far greater, and therefore a lesser option for application. Having a Blue tube body would also decrease the chances of zippering which occur with less strong materials like cardboard.

Zippering is an error that occurs in many high powered rockets during deployment of the main or drogue parachutes. Upon deployment, the parachute attached to the kevlar shock cord would deploy quickly and come into contact with the walls of the body tube, ripping the shock cord through the blue tube body. In order to counteract this potential issue, the kevlar shock cord was threaded through the top and bottom bulkheads of the avionics bay in such a way that it created four separate leads on each bulkhead, as shown in Figures 6 and 7. These leads joined together onto a barrel swivel attached to the remaining shock cord that was connected to the parachute as well as the nose cone or eyebolt on the aft assembly bulkhead. This preventative method evenly distributed the tension that the rocket experienced during deployment between the four leads causing the body to rotate about the barrel swivel, self correcting and lessening tension. Additionally, the barrel swivel prevented the shock cord from tangling.

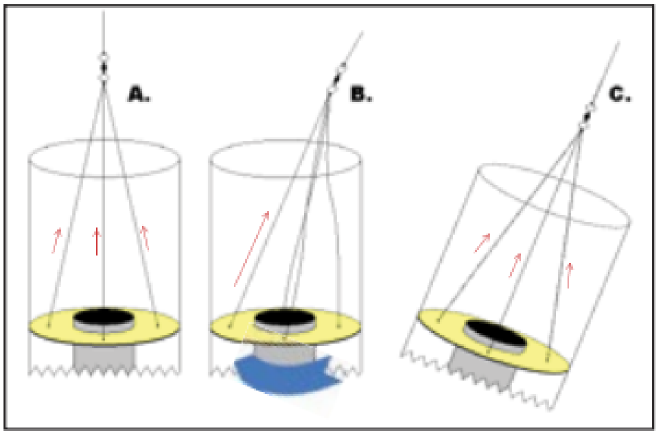

Figure 6. Concept of Anti-Zippering Harness [9]

Figure 7. Actual Anti-Zippering Harness

Security and alignment of the fins were extremely important for the performance of the rocket. To attach the fins to the rocket body, a fin mounting system was created, as shown in Figure 5. Three slotted, plywood centering rings were used to axially position the fins, as shown in Figure C8 in Appendix C. The fins were inserted into these slots and secured within notches cut into the bulkhead. Large fillets of epoxy were also made to further adhere the fins to the rocket body. This system allowed for the fins to not only be positioned at the correct angle, but also be secured onto the blue tube body. For full build steps of the fin mount, see Appendix C.

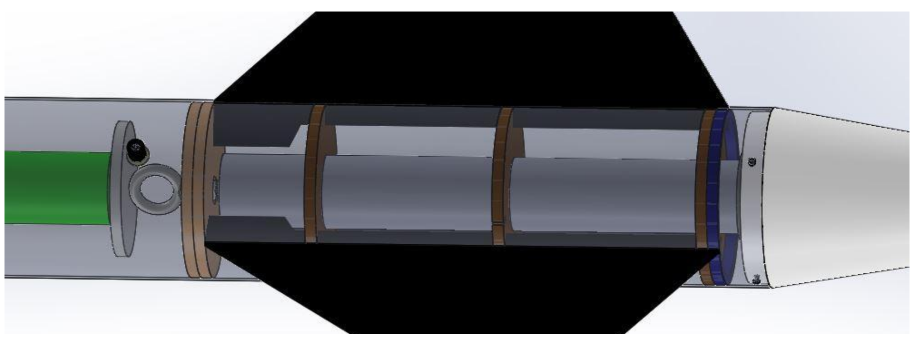

Figure 8. Fin Mount System in SolidWorks

The fins were manufactured such that a pattern of tabs would function to secure the fin into the slotted bulkplate, as seen in Figures 9 and 10. To ensure that the fins would not break upon landing, they were designed in a trapezoidal, swept-back manner and placed above the boat tail.The fins utilized for this design were G-10 Prism Plate Fins made by Public Missiles. The G-10 fins were made of a highly compressed fiberglass laminate, and “[were] extremely tough, waterproof, and solvent-proof…[and were] very rigid, yet [had] just enough flex to keep it from snapping under most loads" [10]. The reflective finish was also chosen to make the rocket easily visible during flight, as well as for aesthetic purposes.

Figure 9. Bulkplate for Fin Mounting System

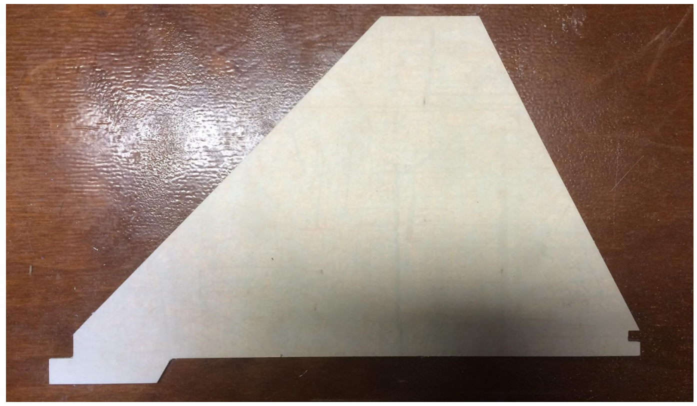

Figure 10. Manufactured Fin with Film Cover

Description

1. *Forward Body Assembly*

Starting with the top of the rocket, the 3D printed nose cone featured a true haack series shape. With a length of 5 inches and a base diameter of 3.9 inches, the 0.6 inch thick nose cone was designed to provide the most suitable balance of drag and streamlining for its application (see Figure C4 in Appendix C). A one inch shoulder was built into it so that it would be able to be inserted into the body tube and secured with 2-56 screws to the outer body.

The body tube was composed of two separate tubes for both the upper and lower segments of the rocket, with lengths of 18 inches and 23 inches respectively. The wood-filler and sanding method was also applied to the body tube in order to achieve a smoother finish. The body tube had an outer diameter of four inches which both fulfilled the preset requirement and allowed for easy access into the rocket. For the full fabrication drawing of the body tubes, refer to Figure C1 in Appendix C. A fiberglass tube coupler with an adequate amount of epoxy was used to join both segments of the body, and had an outer diameter of 3.9 inches to ensure that it would fit snugly inside each of the body tubes.

Figure 11. Unpainted Forward Body Assembly

2. *Recovery System*

The forward half of the body tube was composed of the drogue parachute, shock cord, and avionics bay. The Wildman Crossfire 24-inch Parachute acted as the drogue parachute to aide in the rocket's descent after reaching apogee. It was deployed with the separation of the forward blue tube body and nose cone, which was previously held together by 2-56 shear pins. Similarly, the Wildman Crossfire 36-inch Parachute was used for the main parachute, located between the forward and aft body assemblies. A Kevlar shock cord with a length three times the overall length of the rocket (12 feet 4.5 inches) was used to keep the forward body, nose cone, and aft body connected upon deployment. In order to initiate separation, black powder dual deployment methods were utilized for both charges. The black powder canister was housed on the outside of the Avionics Bay to create a pressure differential that is necessary to separate the bodies. The Avionics Bay housed the StratoLoggerCF-PerfectFlite Altimeter necessary for igniting the electronic matches and in turn black powder charges, which can be seen in Figures 12 and 13.

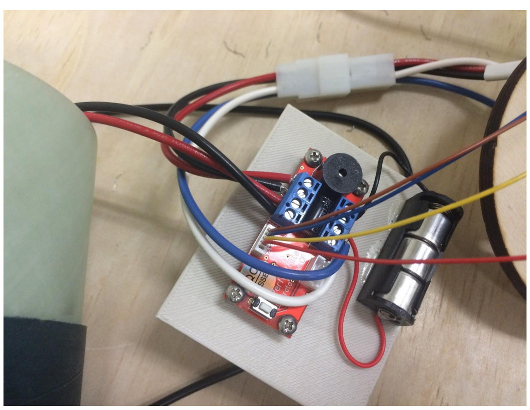

Figure 12. Mounting Board with Components

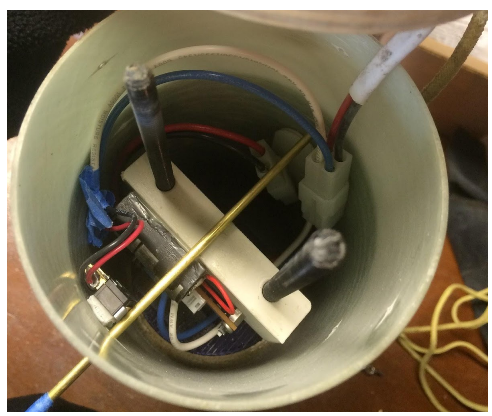

Figure 13. Inside View of the Avionics Bay

3. Aft Body Assembly

The lower portion of the rocket contained the main parachute, motor, inner tube, engine bulkplate, fins, boat tail, and centering rings, as seen in Figure 14. The Aerotech I-1435T motor had a total impulse of 556 N-s, which provided enough thrust to reach the target apogee. In order to hold the Aerotech motor in place, three plywood centering rings were placed along the length of the inner tube. The fins also utilized these centering rings to stay properly positioned. The engine bulkplate was located above the inner tube, separating the main Wildman Crossfire 36-inch parachute from the motor. The boat tail had a shoulder that would fit into the bottom of the body tube and secured with four 2-56 screws. The engine retainer slightly stuck out of the end of the boat tail to minimize contact to the PLA plastic with the engine exhaust. A complete view of the rocket can be seen in Figure 15.

Figure 14. Aft Assembly

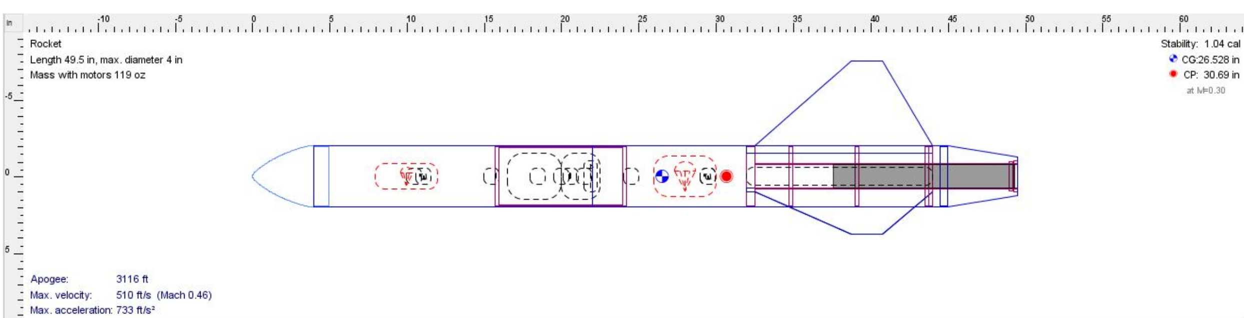

Figure 15. Overview of the Rocket in OpenRocket

Ongoing Design Changes

Multiple issues emerged throughout testing and manufacturing. One problem was with 3D printing the boat tail. After seeing the ABS plastic melt from drilling, concern arose that the flame and heat coming from the motor burn would melt and warp the component, making the rocket unfit for a second launch. In order to combat the issue, simulations were executed on OpenRocket where the inner tube mount was extended out the end of the boat tail. Unfortunately, this affected the stability of the rocket. However, swapping the mounting board sled and payload carrier positions within the avionics bay achieved a higher stability ratio.

On the day of launch, several teams failed deployment due to insufficient black powder sizing. After consulting Dan Larson and an on-site rocket specialist, it was suggested that the black powder charges be increased by 0.5 grams to ensure deployment. The specialist also suggested that the shock cord be taped in a “Z” overlapping formation to weaken the increased ejection force of the nose cone due to the larger black powder charge.

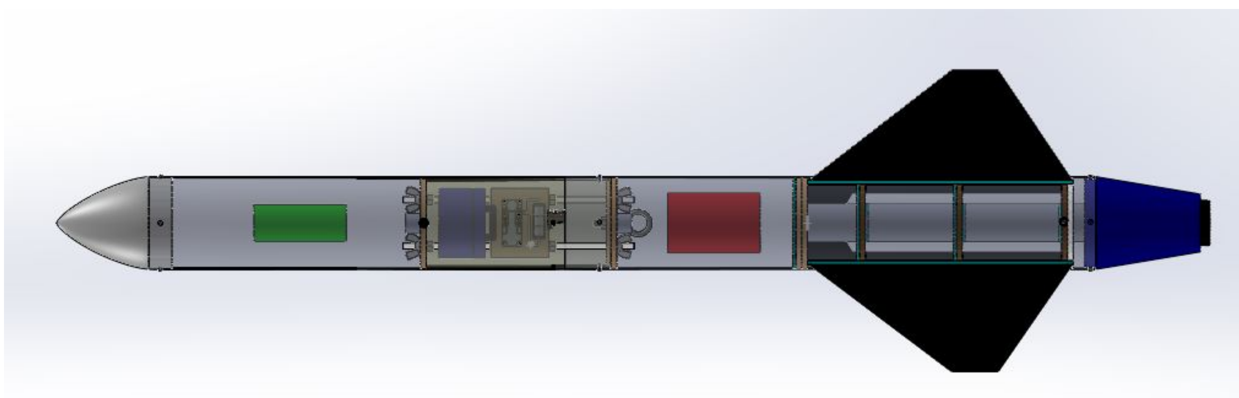

Figure 16. Narwhal Rocket Design in Solidworks

Analysis

Failure Modes and Effects Analysis (FMEA)

A Failure Modes and Effects Analysis (FMEA) was performed in order to identify the five most critical potential failure modes of the rocket. A detailed table of this analysis can be seen in Appendix E. When creating this table, potential failure modes that could occur during the manufacturing, assembly, and launch of the rocket were identified. The goal of this process was to assign each potential failure mode a risk priority number (RPN) using the following equation:

$$RPN = SEV \times OCC \times DET$$

Where,

$SEV =$ *severity of failure*

$OCC =$ *likelihood of occurrence*

$DET =$ *ease of failure detection*

Each of the above variables are rated from 1 (least) to 10 (greatest). The top three most concerning failure modes, ranked according to RPN, can be seen in Table 2. Appendix E contains the full table with numerical values for SEV, OCC, DET and RPN.

Using this analysis, it was found that the highest scoring potential failure mode was dual deployment. This would be due to the inability of the black powder charge to create enough pressure to break the shear pins and separate the rocket. If this occurred during launch, the parachutes would have been unable to eject and would cause the rocket to hit the ground at a high velocity. This could have damaged the rocket and rendered it unusable, showing its inability to comply with the reusability requirement. The dual deployment system was tested multiple times in order to reduce this risk, which can be seen in the Testing section.

Table 2. Top 5 Failure Mode Analysis

#	**Potential Failure Mode**	**Potential Failure Effect**	**Potential Causes**	**RPN**	**Action Recommended**
1	Dual deployment fails	Rocket hits ground at high velocity	Black powder does not eject the parachutes	200	Execute a ground test of dual deployment before launching rocket
2	Payload shifts during flight	This could cause the CG to shift during flight and create instability	This could be due to insufficient hardware fastening or mounting methods	162	Make sure that the payload design is secured with metal hardware
3	Components arrive late or damaged due to shipping	Rushed assembly and reduced time to test	Not ordering parts early enough	126	Order parts ahead of time to ensure their timely arrival

The second highest failure mode identified was the risk of the payload shifting during flight. If the payload moved, the center of gravity of the rocket could have changed and negatively impacted the stability of the rocket. This could have led to the rocket not achieving the correct altitude or becoming damaged during flight. In order to address this problem, stainless steel nuts were used to secure the payload carrier vertically along the rods in the avionics bay. The nuts were tightened and inspected before launch to ensure rigidity. Additionally, wadding was added in the payload carrier to take up any extra space not filled by the payload.

The third most concerning failure mode was the risk of components arriving late or damaged, either because of the manufacturer or the shipping process. This could result in not having enough time to accurately assemble and test the rocket, which could negatively impact its performance on launch day. Ordering the parts early and compiling a list of reliable manufacturers from which each component was purchased ensured that there was enough time to reorder parts when they arrived damaged. Additionally, the need for ordering extra parts in the cost budget was factored.

Subsection Analysis

1. *Hand Calculations*

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To determine the apogee of the rocket without using computer simulations, basic hand calculations were performed. The equations presented in Figure 17 show the process of analysis, while Table 3 describes what each variable represented and their specific values for this rocket. The sum of the altitude at burnout, y_1, and the coasting distance, y_2, equaled the total apogee of the rocket. Assuming a drag coefficient of 0.29, no cross wind and a payload of 2 oz, the apogee of the rocket was calculated to be 3003.7 feet. The drag coefficient was taken from the OpenRocket simulation based on surface finishes of "smooth paint." The hand calculations complemented the OpenRocket result of 3175 feet. This showed a percent difference of 5.54% when comparing the two methods, which gave insight that Openrocket could be trusted when compensated for correctly.

$$k = \frac{1}{2}\rho C_d A$$

$$x = \frac{2\sqrt{(T-mg)k}}{m}$$

$$q = \sqrt{\frac{T-mg}{k}}$$

$$v = q\left[\frac{1-e^{-xt}}{1+e^{-xt}}\right]$$

$$y_1 = \frac{-m}{2k}\ln\left(\frac{T-mg-kv^2}{T-mg}\right)$$

$$y_2 = \frac{m}{2k}\ln\left(\frac{mg+kv^2}{mg}\right)$$

Figure 17. Equations for Hand Calculations

Cd no open rocket fica em Análise de componentes.

testei os valores de massa(kg), It, Eméd, mp e massa do foguete (7,81 lbs), cd de 0,29 no ezalt e obtive apogeu de 2765 m. Bem próximo do apresentado na conclusão do trabalho.

diâmetro: 4 polegadas = 101,6 mm = 10,16 cm

AEROTECH 38MM PROPELLANT KIT – I435T-14

- **Model:** 81354
- **Qty per pack:** 1 motor & 1 igniter
- **Size:** 38 mm Reload
- **Casing (Not Included):** AeroTech 38/600 Case (PN: 60024)
- **Delay:** 14 sec
- **Burn Time:** 1.1 sec
- **Total Impulse:** 568.9 Newton-seconds
- **Motor Length:** 288 mm
- **Max Thrust:** 785.6 Newtons
- **Total Mass:** 527.0 g
- **Propellant Mass:** 273.0 g
- **Igniter Included:** First Fire Starter for High Power Motors
- **Compatible Igniters (Spares):**
  - First Fire Starter for High Power Motors
  - Fat Boy Starters
  - Slim Gem Starters
- **Manufactured by:** AeroTech

Table 3. Hand Calculations

Variable	Representation	Value
m	mass (lbs)	7.31
T	thrust (N)	482
I	impulse (Ns)	561
A	rocket cross-sectional area (m^2)	8.11×10^{-3}
P	air density (kg/m^3)	1.22
C_d	drag coefficient	0.29
t	motor burn time (s)	1.16
y_1	altitude at burnout (ft)	90.6
y_2	coasting distance (ft)	825

2. *OpenRocket*

OpenRocket is an open source program that simulates a rocket launch. Using this software, the rocket design was made into a detailed 2D model with all components, as seen in Figure 18. Weather conditions could also be altered in simulations to see how the rocket would perform under various wind speeds. OpenRocket was a major tool used in determining the design of the rocket as it tracked the stability of the rocket as well as the apogee when components were being added and altered for their best performance. OpenRocket was also used to track the center of pressure and center of gravity of the rocket actively throughout the design process.

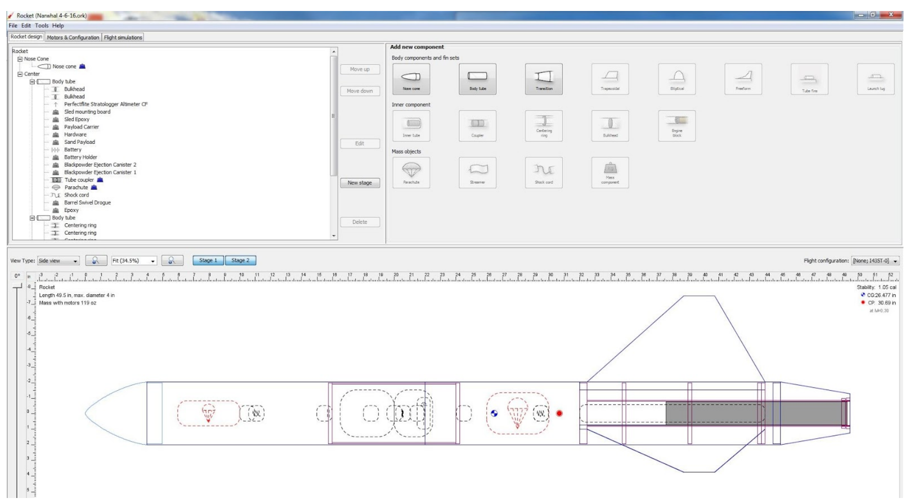

Figure 18. OpenRocket Interface

The objective of using OpenRocket was to simulate whether or not the rocket would achieve an apogee of 3000 feet. The conditions of the Koehn Dry Lake launch site as well as a wind speed at 8 mph were included in the simulation. Running multiple simulations under various conditions allowed for an optimization of design. OpenRocket was used continually throughout the build and testing phases to monitor the center of pressure, center of gravity and the apogee of the rocket.

Some components were not able to be input as OpenRocket features, and were compensated for by using mass objects, as seen in Figure 19. Epoxy for the centering rings was accounted for as a mass object over the aft of the rocket. Hardware, such as hex nuts and wing nuts, were accounted for in a mass object placed in the center of the avionics bay.

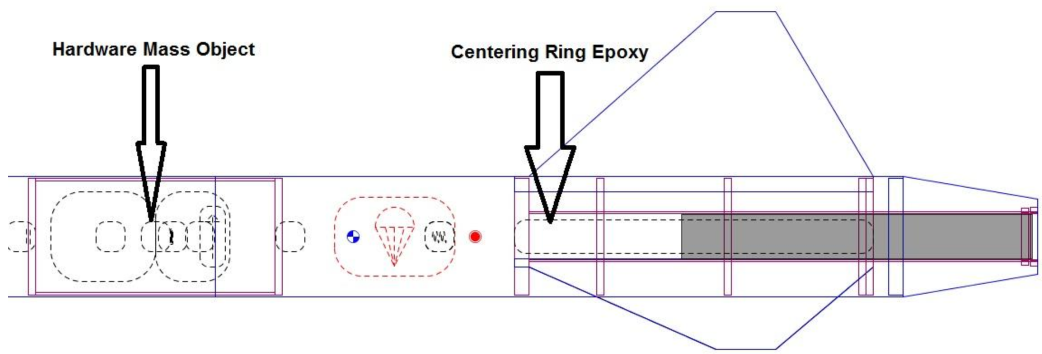

Figure 19. Hardware and Epoxy Mass Objects

Based on other users' experiences with OpenRocket overshooting, it was found that OpenRocket tends to exceed actual launch results by about 10% [10]. A discrepancy of 5% was found as seen in the hand calculations above. In order to compensate for this, the target apogee that OpenRocket created was decreased by 100 feet and the payload was reduced from 0.47 oz to 0.25 lbs. The apogee that was calculated by OpenRocket with 8 mph wind speeds was 3105 feet which translated to about 3005 feet after compensating for OpenRocket's tendency to overshoot.

3. RockSim

The purpose of using RockSim was to verify the findings from OpenRocket. This verification was important because OpenRocket is an open source program that cannot be fully trusted. The OpenRocket file was exported to RockSim and launched with the weather condition of a light breeze (8-14 mph). An average wind speed could not be specified; therefore, multiple launches were executed, as seen in Table 4, to compare to the OpenRocket launches. For OpenRocket, the conditions were set at an average wind speed of 11 mph with a 3 mph speed deviation. Both simulations had the rocket carry a payload of 0.25 lbs.

Table 4. RockSim launch reports

Sim #	Results	Engines loaded	Max. Altitude	Max. Velocity	Max. Acceleration	Time to apogee	Velocity at deployment	Altitude at deployment	Optimal delay
			Feet	Feet / Sec	Feet/sec/sec	Seconds	Feet / Sec	Feet	Seconds
5		[I435T-None]	3070.25	497.31	722.06	13.47	31.37	3070.25	13.47
4		[I435T-None]	3070.34	497.31	722.06	13.47	31.32	3070.34	13.47
3		[I435T-None]	3072.48	497.39	722.06	13.48	30.21	3072.48	13.48
2		[I435T-None]	3082.91	497.74	722.06	13.50	24.02	3082.91	13.50
1		[I435T-None]	3071.47	497.35	722.06	13.47	30.73	3071.47	13.47
0		[I435T-None]	3090.66	498.00	722.06	13.52	18.06	3090.66	13.52

RockSim calculated an average apogee of 3076.4 feet. It was concluded that OpenRocket and RockSim overshoot as they both displayed an apogee above the hand calculations and other rocket specialists' experiences with simulations. However, due to its easy-to-use interface, OpenRocket was chosen over RockSim to track the apogee as design changes were made. Masses and approximate coefficients of drag were overridden in the RockSim and OpenRocket calculations to generate accurate simulations. At any point before the launch, the payload was easily adjustable from 0 to about 0.5 lbs. This allowed the rocket to have a variable weight, which could be used to fine-tune the apogee. The aim of this variable payload system was to achieve an apogee within a 10 feet margin of error of the 3000 foot apogee goal.

4. *Wind Analysis*

Precise launch day wind conditions were unknown prior to arriving at Koehn Dry Lake, which meant that specific payloads had to be known for different wind speeds to ensure that the rocket reached the correct apogee. By changing the wind speeds on OpenRocket and then incrementally adding mass to the avionics bay, the appropriate payload was determined. Table 5 below shows the relationship between wind speed and payload necessary to reach 3100 feet in order to compensate for OpenRocket's tendency to overshoot.

Table 5. Wind Analysis Results

Wind Speed (mph)	Apogee (ft)	Payload Addition (lb)
15 (Heavy Breeze)	3107	0.18
10 (Moderate Breeze)	3106	0.22
5 (Light Breeze)	3110	0.25
0 (Calm)	3085	0.31

The rocket was able to hold over an eighth of a pound even in harsh weather conditions. The payload decreased by a few hundredths of a pound in order to go from perfect wind conditions to a heavy breeze.

Cost and Mass Analysis

The cost of manufacturing the rocket was split up into sections according to what part of the rocket the components belonged to. Tables F2 through F4 in Appendix F show the distribution of cost within the body, avionics bay and dual deployment system, motor, and shipping respectively. An overview of the cost and mass budget can be seen in Table 6. The initial cost specified at the Critical Design Review was $898.30 before building the rocket. This included a 9.5% sales tax and shipping from the appropriate retailers and manufacturers. A memorandum was written in order to extend the budget from $1000 to $1250 in order to accommodate the overrun. This left $351.70 leftover for testing, paint, and unexpected occurrences. The motor propellant costed the most at $169.98 as two reloads of the motor and the casing were budgeted for. The nose cone and boat tail were 3D printed for free and were not included in the budget. The section of the rocket that accounted for the most weight was the body as it made up 3.69 lbs of the total 7.29 lbs.

Table 6: Cost and Mass Budget Summary

Rocket Section	**Total Cost**	**Overall Weight (lbs)**
Body	$289.21	3.68
Avionics Bay	$391.81	2.25
Motor	$316.98	1.40
Shipping and Tax	$189.86	N/A
Totals:	$1187.86	7.29

It can be seen that a few components' cost or weight were listed as zero in the Appendix F tables. This may be due to the fact that the weight was negligible when weighed. The zero value can also be attributed to an incorrect component bought and not included in the rocket, such as the 38mm blue tube coupler or the helical inserts. Also, shipping may appear as $0 on some tables as the part was coming from a manufacturer whose shipping cost was already accounted for in a previous table. It may be noted that over $50 was spent on one shipment from Apogee Components. This was due to the fact that vital parts were required in an immediate rush before black powder testing that occurred on March 12, 2016. The cost of shipping was justified because the total cost was under the $1400 maximum limit and budgeted for an overhead in these types of situations. It should also be noted that there were no labor costs included as a majority of it came from student labor or from LMU's machinist. Custom parts that were manufactured were the fins, whose cost has been fully factored into the budget, and the fins slots of the body tube, which was done for free through LMU's machine shop. Tooling was also not a part of the budget as the tools necessary to assemble the rocket were readily available or could be 3D printed for free, such as the centering ring alignment tools.

The final cost of the rocket was $1187.86. This was a large discrepancy from the original cost at the Critical Design Review due to several reasons. One reason was that there was an unexpected rush shipping cost due to a schedule conflict. In order to have vital parts (ie. extra shock cord, shear pins, and barrel swivels) for the black powder test day, an Apogee order had to be rushed at a cost of $53.75 to make the total order $97.93. Another reason for the cost overrun was parts that were not originally anticipated in the budget. This included wood filler, different disconnect wires, an extra snap action switch, a pull pin for the switch and miscellaneous screws. These costs could not have been avoided as minor design changes required large amounts of money due to shipping and an accrual of minor parts. Also, manufacturing knowledge was obtained through the build process which required changes unforeseen in the design phase. An example of this was that after receiving the quick-disconnect wires, it was determined that they would not survive the vibrations and forces during the launch. This required new disconnect wires that were more expensive. A full breakdown of the costs can be found in Appendix F.

Testing

Various tests were run in order to affirm the design choices made and investigate any risks that could have endangered the rocket. The tests fell into two broad categories: Developmental Testing, which documented tests done in order to aid the design process, and Performance Testing, which included tests that were performed to validate expected performance of the final physical design. To see the schedule for the tests performed, see Table G1 in Appendix G. An overview of these tests, their objectives, and final results can be seen in Table 7 below.

Table 7: Developmental and Performance Testing Summary

Test	**Objective**	**Result**
SolidWorks Flow Simulation	Find drag coefficient	Cd = 0.33
Nose Cone Drop	Ensure strength on impact	No structural damage
Altimeter	Test functionality of altimeter and wiring	Current was sent to LEDs
Dual Deployment	Successfully deploy drogue and main chutes	Both chutes were deployed

Developmental Testing

1. *SolidWorks Flow Simulation*

A flow simulation was ran to acquire the drag coefficient of the rocket in flight. Another purpose of the test was to visualize the pressure concentration locations on the rocket so that reinforcement could be added to the areas with inadequate strength. The test was run through Solidworks by importing the rocket design and running a simulation. The variables controlled were the orientation of the rocket in the flow, control volume, shown in Figure 20, velocity of the fluid, density of the fluid, number of flow lines, and thickness of the flow lines.

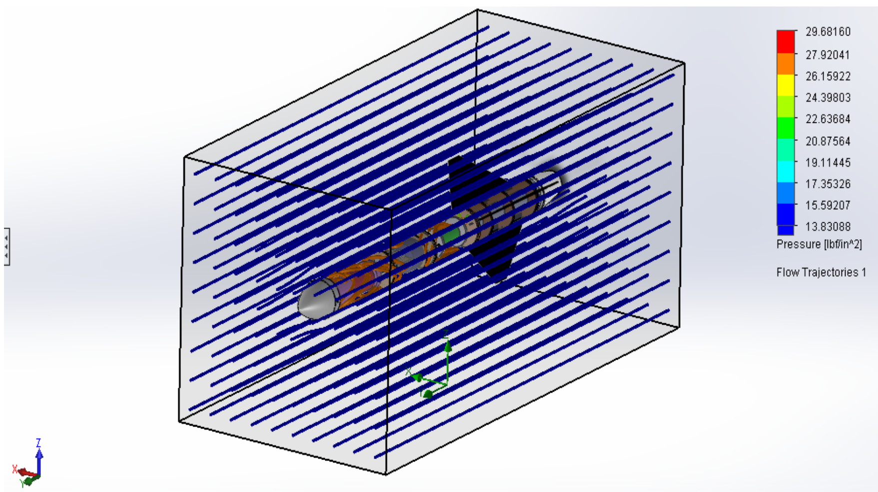

Figure 20. SolidWorks Flow Simulation

Based on the results of the flow simulation, the drag coefficient as well as the pressure across the rocket was determined. In a simulated flight, the maximum pressure the rocket would experience was 13.83 lbf/in^2, thus negating the need for reinforcement. The drag coefficient was determined to be 0.33 which was close to OpenRocket's predicted drag coefficient of 0.28, as seen in Figure 21. This discrepancy in drag coefficients was due to the lack of SolidWork's material data on blue tube. OpenRocket predicted a low coefficient of drag due to the use of a smooth paint finish on the nose cone and boat tail, as well as a rough paint finish along the body. The rocket's haack series nose cone gave the best drag conditions at a short length, and the large fins provided stability to the rocket at the cost of the drag coefficient. Based on the results of the test, it was concluded that the rocket's finish should be as smooth as possible in order to reduce drag. To accomplish this, wood filler was used to cover holes and divots within the body tube, nose cone, and boat tail. The wood filler was then sanded flush with the component and finished with a paint.

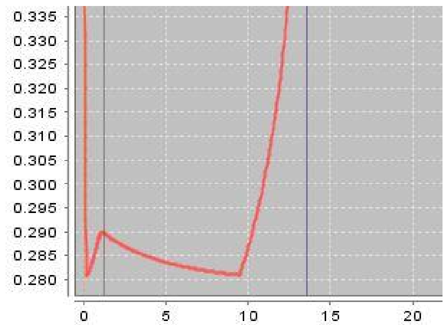

Figure 21. OpenRocket drag graph

Performance Testing

1. *Nose Cone Drop Test*

The nose cone was a vital component of the rocket and if it broke it would have rendered the rocket unusable. The nose cone drop test determined whether the strength and design of the nose cone was sufficient to withstand various impacts at landing as well as forces that were beyond the expected impact. The expected landing velocity was determined through OpenRocket to be 13 miles per hour. It was determined that the nose cone must be dropped from 5.6 feet to achieve the expected OpenRocket landing velocity. A 10% margin for factor of safety was added when dropping the Nose Cone as a buffer. The nose cone was also dropped from a higher height of 12 feet to further increase the confidence in the structural integrity of the part. The impacted ground was compacted soil, as was expected on launch day, and the nose cone was dropped with the point facing down.

The nose cone did not sustain any damage from either of the drop tests. Minor scratches to the exterior were found but were far from being structurally damaging. It was determined that the nose cone could withstand higher landing velocities if necessary. The tested nose cone design and physical part was deemed sufficient for launch day. The possibility that it might fail, how it might fail, and what the outcome of such failure can be found in the FMEA table in Appendix E. The testing was sufficient that the risks outlined in the FMEA table were considered negligible.

2. *Altimeter Test*

Upon failure of the altimeter, the rocket may not have received flight data for the launch or ignite the ejection charges for dual deployment. The objective of the altimeter test was to determine whether the altimeter and connected wires operated correctly in simulated flight conditions. The altimeter sled, which included the altimeter, battery and wires, were placed in the vacuum bag. LED lights were attached to the altimeter "DROGUE" and "MAIN" ports in place of black powder charges and e-matches. The altimeter was turned on and left outside of the bag until there were continuity beeps, confirming full electrical connection. It was then placed in the vacuum bag and a pump was used to apply a vacuum to the bag. After allowing the pressure gauge on the pump to increase and most of the air sucked out of the bag, as seen in Figure 22, the pump was turned off. The bag reaching a low-pressure vacuum state simulated the rocket's apogee at which the drogue LED light was predicted to light up. When air was let back into the bag, the pressure increase simulated the descent of the rocket at which point the altimeter would light the main LED light when the pressure simulated an 800 foot height. This test was conducted multiple times in order to confirm that the avionics bay would consistently function properly.

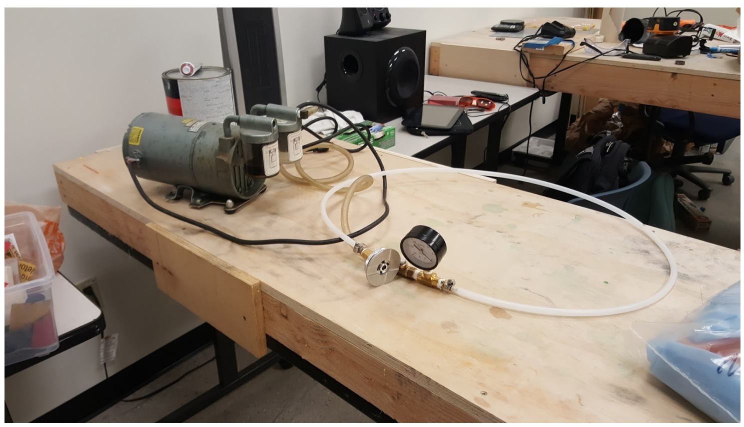

Figure 22. Pump used for the altimeter testing

As a result of these tests, the drogue and main LED lights went off at the two separate events as predicted. The altimeter along with its corresponding wires were concluded to be in working order and ready for use on launch day.

3. Dual Deployment Testing

The purpose of the dual deployment test was to ensure that the black powder charges for dual deployment were sufficient to pressurize the body tube and separate the rocket by breaking the shear pins. If the dual deployment failed, the rocket would impact the ground at a high velocity, possibly rendering it unusable. If the shear pins did not properly shear during ejection, the parachutes would not deploy. Therefore, the dual deployment testing day was critical to the success of the rocket's reusability and overall success. Dual deployment was tested at the ROC launch site in Lucerne Dry Lake on March 12, 2016. On test day, the rocket was completely assembled excluding paint and parachutes.

The black powder charges were sized based on three websites that required information such as body diameter (3.9 inches), length pressurized (11.6 inches for the main and 8 inches for the drogue), and pressure required (16 psi) [12][13][14]. The black powder charges were sized at 0.8 grams and 0.68 grams for the main and drogue parachutes respectively. First, the drogue charge test was set up with a tarp and weights, as shown in Figure 23, in order to safely test nose cone ejection. A 20 foot USB cable attached to the avionics bay was used to connect to the altimeter to ignite the drogue charge from the PerfectFlite computer program. The main charge was tested second and setup as shown in Figure 24. Due to the design of the rocket, the USB cable could not be used, as the avionics bay was unaccessible in this setup. Instead, long wires were connected to the main black powder charge and ran through the aft of the rocket past the engine retainer ring. These wires were then connected to a 9V battery once the charge was ready to be set off.

Figure 23. Setup for the drogue black powder charge test

Figure 24. Setup for the main black powder charge test

The first drogue deployment test was successful; however, the first main deployment test failed as there was no separation of the forward body and aft. This was attributed to an incorrect sizing of black powder. A second test was executed ensuring that the charge was sized correctly, resulting in a successful second main deployment test. In both successful tests, the shear pins were properly sheared and the shock cord became taut due to the ejection forces. From the test, it was concluded that the black powder charges were sized sufficiently to be used on launch day.

Safety

Safety Specifications

The safety codes used for this project came from the NAR and NFPA. Standards that applied to the rocket were the use of lightweight material (Ex. paper, rubber, wood, plastic, fiberglass, ductile metal, or material of similar density), implementation of an adequate flame resistant recovery system, and that the weight of the rocket couldn't be more than one-third of the average certified thrust of the motor. Standards that applied to the motor were that the motor could not be tampered with, kept near heat sources at any time away from the launch site, the motor impulse couldn't exceed 40,960 Ns and the motor igniter could only be installed on the launch pad. The motor, as seen in Figure 25, was not received until launch day so meeting these standards were not a problem. Several standards for the launch site, in terms of the launch pad and electrical launch systems, were listed and handled by the launch sites themselves. The team maintained awareness of these standards.

Figure 25: Aerotech I-435T Motor

The NFPA 1127 code specified standards for launching. A five-second countdown should have been administered before launch. In the scenario of the wind speed exceeding 5 mph, the launcher length must be varied to permit the rocket to attain this safe velocity. The rocket should never be launched at targets, into clouds, near airplanes, or on trajectories that take it directly over the heads of spectators or beyond the boundaries of the launch site. Finally, the rocket could not be launched at wind speeds exceeding 20 mph. All of the safety codes were complied with throughout the project.

In order to use an "I" impulse class motor, a National Association of Rocketry (NAR) Level 1 High Power Rocket (L1 HPR) Certification was required. The team member attempting the certification must have been observed and judged by an L1 certified individual, in this case, Dan Larson. All conditions and restrictions imposed by the Federal Aviation Administration were to be satisfied and followed. The member attempting certification was required to build the certification rocket with an H or I impulse motor, as seen in Figure 26. Spectators should also stand an adequate distance away from the launch pad.

Before, during, and after launch, the certification team used a checklist to assess the safety of the rocket [16]. During the flight, the model must be stable, have a functioning recovery system deploy, and be safely recovered. After the flight, the certification team verified that no major damage was incurred to the rocket, especially zippering, and that the motor was present [17]. Three of the four members of the team successfully acquired their L1 Certification. The fourth member successfully launched their L1 HPR, but was unable to find the rocket afterwards.

Figure 26. Certification Rocket

Conclusion

Comparison

Table 8 shows the results of the overall design and performance of the rocket based on key objectives that were made at the beginning of the project.The final rocket design was revolved around these objectives to ensure that they would be met. Aspects such as the anti-zippering harness and the motor selection proved to be successful in the first launch of the rocket, but an oversight in nosecone thermal expansion was the root cause of the failure of the second launch. This resulted in the failure of meeting certain requirements relating to full reusability and damage after launch, rendering the rocket unusable after the second attempt.

Table 8. Outcomes of the Final Design and Launch Based on Major Requirements

#	Requirement	Outcome
1	Design goal shall be to build a high-power rocket targeting 3,000 feet	First Launch: 2769 feet Second Launch: 2778 feet
4	Body diameter must be >2.61"	Body diameter: 4 inches
5	Rocket must demonstrate full reusability	First Launch: Success Second Launch: Failure due to zippering
8	"I" motors are the highest impulse class motor allowed for this design project	Aerotech I-435T motor used
14	Avoid damage to the rocket and zippering	First Launch: Successful Second Launch: Zippering
15	Black powder use is acceptable for dual deployment if receiving training on March 12, 2016	Successful preliminary test in both drogue and main parachute charges

Evaluation

The final design prior to launch day met all of the requirements presented at the beginning of this project. Since the design revolved around the basic requirements, technical aspects such as body diameter and the impulse class of the motor were reflected in the physical design of the rocket. However, there were some aspects pertaining to launch day that could have been improved to meet the objectives of the project. The second launch was considered a failure because the nose cone was unable to separate from the forward body tube to release the drogue parachute. Though the black powder charge did ignite, it was not enough force to separate the nose cone, causing the failure of the drogue parachute deployment. The increased speed on the rocket prior to deploying the main parachute caused the rocket body to zipper during main parachute deployment. It was determined upon retrieval that the body zippered approximately 3.5 inches up the length of the upper body tube, shown in Figure 27, and 3.25 inches down the length of the aft body tube. Additionally, the high speed during the main deployment caused the shock cord attached to the nose cone to snap from the main body, causing

Figure 27: Zippering on Main Deployment

it to descend with the main parachute separately from the rest of the body which was attached to the drogue parachute.

Despite the analytical methods used to support the idea that the rocket would be able to reach 3000 feet, the target apogee was unable to be reached for both launches. Though the first launch was considered a success since dual deployment methods were successfully implemented, the rocket was unable to reach its target apogee despite the calculated result of the flight under the given launch conditions. The same could be said about the second launch, which was unable to get significantly closer to the 3000 foot goal after modifications in the payload were made. Flight graphs for both launches can be seen in Figures 28 and 29. For the complete Anomaly Investigation of the results of the two launches, see Appendix H.

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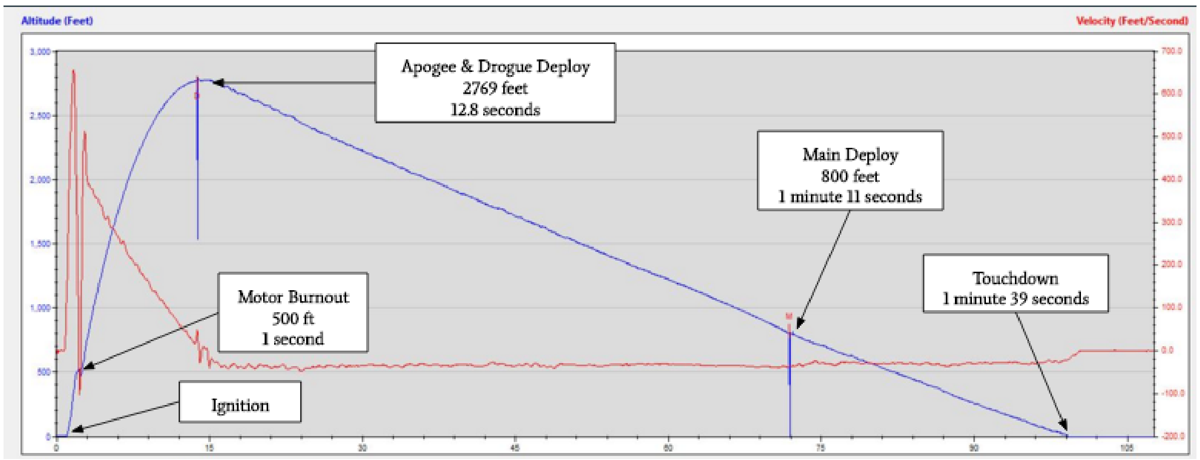

Figure 28: First Launch Flight Graph

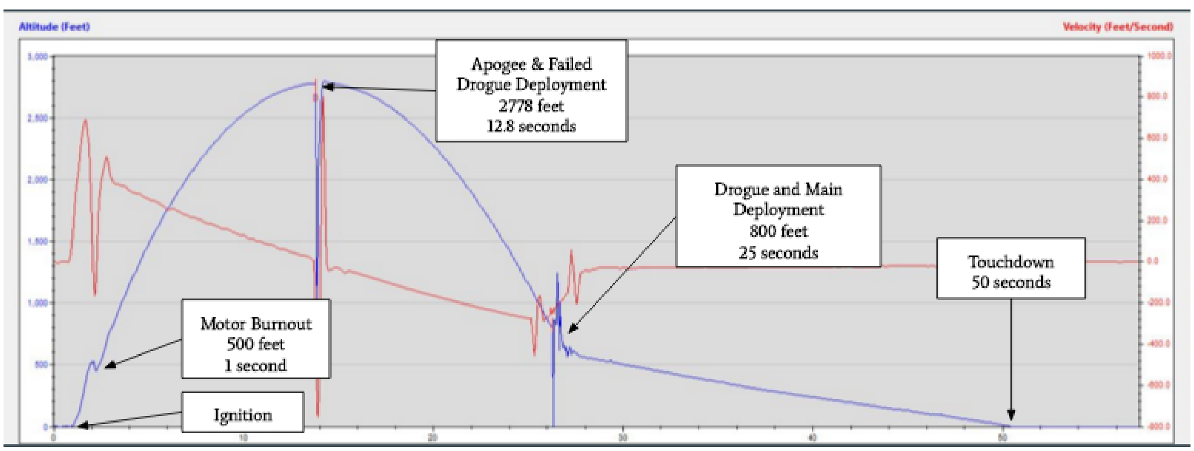

Figure 29: Second Launch Flight Graph

The estimated recovery distance according to OpenRocket was 1,400 feet. This seemed to be similar to the distance traveled by the second launch, which did not have a successful drogue deployment. The first launch, however, seemed to land approximately 4,000 feet away. It is assumed that the first launch traveled farther through wind drift because of the strong wind gusts during the slower descent. Because the first launch took longer to descend, it was pushed farther away from the launch pad.

Recommendations

Improvements on the performance of the rocket could have been made in the design process, manufacturing, and during the setup for launch. In the design process, a major change that could have been made to improve the stability would be to increase the length of the body and decrease the weight of the nose cone by decreasing the thickness. Based off of the root causes for the failure of the second launch, a more thermally resistant material could have been used to create the nose cone. Creating larger tolerances for the parts being manufactured could have also helped to ensure that the body tubes and the nose cone would separate easily during flight. Additionally, the increase in black powder charges to create such a separation that were implemented on launch day could have been further verified by referencing additional sources for black powder sizing calculations. Following through with the idea to add a GPS tracking device could have also helped to locate the rocket quicker, thus giving more time for preparation for the second launch. Seeing as though certain parts such as the motor or the slotting of the blue tube body took longer to obtain, ordering parts directly from the dealer rather than a third party would have helped in receiving the parts quickly and therefore cut down the assembly time.

During the manufacturing process, bigger steps could have been taken in order to improve the rocket's performance. Sanding the nose cone and coupler such that the separation of those two components and the body tube was suitable for launch

Figure 30: Launch Day

conditions was an oversight that could have dramatically changed the outcome of the second launch. Though it would not contribute much to the performance of the rocket, making the avionics bay removable would allow better access to the electronics and wiring enclosed within the coupler.

Launch day procedures could have been more streamlined, as the steps taken on that day proved to attribute to the failed performance of its second flight. Although the pre-flight checklist, as seen in Appendix I, was followed to ensure a safe flight, measures like performing a pull test could have been performed more carefully. Recording the wind speed with more accuracy could have also helped in determining an appropriate payload size, therefore helping the rocket reach its target apogee. Pictures of the launch can be seen in Figure 30.

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Appendix A: Requirements Table

Table A1. Full requirements table set by Dan Larson

#	Requirement	Outcome	Margin
1	Design goal shall be to build a high-power rocket targeting 3,000'	First Launch: 2769 feet Second Launch: 2778 feet	First Launch: 7.7% Second Launch: 7.4%
2	All rocket requirements must comply with National Association of Rocketry standards and best practices	All NAR standards were complied with while building and launching	
2.1	Above requirement includes full compliance with NFPA 1125 and NFPA 1127 governing rocketry	All NFPA standards were complied with while building and launching	
3	No design kits, pre-assembled sections, etc. shall be employed	All parts were stock or custom made and assembled by the team	
3.1	Exceptions to requirement of "no kits" require a written waiver - e.g., a preassembled altimeter assembly	No pre-assembled kits were used	
4	Body diameter must be >2.61"	Body diameter: 4 inches	
5	Rocket must demonstrate full reusability	First Launch: Success Second Launch: Failure due to zippering	50% success
6	Rocket must utilize dual deploy recovery methods; recommend prior successful ground testing - **Dual deploy altitude shall be between 500' and 800'**	Rocket contained dual deployment with altimeter deploying parachute at apogee and 800 feet	
7	Rocket shall record its peak altitude - Team must use their own altimeter assembly - no electronics bay kits allowed	Altimeter recorded two flights that were synced to a computer	
8	"I" motors are the highest impulse class motor allowed for this design project	Aerotech I-435T motor used	
8.1	All other motor sizes are allowed - teams that wish to share motor casings will be allowed to do so, while splitting the budget for the motor casing	A 38mm diameter motor used and the forward and aft closures were shared with Group B	

9	A minimum of 1 team member must become high-power NAR Level 1 certified prior to launch date	3 team members became Level 1 certified prior to launch	
10	Detailed rocket mass budget shall be reported at all design meetings with changes well known	Mass budget is available in Appendix C	
11	CP and CG locations must be tracked throughout the design process to ensure stability	OpenRocket was used to track the CP and CG	
12	Firing Electronics and Launch Rails (8020 rail) will be provided and/or shared among all groups	Appropriate rail buttons were utilized to use the available launch rail and electronics	
13	Requirements may be added, deleted, or amended at any time by program lead (Dan Larson)		
14	Avoid damage to rocket and zippering	First Launch: Successful Second Launch: Zippering	50% success
15	Black powder use is acceptable for dual deployment if receiving training on March 12, 2016	Successful preliminary test in both drogue and main parachute charges	100% success

Appendix B: Initial Designs

In order to develop a design that met the requirements stated in the requirements, the team designed five rockets that had a defining characteristic for each one. One rocket had a large diameter of four inches (Concept 3), one was a hybrid motor rocket (Concept 4), two contained a solid rocket motor (Concept 1 and 2) and one was a safe design that would reach 3000 feet but disregarded aesthetics (Concept 5). The difference between the two solid rocket motor designs were their length and nose cone shape.

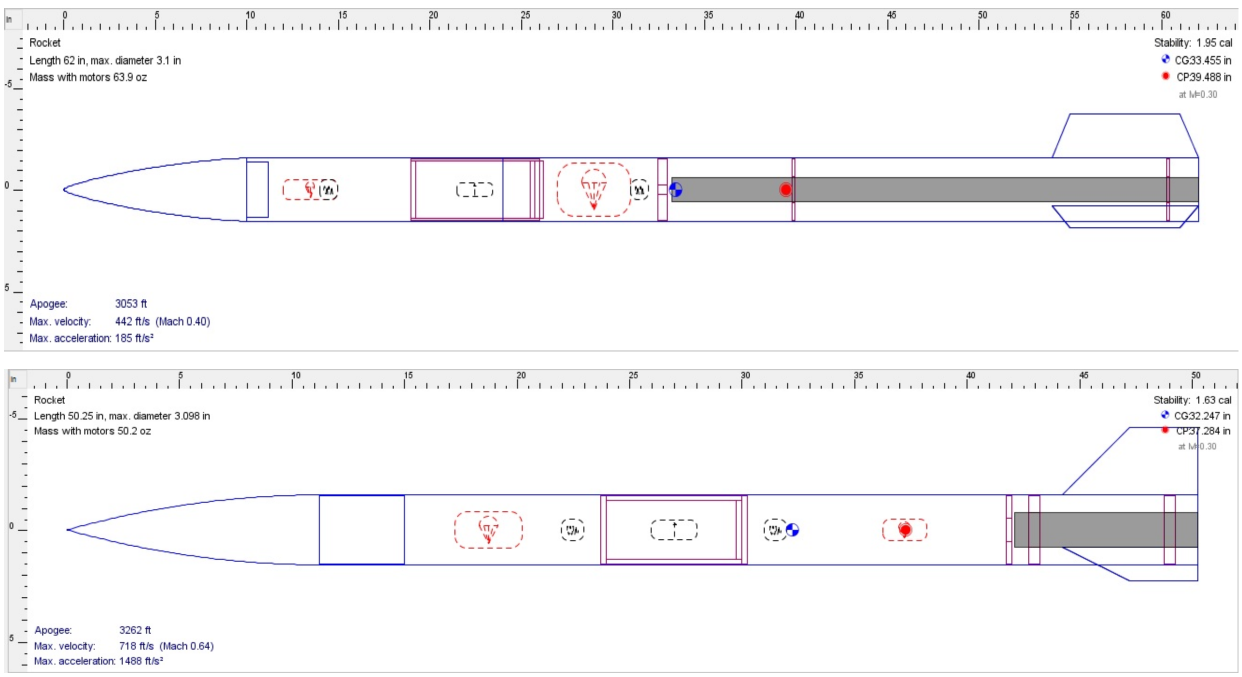


Figure B1. Initial Conceptual Designs for the Rocket

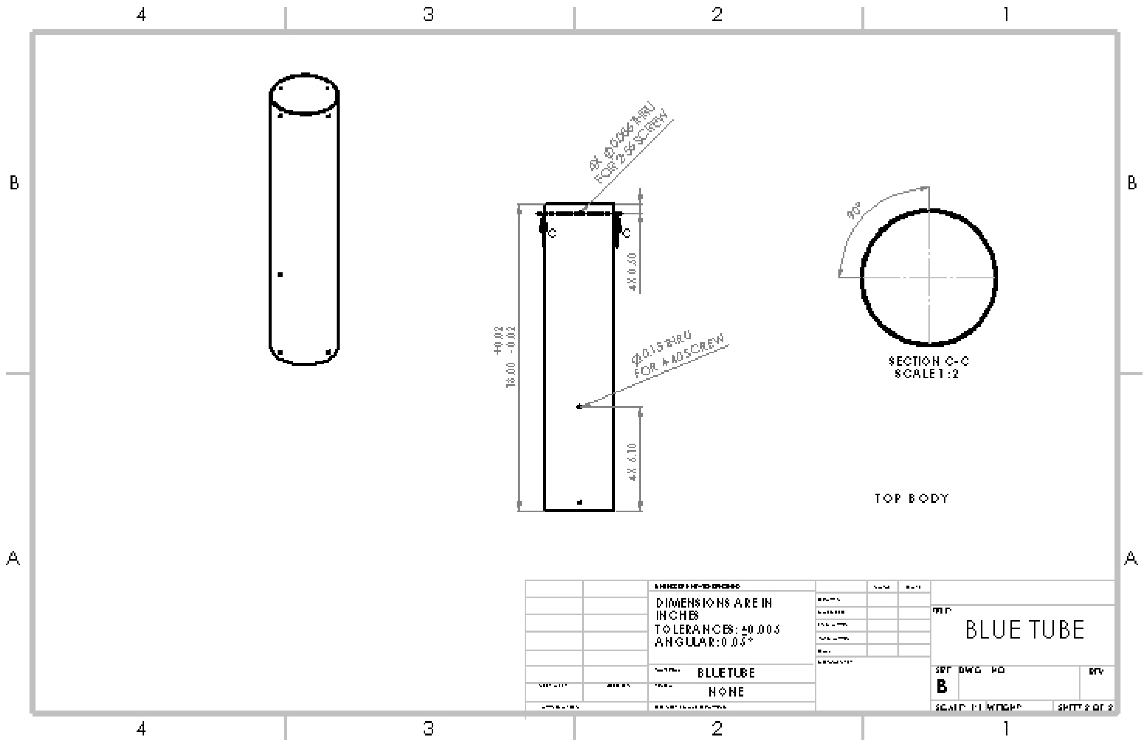
To determine the dominant design, Pugh's Concept Selection Technique was used and a concept scoring matrix was developed as seen in Table B1 [6]. The categories used to determine a well-designed rocket were the rocket's accuracy in achieving 3000 feet, the rocket's stability in terms of calibres, the robustness of the rocket's design, the rocket's reusability, the safety of the design of the rocket, the overall cost of the rocket, the ease of manufacturing, the weight of the rocket, the portability of the rocket, and the aesthetics or appearance of the rocket. Each category was weighted subjectively by a collective collaboration of the group. The rocket ratings for each category were subjective as well. A category to take note of for the rockets was the aesthetics category as they are all rated zero due to the fact that paint finishes, rocket motor smoke color, etc. were not a part of the initial designs. In terms of accuracy, the rocket was rated on how close it reached 3000 feet without a margin of error. Stability rating was determined by how many calibres the center of gravity and center of pressure were apart from each other. Reusability was rated on how fast the rocket could be prepped for re-launch as well as how accessible each component was on the rocket in case of damage. The total scores for each rocket were within a tenth of each other. Thus, it was concluded that the most innovative, effective and unique parts of certain rocket designs should be taken to create one rocket collectively. This included the concept of trapezoidal fins, a haack series nose cone, and a boat tail.

Table B1. Concept scoring matrix for all preliminary rocket designs.

	Concepts										
		1		2		3		4		5	
	Weight	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted
Accuracy	0.2	3	0.6	4	0.8	4	0.8	3	0.6	3	0.6
Stability	0.15	5	0.75	5	0.75	4	0.6	3	0.45	4	0.6
Robustness	0.1	3	0.3	3	0.3	1.5	0.15	1	0.1	3	0.3
Reusability	0.15	4	0.6	4	0.6	5	0.75	4	0.6	3	0.45
Safety	0.05	5	0.25	5	0.25	5	0.25	5	0.25	5	0.25
Cost	0.1	4	0.4	4	0.4	4	0.4	4	0.4	4	0.4
Ease of Manufacture	0.1	3	0.3	4	0.4	5	0.5	4	0.4	4	0.4
Weight	0.05	4	0.2	4	0.2	2	0.1	4	0.2	4	0.2
Portability	0.05	5	0.25	3	0.15	4	0.2	2	0.1	3	0.15
Aesthetics	0.05	0	0	0	0	0	0	0	0	0	0
TOTAL			3.65		3.85		3.75		3.1		3.35

The idea of a hybrid motor was disregarded due to the amount of weight the motor casing presented and the difficulty of reloading the motor. Key design features used on the final rocket were an I impulse class solid rocket motor, custom swept back trapezoidal fins, a haack series nose cone, and a motor mount using three center rings and a bulkhead.

Appendix C: 2D CAD Drawings



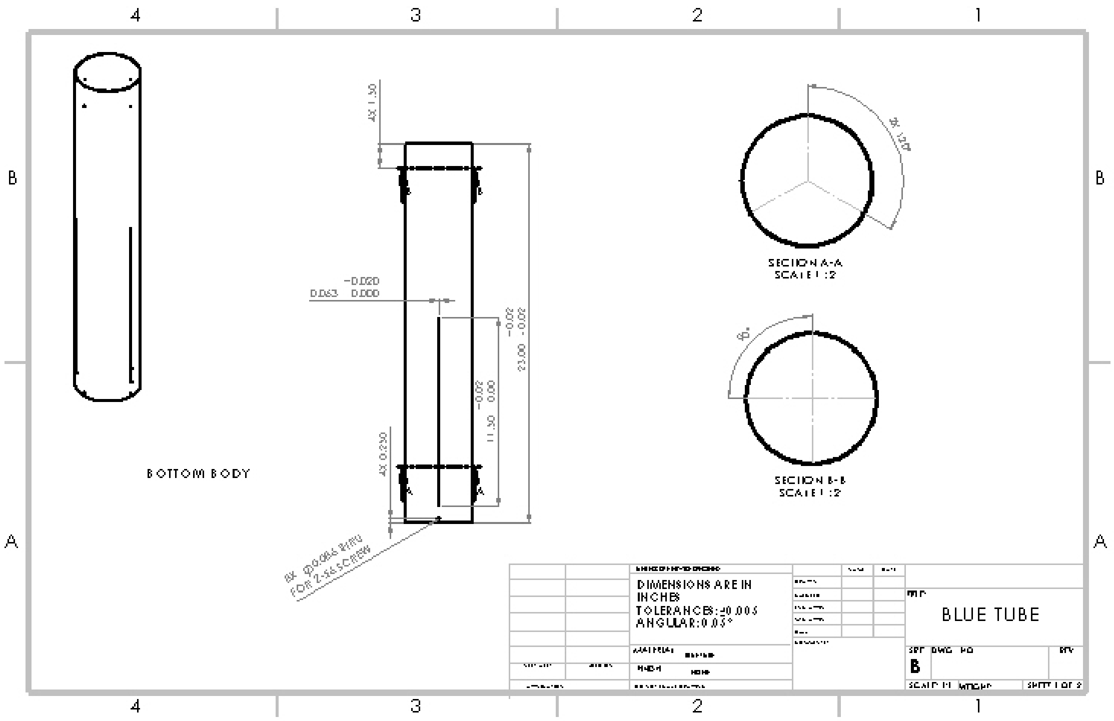
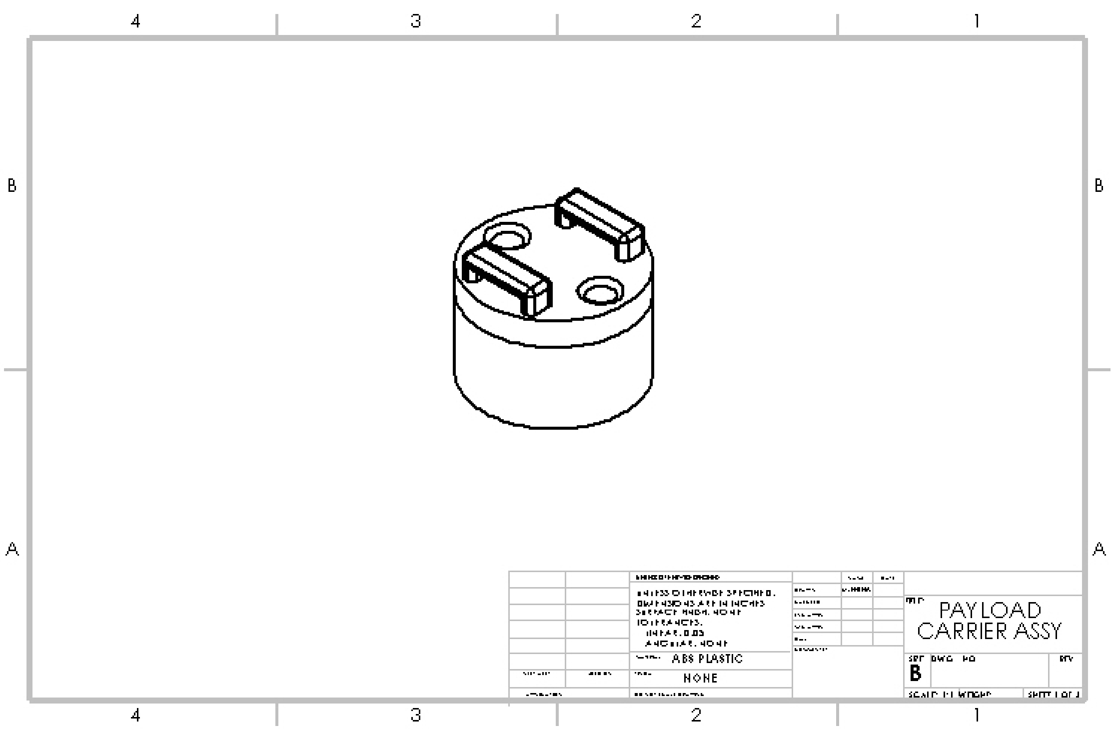


Figure C1. Blue Tube Body



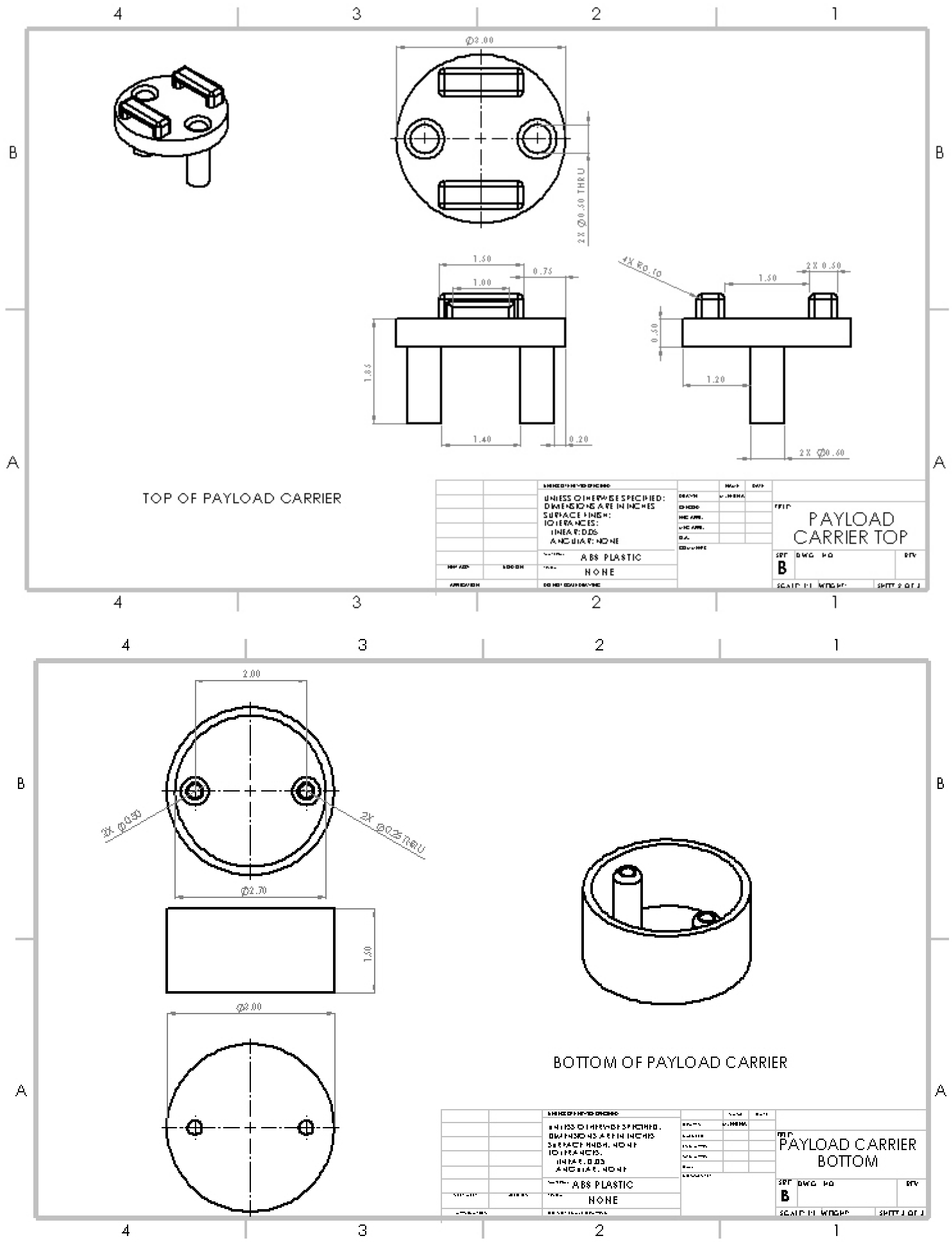


Figure C2. Payload Carrier

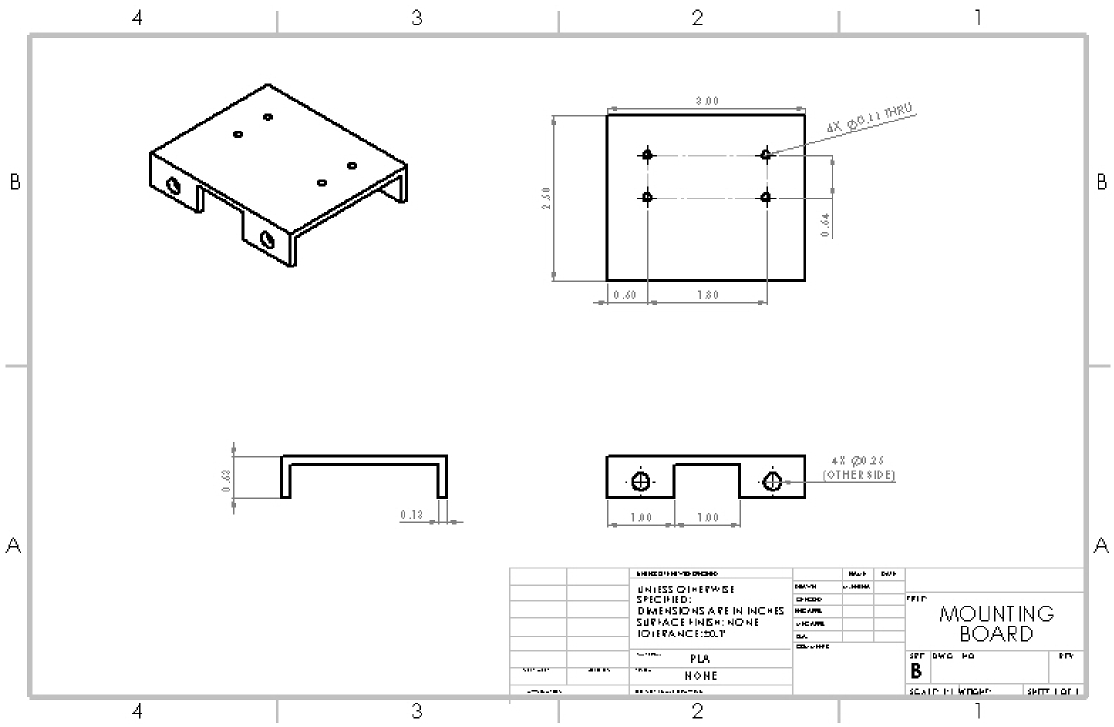


Figure C3. Mounting Board

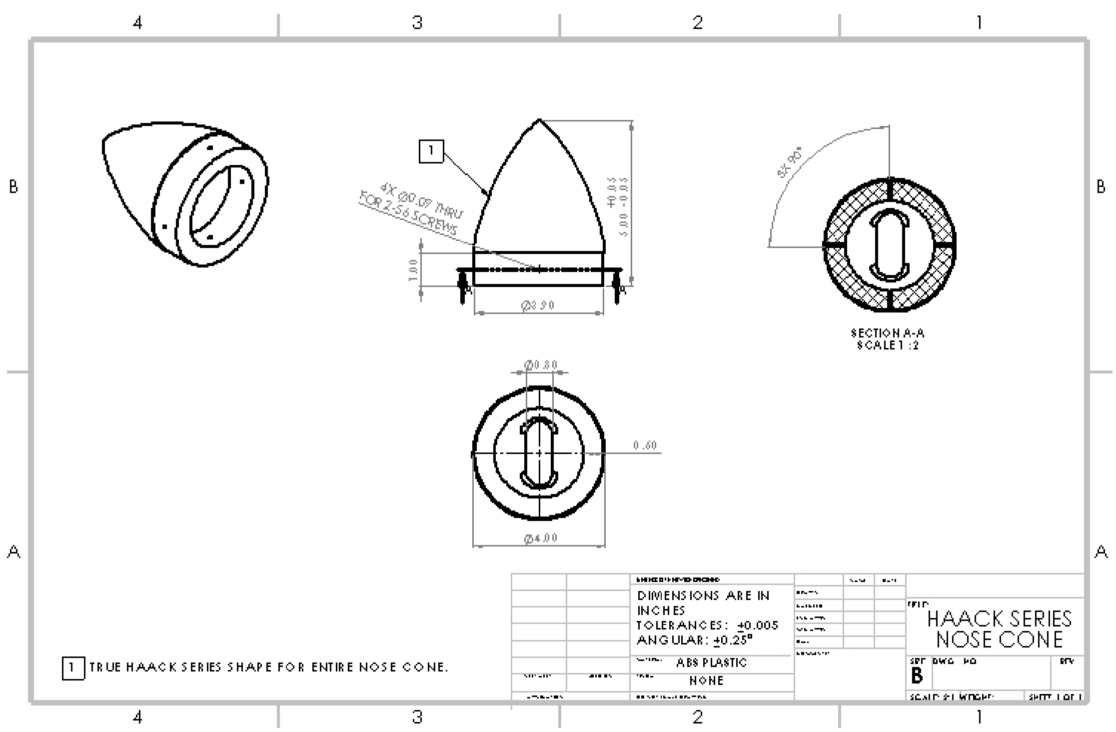


Figure C4. Haack Series Nose Cone

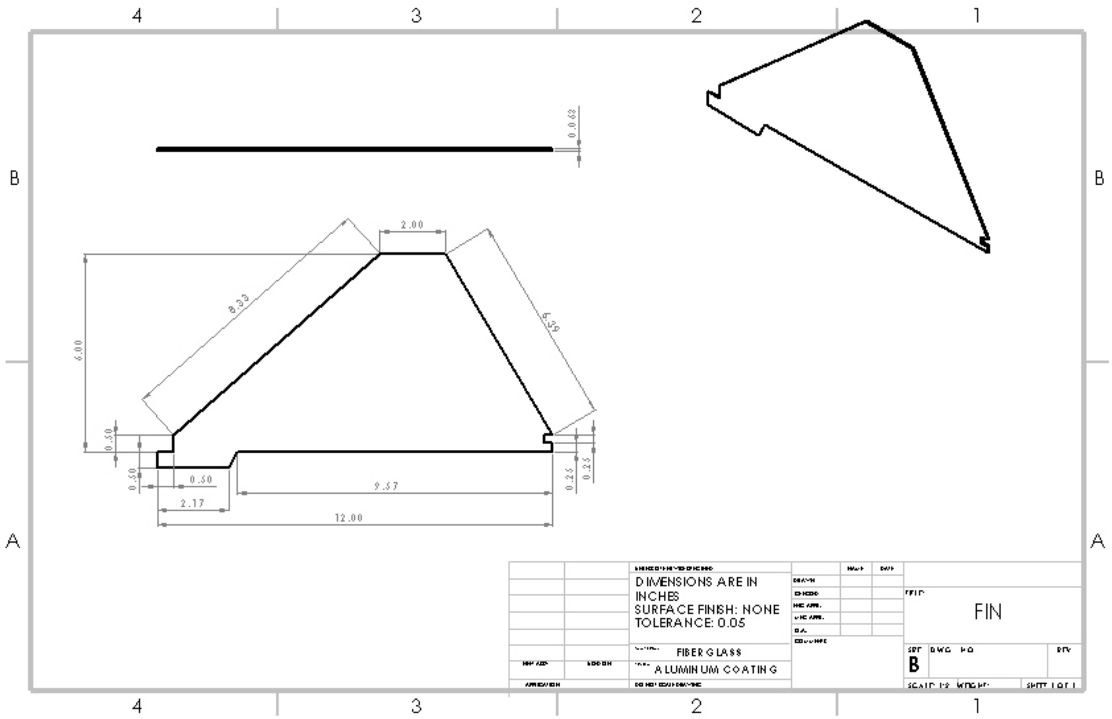


Figure C5. Fins

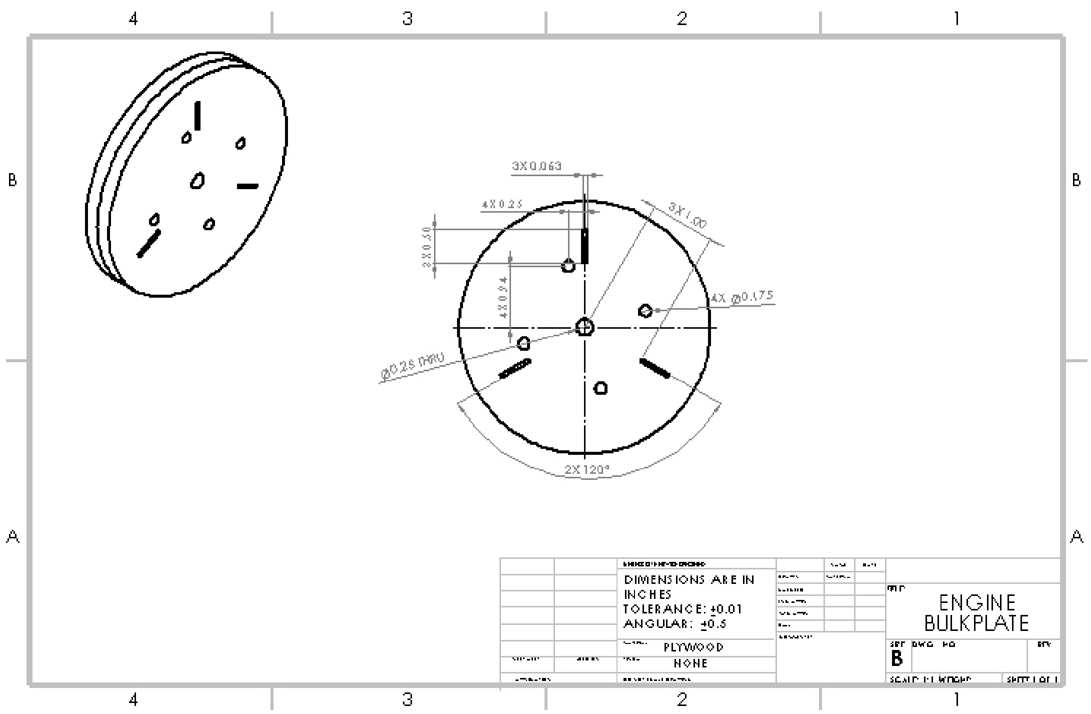


Figure C6. Engine Bulkplate

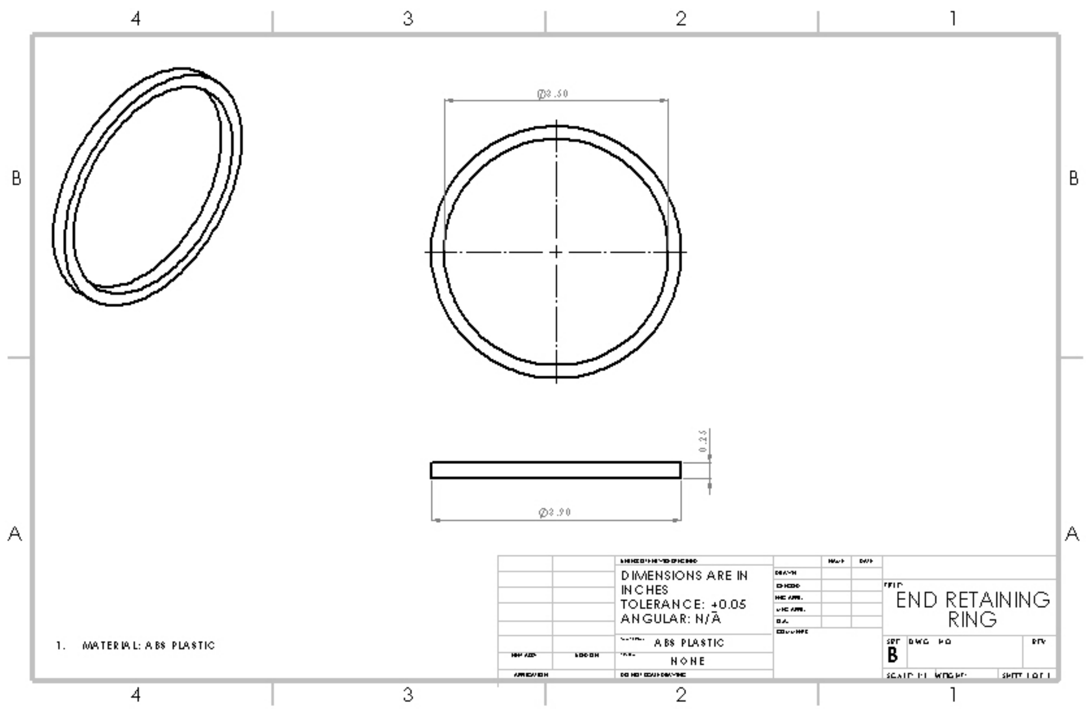


Figure C7. End Retaining Ring

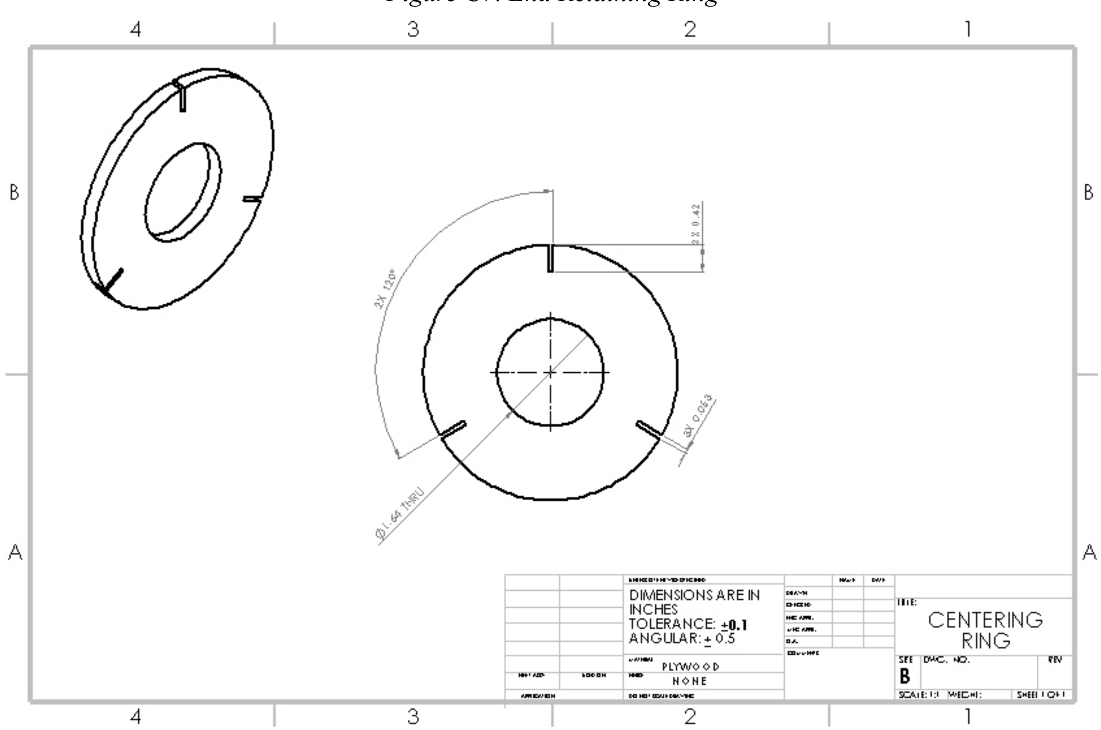


Figure C8. Centering Ring

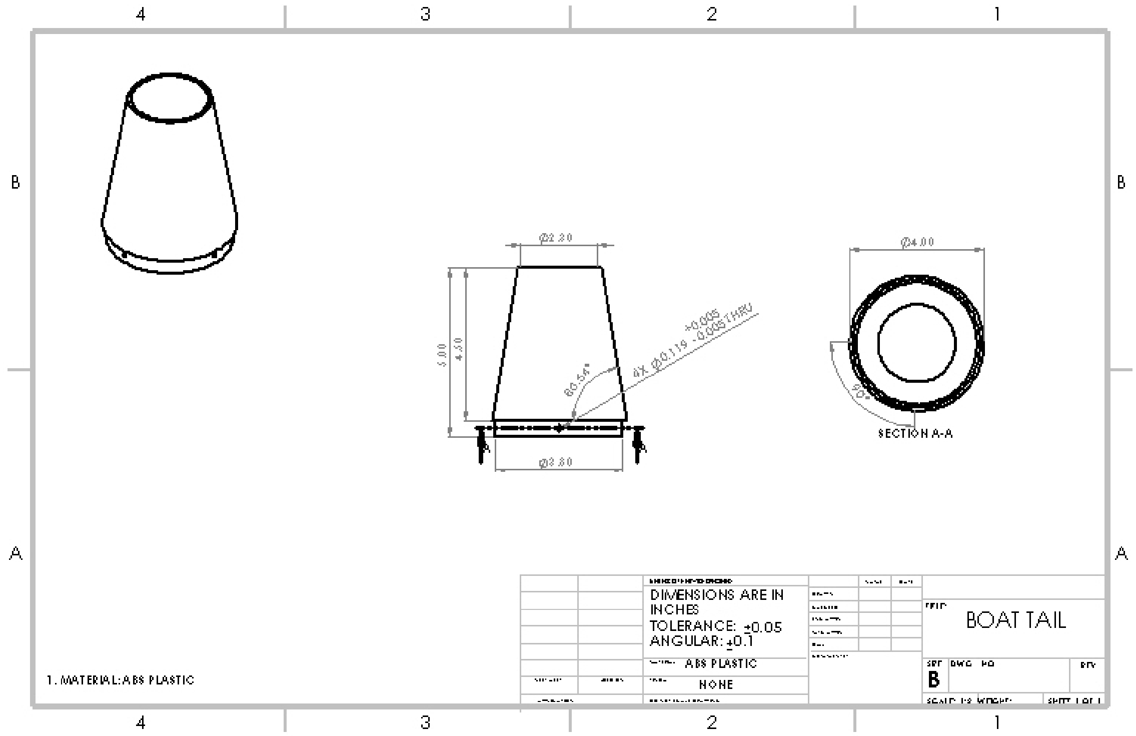


Figure C9. Boat Tail

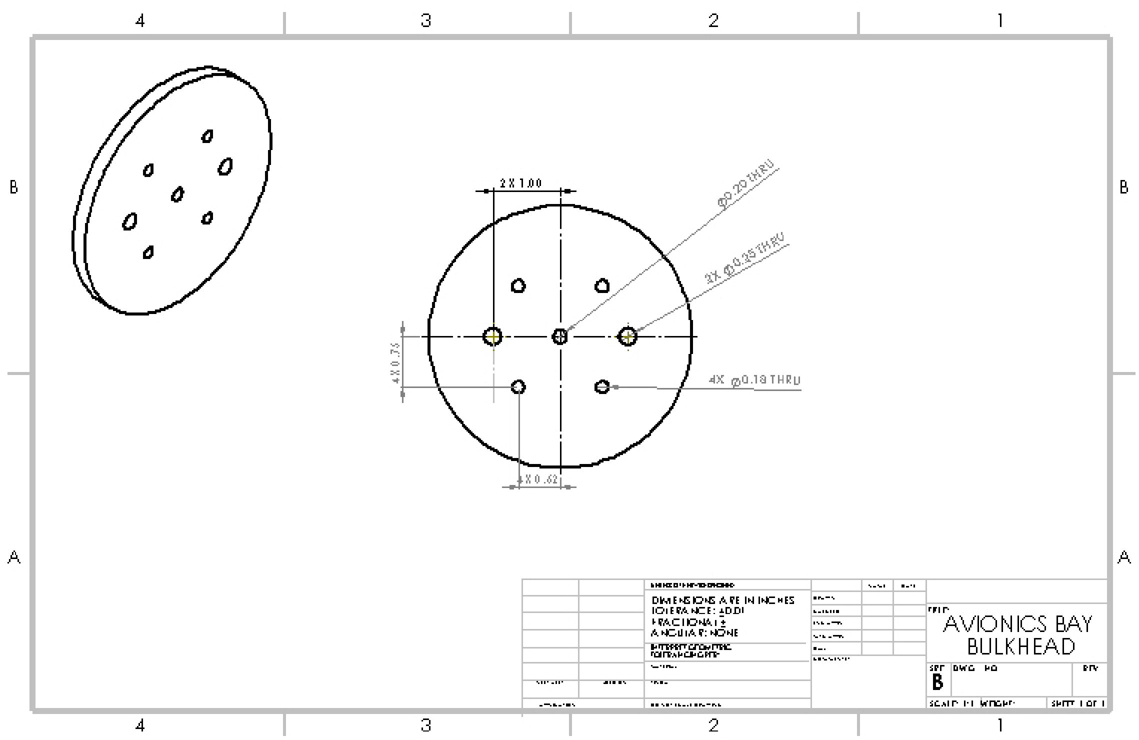


Figure C10. Avionics Bay Bulkhead

Appendix D: Manufacturing, Build Steps, and Testing

MANUFACTURING PREPARATION

1. Tooling
    a. 3D Print (MakerBot Replicator 2) with PLA Plastic
2. Avionics Bay
    a. Drill holes for shear pins
    b. Tools: Drill, epoxy, wire cutters, solder
3. Nose Cone
    a. 3D print (MakerBot Replicator 2) with PLA Plastic
    b. Acetone wash or lathe and sandpaper if needed
    c. Drill holes for shear pins
    d. Shear Pins to attach to blue tube
    e. Paint before assembly
    f. Tools: Acetone, sandpaper, lathe, drill
4. Boat Tail
    a. 3D print (MakerBot Replicator 2) with PLA Plastic
    b. Acetone wash or lathe and sandpaper if needed
    c. Holes for threaded inserts
    d. Paint before assembly
    e. Tools: Acetone, sandpaper, lathe, drill
5. Fins
    a. none
6. Centering Rings
    a. Cut notches into centering rings for the fins using Figure C8.
    b. Tools: CNC Mill (2-axis) or dremel
7. Blue Tube
    a. 16”➡shear pin female connector
    b. 23”➡cut holes for threaded inserts and slot body tube
    c. Coat inner edge with epoxy to prevent zippering
    d. Sand inside of tube so the tube coupler can slide in.
    e. Tools: Band Saw
8. Parachute and Shock Cord
9. Fiberglass Tube Coupler
    a. Sand until the coupler can move in and out of the blue tube
10. Nylon Threaded Rods
    a. Cut both rods to 10 inches.

11. Engine Bulk Plate
    a. Epoxy two bulk plates together and drill holes/notches in two bulk plates using Figure C6
    b. Drill holes in one bulk plate using Figure C10.
    c. Drill holes in one bulk plate using Figure C11.
    d. Install eyebolt into Figure C11 engine bulk plate with washers (2) and hex nut. Ensure hex nut and washer is sitting inside counterbore.
    e. **Tools:** CNC Mill (2-axis), Drill

BUILD STEPS

1. Create Avionics Bay/Payload Bay
    a. Tools: Epoxy, Wire Cutters, Screwdriver, Electrical Tape, Power Drill w/ 1/16” bit
    b. Steps:
        i. Secure nylon rods (2 PL) into upper bulkhead with butterfly nuts (2PL) and hex nuts (2 PL) ensuring that 0.5in of rod is exposed on eyebolt side. Butterfly nuts should be on the same side as the eye bolt.
        ii. Epoxy black powder canisters on eyebolt side of upper bulkhead (Figure C10). Allow to dry. Drill through the canister and apply the screw and nut given within the black powder canister package.
        iii. Assemble mounting assembly
            1. Screw altimeter onto wooden mounting block with 91075A460 standoffs (4 PL) and secure with 91735A101 fasteners (4 PL) and 4-40 hex nut (4 PL)
            2. Wire altimeter to 9V battery as seen in Figure F1.
            3. Epoxy battery terminal with three 3V coin cell batteries onto wooden mounting block
            4. Attach one end of the two pin assembly compact push-in connector to the “MAIN” terminal blocks on the altimeter.
            5. Attach one end of the four pin assembly compact push-in connector to “DROGUE” and “SWITCH” terminal blocks on the altimeter.
        iv. Thread the other side of the two pin assembly compact push-in connector through hole on upper bulkhead. Reconnect the wires.
        v. Slide payload bay onto nylon rods (2 PL)
            1. Connect two ends of payload bay (Payload Top and Payload Bottom) before sliding onto nylon rods

2. Make sure Payload Bottom is inserted such that it is oriented closest to the upper bulkhead
3. Leave space for the wires to pass by the payload bay

vi. Slide mounting assembly onto the two nylon rods so it is up against the payload carrier. Secure down mounting assembly with two nylon hex nuts on both of the nylon rods.

vii. Apply epoxy to the inside of the forward body tube. Slide the forward blue tube body over the avionics bay assembly so 2in of the tube coupler is exposed.

viii. Feed two nylon rods through the upper Avionics Bay bulkplate inside of the 16” blue tube body and slide the Avionics Bay assembly inside of the tube coupler

ix. Epoxy drogue parachute black powder canister to the eyebolt side of the lower bulkhead (Figure C11). Let dry.

x. Drill into the center of the black powder canister and apply the screw and nut from the black powder canister package.

xi. Thread 2 wires of the other side of the 4 pin compact push-in connector wires through hole in lower bulkhead.

xii. Slide lower bulkhead onto rods and affix with butterfly nuts (2 PL) when ready to seal off avionics bay for flight. Keep bulkhead off for next step.

2. Complete Wiring
   a. Tools: Altimeter Wiring Diagram (Figure D1)
   b. Steps:

i. Solder switch to the two wires of the 4 pin connector that were <u>not</u> threaded through the bulkhead, as seen in Figure D1.

ii. Attach wires connecting to drogue block terminal to drogue chute e match, as seen in Figure D1. Place inside drogue chute black powder canister and tape down until further use.

iii. Attach wires connecting to main block terminal to main chute e match, as seen in Figure D1. Place inside main chute black powder canister and tape down until further use.

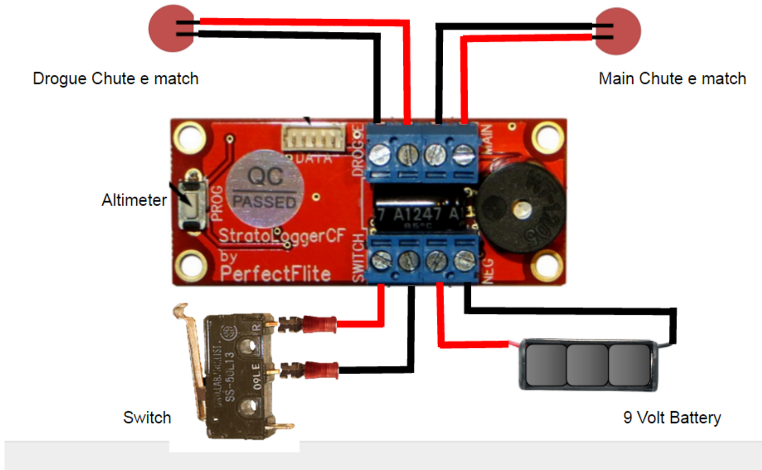


Figure D1: Altimeter wiring diagram

3. Epoxy Avionics Bay/Payload Bay to 16” blue tube body
4. Epoxy centering rings to inner tube mount
    a. Tools: Pencil, Electric Saw, Epoxy, T-guide, Pool Tube
    b. Steps:
        i. Mark ends of inner tube mount with the words “top” and “bottom”
        ii. Take inner tube mount and mark 2.05” from “top” end and 5.50” from “bottom”; these marks indicate where the two middle centering rings are positioned
        iii. Cut two pieces of pool tube to 2.05” and 5.50” long, ensure that all cuts are level
        iv. Place inner tube mount with “top” side down on table. Place 2.05” pool tube around tube so that it is resting on the table. Ensure that the earlier 2.05” mark is in line with top of pool tube.
        v. Place centering ring over inner tube mount and epoxy a fillet where the inner tube mount and centering come in contact. Wait to dry
        vi. Remove pool noodle, flip inner tube mount so that “bottom” side is in contact with table and epoxy a fillet on opposite side of centering ring. Wait to dry.
        vii. Slip second centering ring over inner tube mount.
        viii. With “bottom” side of inner tube mount in contact with table, slip 5.50” pool tube around tube so that it is resting on the table with the second centering ring resting on top. Ensure that the earlier 5.50” mark is in line with the top of pool tube.

ix. Place T-guide tool so that it lines up the notches on the first and second centering rings.
x. Apply fillet of epoxy where the second centering ring and inner tube mount come in contact. Wait to dry
xi. Remove pool noodle, flip inner tube mount, and epoxy a fillet on opposite side of centering ring. Wait to dry.

5. Epoxy bottom centering ring and inner tube mount system into 23” blue tube
   a. Tools: Pencil, Electric Saw, Pool Noodle, Slot Tool, Centering Ring Alignment Tool, Epoxy
   b. Steps:
      i. Label the end with the four holes closest to the end “bottom” and the other side “top”
      ii. Mark inside of blue tube 12.75” from top. This marks where the top of the centering ring should line up
      iii. Cut 5.80” pool noodle.
      iv. Stand blue tube on table so that “bottom” side is in contact with the table.
      v. Slide 5.80” pool noodle inside blue tube.
      vi. Slide inner tube mount assembly so that the “bottom” side is closest to the “bottom” side of the blue tube. Ensure that the top of the topmost centering ring is in line with the 12.75” mark inside the blue tube.
      vii. Insert and secure slot tool from outside blue tube so that the cuts in the blue tube line up with the notches in the centering rings.
      viii. Epoxy a fillet between the top centering ring and the inside of the blue tube. Wait to dry.
      ix. Remove pool noodle. Flip blue tube so that “top” side is in contact with table. Epoxy fillet between other centering ring and inside of blue tube. Wait to dry.
      x. Use centering ring alignment tool to suspend third centering ring 1.25” from “bottom” of blue tube. Epoxy a fillet between third centering ring and inside of blue tube. Epoxy a fillet between third centering ring and Wait to dry.
      xi. Remove all tooling.
      xii. Place end retaining ring on top of third centering ring. Apply dots of epoxy between end retaining ring and blue tube, and end retaining ring and third centering ring. Ensure that epoxy application allows for the end retaining ring to be secured, yet easily sanded off so that the fins can be replaced.

6. Fin Etc. Installation
    a. Tools: Fin mounting system (if necessary), Epoxy
    b. Steps:
        i. Place blue tube so that “bottom” side is in contact with table.
        ii. Have a two people insert the fins and hold them in place.
        iii. Slide engine bulk plate through “top” of blue tube so that eyebolt is facing up. Ensure that the fin tabs slide into slots of bulk plate. Ensure engine bulk plate is bottomed out on top of fins.
        iv. Epoxy fillet between engine bulk plate and inside of blue tube. Wait to dry.
        v. Epoxy thin fillet between the outside of the blue tube body and the fins. Wait to dry.
        vi. Flip blue tube assembly so that “top” is in contact with top of table. Epoxy engine retainer system to end of inner tube mount. Wait to dry.
7. Attach rail buttons (2 PL) to 23” and 16” blue tubes
8. Pack 23” blue tube body with parachute and shock cord
    a. Tools: N/A
    b. Steps:
        i. Using the four holes located on the fin mounting bulkhead, feed shock cord through each to create harness assembly as shown in Figure 3.
        ii. Join looped shock cord and its two loose ends onto barrel swivel
        iii. Tie additional Kevlar Shock Cord onto other end of barrel swivel
            1. Tie Kevlar Shock Cord onto eye bolt on fin mounting bulkhead
        iv. Tie free end of Kevlar Shock Cord onto eye bolt located on the bottom end of the Avionics Bay
            1. Do not insert Avionics Bay into 23” blue tube body before doing this step
        v. Insert Kevlar Shock Cord and 36” Crossfire parachute into 24” blue tube body
            1. Do not insert Avionics Bay into 23” blue tube body for this step
            2. Ensure that Kevlar Shock Cord will not get caught onto any features within the 23” blue tube body during deployment of 36” Crossfire parachute
9. Insert Wadding into all empty spaces of the 23” blue tube body
10. Apply shear pins to outside of blue tube body
    a. Tools: N/A
    b. Steps:
        i. Insert Avionics Bay into Fiberglass tube coupler 23” blue tube body

    ii. Press Shear Pins into given locations on rocket body

11. Drill four atmospheric port holes 0.086” in diameter through both the blue tube and fiberglass tube coupler as shown in Figure C1
12. Epoxy switch attached to Avionics Bay assembly close enough to one atmospheric port hole in which the pull pin will be able to activate and deactivate it.
13. Pack 16” blue tube body with parachute, shock cord, and parachute protector
    a. Tools: N/A
    b. Steps:
        i. Using the four holes located on the Avionics Bay Bulkhead, feed shock cord through each to create harness assembly as shown in Figure 3.
        ii. Join looped shock cord and its two loose ends onto barrel swivel
        iii. Tie additional Kevlar Shock Cord onto other end of barrel swivel
            1. Tie Kevlar Shock Cord onto extrusion feature inside of Nose Cone
        iv. Feed ring of 24” Crossfire parachute through the Kevlar Shock Cord
        v. Feed free end of Kevlar Shock Cord around the shock cord mounting feature on the inside of the Haack Nose Cone
            1. This must be done before the Haack Nose Cone is secured onto the blue tube body
        vi. Tie free end of Kevlar Shock Cord to itself to ensure that the entire subassembly is secured.
        vii. Insert Kevlar Shock Cord subassembly and 24” Crossfire parachute into 16” blue tube body
            1. Do not insert or attach Haack Nose Cone for this step
            2. Ensure that all of the Kevlar Shock Cord is inside of the 16” blue tube body and away from features that it could potentially get caught onto during deployment of 24” Crossfire parachute
14. Insert Wadding into all empty spaces of 16” blue tube body
15. Press fit nose cone onto 16” blue tube body and secure with shear pins
    a. Tools: Screwdriver, shear pins
16. Screw boat tail onto 23” blue tube body
    a. Tools: Power drill, fasteners
17. Apply primer to ensure smooth finish for spray paint
18. Apply spray paint

TESTING

Table 1D. Nose Cone Drop Test Calculations

Drop Testing of Nose Cone					
	mph	m/s	m/s^2	m	feet
Impact Velocity	13	5.8115			
Gravitational Acceleration			9.81		
Height				1.721382887	5.64

Appendix E: Requirements and FMEA Analysis

Table E1. Full FMEA table

Process	Potential Failure Mode	Potential Failure Effect	SEV	Potential Causes	OCC	Current Process Controls	DET	RPN	Action Recommended
Mfg.	fins measurements are inaccurate	fins wouldn't install into blue tubing or would negatively affect flight	5	manufacturing error	2	order parts from a reliable manufacturer	2	20	-Measure fins upon arrival and model and adjust the simulations for any error -Order fins in advance to ensure their accuracy and send them back if necessary
	components arrive late or damaged due to shipping	-Rushed assembly -reduced time to test	9	Parts not ordered early enough	2	Compiling a list of manufacturers to order parts from	7	126	-Order parts ahead of time to ensure their timely arrival -Keep track of shipping process
Assembly	run out of supplies or components break	-Rushed assembly -reduced time to test	10	-Didn't order the correct amount of parts or account for potential mistake -Inexperience in assembling	5	Determine which components are most likely to break, or that are most likely to be assembled incorrectly -Establish a relationship with the tool shed technician	2	100	-Order more components and supplies than necessary to leave room for assembly error -have financial cushion within budget for rush delivery of necessary parts
	fins are not installed accurately	-Need to order more materials	8	-fin mount tooling	2	-design and test fin mount tooling	2	32	-design a fin mount to accurately mount fins on rocket

		-Increase in flight instability		was not accurately designed -blue tubing slots were too large		with dummy parts - test cutting the blue tubing			-practice removing epoxy fillet with dremel or sandpaper to remove fin if not installed accurately
	components are not placed accurately within the rocket to match the simulation	-weight distribution of the rocket would be off and cause instability in flight	3	Didn't take time to verify correct position of components in rocket before epoxying them in place	3	Layout the components in OpenRocket and record their exact positions	4	36	-assemble the rocket in a way that can be altered in case the mounting of a component was not accurate. (i.e. mount avionics bay, measure, and run analysis in OpenRocket) - Measure component distances after and then compensate for the errors by adjusting payload position and weight
Launch Day	fins are damaged on landing	Unable to relaunch rocket, reusability affected	10	Fins are too thin and the material isn't strong enough to resist impact on landing	3	Test durability of fins through drop testing	2	60	-Test fins for durability -have backup fins on the day of launch -install fins with only a fillet of epoxy so that they can be replaced relatively easily
	Nose Cone breaks	The rocket might not be reusable afterwards.	5	If the impact at landing was too much, the nose cone could break.	1	3D print a robust nose cone and perform testing to ensure strength	1	5	-Conduct developmental testing and redesign if necessary. - Print an extra nose cone for the day of launch
	shock cord breaks	Parachutes become detached and rocket impacts	10	Shock cord was not attached properly	1	Design a method of attaching shock cord	2	20	-conduct stress test on shock cord -Bring extra shock cord on launch day to reattach

				or the material was compromised					
	zippering	Body tube will be ripped and unable to relaunch	10	-Shock cord was not long enough -deployment charge was too late after apogee	3	-using a shock cord three times the length of the rocket -performing calculations to determine when the deployment charge should go off -wrapping the shock cord in padding to cushion the contact with the tubing	1	30	- Anti-zippering harness using shock cord to avoid zippering at all costs - Swab epoxy around the inside edges of the rocket tube to stop zippering
	Rocket launches at undesirable angle	Rocket does not reach apogee	10	Rail buttons installed at an angle	1	Use level when laying out positions for rail button positions	2	20	- Use an angle iron to install rail buttons
	Shear pins don’t shear	Body tube/ nose cone not separating on parachute deployment, rocket potentially destroyed	10	-Black powder charge was not big enough -shear pins installed at	2	-high level of control during installation	2	40	-Double check before launch that all shear pins are accounted for and perpendicular to body tube -Use the BP test day to size charges appropriately to shear the pins (have full rocket ready to ensure accuracy)

				improper angle					
	dual deployment fails	rocket would hit the ground at an incredibly high velocity and potentially be destroyed	10	Black powder does not eject the parachutes	5	Correctly size black powder to generate enough pressure	4	200	-Execute a ground test of dual deployment before launching rocket
	motor failure	Rocket would not launch off of launch pad	10	Manufacturer sent a malfunctioning motor	1	Purchase motor from reliable supplier	1	10	-Have multiple motors on sight to act as replacements -Practice assembling the Aerotech motor
	Rocket loses stability	Rocket would not maintain calculated trajectory and may crash in consequence.	10	There could be an unforeseen imbalance during the flight.	2	Performing stability computational analysis.	5	100	-Design for stability. Run wind and flow analysis to ensure rocket stability upon ascent. -Track stability within OpenRocket simulations
	Engine Retainer breaks	The engine might slide backwards and break the bulkhead or fall out of the body tube.	10	The forces of the motor on the engine could be greater than was accounted for.	2	Performing a computational analysis on the force that each ring can withstand.	1	20	Remove engine retainer from L1 cert rockets using hot water and sandpaper to use on the broken rocket
	Altimeter fails	This could either mean the proper readings aren't given, or that the ejection charges won't go off.	10	The power supply to the altimeter could become dislodged during ascent, due to	2	We would be purchasing a reliable and well-tested altimeter.	6	120	-Perform vacuum and black powder tests on the altimeter to ensure that it works properly during launch. -Zip tie or secure batteries in the holder

				vibration.					
	Ejection Charge fails	This could cause the rocket to impact the ground at a high velocity.	10	This could be due to the wiring, or that not enough power was sent to the ejection charge.	1	We would be designing an ejection charge to be reliable and repeatable.	5	50	-Execute black powder tests to confirm that the ejection charges fire properly. -Vacuum test the altimeter with LEDs and e-matches to ensure the altimeter can send enough current
	Parachute fails	This would cause the rocket to hit the ground at a high velocity.	10	This could be due to entanglement, failed ejection charge, or a rip due to high force.	3	We would be purchasing a reliable parachute and make sure to package it in a way that it would open easily.	2	60	-Use developmental tests to ensure that the parachute can handle the forces of deployment during freefall -Research and apply packing methods with the parachute and shock cord to ensure deployment (experience from L1)
	Epoxy joint fails	This could cause the rocket to fall apart mid-air or other parts to fail.	6	This could be due to a misapplication of epoxy or a force too great for epoxy to withstand.	1	We would be applying epoxy carefully to make sure it would withstand flight conditions.	5	30	Will perform developmental testing on the strength of an epoxy joint. Also, during assembly, would be careful to properly apply epoxy to joints.
	Boat Tail melts	This could cause for an irregular thrust and an imbalance of the rocket.	5	This would be due to the high temperature and pressure of the motor.	2	We analyzed the boat tail material and conditions at the exhaust to be sure that the part was safe from	1	10	-Will perform developmental testing to ensure that the heat and pressure of the engine would not melt the boat tail. -Move engine retainer and motor lower on the rocket to move it outside of the boat tail

						such melting.			
	Hardware fails	This could cause other parts to fail and come apart in the rocket.	7	This could be due to unforeseen high forces within the rocket during ascent.	5	We would use high quality and strong materials that are suitable for the forces that would be experienced.	1	35	-Ensure that hardware is assembled with proper tightening. -Use high strength materials where necessary to secure vital components
	Tube Couplers don't decouple	This would cause the parachute to be unable to deploy.	8	This could occur if the ejection charge was not strong enough, or because the coupler was too tightly closed.	1	We would use high quality tube couplers and ejection charges to ensure reliability.	4	32	- Use field tests to make sure that the ejection charge decouples the tube coupler. -Sand the tube coupler and perform a dry fit test
	Body Tube fails	The rocket could gain more drag, or fall apart entirely.	9	This could be due to unusually large forces from components inside the rocket impacting the blue tube.	2	We would fasten everything inside the blue tube so that it would be static.	5	90	Perform developmental testing on the blue tube body to confirm its strength is sufficient to forces experienced during flight with a factor of safety.
	Bulkhead breaks	This could cause the ejection charge to fail or	4	This could be due to the force of the	2	We would ensure that the bulkhead is strong	1	8	-Perform developmental testing on the component to ensure its strength.

		cause damage to the rocket.		ejection charge or the motor.		enough that it would not break.			-Epoxy the bulkhead with fillets to ensure it stays in place even under failure
	Payload shifts during flight	This could cause the CG to shift during flight and create instability.	6	This could be due to insufficient hardware fastening or mounting methods.	3	Tighten everything and design the mounts properly.	9	162	Make sure that the payload design is secured with metal hardware
	Parachute gets hung up on rail button	This could cause the parachutes to fail.	8	This would be due to improper assembly of the rail button.	2	We would make sure to properly apply the epoxy to the rail buttons.	6	96	Drill rail buttons into a bulkhead or centering ring to ensure no shock cord would snag on the screw
	Centering Rings break	This could cause the motor to move within the blue tube body.	5	This could be due to high forces from the motor.	2	We would use centering rings that are strong enough to withstand the forces of a rocket during launch.	3	30	Perform developmental testing on the centering rings. Apply epoxy to ensure structural integrity around the centering rings
	harsh weather conditions	Wind can blow rocket far from launch site	6	External factor	1	Test robustness of rocket in a wind tunnel	4	24	Create a robust rocket design that take on additional mass to compensate for weather conditions Use OpenRocket to adjust the payload according to the weather conditions

Appendix F: Bill of Materials, Cost Budget and Mass Budget

Table F1. Full Bill of Materials

Section	Vendor	Part Number	Quantity	Component	Cost w/ Tax	Fabrication Costs	Description
Body	Apogee Components	10505	1	98 mm Blue Tube	$42.65	$0.00	2.95" diameter (75 mm) 48 inches long OD: 4" Total Length: 48"
	Apogee Components	29615	8	Shear Pins	$6.46	$0.00	Pack of 20
	Apogee Components	13060	1	Standard Rail Buttons (fits 1" Rail -1010)	$3.36	$0.00	Length: 0.38" OD: 0.381" Plastic. Pack of 2
	Apogee Components	30511	1	RocketPoxy - 2 pint kit	$38.25	$0.00	Epoxy for rocket
	McMaster-Carr	90087A101	4	Thread-Cutting Screw for Metal&plastic (Type F), Pan Head Phillips, Zinc-Plated Steel, 2-56 Thread, 3/8" L	$6.22	$0.00	Screws to mount boat tail
	Public Missiles	Custom	3	G10 Reflective Fins	$88.66	$0.00	Custom fins
	LMU	N/A	1	Nose Cone	$0.00	$0.00	3D printed nose cone
	LMU	N/A	1	Boat Tail	$0.00	$0.00	3D printed boat tail
	LMU	N/A	1	Fin Retainer Ring	$0.00	$0.00	3D printed
	Home Depot	N/A	1	Rust-Oleum Painters Touch White Primer	$8.48	$0.00	Primer for rocket

	Home Depot	N/A	1	Rust-Oleum Satin Aqua	$4.24	$0.00	Paint
	Home Depot	N/A	1	Rust-Oleum Charcoal Paint	$4.24	$0.00	Paint
	Home Depot	N/A	1	Rust-Oleum Universal Gloss Black	$4.24	$0.00	Paint
	Home Depot	692301	1	Minwax High Performance Wood Filler 12 oz	$14.19	$0.00	Wood Filler for cracks
	Home Depot	1001009252	2	JB Weld Clearweld 5 minute epoxy	$12.42	$0.00	Epoxy for rocket if fin broke
	Home Depot		2	Sheet Metal Screw Flat Head Zinc #10 X 3/4"	$1.18	$0.00	Screws for rail buttons
Avionics Bay	PerfectFlite	SLCF.	1	StratologgerCF Altimeter w/audio and LED	$56.35	$0.00	Altimeter
	PerfectFlite	SAS5	1	Switch	$2.96	$0.00	Turn on altimeter
	McMaster-Carr	91075A460	4	18-8 Stainless Steel Male-Female Threaded Hex Standoff	$12.35	$0.00	2.82/standoff
	McMaster-Carr	91841A005	4	18-8 Stainless Steel Hex Nut	$3.21	$0.00	4-40 Thread size, 1/4" Wide, 3/32" high
	McMaster-Carr	91735A101	4	Type 316 Stainless Steel Pan Head Phillips Machine Screw	$6.19	$0.00	4-40 Thread, 3/16" Length Pack of 50
	LMU	N/A	4	Stainless Steel Flange nuts	$0.00	$0.00	1/4"-20 Thread Size,found in shed

	McMaster-Carr	7821K61	3	3V Coin cell Battery	$26.28	$0.00	Lithium coin cell
	McMaster-Carr	7712K91	1	Battery Holder N cells	$1.28	$0.00	Battery holder
	McMaster-Carr	93575A029	4	315 Stainless Steel Wing Nut	$7.40	$0.00	1/4"-20 Thread Size Pack of 5
	McMaster-Carr	98831A360	2	Nylon 6/6 Fully Threaded Rod	$7.95	$0.00	1/4"-20 Thread 2 Feet Long
	McMaster-Carr	8414T22	4	Quick Disconnect Terminal	$21.48	$0.00	Vibration resistant
	Apogee Components	12221	2	Tube Bulkhead Disk 98MM	$22.17	$0.00	Plywood Bulkhead Length: 0.25" OD: 3.891"
	Apogee Components	13607	1	4" X 8" FW Fiberglass Coupler	$27.69	$0.00	Length: 8" OD: 3.892" ID: 3.742"
	Apogee Components	24027	1	22GA Stranded Wire Set	$6.60	$0.00	5 feet of wire
	Mcmaster-Carr	9552T1	1	Assembled Compact Push-in Connector, with 6" Wire leads, 2 Pole	$4.85	$0.00	Quick disconnects
	Mcmaster-Carr	9552T4	1	Assembled Compact Push-in Connector, with 6" Wire leads, 4 Pole	$8.87	$0.00	Quick disconnects
	LMU	N/A	1	Payload Carrier	$0.00	$0.00	3D printed
	LMU	N/A	1	Mounting Board Sled	$0.00	$0.00	3D printed
	LMU	N/A	8	Washers	$0.00	$0.00	found in shed
	Mcmaster-Carr	8953K101	1	Ultra Machinable 360	$1.46	$0.00	Pull pin for switch

				Brass, Rod, 1/8" Diameter, 1/2" Long			
Dual Deployment	Wildman Rocketry	N/A	1	Crossfire 24" Parachute	$22.94	$0.00	Cd: 1.6 Shroud Line Length: 28" Parachute Area: 0.06 ft^2 Carrying Cap: 2.4 lbs
	Wildman Rocketry	N/A	1	Crossfire 36" Parachute	$38.27	$0.00	Cd: 1.6 Shroud Line Length: 41" Parachute Area: 0.15 ft^2 Carrying Cap: 4.5 lbs
	Apogee Components	30327	30	Kevlar Cord 1500#	$16.12	$0.00	OD: 0.23" price per foot
	Apogee Components	3070	1	Ejection Canister Caps - 2pk	$3.00	$0.00	Black powder holders
	Apogee Components	5750	1	Quest Recovery Wadding	$8.19	$0.00	4 1/2" sheets, 100 per pack
	Apogee Components	14512	2	#500 Ball Bearing Swivel	$14.00	$0.00	Attach harness to shock cord
Motor	Apogee Components	13421	3	CR-38/98 (2 pk)	$24.30	$0.00	ID: 1.212" OD: 2.989" Width: 0.13"
	Apogee Components	60024	1	RMS-38/600 Casing w/Forward Seal Disk	$70.30	$0.00	Length: 10.75"
	Apogee Components	24062	1	Aero Pack 38MM Retainer - L	$29.29	$0.00	Length: 0.5" ID: 1.63" OD: 1.969"
	Apogee Components	60130	1	Aerotech 38 MM Forward Plugged Closure	$22.26	$0.00	

	Apogee Components	60139	1	Aerotech 38 MM Aft Closure	$22.26	$0.00	
	Apogee Components	12221	2	Tube Bulkhead Disk 98MM	$13.30	$0.00	Plywood, Custom OD: 2.991" Thickness: 0.25"
	Apogee Components	81354	2	Aerotech 38MM Propellant Kit - 1435T-M	$120.43	$0.00	Total Impulse: 568.9 Diameter: 1.5" Length: 7.52"
	Apogee Components	13111	1	38mm Blue Tube Inner Tube Mount	$17.95	$0.00	"48"" long Inner Diameter: 38mm"

Table F2: Body Cost and Mass Distribution

Product	Units	Total Cost	Budgeted Total	Difference	Mass (oz)	Mass (lb)
98mm Blue Tube	1	$38.95	$42.65	$3.70	20.8416667	1.302604169
Standard Rail Buttons (fits 1" Rail -1010)	1	$3.07	$3.36	$0.29	0	0
RocketPoxy - 2 pint kit	1	$38.25	$26.86	-$11.39	6.57	0.410625
Removable Plastic Rivets	1	$2.58	$0.00	-$2.58	0	0
Nylon Pan Head Machine Screw Phillips	1	$5.43	$5.95	$0.52	0	0
18-8 Stainless Steel Standard Helical Insert	1	$5.46	$5.98	$0.52	0	0
West Systems Epoxy kit - 1qt 105 resin + 0.43 pt 206 slow hardener	0	$0.00	$19.36	$19.36	0	0
Thread-Cutting Screw for Metal&plastic (Type F), Pan Head Phillips, Zinc-Plated Steel, 2-56 Thread, 3/8" L, Pack of 100	1	$6.22	$0.00	-$6.22	0	0
G10 Reflective Fins	6	$139.92	$88.66	-$51.26	10.8	0.675
Boat Tail	1	$0.00	$0.00	$0.00	4	0.25
Nose Cone	1	$0.00	$0.00	$0.00	16.4	1.025
Fin Retainer Ring	1	$0.00	$0.00	$0.00	0.4	0.025
Rust-Oleum Charcoal Paint	1	$6.48	$0.00	-$6.48	0	0

Rust-Oleum Painters Touch White Primer	2	$7.74	$0.00	-$7.74	0	0
Rust-Oleum Painters Touch Satin Aqua	1	$3.87	$0.00	-$3.87	0	0
Rust-Oleum Universal Gloss Black	1	$5.76	$0.00	-$5.76	0	0
Wood Screw #8 X 1"	1	$1.18	$0.00	-$1.18	0	0
Minwax High Performance Wood Filler 12 oz	1	$12.96	$0.00	-$12.96	0	0
JB Weld 5 minute epoxy	2	$11.34	$5.74	-$5.60	0	0
Total		$289.21	$198.56	-$90.65	59.0116667	3.688229169

Table F3: Avionics Bay and Dual Deployment Cost and Mass Distribution

Product	Units	Total Cost	Budgeted Total	Difference	Mass (oz)	Mass (lb)
Kevlar Cord 1500#	46	$42.32	$16.12	-$26.20	1.892	0.11825
Ejection Canister Caps - 2pk	1	$3.00	$3.00	$0.00	0.4	0.025
Quest Recovery Wadding	1	$7.48	$8.19	$0.71	0	0
22ga Stranded Wire Set - 5ft each of Red and Black	1	$6.03	$6.60	$0.57	0	0
4" X 8" G12 FW Fiberglass Coupler	1	$25.29	$27.69	$2.40	8.4	0.525
Tube Bulkhead Disk 75mm	2	$7.30	$7.99	$0.69	0	0
Tube Bulkhead Disk 98mm	5	$20.25	$22.17	$1.92	9	0.5625
Nylon Shear Pins - 20 pack	4	$11.80	$6.46	-$5.34	0.00375	0.000234375
#500 Ball Bearing Swivel	2	$14.00	$0.00	-$14.00	1.2	0.075
Crossfire 24" parachute	1	$20.95	$20.95	$0.00	2.6	0.1625
Crossfire 36" parachute	1	$34.95	$34.95	$0.00	4.4	0.275
Balsa Wood Block	1	$5.83	$5.83	$0.00	0	0
Type 18-8 Stainless Steel Hex Nut, 4-40 Thread size	1	$2.83	$2.93	$0.10	0	0
18-8 Stainless Steel Male-Female Threaded Hex Standoff 3/16" Hex, 3/16" length 4-40 screw	4	$11.28	$11.28	$0.00	0	0
Type 316 Stainless Steel Pan Head Phillips Machine Screw, 4-40 Thread	1	$5.39	$5.65	$0.26	0.032	0.002
Nylon Flange Nuts, 1/4"-20 Thread size	1	$12.28	$12.28	$0.00	0	0

Disposable Lithium Battery, 3V	8	$38.40	$24.00	-$14.40	0.2	0.0125
Battery Holder, for N Battery	1	$1.17	$1.17	$0.00	0.2	0.0125
Stainless Steel Wing Nut, 1/4"-20 Thread	1	$6.76	$6.76	$0.00	0.8	0.05
Nylon 6/6 Fully Threaded Rod, 1/4"	2	$7.26	$7.26	$0.00	1.2	0.075
Vibration-Resistant Quick-Disconnect Terminal	6	$21.48	$21.48	$0.00	0	0
Assembled Compact Push-in Connector, with 6" Wire Leads, 2 Pole	2	$9.70	$0.00	-$9.70	0.3	0.01875
Assembled Compact Push-in Connector, with 6" Wire leads, 4 Pole	2	$17.74	$0.00	-$17.74	0.6	0.0375
Ultra Machinable 360 Brass, Rod, 1/8" Diameter, 1/2" Long	1	$1.46	$0.00	-$1.46	0	0
PerflectFlite Altimeter w/audio and LED	1	$51.46	$51.43	-$0.03	0.2	0.0125
Switch	2	$5.40	$2.70	-$2.70	0	0
Sled	1	$0.00	$0.00	$0.00	0.76	0.0475
Payload Carrier	1	$0.00	$0.00	$0.00	3.8	0.2375
Hex Nut for Nylon Threaded Rod	4	$0.00	$0.00	$0.00	0.8	0.05
Washer for Hex Nut	8	$0.00	$0.00	$0.00	0.8	0.05
Total		$391.81	$306.89	-$84.92	35.98775	2.249234375

Table F4: Motor Cost and Mass Distribution

Product	Units	Total Cost	Budgeted Total	Difference	Mass (oz)	Mass (lb)
Centering Rings 29mm (Thick wall) to 75mm	3	$20.85	$22.83	$1.98	0	0
Aero Pack 38mm Retainer-L	1	$26.75	$29.29	$2.54	0.6	0.0375
38mm Blue Tube Full Length Coupler	1	$17.95	$19.66	$1.71	0	0
CR-38/98 (2/pk)	3	$24.30	$0.00	-$24.30	0.2832	0.0177
Blue Tube 38/48	1	$16.49	$0.00	-$16.49	3.3276	0.207975
Aerotech 38mm Propellant Kit -I435T	2	$109.98	$109.98	$0.00	18.1	1.13125
RMS-38/600 Casing w/Forward Seal Disk	1	$60.00	$60.00	$0.00	0	0

Aerotech 38mm Forward Plugged Closure	1	$22.26	$0.00	-$22.26	0	0
Aerotech 38mm Aft Closure	1	$22.26	$0.00	-$22.26	0	0
Total		$320.84	$241.76	-$34.56	22.3108	1.394425

Table F5: Shipping and Tax

Product	Spent Total	Budgeted Total	Difference
Apogee (1) Shipping	$23.30	$56.56	$33.26
Apogee (2) Shipping	$19.92	$0.00	-$19.92
Apogee (3) Shipping	$53.75	$0.00	-$53.75
Apogee (4) Shipping	$4.47	$0.00	-$4.47
Public Missiles Shipping	$17.94	$0.00	-$17.94
Wildman Sales Tax	$0.00	$5.31	$5.31
Wildman Rocketry Shipping	$6.65	$0.00	-$6.65
McMaster (1) Sales Tax	$9.83	$14.55	$4.72
McMaster (1) Shipping	$12.72	$10.00	-$2.72
McMaster (2) Sales Tax	$4.46	$0.00	-$4.46
McMaster (2) Shipping	$5.33	$0.00	-$5.33
PerfectFlite Sales Tax	$0.00	$5.14	$5.14
PerfectFlite Shipping	$4.74	$4.54	-$0.20
PerfecFlite (2) Shipping	$3.54	$0.00	-$3.54
Home Depot Sales Tax	$3.20	$0.00	-$3.20
Wildman Motor Sales Tax	$20.01	$0.00	-$20.01
Total	$189.86	$96.10	-$93.76

Appendix G: Schedule

Table G1. Progress Schedule

Category	Task Name	Start Date	End Date	Duration	% Complete
Dual Deployment		**10/20/2015**	**12/18/2015**	**44d**	**100%**
	Model in OpenRocket	10/20/2015	11/3/2015	11d	100%
	Design Black Powder Charges	12/1/2015	12/1/2015	1d	100%
	Contact Local Clubs	10/26/2015	12/18/2015	40d	100%
Design		**11/3/2015**	**12/18/2015**	**34d**	**100%**
	Finalize OpenRocket Design	11/3/2015	11/16/2015	10d	100%
	Verify OpenRocket Design	11/10/2015	11/11/2015	2d	100%
	Complete SolidWorks Model	11/16/2015	12/18/2015	25d	100%
Build Stage		**12/8/2015**	**4/1/2016**	**115d**	**100%**
	Build Rocket	12/8/2015	4/1/2016	115d	100%
	Paint Rocket	3/12/2016	4/1/2016	20d	100%
Parts and Budget		**11/25/2015**	**12/18/2015**	**18d**	**100%**
	Finalize Budget	12/1/2015	12/18/2015	14d	100%
	Custom Fin Quote	11/25/2015	11/30/2015	4d	100%
	Order Fins	12/1/2015	12/1/2015	1d	100%
	3D Print Nose Cone	12/1/2015	12/3/2015	3d	100%
	Order All Parts	11/30/2015	11/30/2015	1d	100%
Computational Analysis		**12/4/2015**	**3/10/2016**	**97d**	**100%**
	Stress	12/4/2015	3/10/2016	97d	100%
	Aerodynamics	12/4/2015	12/18/2015	14d	100%
	Robustness	12/4/2015	3/10/2015	97d	100%
	Stability	12/4/2015	12/18/2015	14d	100%
Developmental Testing		**12/8/2015**	**3/12/2016**	**95d**	**100%**
	Nose Cone Drop	12/8/2015	12/18/2015	10d	100%
	Altimeter	12/8/2015	3/11/2016	94d	100%
	Dual Deployment	3/12/2016	3/12/2016	1d	100%
Launch!		**4/16/2016**	**4/16/2016**	**1d**	**100%**
	Rocket Launch Day	4/16/2016	4/16/2016	1d	100%

Table G2. First Semester Schedule

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15
Project Task	9/7 - 9/11	9/14 - 9/18	9/21 - 9/25	9/28 - 10/2	10/5 - 10/9	10/12 - 10/16	10/19 - 10/23	10/26 - 10/30	11/2 - 11/6	11/9 - 11/13	11/16 - 11/20	11/23 - 11/27	11/30 - 12/4	12/7 - 12/11	12/14 - 12/18
System Requirements Review															
1.1 Benchmarking															
1.2 Determine parameters															
1.3 Prepare design specifications															
1.4 Finalize scope of work															
1.5 Generate concepts															
1.6 Determine schedule															
1.7 Prepare budget															
1.8 Design review				◊											
Preliminary Design Review															
2.1 Generate concepts															
2.2 Determine physical principles															
2.3 Conceptual drawings															
2.4 Evaluate concepts															
2.5 Design review									◊						
Critical Design Review															
2.1 Generate concepts															
2.2 Determine physical principles															
2.3 Conceptual drawings															
2.4 Evaluate concepts															
2.5 Design review															◊

Table G3. Build Phase Schedule

	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Project Task	2/7-2/13	2/14-2/20	2/21-2/27	2/28-3/5	3/6-3/12	3/13-3/19
Weigh Components				S		
Machining Parts (John)				P		
Print 3D Parts				R		
Avionics Bay Assembly				I		
Altimeter Testing				N		
Aft Assembly				G		
Boat Tail Testing				~		
Parachute Packing				B		
Shock Cord Attachment				R		
Nose Cone Inserts				E		
Acetone Bath				A		
Anti-Zippering Assembly				K		
Mini Review 1				!		
Dual Deployment Test				:)		

Appendix H: Anomaly Investigation

Thermal Expansion of the Nose Cone

It was speculated that the failure of dual deployment that occurred on the second launch was possibly due to the thermal expansion of the nose cone. Upon retrieval after the first flight, the nose cone would not slide on and off with ease compared to the first launch. Sanding had to be done in order for the nose cone to fit on the body tube; however, it still took some force to separate the nose cone from the body tube when the second launch occurred. The launch site weather condition was clear skies with moderate winds at 94 degrees Fahrenheit. The temperature near LMU on launch day was around 68 degrees Fahrenheit. This lead the team to believe that the nose cone exposed in the sun for extended periods (Ex. Upon retrieval and during the pre-flight checklist) lead to the nose cone to expand to create a tighter fit in the body tube. It was suggested that the coefficient of thermal expansion of ABS be investigated to determine if the material was the cause for failure. The equation used to calculate the geometric change in a feature length of an object is shown below [18].

$$d_f = d_0(\alpha\ dt + 1)$$

Table H1. Calculations of linear thermal expansion

Variables	**ABS**	**Aluminum**	**Fiberglass**
dt, Change in temperature (degrees F)	94 - 68 = 26	26	26
α, Linear Thermal Expansion Coefficient	0.000041	0.000012	0.000015
d_0, Initial diameter (inches)	3.85	3.85	3.85
d_f, Final diameter (inches)	3.8541041	3.8512012	3.8515015

The diameter of the nose cone changed by four thousandths of an inch which is close to a tolerance on a machined part. This is a major change in diameter and caused the tighter fit between the nose cone and the body tube. If the material was fiberglass the thermal expansion would have been around one thousandth of an inch, which could have been sanded off on launch day. Aluminum was also investigated as a comparison to show how much an aluminum nose cone would have expanded. Based on the calculations, the material of the nose cone as well as launch day conditions caused an unforeseeable change in critical dimensions that ultimately lead to the failure in deployment of the drogue parachute that lead to zippering of the body tube.

Apogee Failure

The data extracted from the altimeter showed that the apogee reached in the first and second flight were 2769 feet and 2778 feet, respectively. The cause of this failure could be attributed to too much reliance on OpenRocket as an accurate predictor for apogee. Based on people's experiences with OpenRocket on rocketry forums, it was stated that OpenRocket overshoots the apogee by 10%. Upon further investigation 90% of the predicted apogee for the first flight (3105 feet) was 2795 feet. This shows a 26 foot discrepancy which is more accurate to what occurred on the actual launch day.

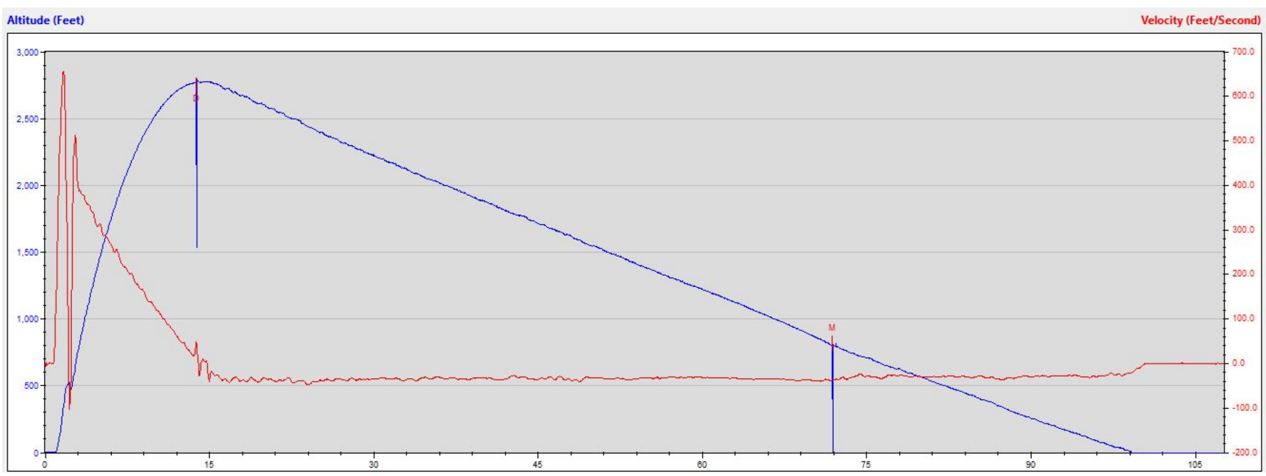


Figure H1. Data from the first flight

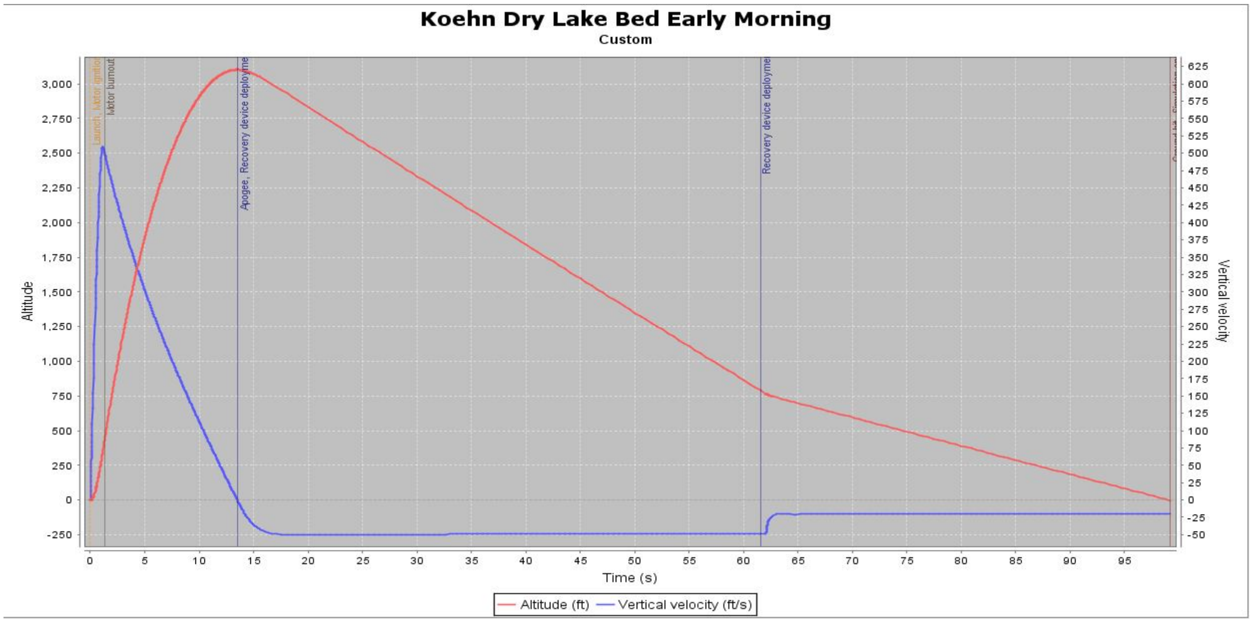


Figure H2. Simulation launch in OpenRocket

The reason for not designing with the 10% overshoot was that the rocket had been built to the point where critical components could not be removed, reordered or altered. This overshoot fact was brought to the team's attention well after the Critical Design Review and only a 100 foot accommodation could be made, even with the adjustable payload carrier carrying minimum weight. Any removal of components, such as the payload carrier itself, would have caused the rocket to have a stability ratio below one which would have caused instability. The design could have easily been altered to change the apogee had the issue been brought up before Critical Design Review.

Appendix I: Pre-Flight, and Post-Flight Checklists

<u>Pre-Flight Checklist</u>

1. Payload Carrier
   - ❏ 1.1 Check the wind speed and direction
   - ❏ 1.2 Input the wind speed into OpenRocket
     - ❏ 1.2.1 Adjust the payload in OpenRocket to achieve an altitude as close to 3000 feet as possible (within a 10 foot error)
     - ❏ 1.2.2 Ensure that the stability is above 1.0 calibres (CG is at least one body tube diameter ahead of the CP)
   - ❏ 1.3 Place payload carrier onto scale and zero the scale
     - ❏ 1.3.1 Place fishing weights and wadding to achieve the specified payload in OpenRocket
     - ❏ 1.3.2 Ensure the payload will not shift in flight
     - ❏ 1.3.3 Close payload carrier
   - ❏ 1.4 Place payload carrier into the avionics bay with the handles facing towards the bottom of the rocket
2. Avionics Bay
   - ❏ 2.1 Connect the two pin and four pin connectors to the altimeter wires
     - ❏ 2.1.1 Check that the altimeter beeps three times consistently when both black powder charge wires are connected together
     - ❏ 2.1.2 Secure the altimeter battery
   - ❏ 2.2Ensure all the wires connected to the altimeter are going to their designated charges
     - ❏ 2.2.1 Drogue wires are going to the top
     - ❏ 2.2.2 Main wires are going to the bottom
   - ❏ 2.3 Ensure there are no exposed wires or short circuits that can occur
     - ❏ 2.3.1 Exposed wires should be covered with electrical tape
     - ❏ 2.3.2 Separate wires from each other
     - ❏ 2.3.3 Verify wire connections are secure
   - ❏ 2.4 Size and assemble black powder charges appropriately
     - ❏ 2.4.1 Measure 1.2 g for the Drogue charge and place in the glove finger
     - ❏ 2.4.2 Measure 1.3 g for the Main charge and place in a separate glove finger
     - ❏ 2.4.3 E-match is coiled and placed in the glove finger
     - ❏ 2.4.4 Black powder charge is tightly sealed with tape
     - ❏ 2.4.5 System Reviewer verified the black powder charge for tightness and no holes

- ❏ 2.5 Place sled onto the nylon rods and push it into the avionics bay so it is touching the payload carrier
- ❏ 2.6 Check that the switch for the altimeter is turned off with the pull pin. If off, proceed to 2.7. If not proceed to 2.6.1.
  - ❏ 2.6.1 Insert pull pin into atmospheric port holes to turn off altimeter
- ❏ 2.7 Attach black powder charges to their appropriate wires and taped down into the canisters
  - ❏ 2.7.1 Drogue charge 1.2 g goes to the top of the rocket
  - ❏ 2.7.2 Main charge 1.3 g goes to the center of the rocket
  - ❏ 2.7.3 Ensure that the black powder charges are secured in the black powder caps
- ❏ 2.8 Place lower bulkhead onto nylon rods and tighten with two wing nuts in order to seal the avionics bay.
  - ❏ 2.8.1 Ensure that the bulkhead is centered on the avionics bay so it does not interfere when the aft body tube slides over it

3. Parachute Packing
- ❏ 3.1 Ensure that the shock cords are not frayed or burned
  - ❏ 3.1.1 Attach Nomex Parachute protector to both shock cords (one on each)
  - ❏ 3.1.2 Tie shock cords on to the nose cone (top shock cord) or eyebolt (bottom shock cord)
- ❏ 3.2 Pack main parachute
  - ❏ 3.2.1 Fold shock cord in an overlapping “Z” form and around the main parachute
  - ❏ 3.2.2 Place the parachute protector, main parachute and shock cord into the aft of the rocket in this order
  - ❏ 3.2.3 Connect aft onto tube coupler and align aft to forward body
- ❏ 3.3 Pack drogue parachute
  - ❏ 3.3.1 Fold shock cord appropriately and around the drogue parachute
  - ❏ 3.3.2 Place the parachute protector, drogue parachute and shock cord into the forward body tube of the rocket in this order
  - ❏ 3.3.3 Connect the nose cone to the forward body tube and align them for the shear pins to go in
- ❏ 3.4 Perform a pull test on the drogue and main parachutes

4. Rocket Assembly
- ❏ 4.1 Check that the rocket and body tube does not have pre-existing damage
  - ❏ 4.1.1 Check that the fins and fin fillets do not have cracks or damage. If they do execute fin replacement procedure
- ❏ 4.2 Place shear pins in the rocket in the specified holes
  - ❏ 4.2.1 Place four shear pins on nose cone

- ❏ 4.2.2 Place four shear pins on the middle of the body
    - ❏ 4.2.3 Ensure that shear pins and fasteners are on tight
- ❏ 4.3 Construct the motor using the Aerotech casing and propellant kit
    - ❏ 4.3.1 Place red seal cap over the after of the motor until the igniter wire needs to be put in
- ❏ 4.4 Insert motor and casing into the inner tube mount
    - ❏ 4.4.1 Screw on engine retainer ring and ensure that it is secure

5. Launch Rail

- ❏ 5.1 Ensure screws or protrusions on the rocket are not interfering with the contact between the rocket and the guide rail. If there are, proceed to 5.1.1
    - ❏ 5.1.1 In the case that the protrusion is epoxy, sand off the epoxy. If not proceed to 5.1.2
    - ❏ 5.1.2 In the case that the protrusion is as screw, remove screw and evaluate whether the rocket can launch without it. If the rocket cannot launch, place the screw in a less obstructive place to secure the component.
    - ❏ 5.1.3 In the case that the protrusion is a major component, do not launch. Remove the component and replace it in a less obstructive place if possible.
- ❏ 5.2 Tip the launch rail over and thread the rail buttons of the rocket onto launch rail
- ❏ 5.3 Remove pull pin
- ❏ 5.4 Listen for three repeated continuity beeps from altimeter. If there are no continuity beeps proceed to 5.4.1.
    - ❏ 5.4.1 Immediately replace the pull pin to disarm rocket and unload the rocket from the launch rail to a safe workstation. For no beeps proceed to 5.4.1.1. For one repeated beep proceed to 5.4.1.2. For two repeated beeps, proceed to 5.4.1.3.
        - ❏ 5.4.1.1 There is no continuity. Check all wire connections.
        - ❏ 5.4.1.2 The drogue parachute ejection charge has continuity. Check the main parachute wire connections.
        - ❏ 5.4.1.3 The main parachute ejection charge has continuity. Check the drogue parachute wire connections.
- ❏ 5.5 Insert igniter wire into the motor grain and push the red seal over it
    - ❏ 5.5.1 Connect the alligator clips to the igniter wire
- ❏ 5.6 Check for continuity on the launcher by pressing the appropriate button. If there is no continuity proceed to 5.6.1
        - ❏ 5.6.1 Check the motor igniter to ensure that it is fully in the grain of the motor

Safety Officer Signature:____

System Reviewer Signature: ______________________________________

Post-Flight Checklist

1. Retrieving Rocket
    - ❏ 1.1 Insert pull pin back into atmospheric port hole to deactivate the altimeter
    - ❏ 1.2 Clear shear pin shrapnel from holes
    - ❏ 1.3 Unload the motor casing from the rocket
2. Data Retrieval
    - ❏ 2.1 Unscrew the wing nuts on the bottom of the avionics bay
        - ❏ 2.1.1 Remove bulkhead without pulling off wires
    - ❏ 2.2 Slide mounting board out enough to reach the altimeter
        - ❏ 2.2.1 Attach the data transfer cord to the altimeter and the computer
    - ❏ 2.3 Extract data from altimeter using the Perfectflite program. If Altimeter did not read flight (crash landing) proceed to 3
    - ❏ 2.4 Analyze data to see if the rocket overshot or undershot 3000 feet.
    - ❏ 2.5 Utilize OpenRocket to adjust the payload according to the results. Proceed to 2.4.1 if overshot and 2.4.2 if undershot.
        - ❏ 2.5.1 Increase the payload on OpenRocket and the payload to an appropriate size
        - ❏ 2.5.2 Decrease the payload on OpenRocket and the payload carrier to an appropriate size
    - ❏ 2.6 Place payload into payload carrier
        - ❏ 2.6.1 Secure the payload in the avionics bay using the hex nuts
3. Component Evaluation
    - ❏ 3.1 Evaluate fins and fillets for damage. If damaged beyond flight, proceed to 3.1.1-3.1.2 below
        - ❏ 3.1.1 Sand or drill the fillet of epoxy off the broken fin
        - ❏ 3.1.2 Place new fin into the slot and epoxy using fast drying epoxy with a 0.25” radius fillet
    - ❏ 3.2 Evaluate body tube for zippering. If body zippered proceed to 3.2.1
        - ❏ 3.2.1 Depending on length of zipper, attempt to mend the zipper with epoxy or zippering repair kit
    - ❏ 3.3 Evaluate bulkheads and centering rings for damage. If damaged proceed to 3.3.1
        - ❏ 3.3.1 Apply epoxy to repair bulkhead or centering ring
    - ❏ 3.4 Evaluate the altimeter wire connections and battery for points of failure
        - ❏ 3.4.1 Reconnect disconnected wires and add electrical tape
        - ❏ 3.4.2 Cover all exposed wires with electrical tape
        - ❏ 3.4.3 Check battery voltage to ensure there is enough voltage for another flight

Safety Officer Signature:____

System Reviewer Signature: ____