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Ascanius Project: MECH 401/402 Senior Capstone Experience

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ASCANIUS Project: MECH 401/402 Senior Capstone Experience

A thesis submitted in partial satisfaction

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ASCANIUS PROJECT

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MECH 401/402: Senior Capstone Experience

ABSTRACT

This report describes the analysis, design, and test, and launch of a high power reusable rocket. The design goals were to reach a target altitude of 3000’, deploy a payload module containing an egg that can be safely recovered, and record flight video. The rocket was 62.13 in long fully assembled, had a dry mass of 2.764 kg (3.077 kg wet), and was propelled using an I-class solid fuel rocket motor (Cesaroni I-216-CL). The body tube and the electronics bay were constructed from Blue Tube, a proprietary vulcanized rubber and cardboard hybrid manufactured by Always Ready Rocketry Inc. The nose cone and tail cone were fabricated by the team from carbon fiber reinforced polymer (CFRP) via wet layup and vacuum bagging. The fins were constructed from a carbon fiber-balsawood sandwich structure and designed to optimize aerodynamic performance (minimize drag and maximize lift). The motor mount consisted of an innovative “tubeless” design utilizing three centering rings and a 3D-printed ABS engine block. In order to ensure reusability, this design includes a dual deployment recovery system that uses a barometric altimeter to trigger flight events. A 15” drogue chute was set to deploy at apogee, which would control the initial descent while minimizing drift, and a 60” parachute deployed at 800’ was used to slow the rocket to a safe ground-hit velocity. At 900’, a self-contained egg module was deployed with its own parachute. The parachutes and the payload were all deployed using FFFFg black powder ejection charges. The rocket achieved an apogee of 3556’, however a failure in the recovery system resulted in catastrophic fuselage damage on main parachute deployment. Design objectives, analyses, specifications, testing, and results are discussed in detail.

ACKNOWLEDGEMENTS

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Johann Kim: For graciously providing high-quality imagery of all the teams' work and flight.

CONTENTS

1. DESIGN

1.1 Objectives

The primary objective of the Aeneas Project was to build a high power rocket to accurately reach a target altitude of 3000 feet. Additionally, the rocket was required accurately record its altitude during the flight and be fully reusable, utilizing a dual deployment recovery system to both ensure a safe landing and minimize drift.

The secondary objectives included lofting and ejecting a payload containing an egg that would land intact separate from the rocket and recording flight video with an onboard camera to document the launch. The four teams from Loyola Marymount University competed to achieve the smallest altitude margin on launch day, with each team having two launch opportunities.

1.2 Background

High power rocketry is a subsection of model rocketry that utilizes rockets which have an impulse of greater than 160 N-s. These are usually greater than 2” in outer diameter and weigh several pounds. Like any object moving at a meaningful relative speed through a fluid (e.g. an airplane), a rocket is subjected to the forces of weight, thrust, lift and drag during its flight (see Figure 1). The weight, drag and lift forces are determined by the design of the rocket assembly.

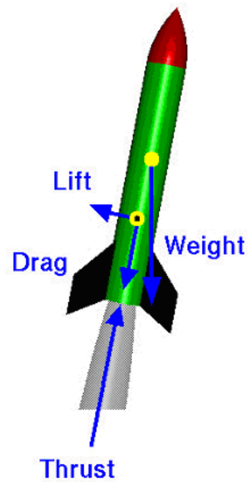


Figure 1: Primary inertial and aerodynamic forces acting on a rocket

The thrust is provided by the rocket motor. These are classified according to the thrust force they can provide and are ranked alphabetically, with “A” being the lowest impulse class available and “R” the highest. Weight is determined experimentally (using a scale) or analytically as the sum of the masses from all the components multiplied by the gravitational acceleration on Earth’s surface. It acts on a single point, known as the center of gravity of the rocket c_g, which is also the center of rotation.

The aerodynamic forces (lift and drag) also act through a single point called the center of pressure c_p, which can be determined based on the geometry of the rocket as described in detail in section 2.6. Drag depends on the density of the air, the square of the rocket’s velocity, the size and shape of the body and its inclination to the flow and the drag coefficient (C_d). The lift force, also determined by the rocket’s size and shape, acts as a restoring force, correcting for deviations from the upwards direction (perpendicular to the horizon) in the rocket’s trajectory during its ascent.

1.3 Prior Work

No design, fabrication, testing, or fabrication was performed prior to the current academic year. However, all team members completed undergraduate courses that relate to the understanding of physics and design processes that were needed to complete this project. Three team members went through process of obtaining a National Association of Rocketry Level 1 certification, with one member being successful.

1.4 Design Specifications

The key system requirements and current capabilities for the rocket are as follows in Table 1 below. A complete detailed description can be found in Appendix D.

Table 1: Summary of Requirements and Capabilities

Requirement	Parameter	Estimated Capability	Basis Of Estimate	Tested	Margin
Rocket shall achieve an apogee of 3000'	3000 ft	3312 ft	Simulation	3556	18.5%
Body diameter must be >2.61"	2.61 in	4.00 in	Design	4.00in	53.26%
Once recovered, the rocket shall be ready for re-launch in at most 1 hour	1.0 hr	Unknown	Test	Not Recovered	N/A
Rocket must utilize dual deploy recovery methods with main parachute deployment between 500 and 800 ft.	500-800 ft	800 ft	Design	Drogue not deployed	N/A
"I" motors are the highest impulse class motor allowed for this design project	"I" Motor Class	Cesaroni I216-CL	Design	Complied	N/A
Stability ratio shall be between 1 and 2 calibers	1 to 2 cal	1.36 cal	Simulation	1.17cal	17%
Payload will successfully record on-board flight video.	Comply	Comply	Design	Not Recorded	0%
Payload will include one egg, which must survive launch, flight, and landing intact.	Comply	Comply	Design and Test	Payload was lost	0%

1.5 Concept Development and Selection Methods

1.5.1 Concept Downselect for SRR

During the downselect process, seven rocket concepts were developed and a concept selection matrix was created based on nine criteria. Each of these criteria was scored on a scale from 1 to 5, with 1 being the worst and 5 the best. Each criterion was also given a weight based upon how mission critical it was determined to be. Table 1 in appendix C shows the criteria, weighting, and description, as well as the "concept cards" for each of the seven concepts considered for the SRR downselect and their individual scoring. Of these, 4 concepts utilized solid motors and 3 utilized hybrid motors.

Table 10 in Appendix C shows the summary scores for the concept selection process. The concept ("F – Solid Fast") selected utilized an AeroTech I600R solid rocket motor (I = 640 N*s), a 3" OD Blue Tube fuselage, 2:1 ogive nose cone, and 3 high aspect ratio elliptical fins. This design was chosen because it had a very high apogee margin, was light, used a relatively conservative fuselage design, and an excellent stability ratio at 1.69. See Figure 2 below for the layout of this concept.

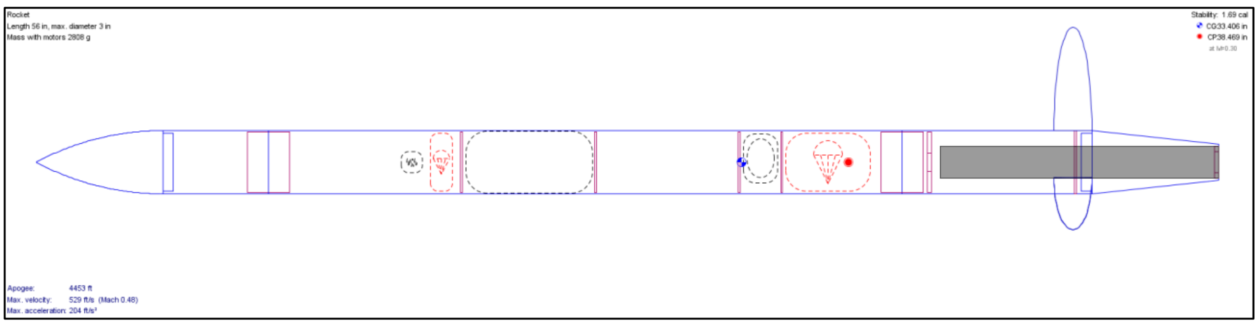


Figure 2: "Solid-Fast" concept selected at SRR

1.5.2 Concept Refinement for PDR

Given the extremely high apogee margin predicted for the selected concept (48% overshoot), a decision was made that secondary functionality could be added to the rocket with minimal cost addition. The changes made were:

- Motor: Cesaroni I-216 38mm (I = 636 N*s), 5 grain solid rocket motor selected due to low cost for casing and reloads and exceptional reputation for reliability and ease of use/reload on popular rocketry forum (rocketryforum.com).
- Fins: A trapezoidal shape was selected instead of elliptical in order to make manufacturing easier and more repeatable.
- Fuselage: A 4" OD was selected instead of 3" in order to increase internal space for ease of access and to make room for additional payloads.
- Payload: 2 payloads were added to the rocket: an egg in an ejecting protection vessel (to deploy at main parachute deploy) and at least 1 video camera to document the flight. Additionally, space was reserved in the fuselage as an adjustable payload bay to add mass for launch day apogee adjustment to compensate for weather conditions.

- Layout: Heavy modifications were made to the internal architecture of the rocket in order to more realistically position the parachutes, electronics bay-coupler, egg module, and camera.

More details were refined in the weeks leading up to CDR, as described in section 1.7. Some of the details include: slotted fin mounting, full carbon fiber nosecone and fins, rear motor retention, and others that are thoroughly described in the following sections.

1.6 Innovation

1.6.1 Egg Module

The egg module design and ejection system are both purely the result of this team's work. A description of the form and function of payload deployment can be found below in section 1.7.

1.6.2 Motor Retention

Unlike most engine blocks, which are machined from wood or aluminum, the engine block used in this rocket is 3-D printed from ABS. This allows for significant weight savings as well as easy compatibility with the engine retention assembly.

1.6.3 Carbon Fiber Components

Rockets using an "I" class motor typically make use of standard parts that are readily available for purchase. Using substantial quantities of carbon fiber for design components is not typical for rockets of this size. This rocket makes use of a carbon fiber nose cone, tailboat, and fins.

1.6.4 Triple Deployment

The deployment of the payload in addition to the two parachutes requires the use of a third, independent ejection charge. To accomplish this, this rocket makes use of a Missileworks RRC3 "Sport" Altimeter, which, unlike most entry-level altimeters, can be configured to fire a third output to ignite the payload ejection charge at the necessary altitude.

1.7 Description

The following section summarizes the design of each component in the rocket. Figure 3 below shows an exploded view of the final design into the three primary subassemblies: fore tube, electronics bay (recovery system), and aft tube. A comprehensive list of all components is shown in Appendix A.

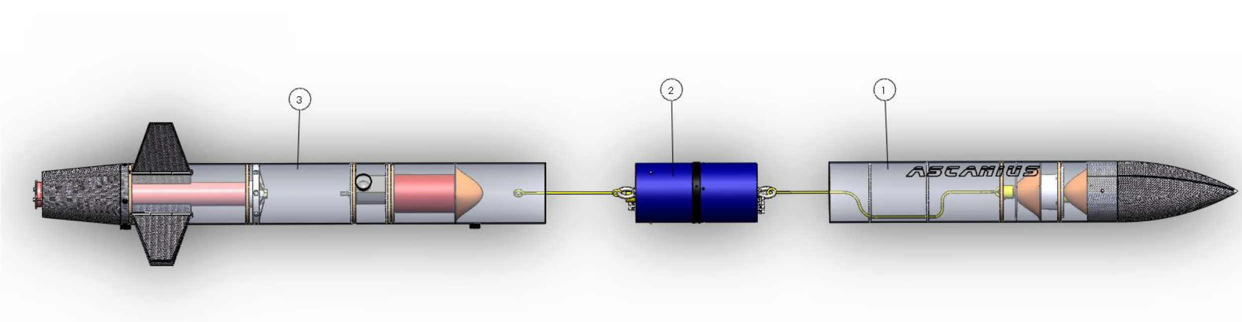


Figure 3: Exploded view of rocket assembly into primary subassemblies; 1 is the fore tube section, 2 is the electronics bay, and 3 is the aft tube section.

1.7.1 Fore End

Figure 4 below shows the exploded view of the fore tube subassembly, including the drogue parachute. Table 2 below contains the top-level BOM for this subassembly. The following section will describe each component in detail.

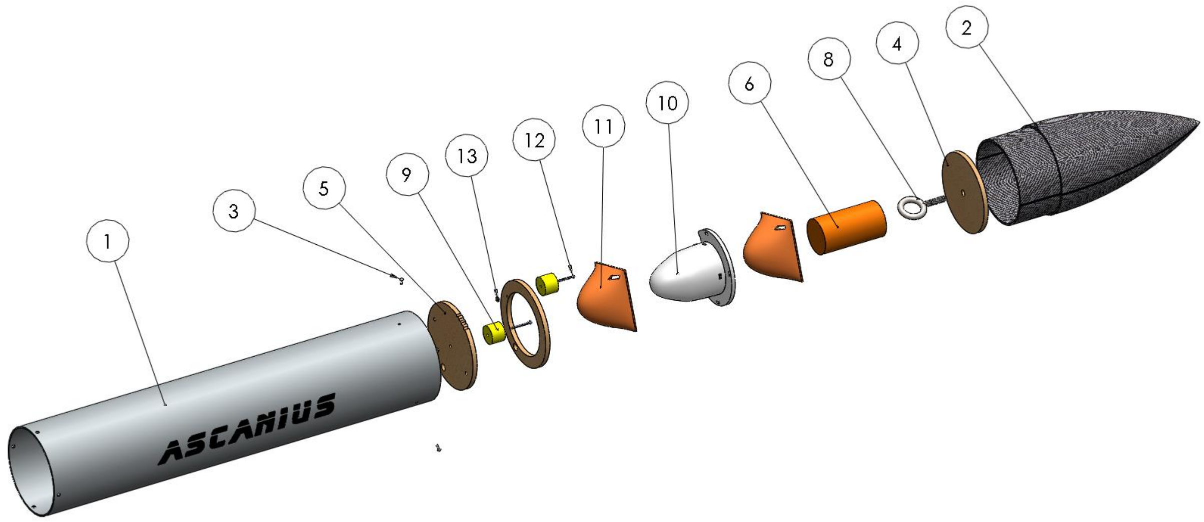


Figure 4: Exploded view of front tube subassembly.

Table 2: Fore End Top-level BOM

ITEM NO.	PART NUMBER	QTY.
1	Fore Body Tube	1
2	Nose Cone	1
3	2-56 Shear Pin Screw	3
4	Nose Cone Bulkhead	1
5	Fore Tube Bulkhead	1
6	Drogue Parachute	1
7	Egg ring	1
8	1/4-20 Eyebolt	1
9	Ejection Cap	2
10	"Dragon Egg" Payload Module	1
11	12"x12" Nomex Chute Protector	2
12	2-56 x 1" Slotted Machine Screw	2
13	2-56 Nut	2

1.7.1.1 Nose Cone

The nose cone has a 4.00’’ base diameter, 2:1 aspect ratio ogive shape with a cylindrical shoulder of 3.82’’ diameter and 2.00’’ length. It was mounted to the front body tube through three shear pins at the shoulder. It was fully manufactured out of carbon fiber (see Appendix E for reference).

1.7.1.2 Balsa Bulkheads and Rings

Bulkheads, centering rings and other structural features were made out of laser cut 3/16" plywood. The process of laser cutting provided a tight tolerance on very critical components. These tolerances resulted a tight fit between the component and body tube internal diameter and reduced the amount of structural epoxy needed to install the components. Other standard components, such as eyebolts, nuts, etc. were epoxied to the bulkheads and rings as necessary. Figure 5 below shows a rendering of this technique applied to a centering ring.

Figure 5: 3/16" laser cut plywood centering ring.

1.7.1.3 Fuselage Construction

The primary fuselage was made entirely of blue tube. Blue tube is a vulcanized rubber proprietary material widely used in high power rocketry due to its superb durability. Blue tube standard stock was purchased with fin slots already cut to spec by the manufacturers. Bulkheads, centering rings and the motor retainer were epoxied to the internal diameter of the fuselage. The fore and aft ends were each equipped with three standard holes for shear pins that coupled the fore end with the nosecone and the aft end with the electronics bay. The coupler band was drilled with 4, 0.125" static pressure ports to ensure that the avionics bay received the correct pressure readings during the course of flight. A 1.25" hole was drilled into the aft tube to provide the optimal field of view (FOV) for the camera payload.

1.7.1.4 Egg Module Payload

Given the fragile nature of an egg, special care was taken to develop a payload module that would ensure the survival of the egg through all stages of flight. The main structural components of the ejected payload were 3D printed per methodology described in section 1.8.5

and fastened using zip ties. The medium-sized egg was cushioned using a rubberized foam material and wrapped in saran wrap to prevent leakage in the case of a break. Part of the plastic was ground away using a Dremel to make room for the module to slide past the ejection cap. Figure 6 below shows the model of the payload module.

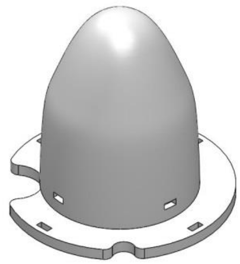


Figure 6: 3D printed payload module; nicknamed the "Dragon Egg"

1.7.2 Dual Deployment Recovery System Description

Figure 7 below shows the overall subassembly view of the electronics bay. The dual deployment system consists of an electronics bay, main chute, and drogue chute. The electronics bay consists of a blue tube coupler, two rods, and an electronics sled, upon which the altimeter, battery, and battery are placed. Table 3 shows the top-level BOM for the electronics bay assembly. For a detailed BOM, see Appendix A.

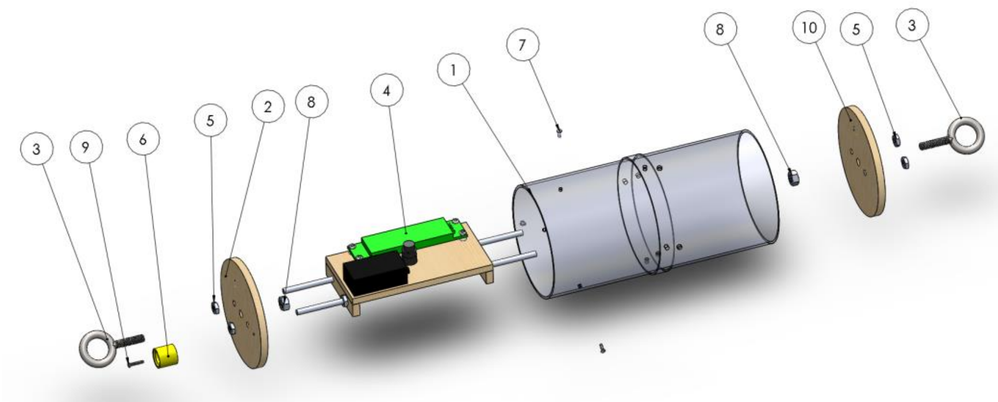


Figure 7: Exploded view of electronics bay subassembly.

Table 3: Electronics Bay Top-level BOM

ITEM NO.	PART NUMBER	QTY.
1	4" Blue Tube Coupler	1
2	Aft E-bay Bulkhead	1
3	1/4-20 Eyebolt	2
4	Electronics Sled Subassembly	1
5	10-32 Nut	4
6	Ejection Cap	1
7	2-56 Nylon Shear Pins	3

8	1/4-20 Nut	2
9	2-56 x 1" Button Head Screw	1
10	Fore E-bay Bulkhead	1

1.7.2.1 Drogue Chute

The drogue chute deploys at apogee and allows for a rapid, yet controlled descent at a maximum velocity of 50 mph. The specific chute chosen was the 15" Fruity Chutes Drogue Chute. The drogue chute, as well as the payload and main chute, were protected from damage from the exhaust gasses coming from the motor burn and ejection charges by 12"x12" Nomex parachute protectors (1 protector per article).

1.7.2.2 Ejection Charges

The ejection charges are explosives that when ignited cause the pressure gradients needed to separate body tube sections/deploy flight components at the appropriate times. Three charges were used, each of which were composed of 4F black powder housed in PVC caps and ignited by e-matches. The drogue chute charge used 0.51g, the payload deployment charge used 0.34g, and the main chute charge used 0.66g. A diagram of the ejection charges can be found in Appendix E3.

1.7.2.3 Main Chute

The main chute deploys at 800 feet and is responsible for slowing the rocket to a safe ground-hit velocity of around 20 fps. The specific chute chosen was the 6ft. Rocketman parachute.

1.7.2.4 Altimeter

The altimeter is housed on a sled inside the avionics bay and is responsible for measuring altitude and sending out the electrical charges to activate the ejection charges at the appropriate times. The specific altimeter chosen is the Missileworks RRC3 "Sport" Altimeter, which is capable of sending out 3 separate outputs.

1.7.2.5 Wiring

The altimeter is connected to battery and the ejection charges using red and black 22-gauge wire. All wires connected directly to the altimeter connect to one of the two terminal blocks on the outside of the avionics bay. The wires that connect directly to ejection charges connect to the corresponding terminal block for ease of separation of the avionics bay from the rest of the rocket. Wiring diagrams can be found in Appendix E3.

1.7.2.6 Battery

A Duracell 9V battery provides power to the altimeter.

1.7.2.7 Bulkheads

The laser-cut avionics bay bulkheads are constructed from laser cut 3/16" plywood.

1.7.2.8 Shock Cord

Two lengths of shock cord are used. The first length of cord connects the nose cone, the drogue chute, and the avionics bay. The second length connects the avionics bay, the main chute, and the aft end of the rocket. The specific shock cord chosen is Apogee Kevlar Cord 1500. The length of shock cord needed is estimated at 30 times the diameter. Since the rocket has a diameter of 4", the length of shock cord chosen to link each section was 10'.

1.7.2.9 Eyebolts

The shock cords connect to the nose cone, avionics bay, and aft end of the rocket by way of ¼”-20 eyebolts purchased online from McMaster-Carr.

1.7.2.10 Shear Pins

Nylon shear pins are used to ensure that body tube sections do not separate until the activation of the ejection charge. Three 2-56 nylon shear pins are used to connect the nose cone to the front end of the rocket and to connect the aft end of the rocket with the avionics bay.

1.7.2.11 Removable Rivets

The avionics bay is held to the fore end of the rocket using Apogee removable rivets. This allowed for the avionics bay to be held securely during flight and removed easily in between launches.

1.7.3 Aft End

Figure 8 below shows an exploded view of the aft end of the rocket, which includes the main parachute, aft body tube, rocket motor and retention system, fins, and tailboat. Table 4 below shows the subassembly level BOM.

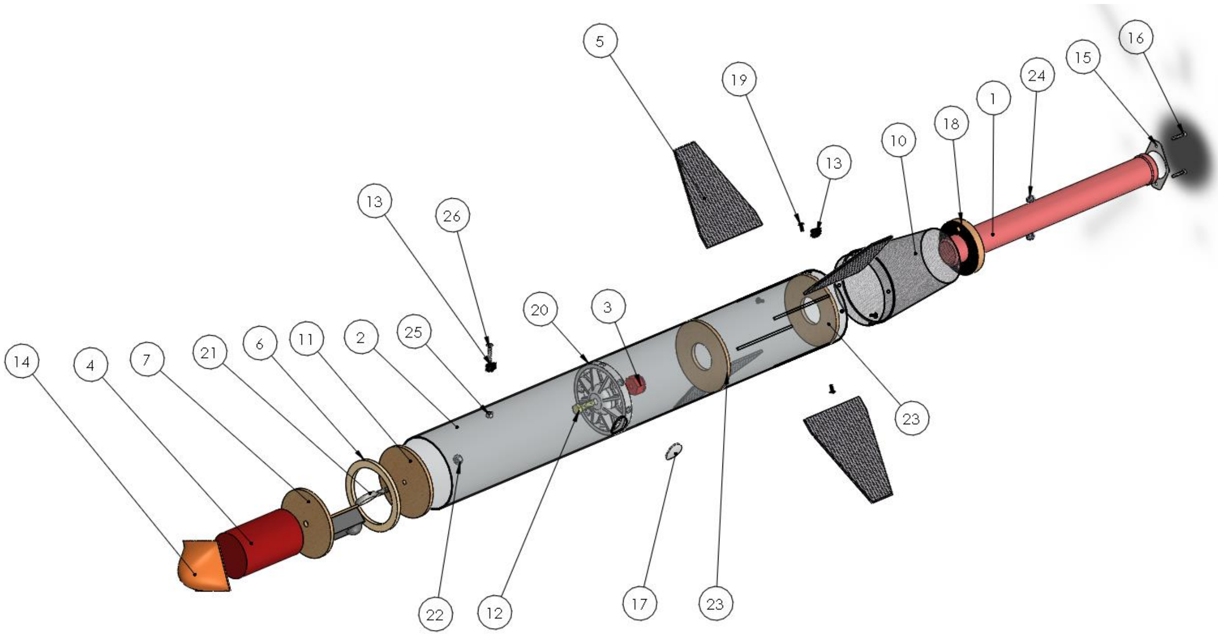


Figure 8: Exploded view of aft end subassembly.

Table 4: Aft End Top-level BOM

Item no.	Part number	Qty.	Item no.	Part number	Qty.
1	I216-CL-11	1	*14*	12"x12" Nomex Chute Protector	1
2	Aft Body Tube	1	*15*	Tail Motor Retainer Plate	1
3	Pro38 delay-ejection closure adapter	1	*16*	6-32 x 2" Socket Cap Screw	2
4	Main Parachute	1	*17*	Camera Window	1
5	CF-Balsa Fin	4	*18*	Aft centering ring	1
6	Camera ring	1	*19*	Removable Rivet	4
7	Main Chute Platform	1	*20*	Engine Block	1
8	Camera Backing	1	*21*	1/4-28 Eyebolt	1
9	GoPro Hero 4	1	*22*	1/4-28 Nut	1
10	Tailcone	1	*23*	Centering Ring 1	2
11	Aft Sealing Bulkhead	1	*24*	6-32 Brass Expansion-fit Threaded Insert	2
12	5/16-18 x 0.75" Hex Cap Screw	1	*25*	10-32 Nylon Locknut	1
13	Airfoil Rail Button	2	*26*	10-32 x 1" Flat Head Socket Cap Screw	1

1.7.3.1 Camera Assembly

The second payload carried to apogee was a GoPro Hero4 camera, which allowed for the recording of a video of the entire flight from the side of the rocket. The camera was not ejected and formed an integral part of the aft end assembly. The camera was press fit between the bulkhead and camera ring and secured by the back extrusion (balsa) of the main chute platform. The video recording could be activated remotely via Bluetooth wireless communication. Figure 9 below shows this subassembly. To cover the hole through which the camera capture video, a 0.030in clear plastic cover was adhered to the interior of the 1.25" hole with a small epoxy fillet applied around the edges to minimize aerodynamic disturbances and bond the window in place.

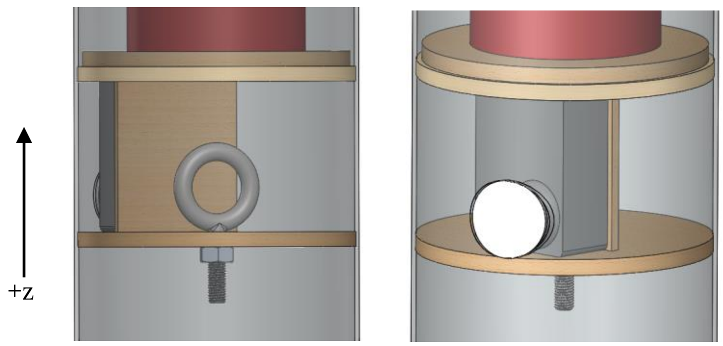
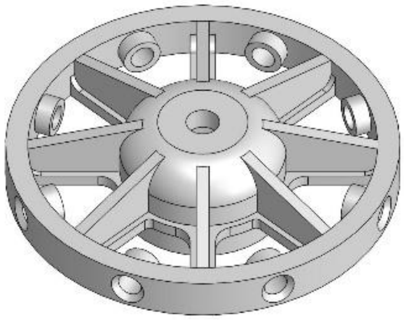


Figure 9: Camera payload subassembly and associated bulkheads; thermoplastic lens cover, shown as opaque for clarity.

1.7.3.2 Motor Retention

The engine block was made out of 3D printed ABS plastic per the method described in section 1.8.5. This was the main component that transferred thrust and momentum from the rocket's motor to the fuselage in shear. The Cesaroni Pro38 5-grain casing made use of an Aeropack MC38 ejection charge adapter mounted in place of its built-in ejection charge. This was threaded onto a 0.75" long 5/16-18 flanged eyebolt epoxied into place on the front engine block. The motor's force was transferred through the engine block in shear via the epoxy mounting the block to the aft end of the fuselage. Motor alignment was achieved using 3 centering rings: two 0.2in laser cut plywood rings, mounted to the interior of the body tube (one directly behind the engine block, the other flush with the fin tabs), and one from 0.4375in thick CFRP-phenolic honeycomb mounted at the rear of the tail cone. The aft centering ring provided a backup load transfer path in the event of failure of the main engine block. This would be accomplished by the motor reload cap pushing on the ring, transferring load through the tail cone and fuselage via epoxy shear and removable rivets. Finally, a secondary motor retention plate was fastened to the tail block via 6-32 socket cap screws into threaded inserts mounted in the aft centering ring. See section "3.1.1 Static Test of Motor Retention" for maximum loading test results. Figure 10 below shows the schematic and key design elements of this subsystem.



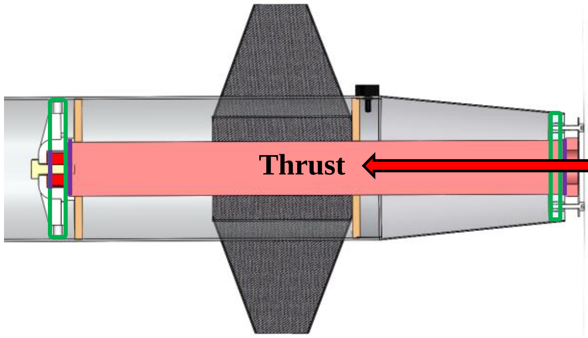


Figure 10: Motor retention system; clockwise from left: ABS front engine block; cross-section of entire motor retention scheme – green rectangles denote areas of load transfer via shear and purple lines denote areas of load transfer via direct thrust; picture of dry fit motor retention scheme.

1.7.3.3 Fins

The rocket had four rectangular cross-section trapezoidal fins of 0.125'' thickness, 3.875'' root chord, 1.50'' tip chord and 4.50'' length. The fins extended 1.00'' into the pre-slotted rocket fuselage and were epoxied on the inside and outside for mounting They were manufactured from 2 layers of 0.020 in thick bidirectional carbon fiber fabric on either side of a 0.0625" balsawood core. The orientation of the weave on the carbon fiber was $[0\text{-}90/\pm45/c]_S$. (see sections 1.8.1 Carbon Fiber Manufacturing" and 1.8.3 Fin mounting" for reference).

1.7.3.4 Tailboat or Tailcone

The conical tailboat reduced the rocket's diameter from a 4.00'' body tube to a 3.00'' rear outer diameter over a length 5.40'' (see Figure 11 below). It had a 0.625'' shoulder which was secured to the body tube using 4 removable rivets. It was fully manufactured out of carbon fiber (see section 1.8.1 for reference). The aft centering ring was epoxied to the inner diameter of the rear of the tail cone.

Figure 11: Carbon fiber tailboat

1.7.3.5 Tail Motor Retention Plate

The motor was retained in the aft direction through the use of a .029" laser cut steel plate (Apogee Rockets P/N 24084) secured via 6-32 cap fasteners into brass threaded inserts, which were mounted in the tail cone centering ring. This guaranteed motor retention and provided a secondary load transfer path in case of main engine block failure. Figure 12 below shows the plate design and subassembly view.

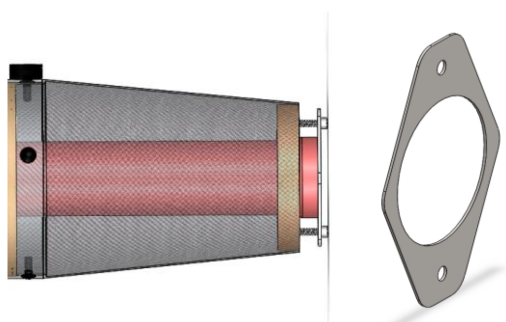


Figure 12: Primary components for aft-end motor retention; on left is the tail cone subassembly, and on right is the tail motor retention plate.

1.8 Manufacturing

1.8.1 Carbon Fiber Manufacturing

To fabricate the nose and tail cone parts from carbon fiber reinforced polymer (CFRP) the following process was used. First, a two-part female mold was machined from high-density urethane machining foam with alignment features on the mating faces. In each mold half, 2 coats of release wax followed by a spray-on coat of PVA were used to prevent the laminate from bonding. The resin used was a vinyl ester laminating resin (Hexion 784-7978 VER). The first layer of reinforcement bidirectional carbon fiber fabric (0.030 in thick, donated by ADM Works, Santa Ana, CA) was wetted with resin, laid up in to the mold, and then wetted again. Each subsequent layer was wetted after laying into the mold. The layer direction pattern used was [0-90/±45] resulting in an initial wall thickness of approximately 0.06". Then, a layer of perforated release film, peel ply, and breather cloth was laid into the assembled mold. The vacuum bag film, seamed down the middle, was inserted into the mold cavity, the protruding threaded rods were covered with breather cloth, the vacuum port was placed into the bag, and the vacuum bag was sealed to the base plate. The vacuum pump was connected to the port, and vacuum was pulled. The two mold halves were allowed to cure for a minimum of 8 hours. For more detail, see Appendix E1. The fins were constructed as flat plate laminates as a CFRP-balsa sandwich; see 1.8.4.3 below for further detail.

1.8.2 Hole Drilling

To accurately place and drill the holes, a simple method that ensured repeatability and kept the cost reasonable was utilized. A strip of masking tape was carefully measured to match the circumference of the body tube and marked with holes that were equidistant from one another ensured that they were spaced equally. Once the masking tape was reapplied onto the outer diameter of the rocket the holes were drilled. This process is often called “match-drilling,” and was used often when mating components (e.g. shear pin holes mating aft end and ebay coupler).

1.8.3 Fin mounting

Without a motor tube upon which to mount the fins, as is typical, an alternative method was deployed to align and secure the fins. To this end, a fin-mounting tool was 3D printed, see Figure 13. Using this tool, the fins were mounted one at a time. In preparation for fin mounting, the outer faces of the fin-mounting tool were coated with release wax to prevent it from becoming epoxied to the inside of the body tube or the fins. Thus prepared, the tool was inserted such that the center of the tool was lined up with the center of the slot, and so that the slots in the tool lined up with the slots in the body tube. The fin was placed through the slot in the body tube, and the body tube was taped to a table such that the fin stuck straight up. Rocketpoxy was used to fillet the two outer corners of the fin to the body tube. Once those fillets cured, the body tube was rotated and the next fin mounted. This process repeated until all of the fins had been filleted on the outside. The tool was then removed, and the inside corners filleted. These fillets could be done in only 2 passes. Acetone and sanding was employed on the corner between the body tube and the fin to remove any release wax that spread from the tooling, although this was required only minimally.

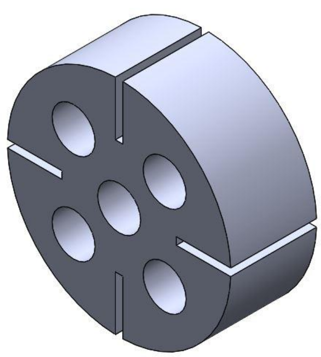


Figure 13: On left, fin mounting tool; on right, fins dry-fit into fin mounting tool and aft body tube.

1.8.4 Molds

To fabricate the CFRP nose cone and tail cone, two-part female molds were machined from blocks of high-density urethane machining foam and surfaced appropriately. Below is a brief description of each mold.

1.8.4.1 Nose Cone

The nose cone mold was machined from Precision Board PBLT-18, an 18 lb/ft^3 closed-cell high density urethane foam ideal for such applications. The outer dimensions of the mold were 7”x10.5”x3”. The mold was sealed by spraying Evercoat Featherfill G2 (gray) polyester primer-filler, and was surfaced by sanding progressively up to 2000 grit sandpaper (see Appendix E3). 6 ¼” through holes were drilled through the mold for inserting ¼-20 threaded rod. When the two halves of the mold were mated, ¼” nuts were placed on either end of the threaded rod & used to apply mating pressure counter to the pressure exerted by the vacuum bag. Alignment was achieved through the use of ¼”x7/16 alignment pins in opposing corners of the mold. The mold comes to a blunt end due to the impossibility of bending the carbon fiber to a sharp point. After the layup was complete, a 3D printed tip was bonded to the remaining portion of the nose cone. See Figure 14 below for CAD model of mold halves.

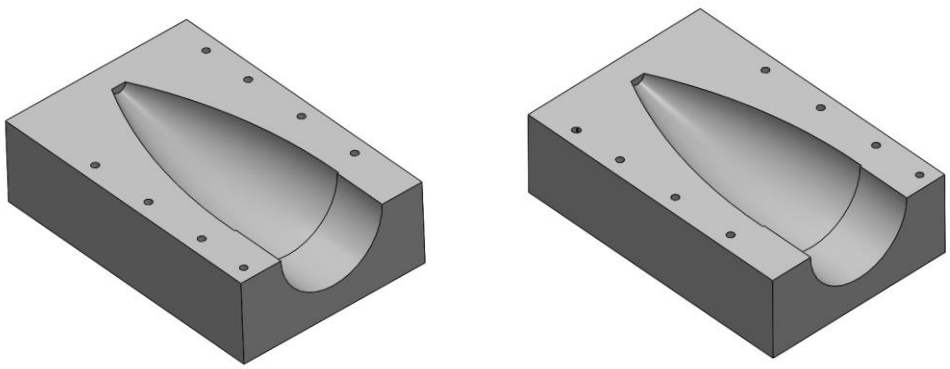


Figure 14: On left, nose cone half-mold shape with press-fit dowel pin holes; on right, nose cone half-mold with opposing slip-fit pin hole and slot.

1.8.4.2 Tailboat

The tailboat mold was constructed in the same manner as the nose cone mold, however its minimum outer dimensions are 7.000”x6.960”x3.000”. Figure 15 below shows the half-mold designs.

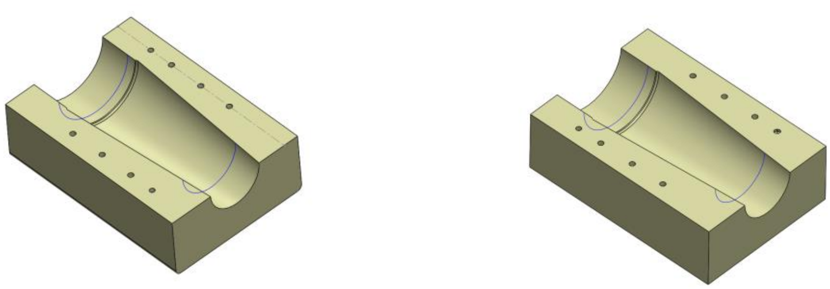
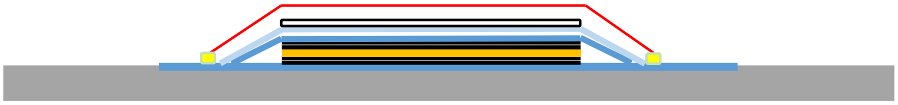


Figure 15: On left, the tailboat half-mold with press-fit dowel pin holes; on right, tailboat half-mold with slip fit hole and slot. The blue lines are scribe lines which mark the intended design length.

1.8.4.3 Fin

The fins were fabricated as a flat laminate, utilizing two layers of 0.020" bidirectional carbon fiber fabricated around a 0.0625 in balsawood core. The layup pattern is $[0\text{-}90/\pm 45]_s$. The resulting fins were sanded to net shape. Figure 16 (a) below shows the laminate schematic used during the vacuum bagging layup. Figure 16 (b) shows the vacuum setup as-fabricated.

(a)



(b)

Figure 16: (a) Fin layup schematic; grey is aluminum base plate, black is carbon fiber fabric, orange is balsa core, dark blue is perforated release film, light blue is peel ply, white with black border is breather cloth, red is vacuum bag film, and yellow with green outline is sealant tape. (b) Vacuum bag setup as implemented for fin fabrication.

1.8.5 ABS 3-D Printing

Additive manufacturing was utilized to fabricate the engine block and both parts of the egg module. The printed components were fabricated on a Stratasys FDM 1650 out of acrylonitride butadiene styrene (ABS). The following settings were used (unless otherwise noted):

- Layer thickness: 0.01"
- Surface finish: Fine
- Interior fill: Solid
- Raster angle: 45°

1.8.6 Tensile testing

In order to perform the tensile tests on the engine block, custom tooling was machined out of aluminum in the LMU machine shop. To simulate the geometry of the connection between the motor casing and the engine block, a flanged hexagonal piece was developed. In order to apply tension to the flange, a tension applicator was developed which fit into the flanged hexagonal piece. These pieces can be seen individually and in their assembled position in Figure 17 below.

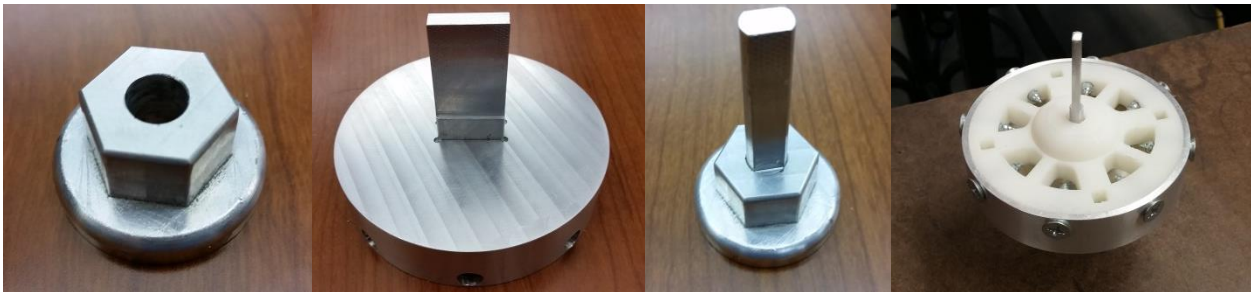


Figure 17: Left to right: Flanged Hexagon, Tension Applicator, and Tension Applicator Assembly

To simulate the placement of the engine block in its final location in the tube, the tension mount was developed. After the tension applicator assembly was put into place, the engine block was bolted into place. The tension mount and full tension tooling assembly can be seen in Figure 18 below.

Figure 18: Engine block tensile testing setup

1.9 Flight Plan

The ideal flight plan is as follows. Once on the launch pad, the rocket motor will be ignited and the thrust generated by the solid motor will propel the rocket in a nearly vertical motion. After motor burnout about 3 seconds into flight, the rocket will coast to an apogee of 3000 feet. To both ensure the safe landing of the rocket and to minimize drift, a dual deployment recovery system is implemented. This system is so named because it makes use of two parachutes deployed at different times. The first event occurs at apogee, the point of maximum height and zero velocity, and is the deployment of the drogue chute. The drogue chute allows for a controlled descent, but at a velocity fast enough to limit drift due to wind. The second event occurs at a set altitude, which in this case is 900 feet, and is the deployment of the payload. The third and final event, which is the deployment of the main chute, occurs at 800 feet. The main chute slows the rocket down to a ground impact-safe velocity, and, while the rocket drifts significantly more, it is close enough to the ground that the actual drift distance is reasonably small. Overall flight time is estimated to be between 120 and 130 seconds. A visual of the flight plan can be seen in Figure 19 below.

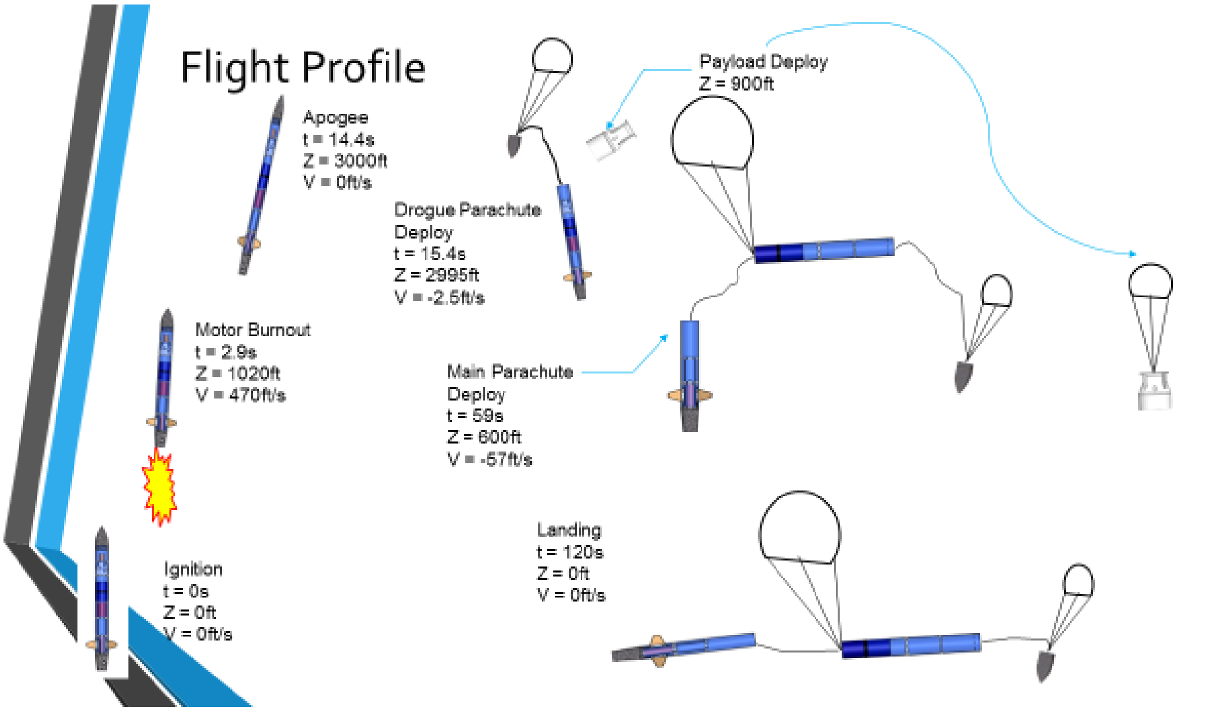


Figure 19: Nominal flight path for the Ascanius rocket utilizing a dual deployment recovery system and ejectable payload.

2. Analysis

The following summarizes the numerical and qualitative analysis the team has performed to inform and validate the design described above. For the analysis, Open Rocket, an open source software, was used primarily for determination of apogee and stability margins. A layout of the Ascanius rocket in Open Rocket is shown below in Figure 20.

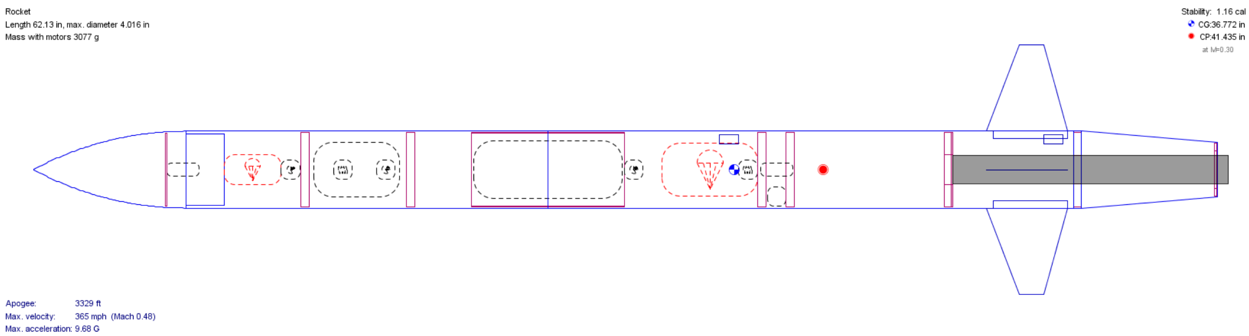


Figure 20: Open Rocket simulation model of final design.

2.1 FMEA

The following Failure Modes and Effects Analysis (FMEA; Table 5) summarizes the 5 critical failure modes identified by the team and their mitigation methods. A detailed FMEA can be found in Appendix F1.

Table 5: Summary of FMEA for critical/high risk components

Potential Failure Mode	**Parachute failure to deploy**	**Payload Recovery Failure**	**Zippering**	**Motor Retention Failure**	**Tailboat and Fin Damage**
Potential Failure Effect	Partial or complete ballistic landing	Catastrophic landing of the payload	Irreparable damage to body tube	Partial or complete ballistic landing	Irreparable damage that prevents 2nd flight
Severity	9 - Danger to those on the ground, damage to all rocket components	8 - Failure to meet "intact egg" requirement.	9-Failure of reusability requirement	9 - Danger to those on the ground, damage to all rocket components	8 - Failure to meet reusability requirement
Potential Causes	1) Altimeter failure 2) Ejection charge failure	Ejection charge failure Incorrect parachute deployment	1) Insufficient shock cord length 2) Delayed Ejection Charge 3) Weak body tube	1) Improper motor mounting or alignment 2) Engine block fracture	1) Incorrect main parachute deployment 2) High impact velocity

(Cont. on next page)

Table 5 (cont.)

Potential Failure Mode	Parachute failure to deploy	Payload Recovery Failure	Zippering	Motor Retention Failure	Tailboat and Fin Damage
Occurrence	8-Successful parachute deployment requires interaction of 3 systems	8- Successful ejection requires interaction of 3 systems	5-Occurs with moderate frequency, but can be easily prevented	5 – Engine block was tested and withstands 400 lb.	5 - Fin and tailboat cracking is a frequent event
Current Detection and Prevention	Ground testing of dual deployment system	Ground testing of egg deployment system	Ejection system testing, body tube reinforcement	Motor retention was tested for tensile strength	Carbon fiber designs are highly impact resistant
Detectability	5- Deployment errors would be observed during test.	5 – Payload recovery errors would be observed during test.	5-Ejection system errors would be observed during test.	3– No engine block fracture observed before 300 lb	3 – Visual inspection of quality.
Risk Priority Number	360	320	225	135	120
Future Action	Ground test of dual deployment system	Ground test of egg recovery system	Ground test of dual deployment system	Fatigue and thermal testing of engine block	Proper carbon fiber layup

2.2 Wind Sensitivity

Launch day atmospheric conditions can affect the aerodynamic performance of the rocket and subsequently impact the attainment of the 3000' target apogee. As mentioned in the flight profile (section 1.9), the duration of the flight is expected to oscillate between 120 and 130 seconds. The ascent of the rocket is completed in a short period of time, nominally around 14 seconds, and therefore any interference of local wind, atmospheric pressure and atmospheric moist conditions can greatly impact the main first design requirement. For this reason the design was driven by simulations of altitude, stability and angle of attack of the rocket over the flight time. A detailed description of this analysis is in Appendix F2. In summary, it was proven that the rocket, because of its mass and size, was barely affected by change in weather conditions. It was also found to be possible to make fine tuning adjustments to perfect apogee without greatly impacting stability and performance.

2.3 Nose Cone

An ogive geometry nosecone was selected for being the most efficient shape to reduce pressure drag. A 2:1 aspect ratio was chosen for its shorter length and smaller area to minimize skin friction. The combined nose cone and body tube drag coefficient was calculated to be 0.249.

A detailed analysis of C_D determination for nose cones can be found in Appendix F4, and drawings can be found in Appendix B.

2.4 Fins

The fins play a big role in determining the rocket's center of pressure position and the lift force that prevents the rocket from deviating from zero angle of attack. Maintaining a small angle of attack throughout the flight is crucial to reduce drag force and achieve apogee. A straight-tapered geometry with a rounded rectangular cross-section was selected for its relatively high lift and low drag coefficients. A thickness of 0.125'' was selected for structural reasons to prevent snapping as the rocket reaches a maximum velocity of Mach 0.4, since thicker fins unnecessarily increase the pressure drag. The straight-tapered geometry has the second lowest self-induced drag after the elliptical profile, but with the advantage of ease of manufacturing.

2.5 Tailboat

The purpose of the tailboat is to reduce the rocket's base drag resulting from boundary layer separation at the rear end of the rocket. The tailboat design has a length of 5.40", a body tube diameter of 4.00" and a base diameter of 3.00". According to the equations from [4] these parameters lead to a base drag coefficient of 0.015. In this way, the tailboat reduces the base drag coefficient by 42.2% for any nose cone and body tube geometry. (See Appendix F4 for design process and detailed calculations).

2.6 Center of Pressure

The Center of Pressure (CP) position depends on the geometric dimensions of the rocket and the angle of attack. For small angles of attack, its location can be calculated using the Barrowman's equations. The procedure involves dividing the body in different regions as outlined in Figure 21. Each is associated with a pressure force coefficient and the distance of the point where the pressure force acts with respect to the tip of the rocket. The individual contributions of each region are then added to determine the CP position.

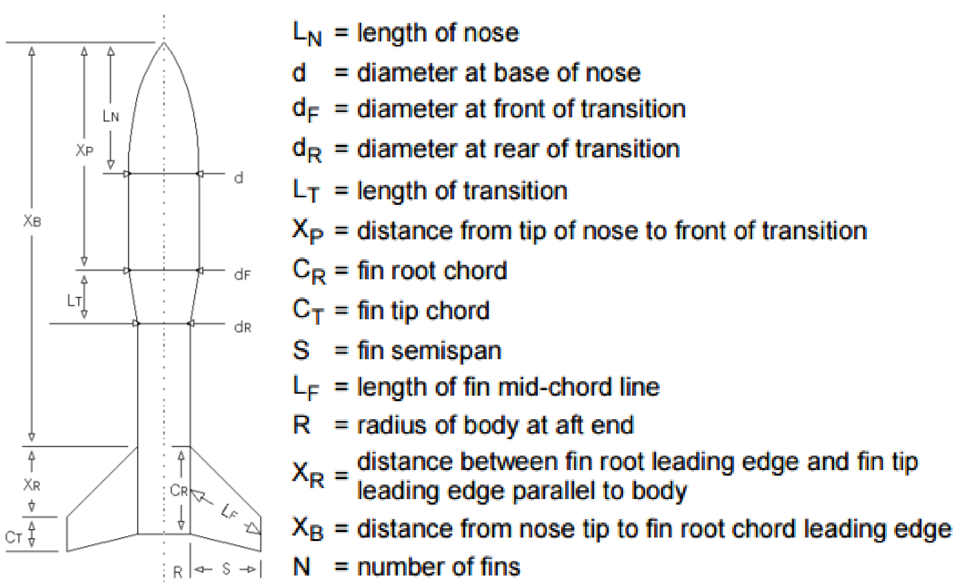


Figure 21: Definitions of parameters for Barrowman's equations

For a 2:1 diameter ratio ogive nose cone, the nose cone coefficient $(C_N)_N$ is 2 and the specific length X_N is 3.73''. The coefficient for the four fins $(C_N)_F$ is 9.08 with a specific length X_F of 51.37''. The tailboat is considered as a transition with a coefficient $(C_N)_T$ of -0.99 and a specific length X_T of 58.37''. Interestingly, the tailboat has a negative pressure coefficient and therefore slightly moves the CP towards the rear end of the rocket. The total coefficient $(C_N)_R$ is calculated to be 10.09 by adding the three previously computed coefficients. Lastly, the position of the center of pressure is given by:

$$X_{CP} = \frac{(C_N)_N X_N + (C_N)_F X_F + (C_N)_T X_T}{(C_N)_R} = 41.24\ in \quad (7)$$

The CP position was calculated to be 41.34'' using Open Rocket software. This implies a 0.46% error between the analytical calculations and the Open Rocket simulation. (See Appendix F3 for detailed calculations).

2.7 Main Chute

The main chute was chosen in order to slow the rocket to a generally recommended 20 feet per second. From iteration in Open Rocket, the specific parachute was selected.

2.8 Drogue Chute Sizing

The drogue chute was chosen in order to ensure that the rocket falls slower than the maximum speed at which the main chute can open, which is around 50 mph. From iteration in Open Rocket, the specific drogue chute was selected.

2.9 Ejection Charge Sizing

The sizes for the 4F black powder ejection charges were calculated using the force guidelines from the manufacturer for breaking the 3 shear pins and verified by test. A detailed breakdown of this analysis can be found in Appendix F6. The results are seen in Table 6 below.

Table 6: Ejection Charge Sizing

Tube Section	Section Length (in)	Estimated Charge Size (g)
Drogue Chute	5.60	0.51
Payload	3.77	0.34
Main Chute	7.25	0.66

2.10 Apogee

The main requirement states that the rocket must hit an apogee target of 3000'. This was a key design driver as the rocket must produce enough thrust initially to overcome its weight and ascent drag. In addition, as the rocket is coasting vertically, the drag force must decrease at a rate such that the rocket reaches zero velocity at the altitude of 3000'. As a preliminary analysis, a simple calculation using simple dynamics equations was performed using the information provided on the rocket motor by the manufacturer. In addition, using the same Open Rocket software for the previous calculations a more advanced computational approach was implemented. A number of cases were preliminarily calculated using the parameters mentioned above and compared with simulations from Open Rocket. Results are shown in Table 7.

Table 7: Comparison of analytic apogee prediction with OpenRocket software

	Max velocity (ft/s)	**Apogee(ft)**
Hand calculation	385.2	2747
Open rocket	495	3312
% Difference	***22.2 %***	***17.1 %***

Again, the hand calculations are to be taken as approximate, since physical aerodynamic effects are neglected by linearizing the process and summing coefficients into a constant.

2.11 Load Simulation

To determine if a 3D printed engine block would be strong enough to withstand the thrust imparted by the rocket motor, an FEA static loading simulation was performed on the design, using a 1.5x maximum load case (517.5N). The results yielded a minimum factor of safety (FOS) of 11.9 for the final design, indicating a large margin for loading.

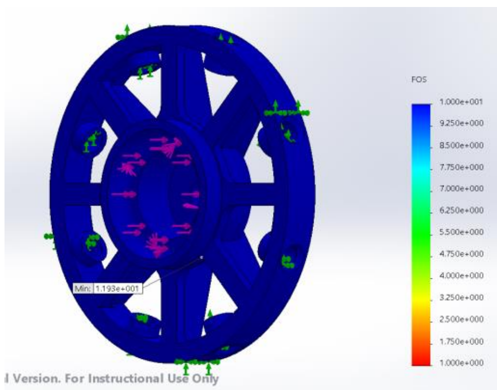


Figure 22: Static loading FEA of engine block design; note the location of the critical stress element is at the joint of the stiffening arms with the central bulge.

2.12 Cost Analysis

As mentioned in the requirements, the cost of the entire project should not have exceeded $1000. However, as the design and manufacturing of the final product underwent much iteration, the projected cost of the rocket exceeded the allowed limit. However, the project received approval from the instructor and chair of the department to proceed. In particular, the choice of CFRP as the material for key aerodynamic components, done to minimize weight and expose the group to a unique “hands on” experience, proved to be the most significant cost driver. A breakdown of the costs associated with major components is laid out in Table 8 below. Note that the “CFRP Components” row includes all materials purchased for the component manufacturing, including consumables such as sandpaper, but not donated material. Bidirectional carbon fiber fabric of varying weave and weight was donated by ADM-Works (Santa Ana, CA), while vacuum bagging film, peel ply, and a portion of the PBLT-18 tooling board was donated by Plastic Materials Inc., (Ontario, CA). Without these vital donations, the fabrication of CFRP components likely would have cost at least $2000, if not much more.

Table 8: Cost Analysis of Major Components & Subassemblies

Component	Cost ($)	% of Total Cost
CFRP Components	$ 835.07	50%
Motor & Motor Retention	$ 192.49	11%
Fuselage/Other	$ 131.12	8%
Recovery System	$ 360.04	21%
Shipping, Tax, & Fees	$ 159.88	10%
TOTAL	$ 1,678.60	100%

3. TESTING

3.1 Developmental Testing

The following section details the methods and results of preliminary testing done to inform and validate the design of critical components prior to CDR.

3.1.1 Static Test of Motor Retention

The motor is designed to deliver a maximum force of 78 pounds, and, as a primary thrust-bearing component, the tensile strength of the ABS engine block is vital. The proof of concept of using ABS was attained using tensile testing. Metal test tooling and a tensile test machine were used in order to simulate the loading on the engine block by the motor. The test was conducted by applying a constantly increasing load at a rate of 120lbf/min. An initial prototype survived a load of over 800lbs (FOS = 10.1), and the subsequent lightened version withstood a load of 400 pounds before failure (FOS = 5.2). Figure 23 below shows the testing set up.

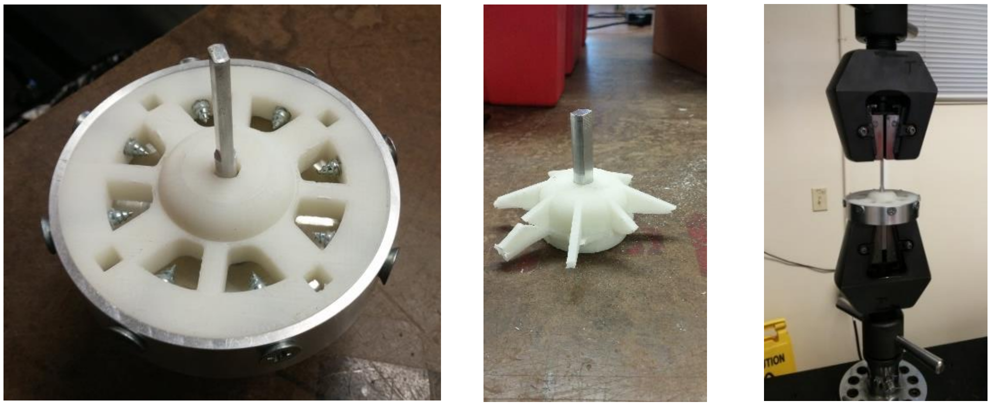


Figure 23: On left, initial engine block mounted in tooling; middle, the block mounted in the Instron tensile testing machine; on right, the central portion of the CDR design tested after failure.

3.1.2 Egg Survival

The egg module was designed to protect and carry the egg during launch, the descent, and ground impact. The egg module was 3-D printed from ABS in two pieces. The lower portion held the egg and the foam padding. It was connected to the upper section using zip ties. The upper portion was a flat circular plate that rested against a ring attached to the inside of the body tube. Until just before main chute deployment, the flat plate sealed the drogue chute section and was held in place by its geometry and a small amount of masking tape. At 900 feet, 100 feet before main chute deployment, an ejection charge was activated. This broke the tape seal and ejected the egg module from the rocket. A small nylon parachute was attached to the top section of the egg module to ensure a safe landing.

After settling on the overall design concept for the egg module, an initial test was carried out on a prototype. An egg wrapped in saran wrap was placed inside the egg module along with a small amount of foam insulation. A makeshift parachute was made from twine and a 1 square foot section of tarp and attached to the egg module. The assembly was then dropped from the top of a two-story staircase onto concrete. The egg cracked after two tests, but the parachute did not have a chance to fully open in either case. This was likely due to the makeshift nature of the parachute and the relatively low height from with the module was dropped.

3.2 Performance Testing

To validate the performance of fabricated components, a series of representative tests was carried out on final design articles to determine if any unforeseen risks required mitigation. These tests were performed primarily on the recovery system and on the motor retention system.

3.2.1 Ejection System Testing

In order to ensure that the parachutes and payload will deploy at the correct times, there are three fundamental actions that need to occur: 1) The altimeter will deploy a charge when it reaches a flight event, 2) The charge will ignite the e-match, and 3) The ejection charge is of the correct size to properly deploy the chute or payload.

3.2.1.1 Altimeter Testing

To determine altimeter activation at flight events, the altimeter was bench tested. This was accomplished using the vacuum pump that was used for vacuum bagging. First, the altimeter was programmed using the USB interface and mDACS software. The payload was programmed to go off higher than normal, so as to provide more time separation from when the main chute charge fired. Next, the avionics bay was wired up, with all of the wires from the altimeter going to their appropriate terminal block. However, instead wiring up e-matches, each altimeter output was wired to a $1k\Omega$ resistor and a small LED. The altimeter was switched on and the assembled avionics bay was placed into a plastic bag. The pump was then switched on, allowed to reach what was estimated to be a sufficient vacuum, and then released. As the vacuum released, the LED's were observed. For all tests, the drogue LED lit up almost immediately after releasing the vacuum, followed by the payload some time later, and finally the main chute. The altitude activation of the charges was subsequently verified by the flight analysis software of the altimeter.

3.2.1.2 Ejection Charge Testing

Ejection testing was performed in order to verify the sizing of the ejection charges. For the protection of the altimeter from exhaust gases and for ease of wiring, the altimeter was removed from the avionics bay during the whole of the test. Wires were instead fed out of the static port holes in the coupler and given their charge from a 9-volt battery. Wind conditions at the lake prevented testing of these charges with the parachutes attached. Nevertheless, the ejection charges all succeeded at separating their respective rocket sections at their nominal size, with the sections separating cleanly. One important reminder derived from this testing was to properly seal the bottom of the payload to its bulkhead ring.

3.2.1.3 Altimeter Charge Testing

To ensure that the altimeter charge would be sufficient to ignite the e-match, the altimeter was bench tested again. In this case the outputs were tested one at a time, with an e-match attached to the altimeter wires and taped to a chair approximately 6 feet away. With the altimeter connected to the software, the built in charge test fire function was activated. Each port was tested with an e-match individually. Without fail, the altimeter charges ignited the e-matches.

3.2.1.4 Recovery System Testing Conclusions

From testing, the ejection system was validated. It was verified that at the proper altitudes, the altimeter would deliver charges. It was then seen that those charges would be strong enough to ignite the e-matches. Then, it was demonstrated that when the e-matches ignited, they would set off a charge of the proper size to separate the rocket sections or eject the payload. Along with great care taken to ensure proper parachute packing and payload preparation, the test results encouraged confidence in the recovery system.

3.2.2 Motor Retention

An additional series of load and thermal tests were performed on the 3D printed ABS engine block in order to establish its capability at and beyond design load.

3.2.2.1 Updated Engine Block Testing

In order to more accurately represent launch conditions, the engine block was subjected to thermal testing and another round of tensile testing. These tests, which, while they produced mostly positive results, have led to minor design changes to mitigate risks.

3.2.2.2 Additional Tensile Testing

To simulate the effects of multiple launches, two test pieces were successively loaded quickly to 160 lbf (ramp rate 80 lbf/s) then unloaded 10 times. Both test pieces survived the test with no visible cracks or breaks, though the results did show a slight deformation of approximately 0.006 in after 10 cycles. However, since this represented several additional cycles than it will be subjected to at significantly more than maximum load conditions, the part was expected to survive.

3.2.2.3 Thermal Testing

To get an idea of how the engine block would behave in response to the heat generated by the motor, the tensile tested engine blocks were placed in a 200ºC oven for 3 minutes. Both pieces showed significant loss of structural integrity. However, these tests were not necessarily representative of actual flight conditions. A more indicative test was conducted in which a piece of bar stock was heated to 200ºC, placed in the mating surface for 2 minutes, and then removed. After going through this procedure three times, the engine block was examined and showed no appreciable loss of structural integrity or deformation that would be a cause for concern.

3.2.2.4 Testing-Driven Design Changes

Although overall the thermal tests alleviated most concerns, there remained the concern of deformation of the heated and possibly deformable engine block when pulled on by the shock cord after parachute deployment. In order to eliminate this possibility for this outcome, the aft eye bolt was moved to the camera bay bulkhead.

4. SAFETY

4.1 Ballistic Landing

A rocket landing in one piece nose-first poses a significant safety threat to people on the ground. The dual deployment recovery system is employed to prevent this. In order to ensure that recovery system prevents this unfortunate outcome, all components and processes are meticulously designed to avoid failure, and are subsequently tested thoroughly.

4.2 Uncontained Motor

A motor that comes loose from its mount in the rocket poses a safety threat to everyone in the vicinity. The motor mounting system is tested at thrust loads greater than 3 times the highest the load nominally delivered by the motor in order to preclude its failure.

4.3 Tensile Test Injury

Tensile testing uses potentially dangerous machinery, and is therefore always conducted under the direct supervision of the lab manager. When testing until fracture, a Plexiglas shield is placed between the observers and the test apparatus so that no shards of test material strike and potentially injure observers.

4.4 Accidental Ejection Charge Explosion

The explosive nature of black powder means that great care must be taken in the testing and utilization of the ejection system. One of the most important underlying principles of safely using the ejection charges is that someone must never be holding a live ejection charge while it is connected to an active power source. This is vital in preventing an ejection charge from firing when someone is holding it, which could result in serious injury. During testing, this means that the ejection charge must be assembled and put in place and all people are 10 feet away from the charge and clear of the trajectory or any other test articles (nose cone, body tube section, etc.). This must be done before the charge is hooked up to the launch controller or altimeter and said device is powered up. During launch, a switch is incorporated in order to ensure that the altimeter will be powered off while the ejection charges are assembled and placed in the rocket. The altimeter will be powered on only after everything else is ready for flight and the rocket is on the pad.

4.5 Launch Day Safety

All official NAR launch protocols will be followed in order to minimize the risk of injury.

4.6 Carbon Fiber Fabrication

Airborne carbon fibers can be injurious if inhaled, so at a minimum particulate masks will always be worn while working with carbon fiber. Epoxy is dangerous if ingested, so gloves will always be worn in order to prevent accidental ingestion from lingering presence on bare skin. The polyester primer-filler used for surfacing the molds (Evercoat Featherfill G2 Gray) emits significant fumes. Thus team members working with it shall at all times wear NIOSH-approved respirators rated to protect from volatile organic vapors, chemical splash goggles, and long-sleeved attire. Additionally, all painting with the primer will be done either outdoors or in a well-ventilated area, which is kept cool and free of any sparks. All excess paint and solvent (acetone) will be stored in sealed containers, kept in a flammables-rated cabinet until it can be disposed of properly at a hazardous waste disposal facility. Similar precautions shall be taken when handling the vinyl ester resin, as it also emits significant amounts of fumes and is flammable. When not in use, all unmixed polyester resin and primer shall be stored in a flammables-rated cabinet, in a cool and ventilated space.

5. Launch Day & Anomaly Investigation

5.1 Launch Day Procedures

On launch day, April 16, 2016, the rocket was prepared by having the permanent, internal components fully mounted, and the following components and subassemblies requiring assembly:

- Nose cone
- Front tube
- Egg module
- Electronics Bay
- Rear Tube
- Rocket motor & casing
- Tail cone

Appendix J contains the detailed checklists written for launch day assembly procedures, as well as photo evidence of the filled checklists for flight 1. Due to an in-flight anomaly (to be discussed below), the rocket vehicle suffered catastrophic damage and was unable to attempt a second flight.

5.2 Apogee and Drift

The rocket reached an apogee of 3556 ft., which represented an 18.5% overshoot of expected apogee assuming a 10% overshoot in the Open Rocket simulation.

5.3 Failure Analysis

During the first launch, the drogue chute failed to deploy, leading to a chain of events that caused catastrophic damage to the airframe that prevented the rocket from being flown a second time. The most likely cause of failure was too small an ejection charge, resulting using a different nosecone than was used during testing without a subsequent test to ensure correct sizing and separation. Additional pictures, force estimations, and the raw altimeter data with annotations can be found in Appendix I.

From the flight profile, as seen in Appendix I, the drogue chute deployment charge was activated at apogee. However, the charge was likely undersized and the nose cone did not separate from the fore tube. Without a deployed drogue chute, the rocket descended nose-first from apogee until 900 ft., when the payload charge went off. The combination of the force from the payload charge and the payload deployment caused the nose cone to separate and the drogue chute to deploy. The opening drogue chute, which had much more drag than the descending rocket, pulled toward the back of the rocket. The force of this pulling caused extreme zippering of the fore tube, as seen below in Figure 24.

Figure 24: Zippering of fore tube caused by drogue shock cord.

0.05s later, at 800 ft., the main chute deployed. Despite the rocket's very high downward velocity, (225 mph), the chute opened completely. The tension in the shock cord due to this sudden deceleration pulled the aft coupler eyebolt completely through the bulkhead, separating the fore section of the rocket from the aft section. The violence of the deceleration also caused zippering on the aft tube. Additionally, since a fin was missing and was not found anywhere around the landing site, it is hypothesized that as the main chute opened and was pulled to the back by drag, the gores or shock cord wrapped around one of the fins and levered it in a tangential direction. This broke it completely free from its epoxy fillets and cracked the body tube. This damage can be seen below in Figure 25.

Figure 25: Damage caused by deployment of main chute at high velocity

Since both the fore and the aft ends of the rocket fell the remaining distance with deployed parachutes, no damage was sustained on landing.

Additionally, during launch, the temperature of the exhaust gases caused the Rocketpoxy securing the tail plate to the aft end of the tailboat to exceed its glass transition temperature. Although it did not come loose during flight, the aft centering ring was broken completely free from the tailboat with a single, very gentle push.

6. CONCLUSION

The Eneas Rocket Team travelled to the Friends of Amateur Rocketry (FAR) site in the Mojave Desert on April 7 to test fly the final product of two semesters of design and fabrication. The rocket was launched at approximately 10:30am in 10-15 mph winds. The ascent followed the aforementioned procedure; however upon apogee the first event charge was not powerful to fully deploy the drogue parachute. Within a few seconds after apogee the rocket experienced a rapid unscheduled disassembly (RUD) and came to the ground in pieces. The possibility of failure is always present when taking up complex engineering project, but nonetheless the lessons learned from such failures provide invaluable experience and help make projects like this worthwhile. Throughout the design review phase and the build phase there were priceless engineering lessons learned that the group member will carry throughout their academic and professional career.

Specific technical recommendations for a future iteration of this project are the following:

- Ensure that all ejection systems are tested and characterized for flight articles.
- Consult standard design practices for key components.
- Cross-check simulation results with other methods.
- Fully employ a mass-adjusting payload module to allow for on the field apogee and CG adjustments.
- Mount all eyebolts with fender washers.

References

[1] National Association of Rocketry, "About NAR: America's Largest and Oldest Rocketry Association," web page, 2015, available: http://www.nar.org/about-nar/
[2] National Association of Rocketry, "Standard Motor Codes," web page, 2015, availab;e http://www.nar.org/standards-and-testing-committee/standard-motor-codes/
[3] National Association of Rocketry, "High Power Rocketry," web page, 2015, available: http://www.nar.org/high-power-rocketry-info/
[4] G. P. Sutton and O. Biblarz, *Elements of rocket propulsion*, 2nd ed., John Wiley & Sons: New York, 2001.
[5] Benson, Tom, "Determining Center of Pressure – C_p (simplified)," web page, last updated Oct. 22, 2015, available: https://spaceflightsystems.grc.nasa.gov/education/rocket/rktcp.html
[6] Nokes, Jim, class lecture for MECH 515, 28 Jan 2016.
[7] https://www.apogeerockets.com/Building_Supplies/Parachutes_Recovery_Equipment/Parachutes/High_Power/15in_Classic_Elliptical_Parachute
[8] http://www.matweb.com/search/datasheetText.aspx?bassnum=PTSPLY

Appendices

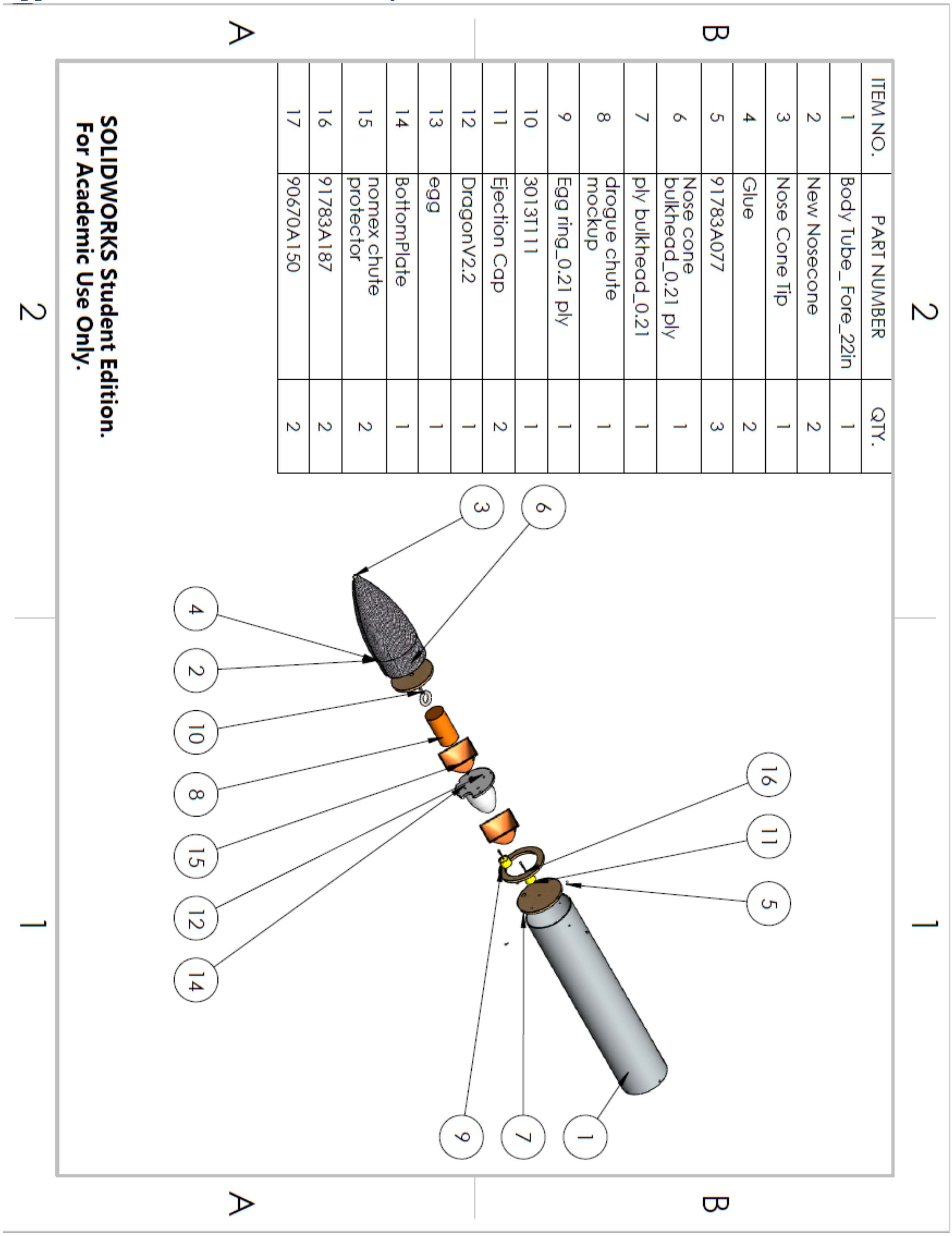
Appendix A: Bill of Materials

Part #	Part Name	Flown Quantity	Primary Material
	Fore Subassembly		
1	Fore Body Tube	1	Vulcanized Rubber
2	Nosecone	1	Carbon Fiber Composite
3	2-56 Shear Pin	6	Nylon
4	Nosecone Bulkhead Assembly	1	Plywood
5	1/4-28 Eyebolt	3	Carbon Steel
6	1/4-28 Nut	3	Carbon Steel
7	Shock cord	2	Kevlar Fiber
8	Drogue chute	1	Nylon
9	Parachute Protector	3	Nomex
10	Ejection cap	3	PVC
11	Ejection charge	3	Black Powder
12	Terminal strip	3	Various
13	Payload Ring	1	Plywood
14	Payload Assembly	1	Various
15	Adjustable Mass Ring		Carbon Steel
16	6-32 Nut	4	Aluminum 6061-T6
17	6-32 Bolt	2	Aluminum 6061-T6
18	Airfoil Rail Button	2	Delrin
19	Payload Bulkhead Assembly	1	Plywood
	Ebay Subassembly		
20	Ebay Coupler Tube	1	Vulcanized Rubber
21	3.75x0.25 Bulkhead	2	Plywood

22	10-32 Threaded rods	2	Aluminum
23	Sled	1	Plywood
23a	Sled bed	1	Plywood
23b	Sled Hole guide	2	Plywood
24	10-32 Hex nut	10	Steel
25	1/8 Standoff	4	Nylon
26	4-40 ¾ screw	4	Nylon
27	4-40 nut	4	Nylon
28	9V Battery	1	Carbon-zinc
29	2-56 Ejection cap screw	3	Steel
30	2-56 Ejection cap nut	3	Steel
31	Removable rivets	4	Plastic
32	Mini Clamp	2	Plastic
33	Rotary Switch	1	Plastic
34	Terminal Block	3	Plastic
	Aft Subassembly		
35	Aft Body Tube	1	Vulcanized Rubber
36	Camera Cap	1	Plywood
37	Camera Ring	1	Plywood
38	GoPro Hero 3	1	Various
39	Aft Bulkhead Assembly	1	Plywood
40	5/16-18 Shouldered Eyebolt	1	Steel
41	ABS Engine Block	1	ABS Plastic
42	3-16 Blind Rivets	16	Aluminum
43	Motor Casing	1	Aluminum
44	Motor Reloads	3	Various
45	Carbon Fiber Fins	4	Carbon Fiber
46	Tail cone	1	Carbon Fiber
47	Tail Block	1	ABS Plastic
48	Motor Retainer Cap	1	Plastic
49	Retainer Plate	1	Aluminum
50	6-32 Threaded Insert	2	Steel
	Payload Assembly		
51	ABS Top Cap	1	ABS Plastic
52	ABS Capsule	1	ABS Plastic
53	Zip Ties	4	Plastic
54	Protective Rubber Foam		Rubber Foam
	Additions		
55	Igniters	3	
56	Fin Tool	1	Aluminum
57	Centering Ring	1	Plywood
58	Hole Drilling Tool	3	Aluminum
59	Molds	variable	HDPE

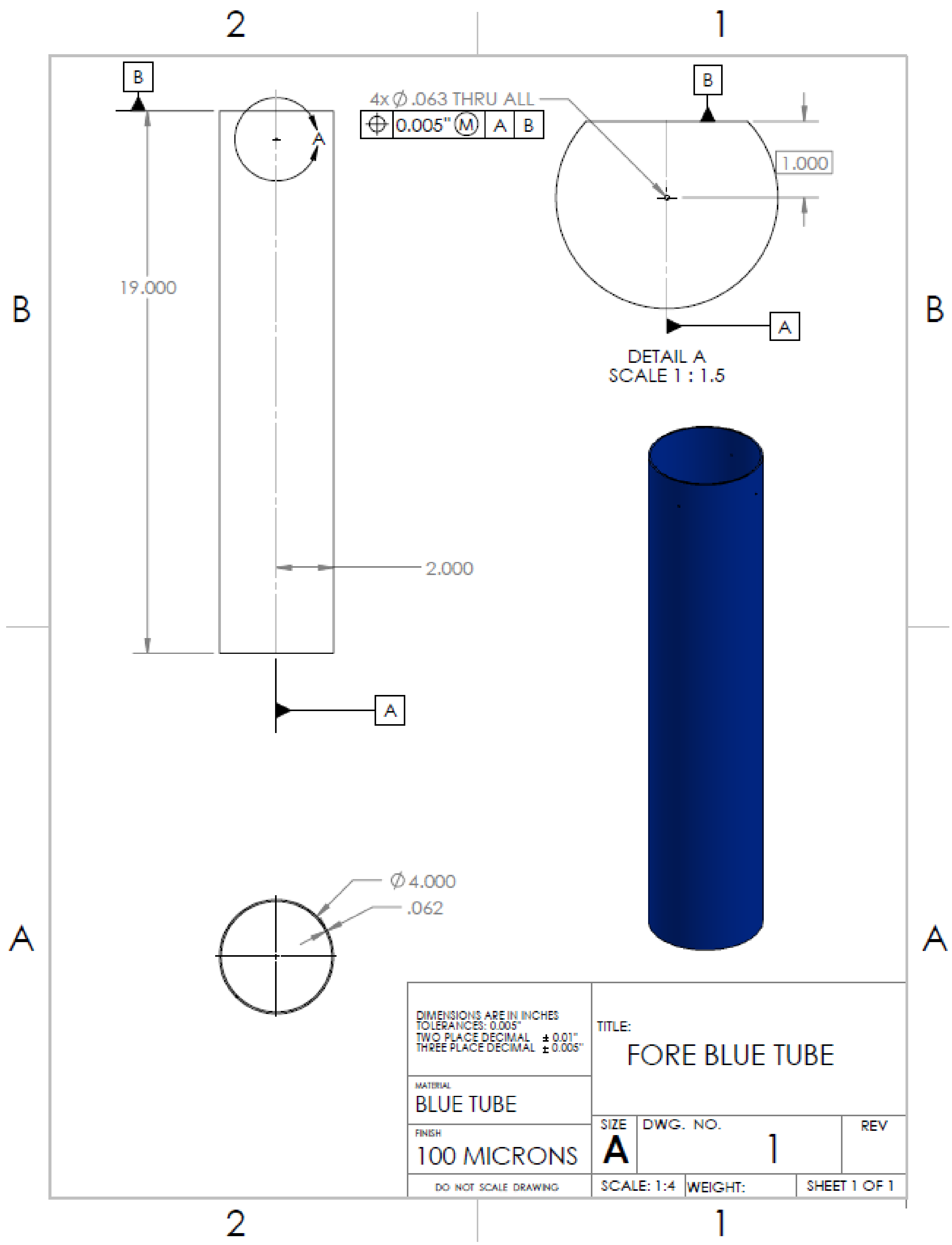
Appendix B: Manufacturing Drawings

Appendix B1: Fore End Subassembly

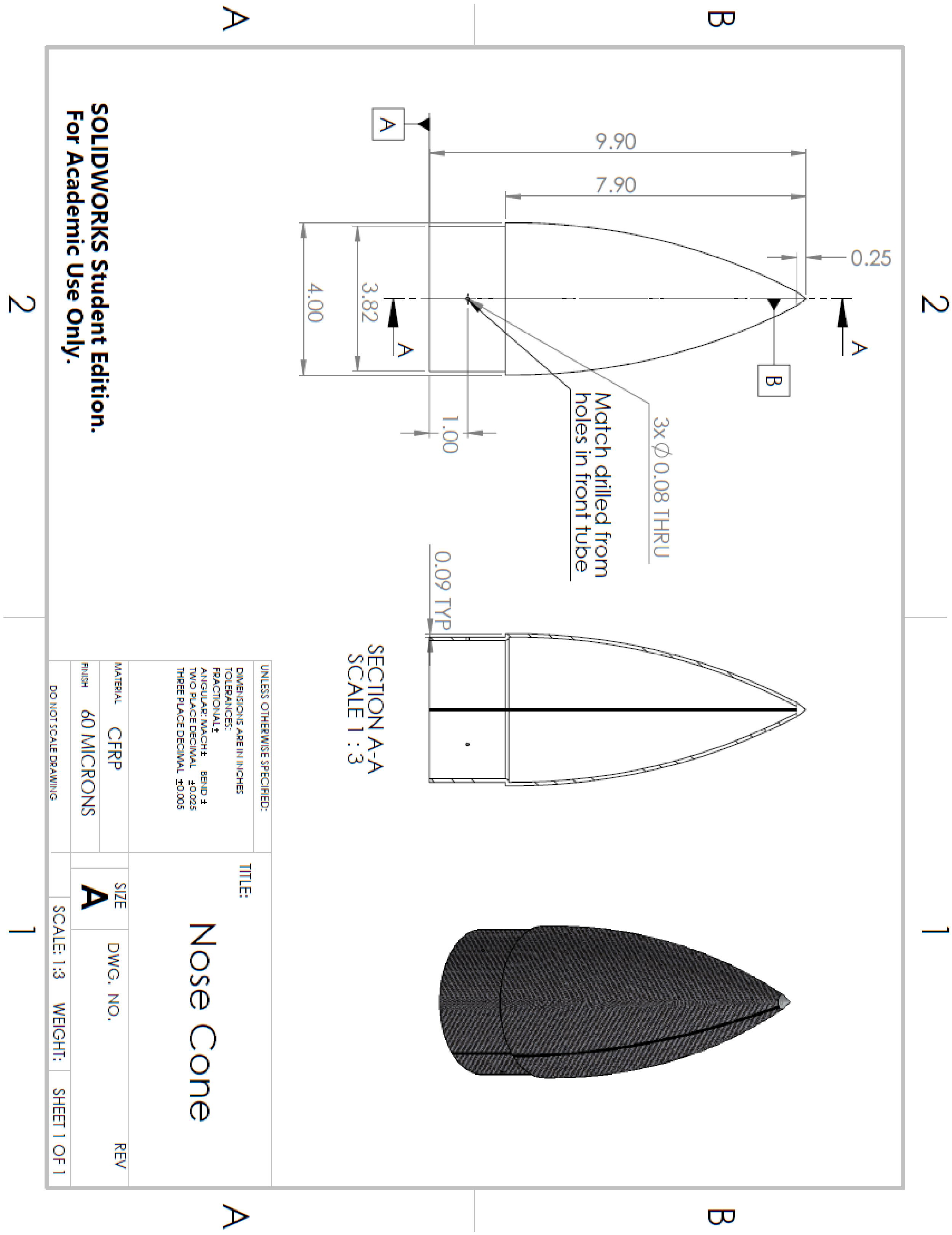


ITEM NO.	PART NUMBER	QTY.
1	Body Tube_Fore_22in	1
2	New Nosecone	2
3	Nose Cone Tip	1
4	Glue	2
5	91783A077	3
6	Nose cone bulkhead_0.21 ply	1
7	ply bulkhead_0.21	1
8	drogue chute mockup	1
9	Egg ring_0.21 ply	1
10	3013T111	1
11	Ejection Cap	2
12	DragonV2.2	1
13	egg	1
14	BottomPlate	1
15	nomex chute protector	2
16	91783A187	2
17	90670A150	2

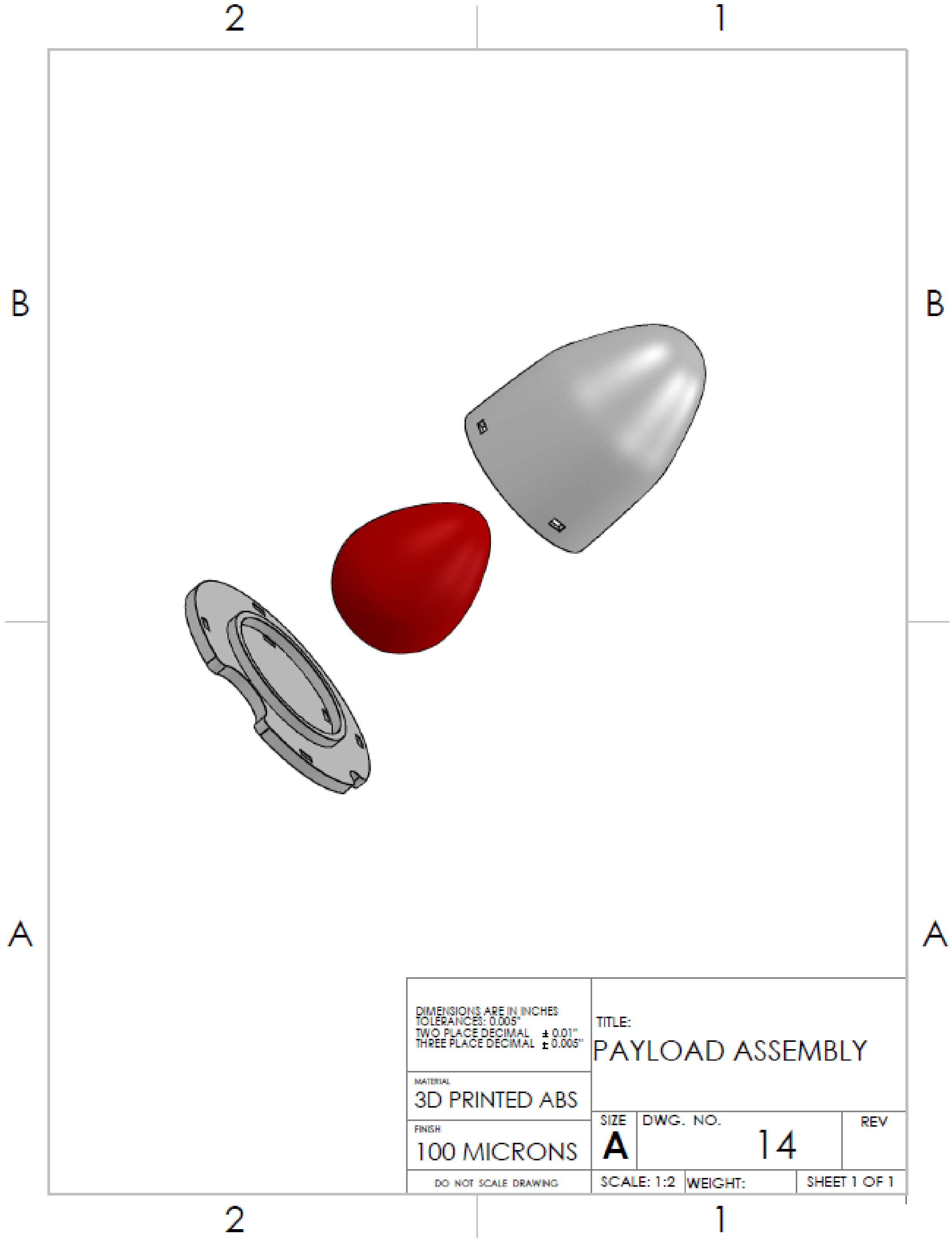
Appendix B2: Fore Body Tube



Appendix B3: Nose Cone

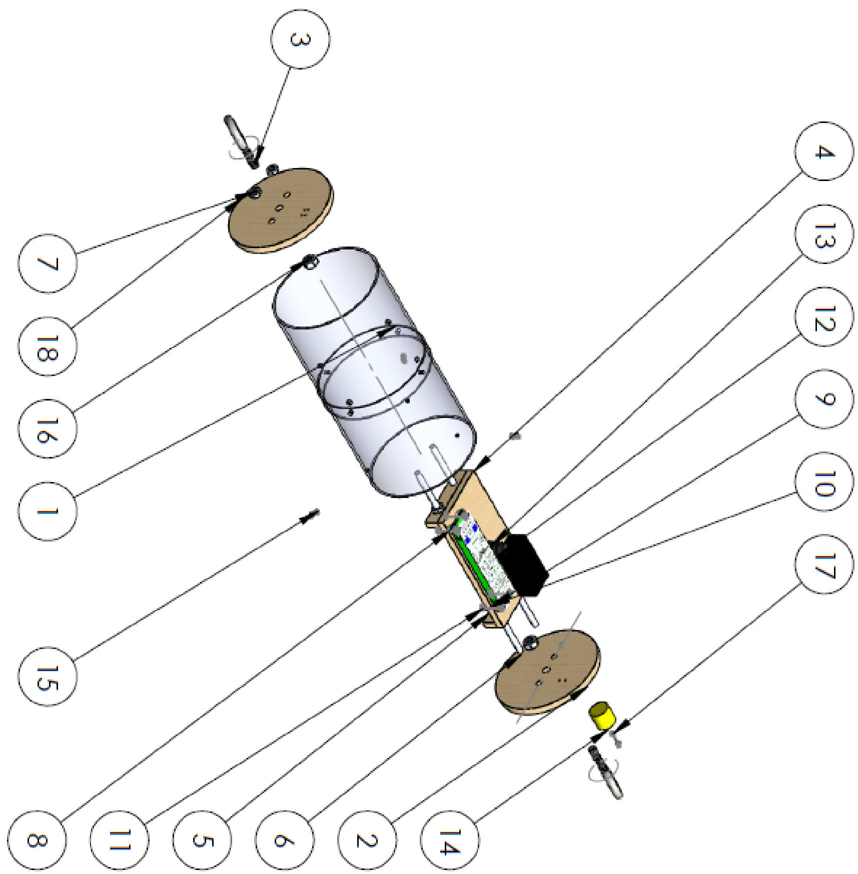


Appendix B4: Payload Assembly



Appendix B5: Ebay Assembly

ITEM NO.	PART NUMBER	QTY.
1	4in coupler_blue tube	1
2	3.75x.25 bulkhead plywood	1
3	3013T111	2
4	Sled	1
5	Sled Hole Guide	2
6	Rod	2
7	93181A411	6
8	Mock RRC3 Altimeter	1
9	96110A001	4
10	93135A278	4
11	94812A112	4
12	9V Battery	1
13	Rotary Switch	1
14	Ejection Cap_3-8	1
15	91783A077	3
16	90670A155	2
17	91735A021	1
18	3.75x.25 bulkhead plywood2	1



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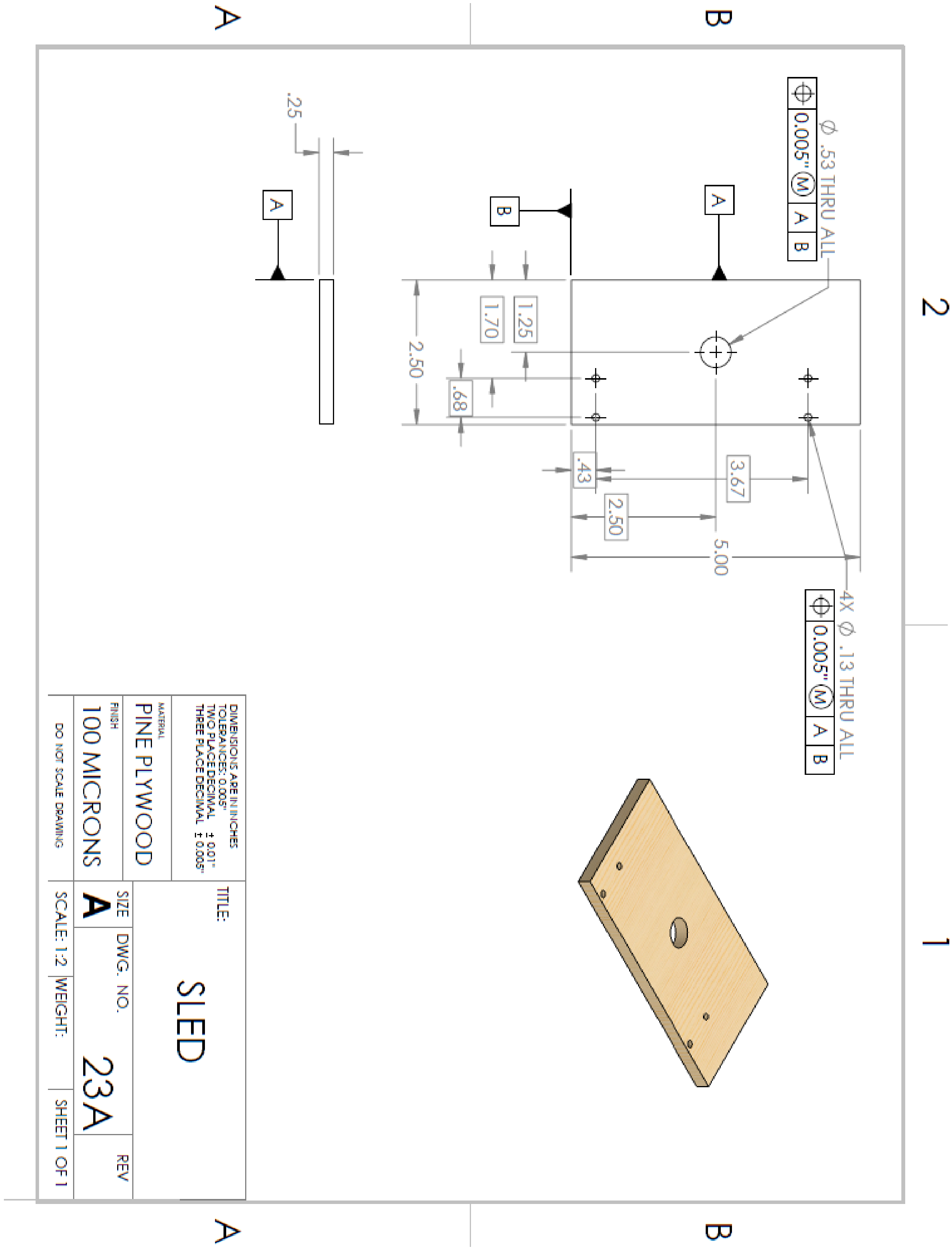
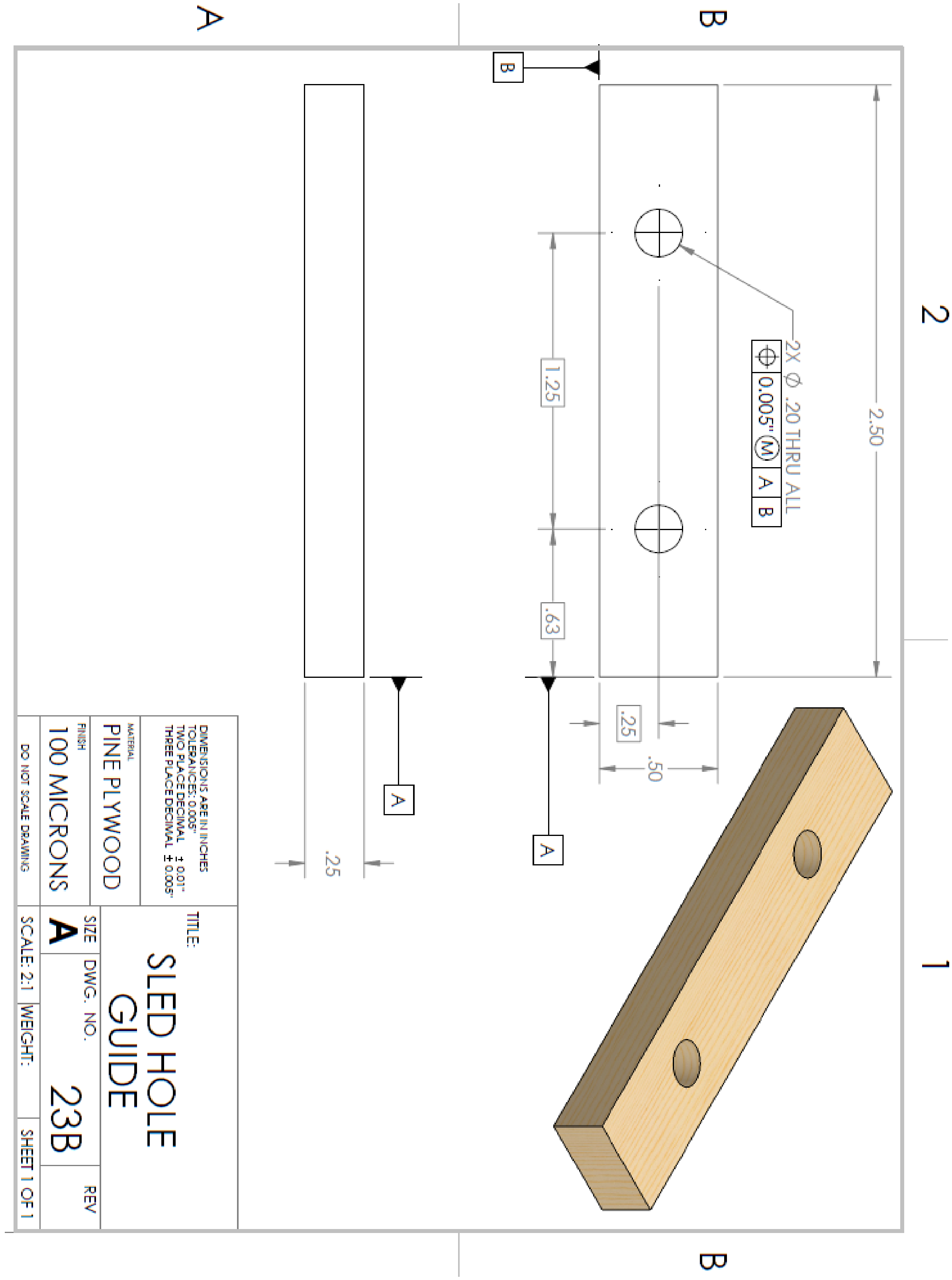
Appendix B6: Sled Base

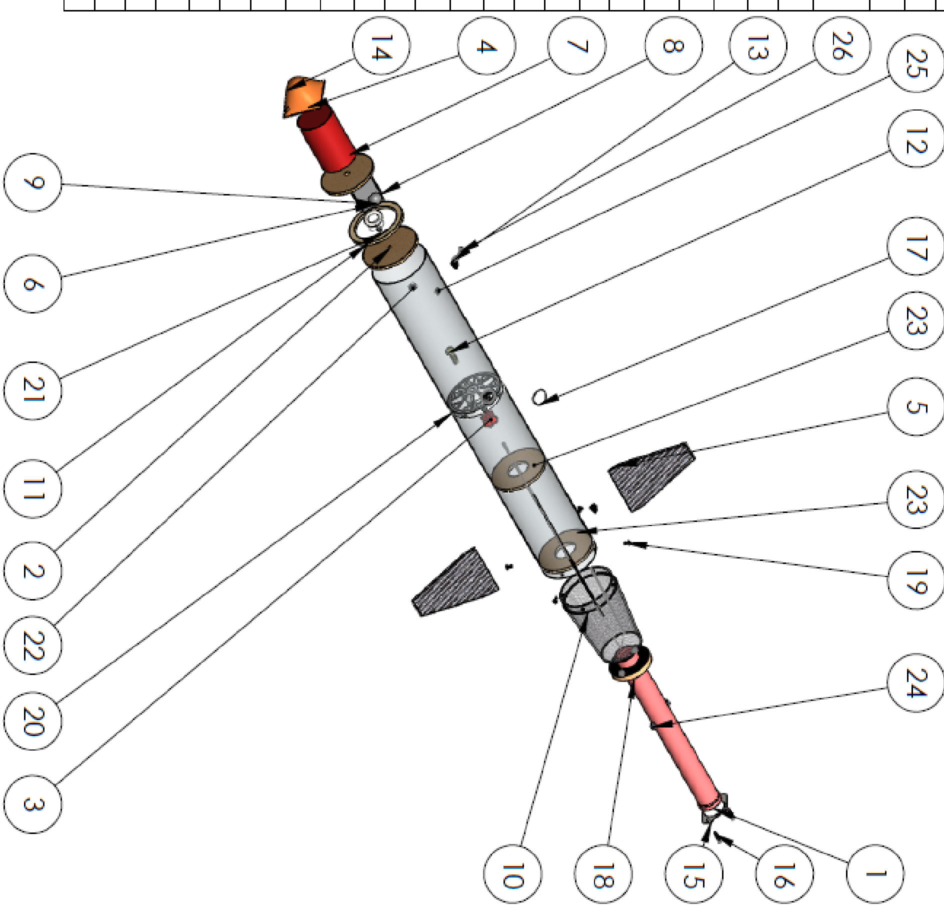


Appendix B7: Sled Hole Guide:



Appendix B8: Aft End Subassembly:

ITEM NO.	PART NUMBER	QTY.
1	I216-CL-11	1
2	Body Tube_Aft_28	1
3	Pro38 delay-ejection closure adapter	1
4	main chute mockup	1
5	Fin8	4
6	camera ring_0.21 ply	1
7	main chute platform_0.21 ply	1
8	camera backing	1
9	gopro hero 3 mockup	1
10	Tailcone_4in_1.3	1
11	aft_ply bulkhead_0.21	1
12	92941A583	1
13	airfoil rail button_1.0	2
14	nomex chute protector	1
15	tail motor retainer plate_final	1
16	98511A341	2
17	Camera window	1
18	Tailcone rear centering ring_.20 ply	1
19	removable rivet mockup	4
20	endo bulkhead_engine block 3.9	1
21	3013T111	1
22	90670A155	1
23	ply centering ring_3.9_0.21	2
24	90016A007	2
25	91831A009	1
26	91253A199	1



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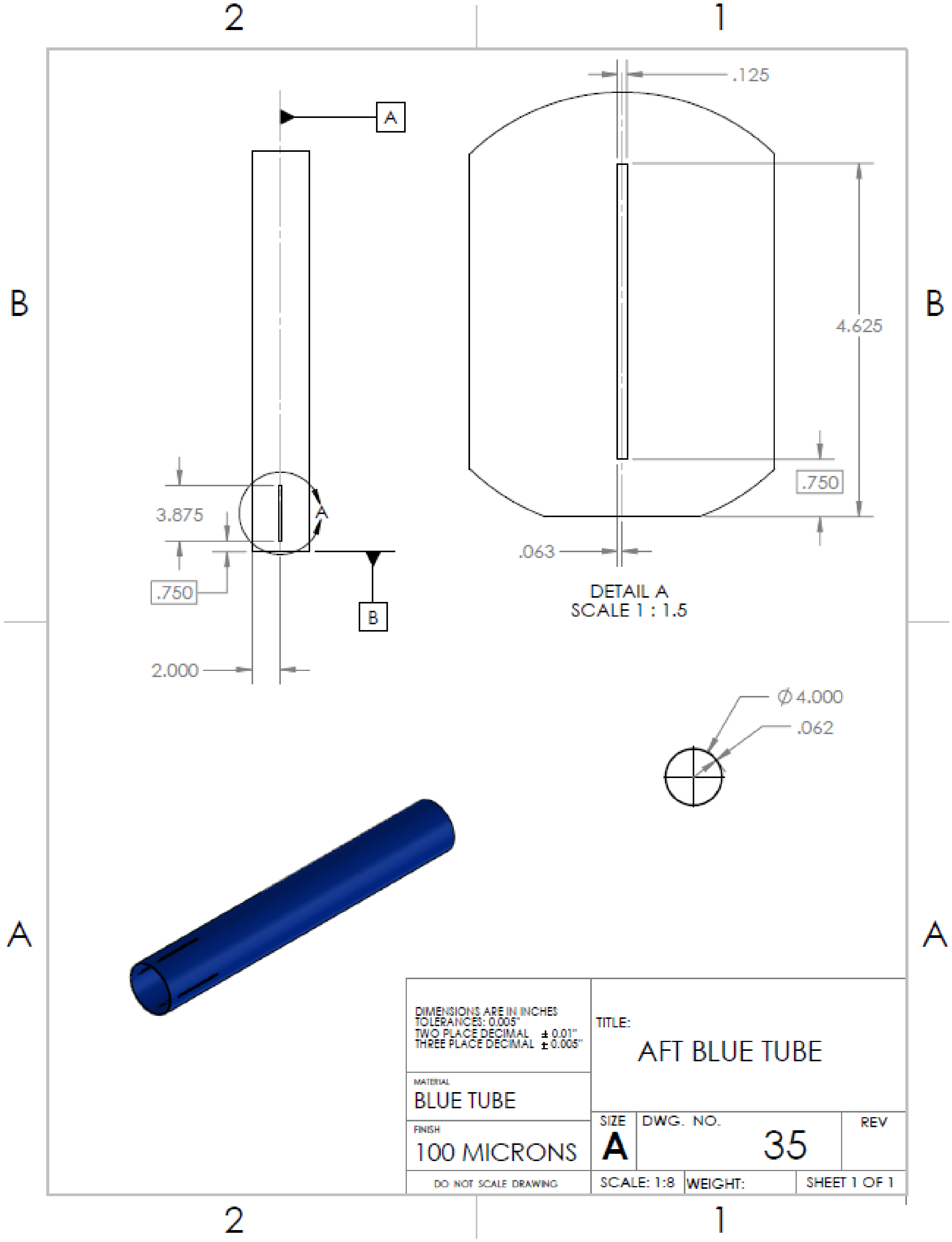
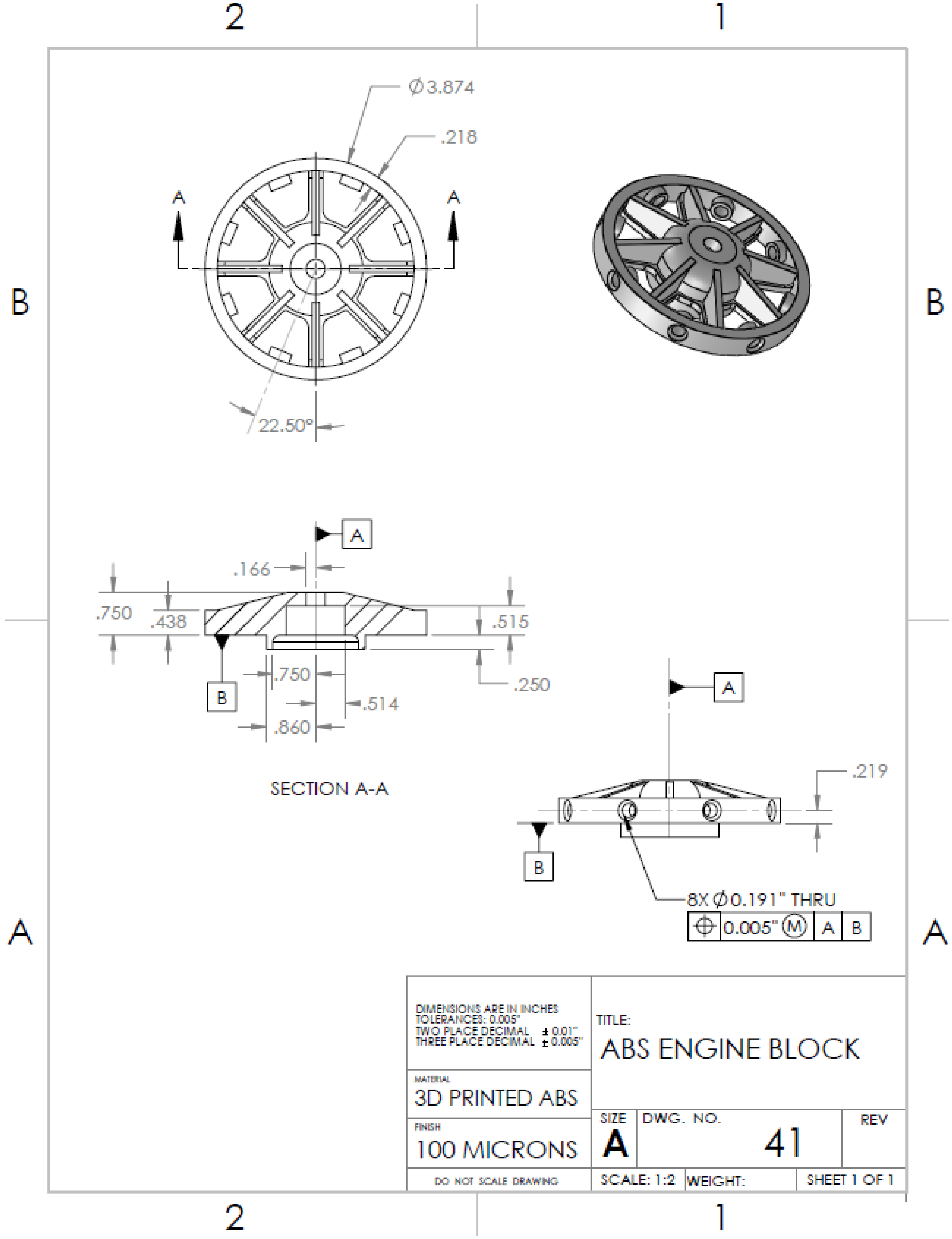
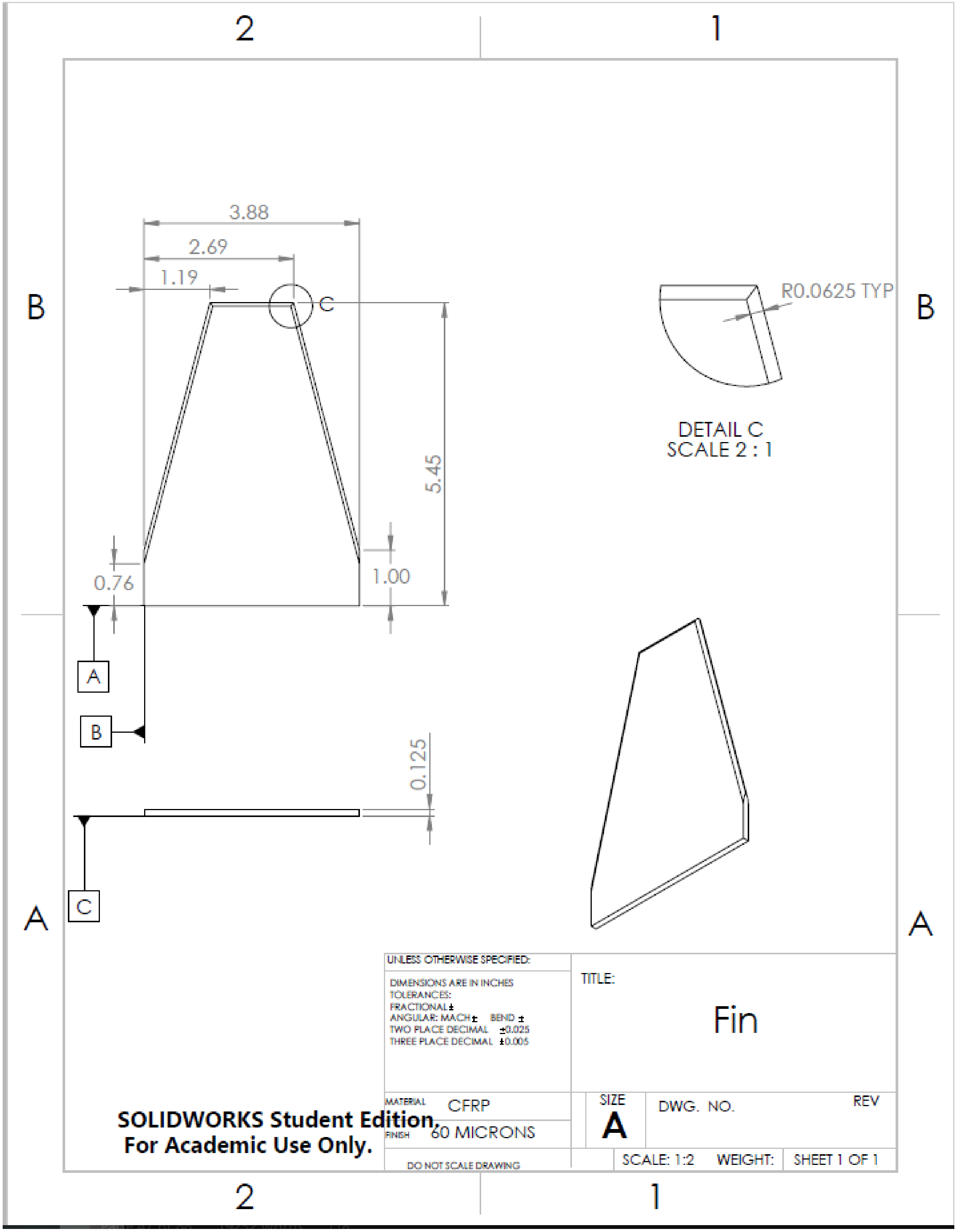
Appendix B9: Aft Body Tube:



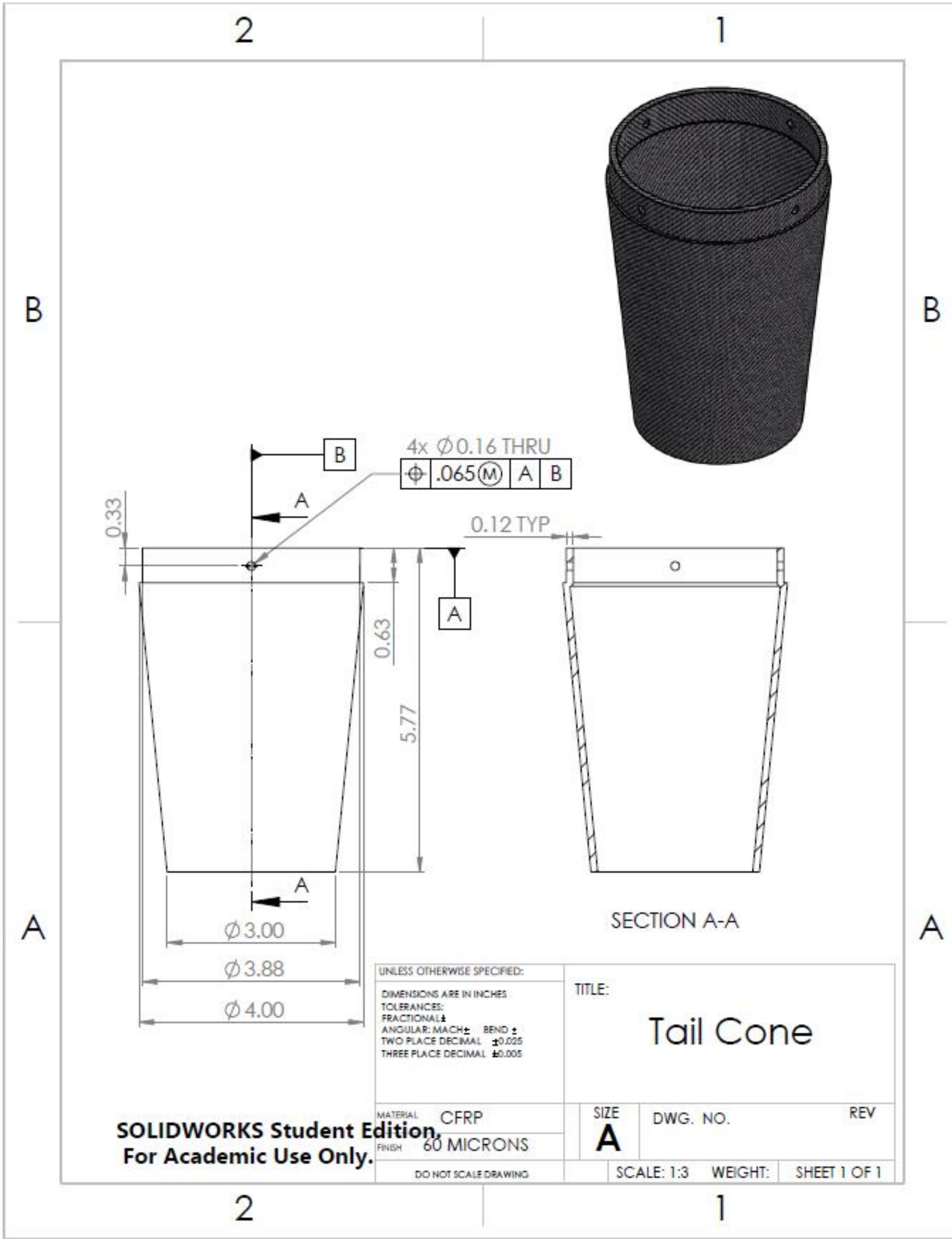
Appendix B10: ABS Engine Block:



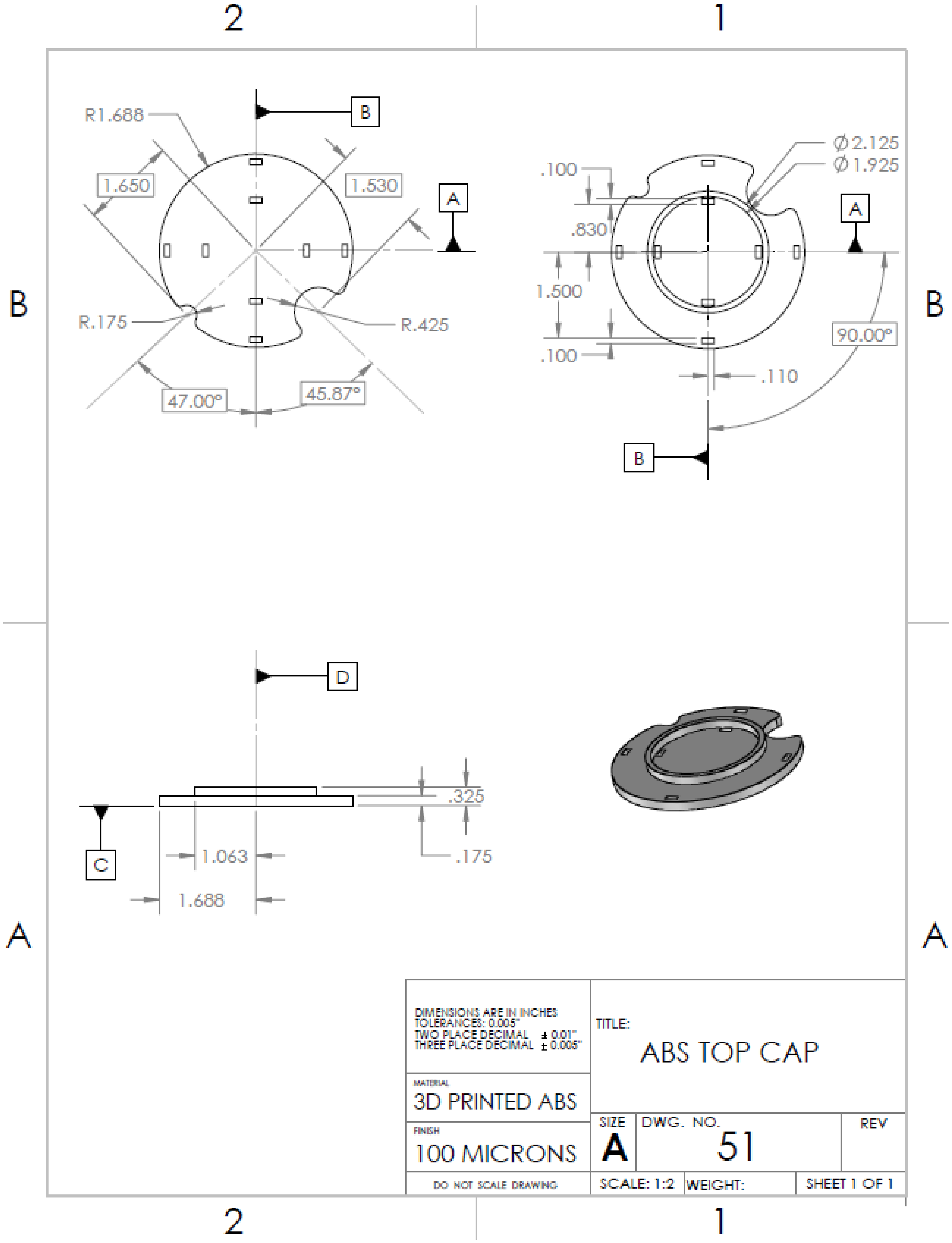
Appendix B11: CF-Balsa Fin:



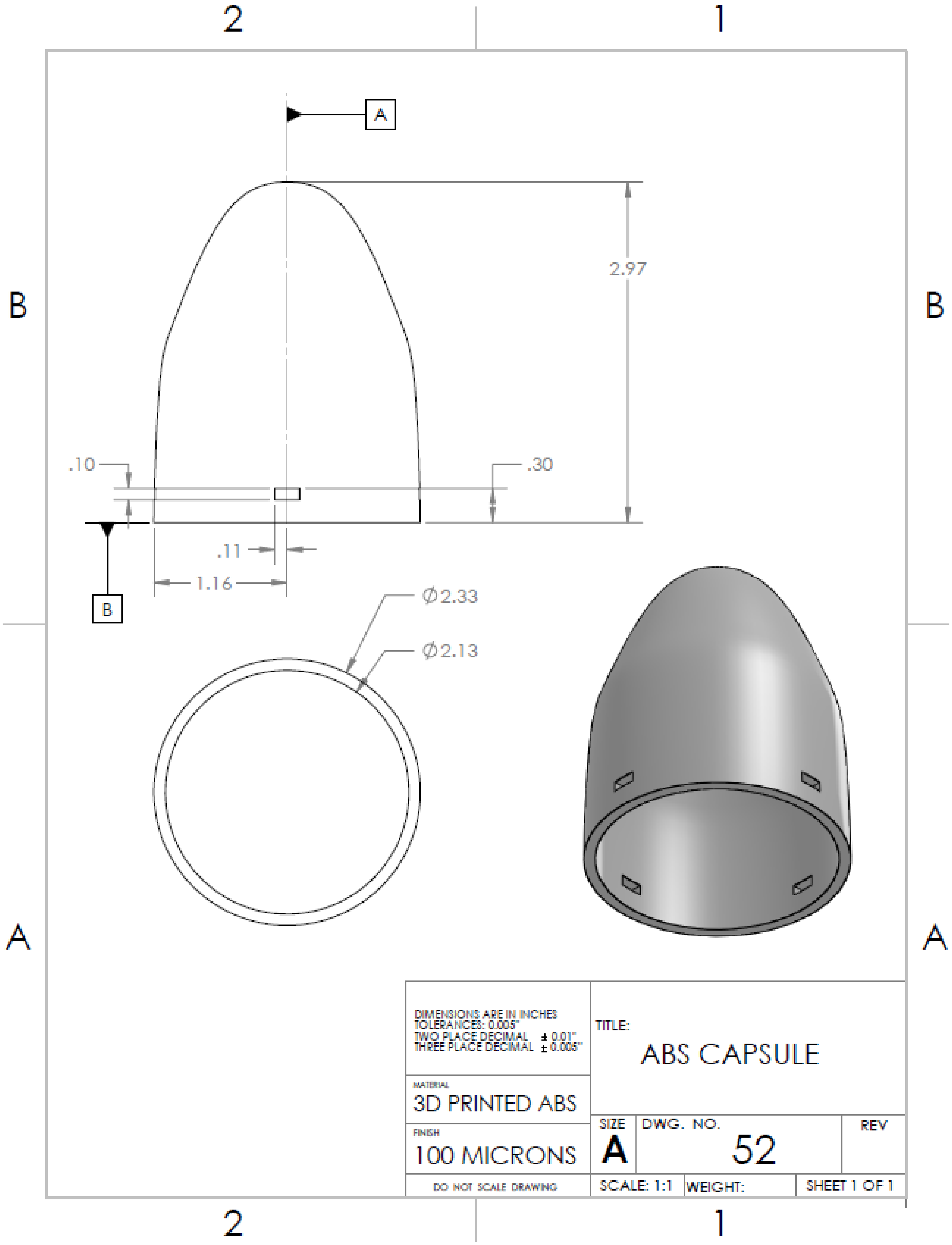
Appendix B12: Tail Cone:



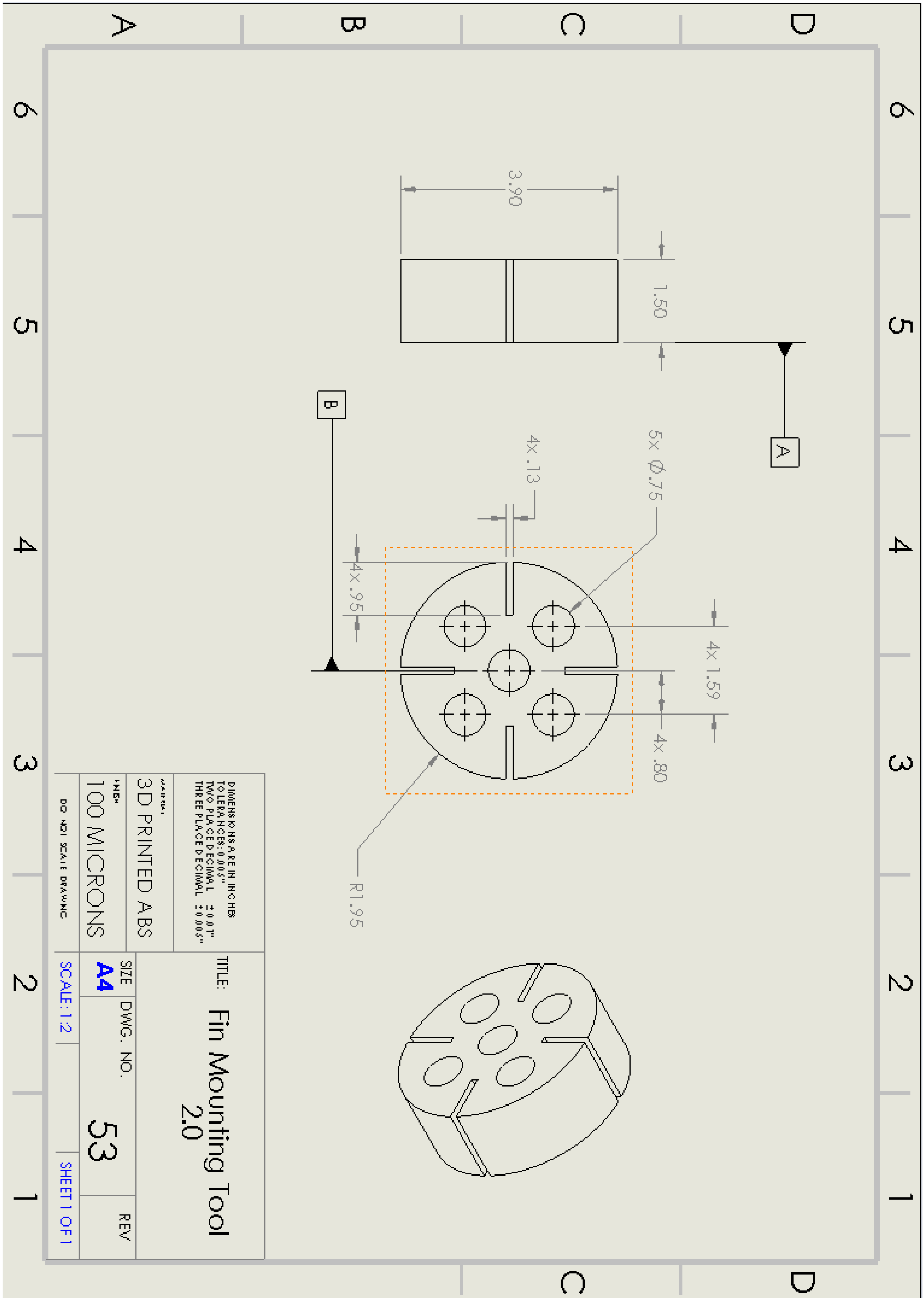
B13: ABS Egg Module Bottom Plate



Appendix B14: ABS Egg Module Capsule



Appendix B15: Fin Mounting Tooling

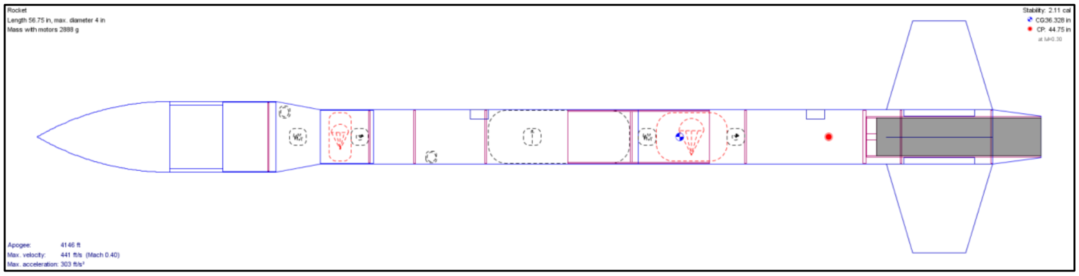


Appendix C: Design Concepts for SRR Downselect

Table 9: Selection Criteria for Concept Scoring

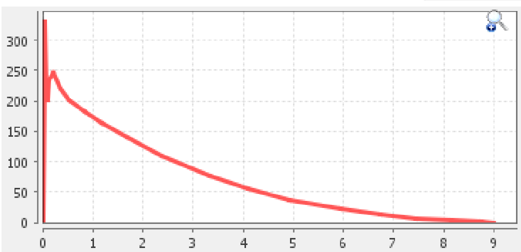
Selection Criteria	**Weight**	**Description**
Apogee	20%	Measure of how close to target apogee the rocket was simulated to achieve. Weighted at 20% because it is the primary requirement of the system.
Stability Ratio	20%	Scored based on stability ratio of design; a ratio of 2 cal scored a 5, anything below 1 scored 1, and lower scores were given to stability ratios much larger than 2 due to possible weathervaning.
Manufacturing Ease	15%	Scored based on the perceived ease of manufacturing. Weighted at 15% because, for components manufactured in-house, ability to produce parts with accuracy and precision will be vital in ensuring the flight performance.
Design Risk	10%	Scored based on predicted design challenges that may be encountered. Weighted at 10% because large design challenges could put the project behind schedule and cost more to prototype, test, and qualify and/or verify.
Cost	10%	Scored based on how inexpensive the design is, considering the motor selection, body tube material, fin material, etc. Weighted at 10% because it is a significant concern, however a more expensive critical component (altimeter, motor, etc) which significantly increases the performance is a worthy trade.
Cool Factor	7.5%	Scored based on how aesthetically exciting the design is. Weighted at 7.5% because a device a designer is proud to look at is generally one which performs well.
Testing Required	7.5%	Scored based on the amount of testing the team estimated would be necessary to fully characterize and refine the design for flight qualification (less being better). Weighted at 7.5% because is a time and budget consideration, but performance gains from innovative designs could be worth the effort.
Weight	5%	Scored based on how much the concept weighed; an excessively low or high weight was scored low, while a midpoint around 2.5-3kg was considered an ideal balance. Weighted at 5% because mass is both a driver and byproduct of rocket design.
Analysis Required	5%	Scored based on how much analysis was predicted to be necessary to characterize critical features of the design. Weighted at 5% because is primarily a time consideration.

Design A – Blue Tube/Red Lightning



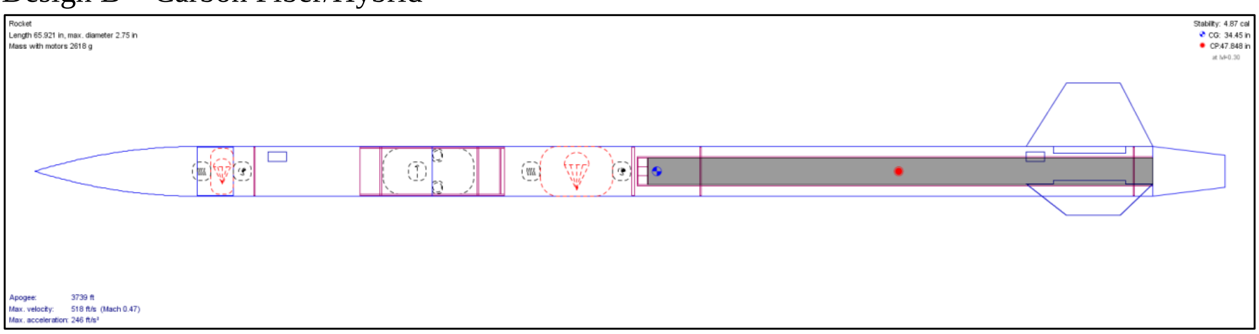
Specifications	
Stability Ratio (cal)	2.11
Primary Fuselage Material	Blue Tube
Max OD (in)	4
Min OD (in)	3
Length (in)	56.75
Launch Mass (g)	3091.3
Apogee (ft)	4034

Motor	Cesaroni 614-I100-RL-17A-11
Type	Solid
Impulse (N*s)	629 (I)
Diameter (mm)	54
Fins	
Type	Trapezoidal
Number	4



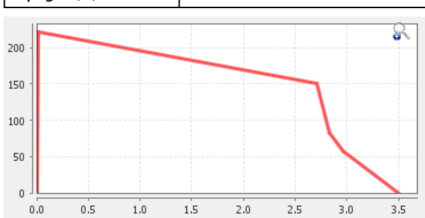
Selection Criteria	Weighted Score
Apogee	0.8
Weight	0.2
Stability Ratio	0.6
Design Risk	0.3
Cool Factor	0.3375
Manufacturing Ease	0.375
Analysis Required	0.075
Testing Required	0.15
Cost	0.5
Total Score	**3.1375**

Design B – Carbon Fiber/Hybrid



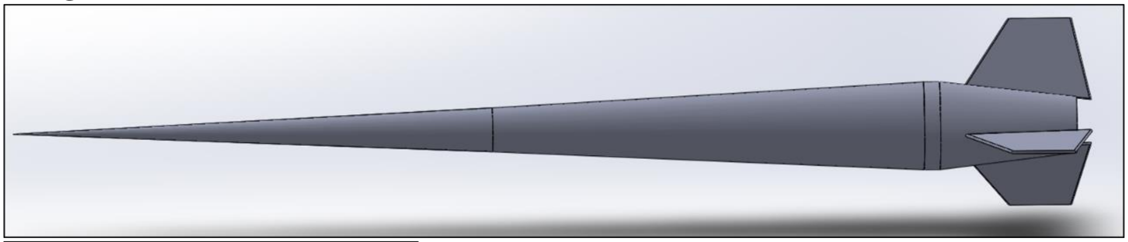
Specifications	
Stability Ratio (cal)	4.87
Primary Fuselage Material	Carbon Fiber
Max OD (in)	2.75
Min OD (in)	2.75
Length (in)	65.9
Launch Mass (g)	2764
Apogee (ft)	3661

Motor	Contrail I155
Type	Hybrid
Impulse (N*s)	544 (I)
Diameter (mm)	38
Fins	
Type	Trapezoidal
Number	3



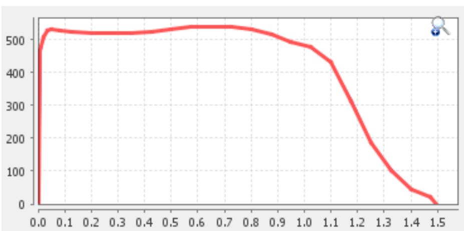
Selection Criteria	Weighted Score
Apogee	0.4
Weight	0.02
Stability Ratio	0.4
Design Risk	0.3
Cool Factor	0.225
Manufacturing Ease	0.375
Analysis Required	0.25
Testing Required	0.225
Cost	0.05
Total Score	**2.225**

Design C – Conehead



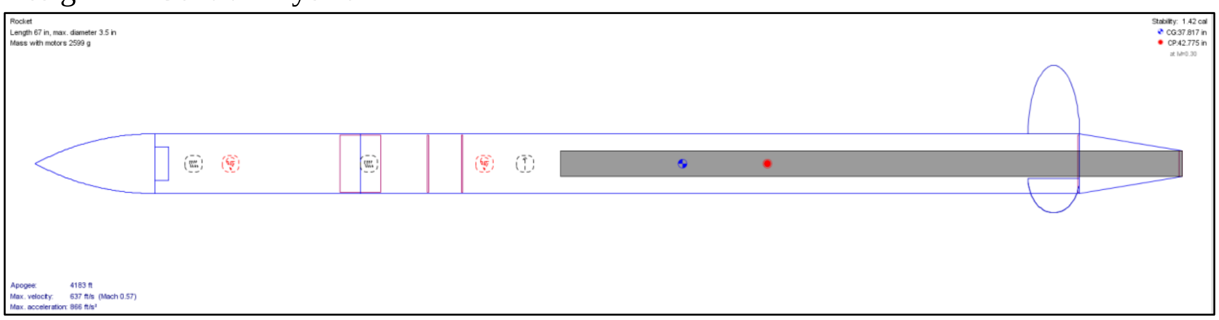
Specifications	
Stability Ratio (cal)	0.498
Primary Fuselage Material	Carbon Fiber
Max OD (in)	5.5
Min OD (in)	2.75
Length (in)	65.9
Launch Mass (g)	2100+
Apogee (ft)	Unknown

Motor	Animal Motor Works J440B
Type	Solid
Impulse (N*s)	635 (I)
Diameter (mm)	38
Fins	
Type	Trapezoidal
Number	3



Selection Criteria	Weighted Score
Apogee	0.5
Weight	0.05
Stability Ratio	0.2
Design Risk	0.1
Cool Factor	0.4125
Manufacturing Ease	0.225
Analysis Required	0.05
Testing Required	0.075
Cost	0.05
Total Score	**1.6125**

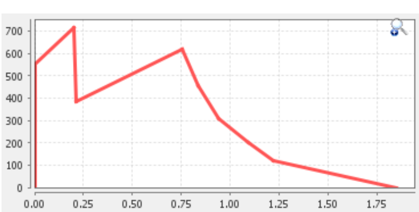
Design D – Contrail Hybrid



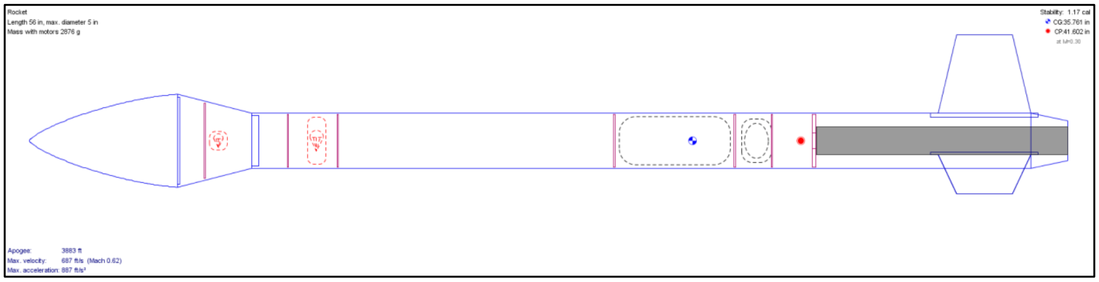
Specifications	
Stability Ratio (cal)	1.42
Primary Fuselage Material	Fiberglass
Max OD (in)	3.5
Min OD (in)	3.5
Length (in)	67
Launch Mass (g)	2599
Apogee (ft)	4183

Motor	Contrail I307
Type	Hybrid
Impulse (N*s)	586 (I)
Diameter (mm)	38
Fins	
Type	Elipitical
Number	3

Selection Criteria	Weighted Score
Apogee	0.8
Weight	0.2
Stability Ratio	0.4
Design Risk	0.4
Cool Factor	0.1875
Manufacturing Ease	0.45
Analysis Required	0.25
Testing Required	0.225
Cost	0.1
Total Score	**2.8125**

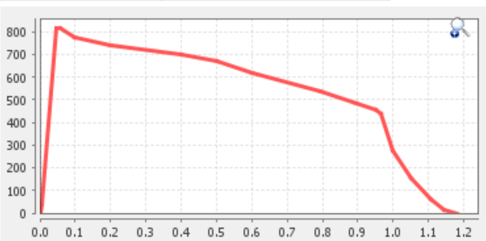


Design E – Sounding Solid



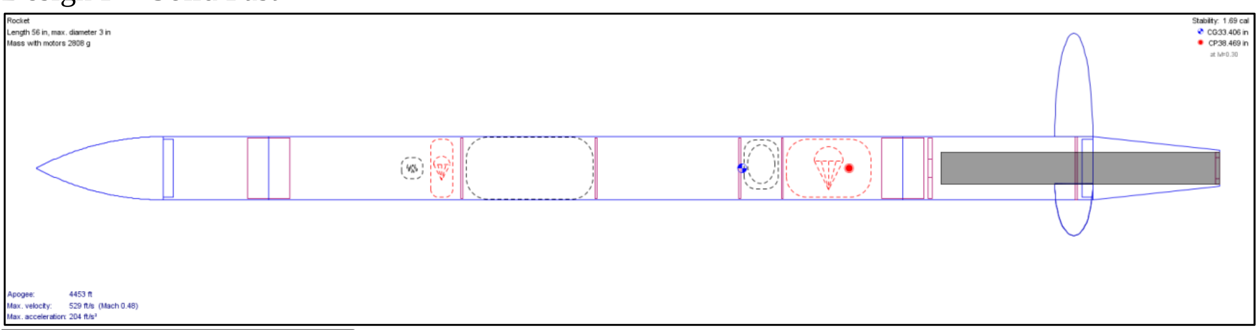
Specifications	
Stability Ratio (cal)	1.17
Primary Fuselage Material	Blue Tube
Max OD (in)	5
Min OD (in)	3
Length (in)	56
Launch Mass (g)	2876
Apogee (ft)	3885

Motor	AeroTech I600R
Type	Solid
Impulse (N*s)	640 (I)
Diameter (mm)	38
Fins	
Type	Trapezoidal
Number	3



Selection Criteria	Weighted Score
Apogee	0.7
Weight	0.2
Stability Ratio	0.5
Design Risk	0.1
Cool Factor	0.375
Manufacturing Ease	0.225
Analysis Required	0.05
Testing Required	0.15
Cost	0.35
Total Score	**2.45**

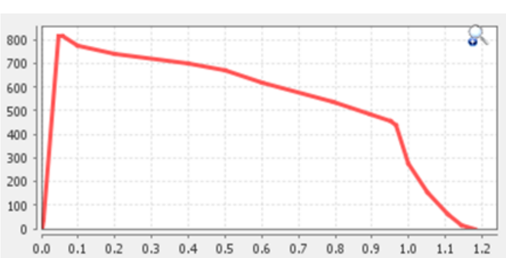
Design F – Solid Fast



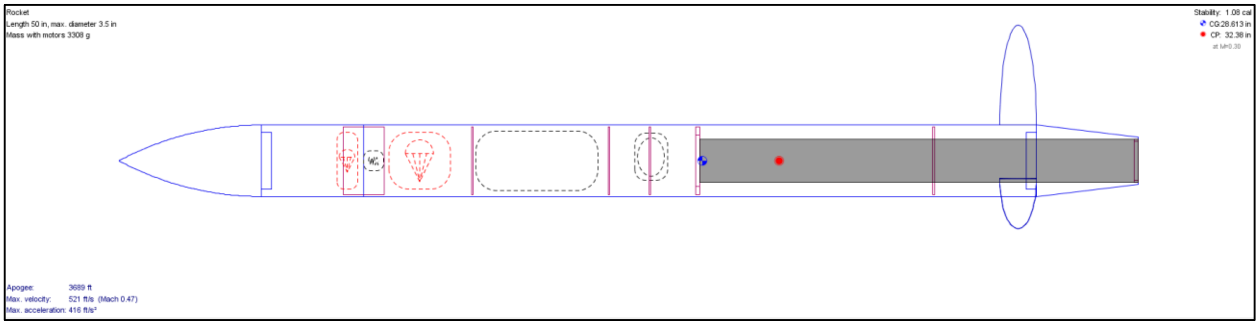
Specifications	
Stability Ratio (cal)	1.69
Primary Fuselage Material	Blue Tube
Max OD (in)	3
Min OD (in)	3
Length (in)	56
Launch Mass (g)	2808
Apogee (ft)	4453

Motor	AeroTech I600R
Type	Solid
Impulse (N*s)	640 (I)
Diameter (mm)	38
Fins	
Type	Elliptical
Number	3

Selection Criteria	Weighted Score
Apogee	1
Weight	0.2
Stability Ratio	0.6
Design Risk	0.4
Cool Factor	0.15
Manufacturing Ease	0.525
Analysis Required	0.25
Testing Required	0.3
Cost	0.35
Total Score	**3.575**

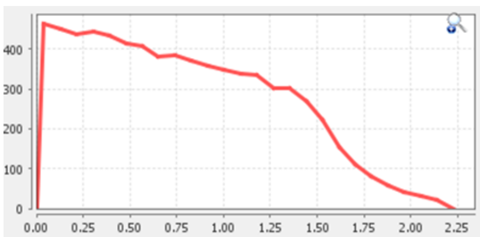


Design G – Fat Hybrid



Specifications	
Stability Ratio (cal)	1.08
Primary Fuselage Material	Carbon Fiber
Max OD (in)	3.5
Min OD (in)	3.5
Length (in)	52
Launch Mass (g)	2764
Apogee (ft)	3661

Motor	HyperTEK I310
Type	Hybrid
Impulse (N*s)	616 (I)
Diameter (mm)	54
Fins	
Type	Elliptical
Number	3



Selection Criteria	Weighted Score
Apogee	0.2
Weight	0.15
Stability Ratio	0.8
Design Risk	0.35
Cool Factor	0.225
Manufacturing Ease	0.525
Analysis Required	0.25
Testing Required	0.3
Cost	0.25
Total Score	**2.9**

Table 10: Concept Scoring Matrix Summary

Rank	Design	Total Weighted Score
1	F	3.775
2	A	3.3375
3	G	3.05
4	D	3.0125
5	E	2.65
6	B	2.425
7	C	1.6625

Appendix D: Design Requirements

Table 11: Table of Requirements and Capabilities

Requirement	**Parameter**	**Estimated Capability**	**Margin**	**Basis Of Estimate**
Rocket shall achieve an apogee of 3000'	3000 ft	3312 ft	10.4%	Analysis
All rocket requirements must comply with National Association of Rocketry standards and best practices	Comply	Comply	Comply	Design
Above requirement includes full compliance with NFPA 1125 and NFPA 1127 governing rocketry	Comply	Comply	Comply	Design
No design kits, pre-assembled sections, etc. shall be employed	Comply	Comply	Comply	Design
Exceptions to requirement of "no kits" require a written waiver - e.g., a preassembled altimeter	Comply	Comply	Comply	Design
Body diameter must be >2.61" (6.6294 cm)	2.61 in	4 in	53.26%	Design
Rocket must demonstrate full reusability	Comply	Comply	Comply	Design
Once recovered, the rocket shall be ready for re-launch in at most 1 hour	1 hr	Unknown	Unknown	Test
Rocket must utilize dual deploy recovery methods with prior successful ground testing	Comply	Comply	Comply	Design
Main parachute shall deploy between 500'-800'	500-800 ft	500 ft	Comply	Design
Rocket shall record its peak altitude	Comply	Comply	Comply	Design
Teams must use their own altimeter - no electronics bay kits allowed	Comply	Comply	Comply	Design
"I" motors are the highest impulse class motor allowed for this design project	"I" Motor Class	Cesaroni I216-CL	Comply	Design

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	N/A	N/A	N/A	Design
A minimum of 1 team member must become high-power NAR Level 1 certified prior to launch date	Comply	Scheduled for Jan. 2016	Not compliant	Certification
Detailed rocket mass budget shall be reported at all design meetings with changes well known	Comply	Comply	Comply	Analysis
CP and CG locations must be tracked throughout the design process to ensure stability	Comply	Comply	Comply	Analysis
Stability ratio shall be between 1 and 2 calibers	1 to 2 cal	1.36 cal	36%	Simulation
Firing Electronics and Launch Rails (8020) will be provided and/or shared among all groups	N/A	N/A	N/A	N/A
The rocket shall carry a payload, separate from the altimeter and flight electronics, of at least 150g but no more than 500g	150 - 500g	250g	100 %	Analysis
Payload will successfully record on-board flight video.	Comply	Comply	Comply	Design
Payload will include one egg, which must survive launch, flight, and landing intact.	Comply	Comply	Comply	Design and Test
Maximum ascent drag force shall be less than rocket weight at launch (Fd/W < 1)	7.65 lb	9.01 lb	-21%	Analysis
Requirements may be added, deleted, or amended at any time by program lead (Dan Larson)	N/A	N/A	N/A	N/A

Appendix E: Manufacturing Methods

E1: Carbon Fiber Layup Process

A carbon fiber reinforced polymer (CFRP) part is a component which is comprised of two materials: the polymer matrix, usually an epoxy, and the carbon fiber reinforcement. These components are generally fabricated in the following manner. First, a female mold and/or male plug is made from a dimensionally stable material, which may be metal, fiberglass, a machinable polymer, or whichever material suits the design at hand. On this mold a release agent is applied; this may be a thin polyethylene film, a spray-on chemical such as PVA, and/or a carnauba-based wax or similar. Crucially, the release agent does not bond chemically to the epoxy which will form the matrix of the composite piece. If a film is used, then it must be tightly secured to the shape of the mold, otherwise the dimensional accuracy and surface finish of the final piece will be compromised.

Once the release layer is applied, it is wetted with the first layer of epoxy. This application must be even and thorough, making sure the entire surface area of the mold is wetted. This is allowed to reach a “hard tack” [6]. Then, a sheet of carbon fiber reinforcement is “laid up” into the mold. This is pressed and shaped to match the mold curvature. Then, another layer of epoxy is painted onto the carbon sheet, the next layer is laid up, and the process continues until all layers are applied. In the case of a female mold, this is done in one of two ways: either sheets are inserted from a hole in a plane perpendicular to the mold parting line [6], or otherwise by laying up sheets simultaneously in the two halves of the mold and then aligning and compressing the mold to cure. After the laminate has been laid up, a series of films are placed to form a vacuum bagging setup. First, a perforated release film (perf-ply) is laid down in intimate contact with the wet laminate; the material of the film will not bond to the resin, but regular perforations control the rate of resin evacuation under vacuum. Then a fabric called peel ply is placed; the fibers of the fabric are coated with release agent, however it also allows resin through to the breather cloth which will be laid down on it. The breather cloth absorbs excess resin and provides an air path at all times for resin evacuation. On top of the breather cloth the vacuum bagging film is laid, and is sealed with chromate tape either to the plate/table on which the mold sits, or otherwise to the mold itself (depending on the geometry of the part). Prior to completely sealing the bag, a vacuum port is placed inside, and once the bag is sealed, the vacuum pump is connected and sealed, and then activated. By evacuating the air from the bag and providing a constant vacuum, the atmospheric pressure of the air (~15psi) applies even, constant pressure to all surfaces of the laminate, thus consolidating the layers and allowing excess resin to escape via the vacuum tube. This minimizes the presence of voids in the final component, as a void content greater than approximately 2% results in significant strength reduction [6]. Additionally, the side of the laminate in contact with the mold (tool side) will take the surface finish of the mold. Thus, proper surfacing of the mold is crucial to a successful composite layup. Appendix E1.1 below has the process used for the nose cone layup (which was nearly identical to that used for the tail cone).

Multiple layers of reinforcing sheet are laid up because the fiber reinforcement is strongest in the direction parallel to the fibers themselves. A single layer of a fiber-reinforced composite is highly anisotropic, exhibiting strength characteristics reduced by anywhere from a factor of 2 to a factor of 10 when stressed perpendicular to the fiber direction. Thus, in order to achieve isotropy or quasi-isotropy, multiple sheets of fiber are laid up in different directions (in reference to the loading axis).

For the nose cone and tail cone, the female mold process is utilized. The molds were machined from a high-density, closed-cell urethane foam (Precision Board PBLT-18, 18 lb/ft^3 density). They were surfaced with a polyester primer-filler (Evercoat Featherfill G2, gray) sprayed from a HVLP spray gun. The primary mold surface was sanded with 220, 320, 400, 800 (wet), 1000 (wet), 1200 (wet), and 2000 (wet) grit sandpaper. The other faces of the mold were sanded to 220. The molds were released by applying 2 coats of release wax, followed by a spray-on layer of PVA. In order to guarantee even distribution of the PVA layer, the molds were stood upside down and the excess allowed to drip off. See Figure 26 and Figure 27 for reference. The matrix resin is a vinyl ester resin (Hexion 784-7978 VER) which uses a PEEK catalyst at 1.25% by weight concentration. The carbon fiber reinforcement are bidirectional carbon fiber sheets between 0.010 and 0.030 thick, donated by Advanced Digital Manufacturing LLC (Santa Ana, CA). See Appendix B for drawings of the final mold shapes. The layup pattern for the nose cone is [0-90/±45/90-0], and for the tail cone is $[0\text{-}90/\pm45]_s$. Additionally, while the unbalanced layup on the nose cone is not ideal, the performance was more than adequate for the flight required, as the rocket was not be subjected to supersonic speeds and the resultant loading and heat.

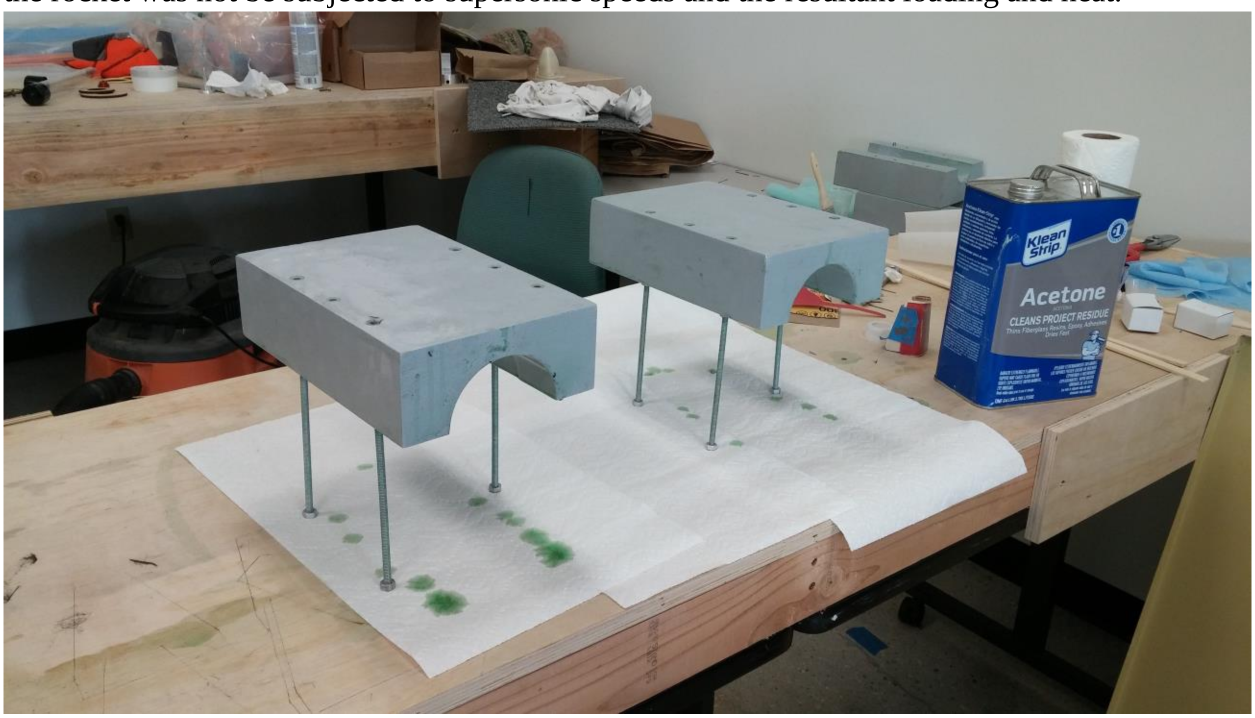


Figure 26: Positioning of molds while PVA layer drying.

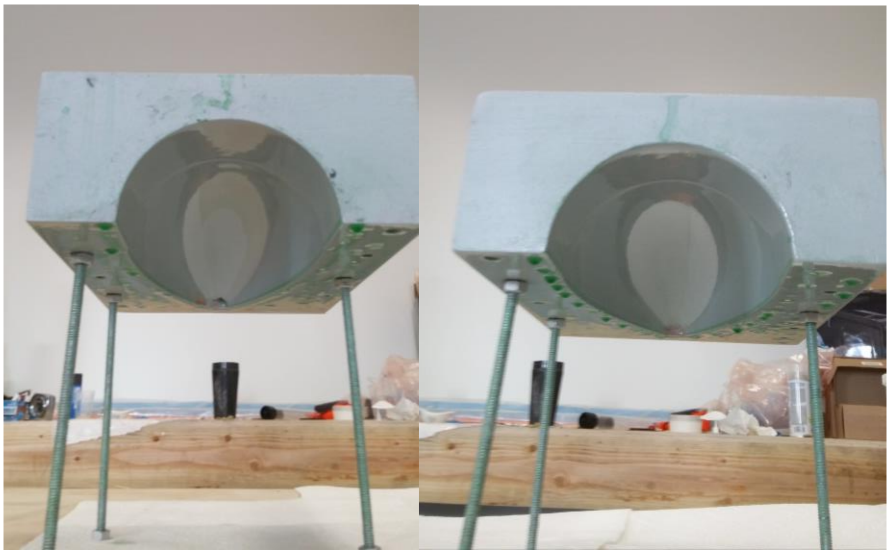


Figure 27: Detail view of primary mold surfaces of nose cone mold during PVA drying.

E1.1: Nose Cone Layup Process

Materials Required:

- 4x .02 bidirectional CF sheets cut to mold
    - 2x w/approximately 0.5in excess tab
    - 2x cut approximately 0.25in short
- 2x peel ply sheets cut in trapezoidal shapes, with two short cuts in the long base end.
- 2x perf ply sheets, cut to mold shape.
- 1x breather cloth, cut in hourglass shape
- 1x vacuum bag approximately 50"x50", cut and seamed with sealant tape as required (see Figure 28).
- 8 fl oz vinyl ester resin and corresponding catalyst (1.25 wt% of resin amount)
- Properly surfaced and prepared molds
- Release wax
- PVA film
- HVLP spray gun
- Disposable brushes (1”-2”) and paint spreaders

PPE Required:

- NIOSH organic vapor respirators
- Chemical splash goggles
- Nitrile gloves (2 pairs recommended)

Procedure:

1. Apply 2 coats of release wax to ALL solid components of layup. This includes the plate, the threaded rods, the nuts, the pins, all surfaces of the mold that are accessible.
2. Spray a coat of PVA with the HVLP gun to ensure redundancy of mold release.
3. Use masking tape to preposition two sheets of peel ply, one for each half, on the tail end of the mold, ready to be folded in.
4. Perform the wet layup. Do not fold in the seam tab yet.
5. On both halves, fold in and wet out the peel ply.
6. On both halves, add and wet out perf ply on top of the peel ply.
7. Carefully mate the 2 halves, and spread the seam into the other half. Secure the two halves with the threaded rod and nuts, making sure no carbon fiber is caught between the mating surfaces.
8. Insert extra pieces of peel ply if necessary to cover any exposed laminate.
9. Insert the breather cloth and unfold.
10. Tape pieces of breather cloth around the exposed nuts to protect the vacuum film.
11. Lay the sealant tape in a square on the plate, around the mold. Do not remove the backing.
12. Insert the bag into the mold cavity. Carefully pull the corners outside the mold into folds and down to the plate.
13. Insert the bottom half of the vacuum port on a folded piece of breather.
14. Begin removing the backing on the sealant tape and securing the bag. At each corner of the bag (on the diagonal of the mold), place a dog ear to seal.
15. Any remaining unforeseen seams, seal with sealant tape.
16. Cut slit in bag over vacuum port, insert other half, seal, and pull vacuum. Ensure that bridging in the mold cavity is minimized, although some folding of the bag is desired.
17. Allow 8-10 hours for cure.
18. To remove, cut bag film away and remove all films from bag interior.
19. Carefully undo nuts on molds, and very carefully separate molds. If released properly, the part should come out with only a little resistance.
20. Inspect part and molds for damage.
21. Trim any excess with a dremel tool (holding a shop vac close to cutting head to minimize airborne CFRP particles), and sand any irregularities.
22. If desired, spray clear coat to finish.

Figure 28: Vacuum bag setup for nose cone layup; notice the bag has been seamed along the diagonals, in order to approximate the interior curvature of the mold. Additionally note the multiple dog ears in order to guarantee vacuum seal.

E2: Recovery system wiring block diagram

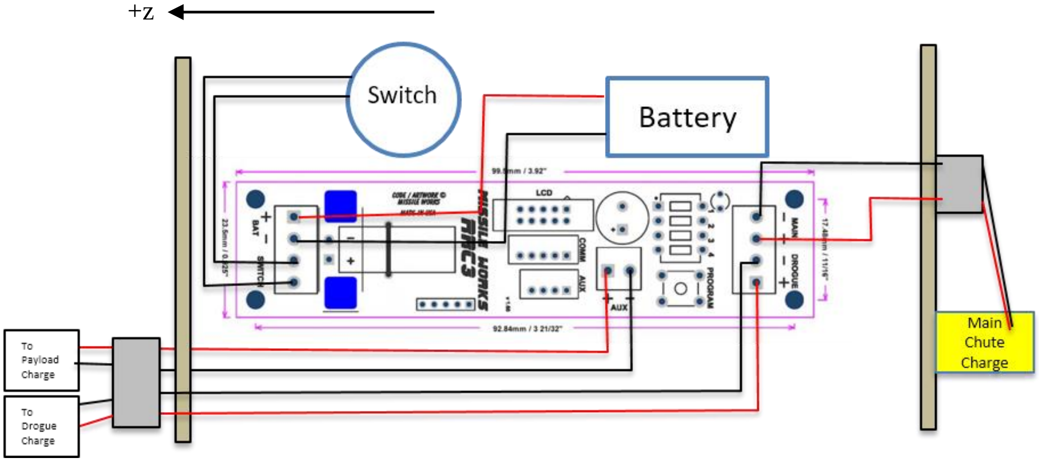


Figure 29: Functional wiring schematic for altimeter

E3. Ejection Charge Preparation

After ejection testing, the method of packing ejection charges was updated. Unlike originally planned, the charges were assembled independently from the ejection caps. The new methodology was as follows: 1) Cut fingertip off of thick disposable rubber glove 2) Place e-match tip all the way against the inside of the glove fingertip 3) Pour measured black powder into fingertip 4) Use electrical tape to secure, ensuring that it is tight and e-match is in contact with black powder 5) Once e-match is wired up, use masking tape to secure packed charge into proper ejection cap. A diagram of a packed charge can be seen in Figure 30 below.

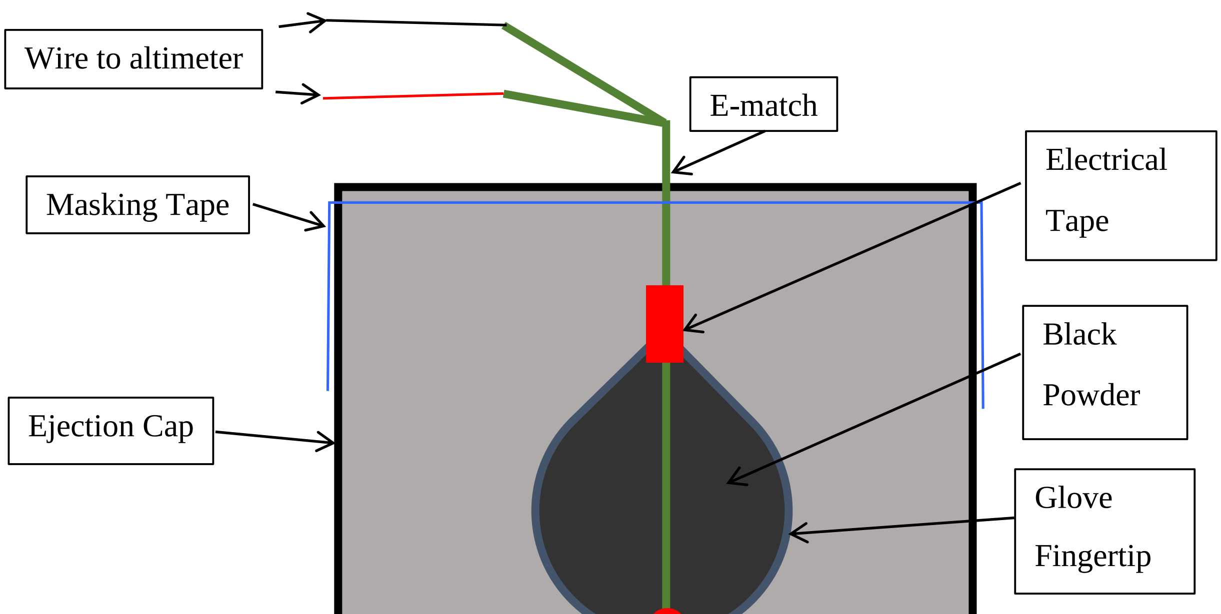


Figure 30: Ejection charge preparation schematic

Appendix F: Analysis

Appendix F1: BACKGROUND

Model rocketry is a popular hobby across the United States, with the National Association of Rocketry (NAR) boasting over 5900 members across 165 clubs across the country [1]. The model rocket industry started in the 1950's in order to provide safe and professional rocket equipment to amateur rocketeers and to create a venue to inspire and educate the next generation of American rocket scientists.

High power rocketry is a variation of this hobby, usually pursued by adult hobbyists, utilizing rockets which have an impulse of greater than 160 N-s, and rockets which generally are over 2" in outer diameter and weigh several pounds. High power rocketry is regulated by National Fire Protection Act (NFPA) 1127, which states [3]:

A rocket exceeds the definition of a model rocket under NFPA 1122 and becomes a High Power rocket under NFPA 1127 if it:

- Uses a motor with more than 160 Newton-seconds of total impulse (an "H" motor or larger) or multiple motors that all together exceed 320 Newton-seconds;
- Uses a motor with more than 80 Newtons average thrust [2];
- Exceeds 125 grams of propellant;
- Uses a hybrid motor or a motor designed to emit sparks;
- Weighs more than 1,500 grams including motor(s); or
- Includes any airframe parts of ductile metal.

In addition, a rocket exceeds the definition of a model rocket under FAA rules (FAR 101.22) if weighs more than 1500 grams (53 ounces).

F1.1 Rocket Dynamics

Like any object moving at a meaningful relative speed through a fluid (i.e. an airplane), a model rocket is subjected to the forces of weight, thrust, lift and drag during its flight (Figure 1). The weight, drag and lift forces are determined by the design of the rocket assembly.

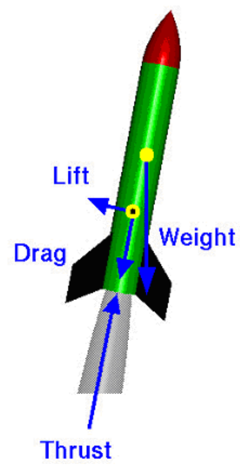


Figure 31: Primary inertial and aerodynamic forces acting on a rocket

The thrust is provided by a rocket motor which can be purchased online or at local stores. For this project, the rocket motor is required to comply with the high power rocketry standards and an "I-class" motor was selected. The designation is based off the thrust force the motor can provide and ranked alphabetically, with "A" being the lowest impulse class available and "O" the highest. The thrust (*T*) a rocket motor can provide is defined by the thrust equation, which is a more specific version of Newton's second law of motion. It is dependent on mass flow rate ($\dot{m}$), velocity (*u*) and pressure (*P*) in the following manner:

$$T = \dot{m}(u_e - u) + A_e(P_e - P_a) \quad (1)$$

Where the subscript e represents the motor exhaust condition and the Pa is the atmospheric pressure surrounding the rocket.

In order to achieve a set altitude, which for this project is set at 3000' feet, the rocket must achieve a specific change in momentum per unit mass (Δv) that can be calculated by:

$$\Delta v = I_{sp} g_0 \ln\left(\frac{m_f}{m_i}\right)^{-1} \quad (2)$$

Because of this equation, the maximum velocity the rocket can achieve is dependent on the weight, the g_0 represents the gravitational acceleration, which can be assumed constant as the apogee requirement is relatively low. The logarithmic term is driven by the ratio of final (at the end of engine burn) to initial mass (fully loaded rocket). The Specific Impulse I_{sp} is a parameter given by the rocket motor manufacturer and it is defined as the time it takes to burn one unit mass of propellant while producing one unit force of thrust. This is defined as the ratio of thrust to fuel mass flow rate:

$$I_{sp} = \frac{T}{\dot{m}_e} = \frac{u_e}{g_0} \quad (3)$$

During the launch of a rocket, the forces counteracting the thrust are weight and drag. Weight is simply determined experimentally or analytically, and the sum of all the masses present in the rocket multiplied by the gravitational acceleration on Earth's surface.

Drag depends on the density of the air, the square of the velocity, the air's viscosity and compressibility, the size and shape of the body, and the body's inclination to the flow. In general, the dependence on body shape, inclination, air viscosity, and compressibility is complex. In order to deal with such dependencies, a single variable is defined as C_d, or drag coefficient. This allows collecting all the effects, simple and complex, into a single Drag Force (*D*) equation:

$$D = C_d * A * \frac{1}{2}\rho u^2 \quad (4)$$

For given air conditions, shape, and inclination of the object, a value for C_d must be defined to determine drag that includes pressure drag and skin friction drag. Drag coefficients are almost always determined experimentally but an analytical approach is outlined in section 2.7. The area *A* given in the drag equation is given as a reference area, which depends on the shape and size of the body. For a rocket, the principal cause of drag is the resistance of the fluid (air) it is flying through. Therefore a logical choice is the frontal area of the body that is perpendicular to the flow direction. A more detailed analysis can be found in Appendix F.

Similar to Drag, the Lift Force (L) is also dependent on the same parameters. The main difference is that in the case of the rocket the lift force is caused by the fins and acts on the rocket as a restoring force. It makes sure the rocket does not deviate much from perpendicularity to the horizon during its ascent. Again, the dependencies are characterized in a single variable, the lift coefficient, designated "C_L." This allows for the collection of all the effects, simple and complex, into:

$$L = C_L * A * \frac{1}{2}\rho u^2 \quad (5)$$

These parameters drive the design of the aerodynamic components such as nosecone, tailboard and fins as it can be seen in the design section 1.7.

Appendix F2: FMEA

Dual Deployment System Failure Modes

Potential Failure Mode	**Parachute failure to deploy**	**Parachute fouls on deploy**	**Ejection charge damages rocket**
Potential Failure Effect	Partial or complete ballistic landing	Partial or complete ballistic landing	Parachute damage resulting in either decrease or loss of parachute function
Severity	9 - Danger to those on the ground, potential for significant damage to all rocket components	9 - Danger to those on the ground, potential for significant damage to all rocket components	9 - Danger to those on the ground, potential for significant damage to all rocket components
Potential Causes	2) Altimeter failure 3) Ejection charge failure (either to ignite or break shear pins)	1) Uneven break of shear pins 2) Fore tube interference (main chute) 3) Poor folding of parachute 4) Excessive rocket velocity at deployment	1) Excessive quantity of black powder 2) Incorrect placement of parachute heat shield
Occurrence	8-Successful parachute deployment requires interaction of 3 systems	3-Rocket is designed for clean section break and avoidance of tube interference. Poor folding is due to human error, and excessive velocity occurs only as result of altimeter delay/failure	3- Charges are carefully measured, and heat shield is easy to position correctly
Current Detection and Prevention	Ground testing of ejection charges, altimeter and dual deployment system	Testing will be done of entire system to ensure that parachute is ejected from body tube cleanly and opens properly at flight events.	Check for proper heat shield placement and proper ejection charge preparation.
Detectability	5-All components except for parachutes can be tested on the ground immediately before launch	3-All components can be tested, and ejection tests can be performed immediately before launch. Obstructions and/or poor packing can be easily seen	3- Poor packing can be easily seen
Risk Priority Number	360	81	81

Future Action	Ground test of dual deployment system	Ground test of dual deployment system	Ground test of dual deployment system

Motor Failure modes

Potential Failure Mode	**Motor Retention Failure**	**Catastrophe At Take Off (CATO)**	**Loss of control in flight**
Potential Failure Effect	Rocket disintegration, motor loss, resulting in partial or complete ballistic landing	Rocket disintegration and explosion on ground, danger to all persons near launch pad	Erratic flight path, unpredictable landing area, possible ballistic landing
Severity	9 - Danger to those on the ground, potential for significant damage to all rocket components	9 - Danger to those on the ground, potential for significant damage to all rocket components	9 - Danger to those on the ground, potential for significant damage to all rocket components
Potential Causes	1) Improper motor mounting or alignment 2) Engine block fracture	1) Improper motor mounting or alignment 2) Manufacturing fault	1) Improper motor mounting or alignment
Occurrence	5 – Engine block was tested and withstands 400 lb.	2- Mentioned as a concern on rocketry forums. Cesaroni motor selected has good reputation for being highly reliable	3 - Bulkheads can fail and the motor can move inside the rocket, therefore not firing along the axis of the rocket
Current Detection and Prevention	Motor retention was tested for tensile strength	1- No prevention mechanism	Stability margin between 1.3 and 1.6 for turbulent weather
Detectability	3 - Engine block design was proof-tested during prototyping phase, Cesaroni has a reputation for highly reliable motors	9- No detectability prior to flight	2 - Motor retention and alignment components will be visually evaluated upon test
Risk Priority Number	135	81	54
Future Action	Fatigue and thermal testing of engine block	No further future action predicted	No further future action predicted

Miscellaneous Failure Modes:

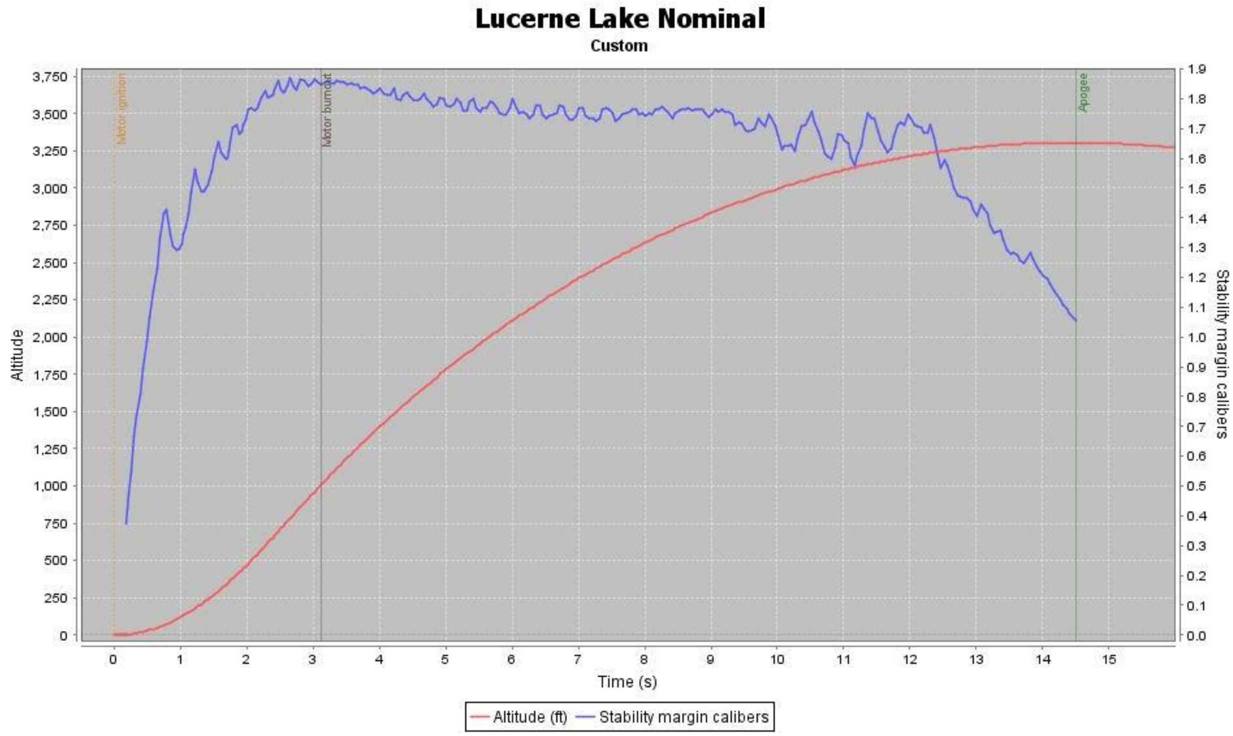
Potential Failure Mode	**Payload Recovery Failure**	**Tailboat and Fin Damage**	**Atmospheric Interference**
Potential Failure Effect	Fail to eject from the rocket or catastrophic landing of the payload	Failure of reusability requirement	Failure to meet target apogee altitude
Severity	8 - Failure to meet "intact egg" requirement.	8 - Failure of reusability requirement	5- Severity depends on day weather conditions
Potential Causes	1) Ejection charge failure (either to ignite or break shear pins) 2) Incorrect parachute deployment	1) Incorrect main parachute deployment 2) High ground impact velocity	1) Relatively strong turbulent winds 2) Launching at non-zero angle of attack
Occurrence	8- Successful ejection requires interaction of 3 systems and correct parachute deployment	5 - Fin and tailboat cracking and/or breakage is a frequent event at rocket launches	8- Weather conditions change from day to day.
Current Detection and Prevention	Ground testing of ejection charges, altimeter and egg system	Carbon fiber design fins and tailboat are highly impact resistant	1.3 to 1.6 stability margin even if the CP moves closer to the CG at angles of attack beyond 5 degrees
Detectability	5 - Ground testing performed on flight article so as to identify and rectify any issues with charge sizing, parachute fouling, shear pin separation, and egg impact protection	3 – Visual inspection of fin and tailboat manufacturing quality	3- Thorough aerodynamics analysis can establish the rocket performance under different adverse scenarios
Risk Priority Number	320	120	120
Future Action	Ground test of egg deployment system and drop test of egg module	Proper carbon fiber layup when manufacturing	Extensive simulations will be conducted on ANSYS to ensure apogee is achieved under any reasonable weather conditions

Appendix F3: Wind Sensitivity Analysis

Launch day atmospheric conditions can affect the aerodynamic performance of the rocket and subsequently impact the achievement of the 3000' target apogee. As mentioned in the flight profile (section 1.9), the duration of the flight will oscillate between 120 and 130 second. The ascent of the rocket is completed in a short period of time, nominally around 14 seconds, and therefore any interference of local wind, atmospheric pressure and atmospheric moist conditions can greatly impact the main first design requirement. Designing rocket hardware to allow for quick adjustments to aerodynamics, lift and drag during ascent is not a viable option for such high power rocket as weight and cost are strict design drivers. For this reason, Open Rocket was utilized to predict the behavior of the rocket in different environmental conditions. In the high power rocketry world, Open Rocket is considered reliable software to simulate the impact of local conditions on launch day on the flight profile. However, it was also reported that often these predictions have a ~10% overestimate, so apogee targets were adjusted accordingly. The simulations tool within Open Rocket was reported to be reliable and it was therefore confidently used to predict the Ascanius rocket performance during flight. It must be noted that these parameters are not final and are contingent upon measurements made once the physical assembly is completed. In particular the factors that most impact the flight profile are:

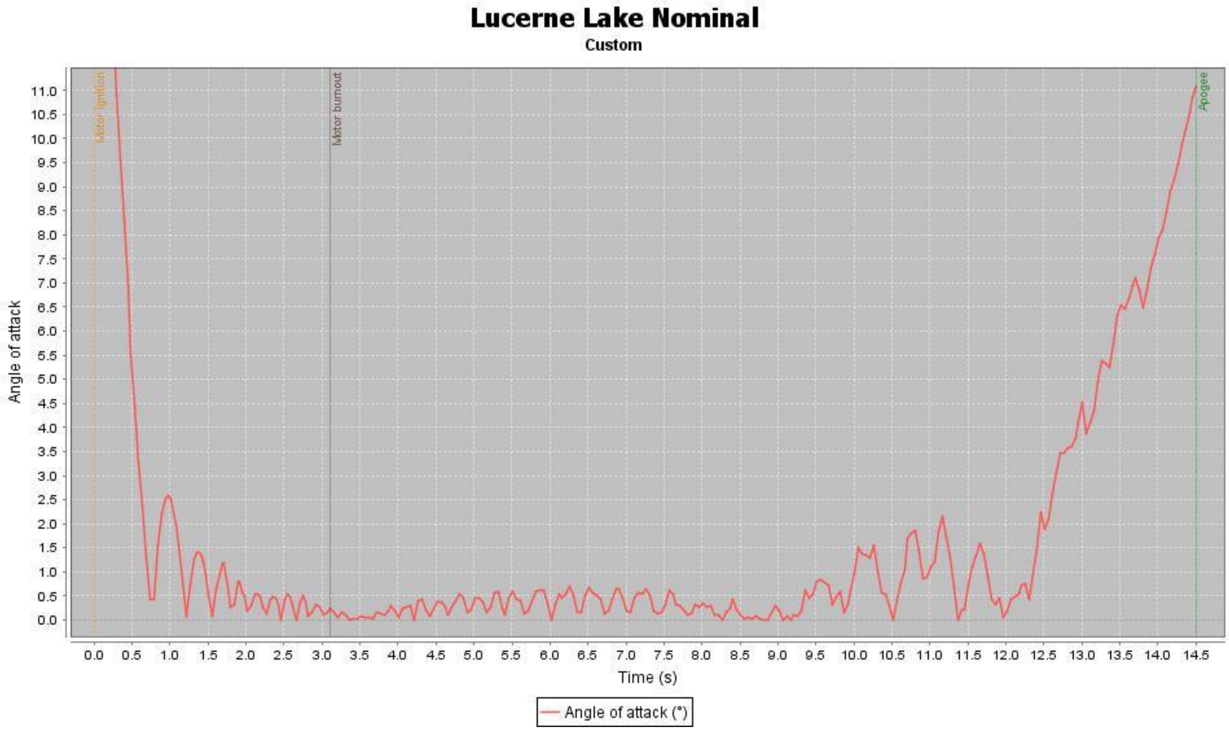
- Aerodynamics: Surface finish of all external components, fin alignment, concentricity of assembled components, imperfections on external components (e.g. damage caused by landing on first flight, camera port, etc.).
- Weight and geometrical accuracy: final measurements of the assembled rocket at launch day.

Of the plethora of events that might occur on the pre-established launch day (4/9/2016) and negatively impact the performance of the rocket the following were identified as critical and were analyzed in Open Rocket. First off, the average weather conditions for April 9th were retrieved from online databases and used as nominal parameters for analysis – labeled "Lucerne Lake Nominal". On average throughout the first two weeks of the month of April, winds are blowing at an average speed of 10.1 ± 1.2 mph with medium turbulence (11.1%). This prediction assumes the winds blow at 90° from the zenith, and therefore impacts the rocket normal to the side. Coordinates for launch are 34.4°N, 117°W at an average altitude of 2848 feet (870m). This condition was taken as the basis for the design envelope and a plot of the flight path and stability is shown in figure below.



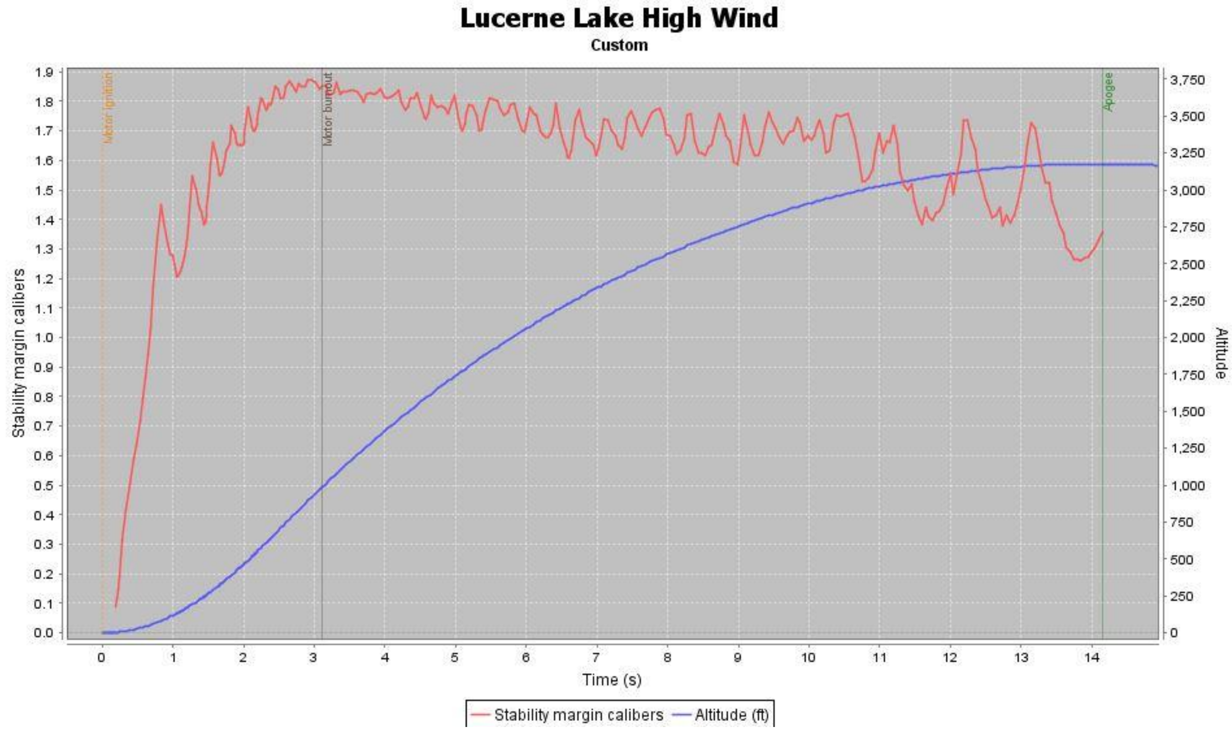
This simulation confirms that the rocket will maintain a high margin of stability (1.65-1.9 calibers) throughout the ascent. This high range of stability also leaves a lot of space for adjustments to the parameters measured at launch day (e.g. surface finish, geometry, weight) which are far from ideal, as assumed by the simulation.

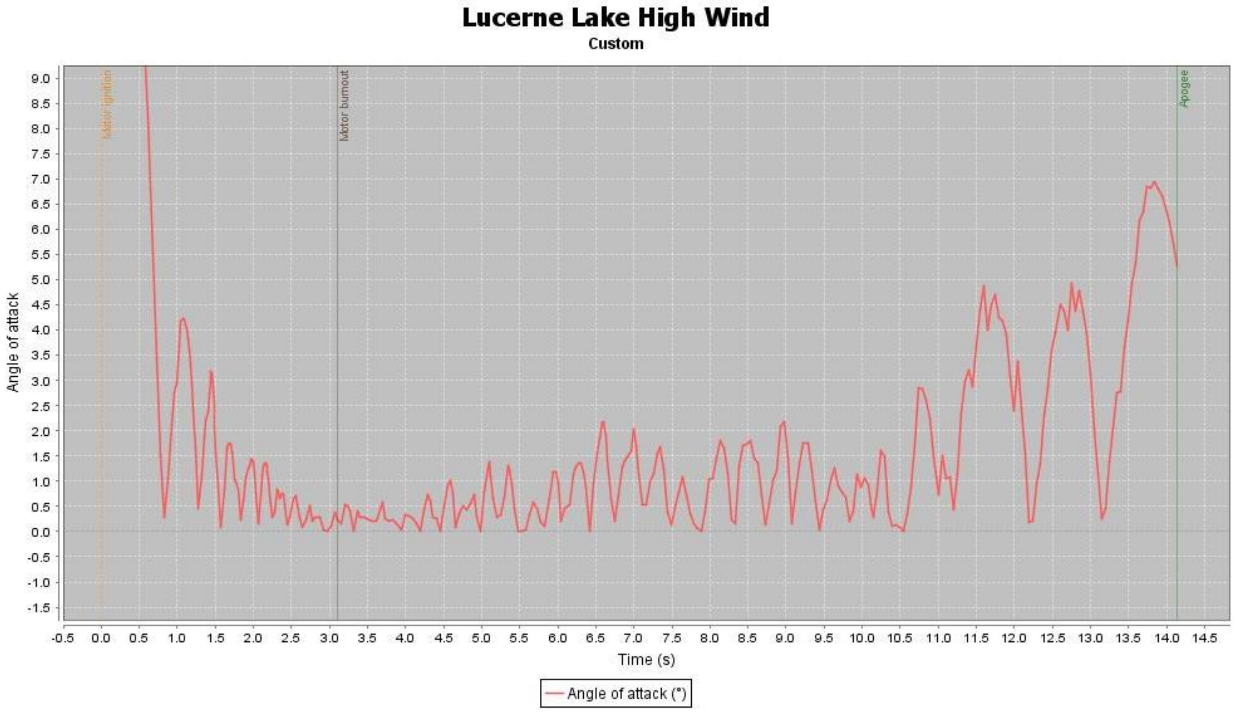
Another aspect critical to this simulation is the rocket's angle of attack throughout the flight. This is critical as the analytical calculations of apogee, lift and drag assume a small angle of attack (±3°) and this is confirmed by the simulation in Open Rocket shown in figure below.



As it can be seen, during the most critical part of the flight (motor burnout to apogee), the angle of attack ranges ±1.1° largely increasing, as expected, in the last few seconds of flight the lead to apogee and drogue parachute deployment. This confirms that the stabilizing effect of the fins is overall positive, fine tuning the ascent angle of the rocket multiple times.

The same study and simulations were performed in worst case conditions and confirm that the rocket's ascent has a large margin of stability and low angle of attack. In particular, worst weather conditions for April 9th were retrieved from online databases [] and used as edge of the envelope design and flight conditions. Labeled "Lucerne Lake High Wind", these conditions represent the edge condition sat witch the Launch Range Safety Officer would allow launches. Limits for launch entail winds blowing at an average speed of 19.8 ± 3.1 mph with high turbulence (15.7%). This prediction assumes the winds blow at 90° from the zenith, and therefore impacts the rocket normal to the side. In addition this simulation assumes a 4° cant on the launch rod making the rocket leave the launch pad at an already high angle of attack making such condition the edge of the design envelope. A plot of the flight path, angle of attack and stability is shown in figure below.





This simulation confirms that during the most critical part of the flight (motor burnout to apogee), the stability stays above 1.4 caliber and below 1.85, while angle of attack ranges within ±2.3° largely increasing, as expected, in the last three seconds of flight the lead to apogee and drogue parachute deployment.

As a conclusion, it is safe to affirm that the design is not heavily impacted by wind and the rocket will be safe to launch within acceptable NAR range conditions.

Appendix F4: C_p Location

The center of pressure, CP is defined as the point in the rocket body where the resultant force of aerodynamic pressure acts. The CP position depends on the geometric dimensions of the rocket and the angle of attack. For small angles of attack, its location can be calculated using the Barrowman's equations. These were developed by James Barrowman and presented in his master's thesis on 1967. Although useful and innovative, these were very calculus heavy equations. Therefore, a set of assumptions to account for the most common rocket designs was made to simplify the equations. For example it assumed that: the angle of attack is near zero, the flow is steady and irrotational, the rocket is a rigid body, the nose tip is a sharp point and that the rocket's diameter is small compared to its length. Furthermore, these equations can only account for either 3,4 or 6 fins and the fins cannot be located at any diameter transition region such as the tail boat.

As outlined by Barrowman, the procedure involves dividing the body in different regions. Each is associated with a pressure force coefficient and the distance of the point where the pressure force acts with respect to the tip of the rocket. Once all these coefficients and distances are calculated, its individual contributions to the center of pressure position can be added. It should be highlighted that this rocket has been purposely designed to simplify with standard shapes and dimensions so as to simplify the analytical calculations as much as possible without sacrificing accuracy. See the below figure, repeated from earlier in the report, for variable definitions. C_N refers to the total coefficient, and the subscripts N, F, T, and R refer to the nosecone, fins, tailboat, and rocket, respectively.

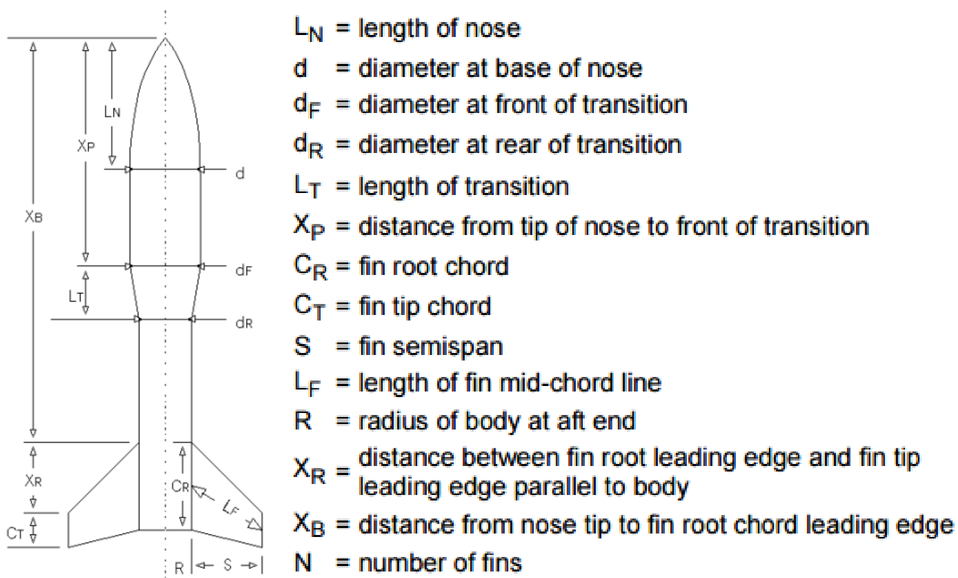


Figure 32: Relevant dimensions for C_p and C_D calculations.

The first section of the rocket to be considered is the nosecone. For a 2:1 diameter ratio ogive nose cone, the nose cone coefficient and specific length can be calculated according to the following equations:

$$(C_N)_N = 2$$

$$X_N = 0.466L_N$$

$$X_N = 0.466(12.042\text{ in}) = 5.612\text{ in}$$

As the diameter of the base of the rocket equals the diameter of the body tube, there is no need to account for transitions in the front end of the rocket for the CP position calculation. It should also be noted that when deriving the equations, Barrowman assumed that the body tube does not affect the CP position, regardless of its length.

Continuing the analysis, the coefficients for the fins can be determined by applying the following equations:

$$(C_N)_F = \left[1+\frac{R}{S+R}\right]\left[\frac{4N\left(\frac{S}{d}\right)^2}{1+\sqrt{1+\left(\frac{2L_F}{C_R+C_T}\right)^2}}\right]$$

$$X_F = \frac{X_R}{3}\frac{(C_R+2C_T)}{(C_R+C_T)}+\frac{1}{6}\left[(C_R+C_T)-\frac{C_RC_T}{(C_R+C_T)}\right]$$

$$(C_N)_F = \left[1+\frac{2.007\text{ in}}{4.45\text{ in}+2.0007\text{ in}}\right]\left[\frac{4(4\text{ fins})\left(\frac{4.45\text{ in}}{4.014\text{ in}}\right)^2}{1+\sqrt{1+\left(\frac{2(4.45\text{ in})}{3.875\text{ in}+1.50\text{ in}}\right)^2}}\right]=8.785$$

$$X_F = \frac{1.1875\text{ in}}{3}\frac{(3.875\text{ in}+2(1.500\text{ in}))}{(3.875\text{ in}+1.500\text{ in})}+\frac{1}{6}\left[(3.875\text{ in}+1.500\text{ in})-\frac{(3.875\text{ in})(1.500\text{ in})}{(3.875\text{ in}+1.500\text{ in})}\right]= 51.622\text{ in}$$

Lastly, it is necessary to account for the tail boat transition. There are two main equations:

$$(C_N)_T = 2\left[\left(\frac{d_R}{d}\right)^2-\left(\frac{d_F}{d}\right)^2\right]$$

$$X_T = X_P+\frac{L_T}{3}\left[1+\frac{1-\frac{d_F}{d_R}}{1-\left(\frac{d_F}{d_R}\right)^2}\right]$$

$$(C_N)_T = 2\left[\left(\frac{1.55\text{ in}}{4.014\text{ in}}\right)^2-\left(\frac{4.014\text{ in}}{4.014\text{ in}}\right)^2\right]=-1.703$$

$$X_T = 56.02\text{ in}+\frac{6.96\text{ in}}{3}\left[1+\frac{1-\left(\frac{4.014\text{ in}}{1.55\text{ in}}\right)}{1-\left(\frac{4.014\text{ in}}{1.55\text{ in}}\right)^2}\right]=58.985\text{ in}$$

Once all these coefficients have been calculated, the total coefficient can be calculates as:

$$(C_N)_R = (C_N)_N+(C_N)_F+(C_N)_T$$

$$(C_N)_R = 2+8.785-1.703=9.081$$

And the position of the center of pressure is given by:

$$X_{CP} = \frac{(C_N)_NX_N+(C_N)_FX_F+(C_N)_TX_T}{(C_N)_R}$$

$$X_{CP} = \frac{2(5.612\text{ in})+8.785(51.622\text{ in})-1.703(58.985\text{ in})}{9.081}=40.11\text{ in}$$

Upon testing these equations in a wind tunnel, Barrowman found that the theory predicts the center of pressure position to within ten percent of the experimental data. It should also be noted that the CP moves forward as the angle of attack increases. This reduces the distance between the CP and the CG, known as static margin. Consequently the rocket becomes less stable as the moment arm to of the force to balance the torques was reduced. The static margin is often measured in units of the rocket's largest cross-sectional diameter or calibers. As a rule of thumb, it is recommended for the static margin to be between 1 and 1.5 calibers to allow for a stable flight without excessive weather venting.

Appendix F3: C_p Location

The center of pressure, CP is defined as the point in the rocket body where the resultant force of aerodynamic pressure acts. The CP position depends on the geometric dimensions of the rocket and the angle of attack. For small angles of attack, its location can be calculated using the Barrowman's equations. These were developed by James Barrowman and presented in his master's thesis on 1967. Although useful and innovative, these were very calculus heavy equations. Therefore, a set of assumptions to account for the most common rocket designs was made to simplify the equations. For example, it assumed that the angle of attack is near zero, the flow is steady and irrotational, the rocket is a rigid body, the nose tip is a sharp point and that the rocket's diameter is small compared to its length. Furthermore, these equations can only account for either 3,4 or 6 fins and the fins cannot be located at any diameter transition region such as the tail boat.

As outlined by Barrowman, the procedure involves dividing the body in different regions. Each is associated with a pressure force coefficient and the distance of the point where the pressure force acts with respect to the tip of the rocket. Once all these coefficients and distances are calculated, its individual contributions to the center of pressure position can be added. It should be highlighted that this rocket has been purposely designed to simplify with standard shapes and dimensions so as to simplify the analytical calculations as much as possible without sacrificing accuracy.

The first section of the rocket to be considered is the nosecone. For a 2:1 diameter ratio ogive nose cone, the nose cone coefficient and specific length can be calculated according to the following equations, where L_N is the length of the nose cone:

$$(C_N)_N = 2$$

$$X_N = 0.466L_N$$

$$X_N = 0.466(8.00\text{ in}) = 3.728\text{ in}$$

As the diameter of the base of the rocket equals the diameter of the body tube, there is no need to account for transitions in the front end of the rocket for the CP position calculation. It should also be noted that when deriving the equations, Barrowman assumed that the body tube does not affect the CP position, regardless of its length.

Continuing the analysis, the coefficients for the fins can be determined by applying the following equations:

$$(C_N)_F = \left[1 + \frac{R}{S+R}\right]\left[\frac{4N\left(\frac{S}{d}\right)^2}{1+\sqrt{1+\left(\frac{2L_F}{C_R+C_T}\right)^2}}\right]$$

Where, according to Figure 32, R is the radius of the body tube, S is the fin semi span, d is the diameter of the nose cone (equal to twice the radius of the base given the homogeneous rocket diameter), C_R is the fin root chord, C_T is the fin tip chord, N is the number of fins and L_F is the length of the fin mid-chord line.

$$X_F = X_B + \frac{X_R}{3}\frac{(C_R+2C_T)}{(C_R+C_T)} + \frac{1}{6}\left[(C_R + C_T) - \frac{C_R C_T}{(C_R+C_T)}\right]$$

$$(C_N)_F = \left[1 + \frac{2.0\text{ in}}{4.5\text{ in} + 2.0\text{ in}}\right]\left[\frac{4(4\text{ fins})\left(\frac{4.5\text{ in}}{4.0\text{ in}}\right)^2}{1+\sqrt{1+\left(\frac{2(4.5\text{ in})}{4.25\text{ in}+1.25\text{ in}}\right)^2}}\right] = 9.08$$

$$X_F = 50\text{ in} + \frac{1.5\text{ in}}{3}\frac{(4.25\text{ in} + 2(1.25\text{ in}))}{(4.25\text{ in} + 1.25\text{ in})} + \frac{1}{6}\left[(4.25\text{ in} + 1.25\text{ in}) - \frac{(4.25\text{ in})(1.25\text{ in})}{(4.25\text{ in} + 1.25\text{ in})}\right] = 51.37\text{ in}$$

Lastly, it is necessary to account for the tail boat transition. There are two main equations:

$$(C_N)_T = 2\left[\left(\frac{d_R}{d}\right)^2 - \left(\frac{d_F}{d}\right)^2\right]$$

$$X_T = X_P + \frac{L_T}{3}\left[1 + \frac{1-\frac{d_F}{d_R}}{1-\left(\frac{d_F}{d_R}\right)^2}\right]$$

$$(C_N)_T = 2\left[\left(\frac{2.85\text{ in}}{4.0\text{ in}}\right)^2 - \left(\frac{4.0\text{ in}}{4.0\text{ in}}\right)^2\right] = -0.99$$

$$X_T = 55\text{ in} + \frac{7.13\text{ in}}{3}\left[1 + \frac{1-\left(\frac{4.0\text{ in}}{2.85\text{ in}}\right)}{1-\left(\frac{4.0\text{ in}}{2.85\text{ in}}\right)^2}\right] = 58.37\text{ in}$$

Once all these coefficients have been calculated, the total coefficient can be calculated as:

$$(C_N)_R = (C_N)_N + (C_N)_F + (C_N)_T$$

$$(C_N)_R = 2 + 9.08 - 0.99 = 10.09$$

And the position of the center of pressure is given by:

$$X_{CP} = \frac{(C_N)_N X_N + (C_N)_F X_F + (C_N)_T X_T}{(C_N)_R}$$

$$X_{CP} = \frac{2(3.73\text{ in}) + 9.08(51.37\text{ in}) - 0.99(58.37\text{ in})}{10.09} = 41.24\text{ in}$$

For comparison, the Open Rocket model for the built rocket predicted the center of pressure to be located at a distance of 41.435 from the tip of the nose cone. The percent difference can therefore be calculated to be:

$$\%ERROR = \frac{|theoretical - experimental|}{theoretical} = \frac{|41.435 - 41.24|}{41.435} = 0.46\%$$

Upon testing these equations in a wind tunnel, Barrowman found that the theory predicts the center of pressure position to within ten percent of the experimental data. It can therefore be concluded that this calculation of the center of pressure location is reliable. It should also be noted that the CP moves forward as the angle of attack increases. This reduces the distance between the CP and the CG, known as static margin. Consequently, the rocket becomes less stable as the moment arm to of the force to balance the torques was reduced. The static margin is often measured in units of the rocket's largest cross-sectional diameter or calibers. As a rule of thumb, it is recommended for the static margin to be between 1 and 1.5 calibers to allow for a stable flight without excessive weather venting.

Appendix F5: Apogee Determination

The main requirement states that the rocket must hit an apogee target of 3000'. This is a key design driver as the rocket must produce enough thrust initially to overcome its weight and ascent drag. In addition as the rocket is coasting vertically, the drag force must decrease at a rate such that the rocket must reach zero velocity at the altitude of 3000'.

As a preliminary analysis a simple calculation using simple dynamics equations was performed by using the information provided on the rocket motor by the manufacturer and by approximately calculating the weight of the rocket using the "mass properties" tool in SolidWorks.

There are three basic equations to find the peak altitude of a high power rocket. Max velocity v, the velocity at burnout

$$v = \sqrt{\frac{T - m*g}{k}} * \frac{\left[1 - \exp\left(-\frac{2*k}{m} * t * \sqrt{\frac{T - m*g}{k}}\right)\right]}{\left[1 + \exp\left(-\frac{2*k}{m} * t * \sqrt{\frac{T - m*g}{k}}\right)\right]}$$

Altitude reached at the end of boost

$$h_{bo} = \left[-\frac{m}{2*k}\right] * \ln\left(\frac{T - m*g - k*v^2}{T - m*g}\right)$$

Additional height achieved during coast

$$h_c = \left[\frac{m}{2*k}\right] * \ln\left(\frac{m*g + k*v^2}{m*g}\right)$$

where m is the mass of the rocket, with motor, (3.4 kg), g is the gravitational constant ($9.81 m/s^2$), T is the average thrust of the motor (217 N), t is the burn time (2.92 s), and k is the sum of all the drag components computed as

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

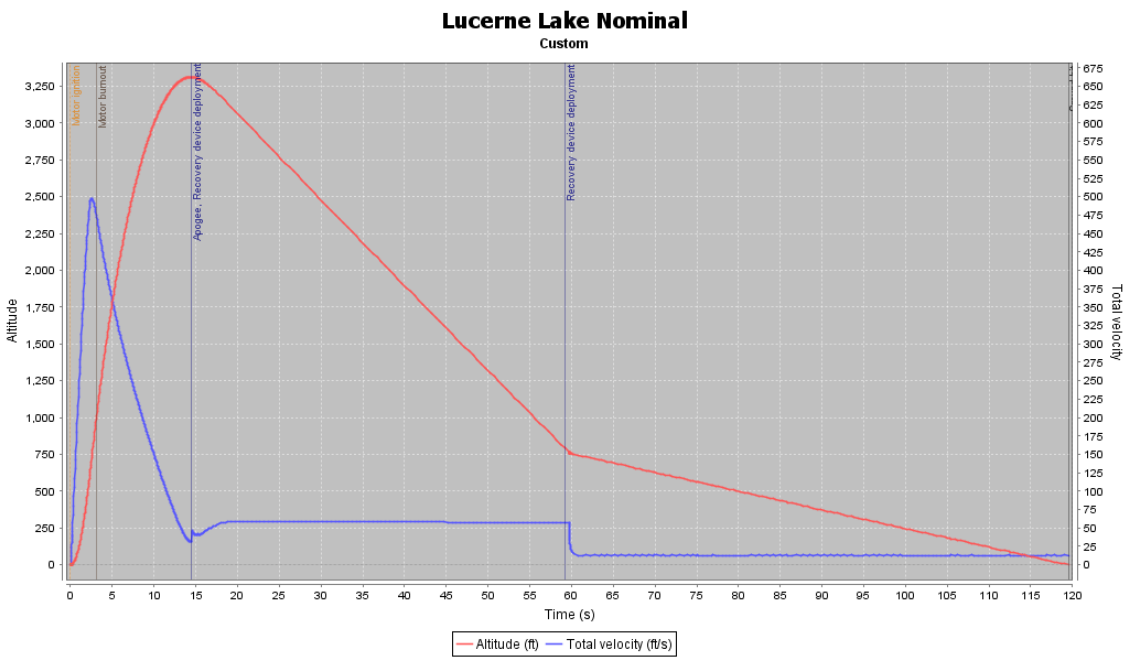
where A is the frontal area of the rocket (0.00785 m^2), C_d is the drag coefficient, assumed to be constant 0.373, rho is density of air (also assumed constant) 1.2 kg/m^3.
The final altitude is simply the sum of the two altitudes:

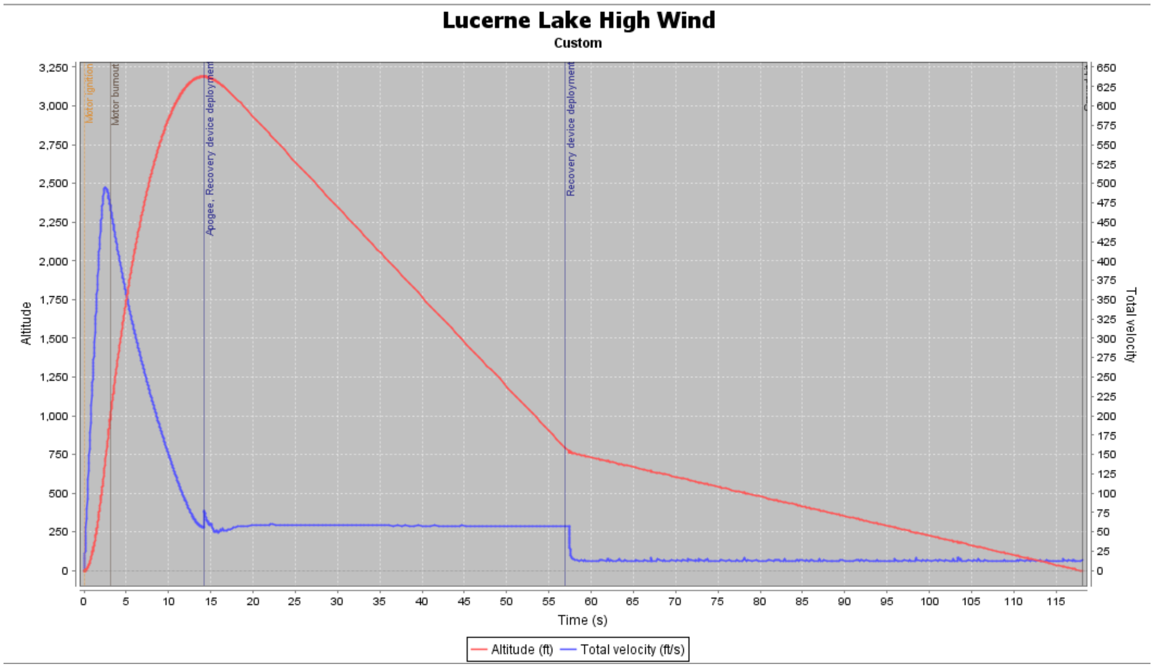
$$h = h_{bo} + h_c$$

Therefore the values that truly drove the design were:

- Motor specifications: Thrust, burn time and mass
- Physical properties of the rocket: mass and size (frontal area)
- Aerodynamic properties: drag as calculated in appendix F.

This approach is non ideal as it contains several assumptions that are far from actually describing the vertical motion of the rocket. In order to compare and contrast the preliminary analyses, computational simulations were carried out using Open Rocket software. The advantage of the software is that it takes in account a number of factors that are either ignored or assumed ideal as the rocket ascends. In particular, the small changes in angle of attack, the rapid change in mass and the changes in stability of the rocket as described in section 2.2 and in appendix F. As it can be inferred from the images below, the current rocket configuration is capable of reaching and theoretically exceed the target altitude in both nominal and critical wind conditions.





A number of cases were preliminarily calculated using the parameters mentioned above and compared with simulations from Open Rocket. Results are shown in table 4.

	Max Velocity (ft/s)	Apogee(ft)
Equations	385.2	2747
Open Rocket	495	3312
% difference	22.2 %	17.1 %

Again, the hand calculations are to be taken with a grain of salt as there is a significance to the assumptions and physical effects that are neglected by linearizing the process.

Appendix G: Assembly & Integration

Assembly and test

Once all the major components are manufactured (e.g. CFB and CF) and all minor subassemblies are integrated as described above, the subassembly integration will take place.

Nose Cone Integration

1. 1/4-28 nut (6) is epoxied to ceter of the nosecone bulkhead (4) and 1/4-28 eyebolt (5) is fastened on the opposite side of the bulkhead (4).
2. Shock cord (7) is tied to the eyebolt (5)
3. Bulkhead assembly (4) is epoxied to the shoulder of the nosecone (2) and is ready for integration.

Fore Tube Integration

1. Measure and mark locations of bulkheads, centering rings, rivet, fastener and static port holes on both Fore Body Tube (1) and Aft Body Tube (35).
2. Drill holes as specified on Drawings in Appendix B.
3. Payload Bulkhead Assembly (19) is going to be epoxied 11.5in in from the top of the Fore Body Tube (1) (side with shear pin holes) while Payload Ring (13) is epoxied 3.8in from top of Payload Bulkhead Assembly (19)
4. Ejection Cap (10) has 6-32 nut (17) epoxied to internal center hole and gets packed with Black Powder charge (11) and igniter.
5. Packed ejection cap is fastened to center of the bulkhead (19) by 6-32 bolt (16)
6. Terminal Strips (12) get epoxied on top of bulkhead (19) and ring (13) and wiring is routed to bottom (to connect to the ebay) and to the top – drogue igniter (55).
7. Shock cord (7) gets routed through assembly and tied to eyebolts (5) on both ebay an nosecone.
8. Adjustable Mass Ring(s)(15) is/are added, as necessary, and fastened using 6-32 bolt (16) and nut (17) previously epoxied to the top of bulkhead (19).
9. Payload assembly (14) and nomex protector (9) are inserted in assembly per exploded view and secured to the payload ring (13) using masking tape and wired.
10. Drogue chute (8) and nomex protector (9) are tied to nosecone eyebolt and packed in body tube (1).
11. Airfoil rail button (18) is bolted to outside of the body tube (35).

Ebay Integration

Aft end integration:

1. Airfoil rail button (18) is bolted to outside of the body tube (35).
2. Fins (45) are positioned and epoxied to the aft body tube (35) per methodology described in appendix.
3. Camera cap (36) and Camera Ring (37) are epoxied to inside of body tube (35) using assembly dowels
4. Shock cord (7) is tied to shouldered eyebolt (40) and ran through the camera bay.
5. Shouldered eyebolt (40) is epoxied to top of engine block (41)
6. Engine block is aligned with rivet holes in body tube (35) and riveted in using 3-16 rivets (42).
7. Fins (45) are epoxied to body tube (35) using fin tool (56).
8. Centering Ring (57) is epoxied to top of the shoulder of the tailcone (46)
9. Tail block (47) is fitted with 6-32 threaded inserts (50) and fastened to tailcone (46) using 3-16 rivets (42).
10. A dry fit and alignment check is performed using the motor casing (43) and body tube assembly (35).
11. After alignment fine tuning, tailcone (46) assembly is epoxied to body tube (35) and motor casing (43) is screwed in the bottom of the eyebolt (40).

12. On launch day the motor reload (44) is screwed in the moor casing (43) and retainer plate (49) is fastened to the bottom using 6-32 bolts (17).

Launch Day Final Integration:

1. Top of ebay is fastened to bottom of fore body tube (1) using removable rivets (31).
2. Fore end assembly is tested for integrity and nosecone assembly is attached to the top using shear pins (3)
3. Aft body tube (35) is secured to ebay assembly by shear pins (3)
4. Rocket is positioned on the launch rod and motor ignition is wired ready to launch!

Appendix H: Schedule and Budget

Appendix H1: Gantt Chart as of 4/28/16

Aeneas Rocket
Team C

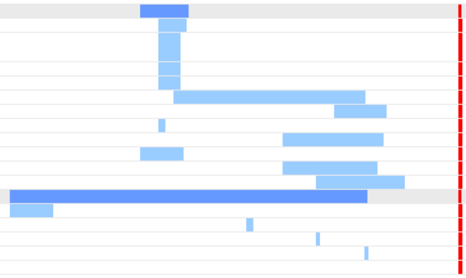
Today's Date: 4/28/2016 Thursday
(vertical red line)

Project Lead: [Name]
Start Date: 9/3/2015 Thursday

First Day of Week (Mon=2): 2

VBS	Tasks	Task Lead	Start	End	Duration (Days)	% Complete	Working Days	Days Complete	Days Remaining
1	**Reviews/Critical**	Team	9/28/15	4/9/16	65	100%	140	65	0
1.1	SRR		9/28/15	9/28/15	1	100%	1	1	0
1.2	Mini Review 2		10/20/15	10/20/15	1	100%	1	1	0
1.3	PDR		11/3/15	11/3/15	1	100%	1	1	0
1.4	Mini Review 3		12/1/15	12/1/15	1	100%	1	1	0
1.5	CDR		12/15/15	12/17/15	2	100%	3	2	0
1.6	dCDR		2/9/16	2/9/16	1	100%	1	1	0
1.7	NAR L1 Cert Group Trip		2/13/16	2/13/16	1	100%	0	1	0
1.8	Dual Deployment Test		3/12/16	3/12/16	1	100%	0	1	0
1.9	Launch Competition		4/9/16	4/16/16	1	100%	5	1	0
1.10	Final Design Review Presentation		4/21/16	4/21/16	1	100%	1	1	0
2	**Design Tasks**		10/13/15	11/3/15	22	100%	16	22	0
2.1	Component Configuration	Team	10/13/15	10/20/15	8	100%	6	8	0
2.2	Fuselage Design	Ray	10/21/15	11/3/15	14	100%	10	14	0
2.2.1	Motor Mount &	Ray	10/20/15	10/21/15	2	100%	2	2	0
2.2.2	Fin Mounting	Martin	10/13/15	10/26/15	14	100%	10	14	0
2.2.3	Bulkhead Design	Ray	10/17/15	10/23/15	7	100%	5	7	0
2.2.4	Ejection Charge Baffles	Ray	10/24/15	10/24/15	1	100%	0	1	0
2.2.5	Body Tube Mounting	Ray	10/23/15	10/23/15	1	100%	1	1	0
2.2.6	Nose Cone	Ray	10/23/15	10/29/15	7	100%	5	7	0
2.2.7	Tailboat	Ray	10/23/15	10/29/15	7	100%	5	7	0
2.3	Electronics Bay	Josh	10/13/15	10/29/15	17	100%	13	17	0
2.3.1	Altimeter		10/13/15	10/27/15	15	100%	11	15	0
2.3.2	Sled & Bulkhead Construction		10/20/15	10/26/15	7	100%	5	7	0
2.3.3	Wire Routing		10/20/15	10/26/15	7	100%	5	7	0
2.4	Egg Module	Manu	10/13/15	11/3/15	22	100%	16	22	0
2.4.1	Ejection		10/23/15	10/29/15	7	100%	5	7	0
2.4.2	Impact Protection		10/13/15	10/22/15	10	100%	8	10	0
2.5	Camera Mounting	Ray & Manu	10/27/15	11/2/15	7	100%	5	7	0
2.6	Adjustable Payload Bay	Ray & Manu	10/27/15	11/2/15	7	100%	5	7	0
3	**Analysis Tasks**		10/25/15	11/17/15	24	100%	17	24	0
3.1	Fuselage Stress FEA	Ray	11/15/15	11/16/15	2	100%	1	2	0
3.1.1	Bulkhead		10/25/15	10/25/15	1	100%	0	1	0
3.1.2	Engine Block bulkhead		10/26/15	10/26/15	1	100%	1	1	0
3.2	Flight Simulation	Manu & Mart	11/15/15	11/17/15	3	100%	2	3	0
3.2.1	Simulation		10/27/15	11/2/15	7	100%	5	7	0
3.2.2	Open Rocket	Manu & Mart	11/15/15	11/15/15	1	100%	0	1	0
3.2.2.1	Nominal Case		11/15/15	11/15/15	1	100%	0	1	0
3.2.2.2	Worst Case		11/15/15	11/15/15	1	100%	0	1	0
3.2.2.3	80% Worst Case		11/15/15	11/15/15	1	100%	0	1	0
3.3	FMEA		11/1/15	12/15/15	45	100%	32	45	0
4	**Prototyping Tasks**		10/21/15	11/15/15	26	72%	18	18	8
4.1	Egg Module Drop Survival	Manu	10/21/15	11/4/15	15	50%	11	7	8
4.2	Engine Block bulkhead	Ray	11/4/15	11/10/15	7	100%	5	7	0
4.3	Dual Deployment system	Josh & Manu	11/11/15	11/15/15	5	100%	3	5	0
4.3.1	Altimeter current pulses		11/11/15	11/12/15	2	100%	2	2	0
4.3.2	Current split for egg		11/13/15	11/15/15	3	100%	1	3	0
4.3.3	Egg parachute	Manu	11/13/15	11/14/15	2	100%	1	2	0
4.3.4	Egg Ejection	Manu	11/13/15	11/14/15	2	100%	1	2	0
5	**Report**	Team	10/27/15	5/3/16	189	100%	136	188	1
5.1	Design		10/27/15	11/2/15	7	100%	5	7	0
5.1.1	Objective		10/27/15	11/2/15	7	100%	5	7	0
5.1.2	Background		10/27/15	11/2/15	7	100%	5	7	0
5.1.3	Prior Work		10/27/15	11/2/15	7	100%	5	7	0
5.1.4	Design Specifications		10/27/15	11/2/15	7	100%	5	7	0
5.1.5	Concept Development & Selection Methods		10/27/15	11/2/15	7	100%	5	7	0
5.1.6	Innovation		10/27/15	11/2/15	7	100%	5	7	0
5.1.7	Description		10/27/15	11/2/15	7	100%	5	7	0
5.2	Analysis		10/27/15	12/15/15	49	100%	36	49	0
5.2.1	FMEA		10/27/15	12/15/15	49	100%	36	49	0
5.2.2	Rocket Analysis		10/27/15	12/15/15	49	100%	36	49	0
5.2.2.1	FEA		10/27/15	12/15/15	49	100%	36	49	0
5.2.2.2	Apogee Estimate		10/27/15	12/15/15	49	100%	36	49	0
5.2.2.3	Stability Ratio		10/27/15	12/15/15	49	100%	36	49	0
5.2.3	Cost Analysis		10/27/15	4/25/16	181	100%	130	181	0
5.3	Testing		10/27/15	11/19/15	24	100%	18	24	0
5.3.1	Developmental Testing		11/5/15	4/1/16	148	100%	107	148	0
5.3.2	Performance Testing		11/5/15	4/1/16	148	100%	107	148	0
5.3.3	Additional Testing subsections		11/5/15	4/1/16	148	100%	107	148	0
5.4	Safety		10/27/15	12/15/15	49	90%	36	44	5
5.5	Conclusion		4/28/16	4/28/16	1	100%	1	1	0
5.5.1	Comparison		4/28/16	4/28/16	1	100%	1	1	0
5.5.2	Evaluation		4/28/16	4/28/16	1	100%	1	1	0
5.5.3	Recommendations		4/28/16	4/28/16	1	100%	1	1	0
5.6	References		10/27/15	4/28/16	184	100%	133	184	0
5.7	Appendix A		4/15/16	4/28/16	13	100%	10	13	0
5.7.1	BOM		4/15/16	4/28/16	13	100%	10	13	0
5.8	Appendix B		4/15/16	4/28/16	13	100%	10	13	0
5.8.1	2D CAD Drawings (fabrication)		4/15/16	5/7/16	23	100%	16	23	0

6	**Manufacturing**	1/14/16	4/9/16	16	100%	62	16	0
6.1	Electronics Bay	1/20/16	1/29/16	9	100%	8	9	0
6.1.1	Sled & Bulkhead Construction	1/20/16	1/29/16	7	100%	8	7	0
6.1.2	Altimeter Wiring	1/20/16	1/29/16	7	100%	8	7	0
6.1.3	Total Assembly	1/20/16	1/29/16	7	100%	8	7	0
6.2	Carbon Fiber Layup	1/25/16	3/28/16	63	100%	46	63	0
6.3	Fin Mounting	3/18/16	4/4/16	17	100%	12	17	0
6.4	Body Tube	1/20/16	1/21/16	2	100%	2	2	0
6.5	Aft End Subassembly	3/1/16	4/3/16	33	100%	24	33	0
6.6	Egg Module	1/14/16	1/27/16	14	100%	10	14	0
6.7	Fore End Subassembly	3/1/16	4/1/16	31	100%	24	31	0
6.8	Dual Deploy Alterations	3/12/16	4/9/16	29	100%	20	29	0
7	**Testing Tasks**	12/2/15	4/9/16	118	100%	93	118	0
7.1	Tensile Testing	12/2/15	12/15/15	14	100%	10	14	0
7.2	Altimeter Testing	2/18/16	2/19/16	2	100%	2	2	0
7.3	Dual Deploy Testing	3/12/16	3/12/16	1	100%	0	1	0
7.4	Engine Block thermal	3/28/16	3/28/16	1	100%	1	1	0



Appendix H2: Project Cost Budget

Balance (including projected costs)	**Date**	**Vendor**	**Description**	**Total Cost**
-$678.60	11/11/2015	McMasterCarr	raw materials for engine block testing tool: 1x 0.375x1x6in Al 6061 bar, 1x 0.25x6" Al 6061-T6 rod	$9.22
Spent	1/6/2015	McMasterCarr	Fastening hardware for rocket assembly	$103.04
$1,678.60	1/6/2015	Giant Leap Rocketry	1010 Delrin Airfoil Rail Buttons (pair)	$16.04
Allotted	1/6/2015	Always Ready Rocketry	1x 4" OD Slotted Blue Tube body tube	$67.90
$1,000.00	1/11/2016	Giant Leap Rocketry	RRC3 altimeter and USB interface	$94.90
	1/11/42016	Apogee Rockets	Shock cord, electronics switch, mini clamp sets, various fastening and other hardware	$76.56
	1/12/2016	Apogee Rockets & the-rocketman.com	Parachutes	$115.00
	12/8/2015	Home Depot	rubber pipe insulation	$6.81
	1/13/2016	Apogee Rockets	Cesaroni Pro38 Delay ejection adapter	$19.08
	1/22/2016	Plastic Materials Inc.	Vinyl ester resin & catalyst, vacuum bag material, peel ply, tooling board	$254.41
	1/25/2016	Apogee Rockets	Nomex parachute protectors, 2x 20pk shear pins	$35.93
	2/2/2016	McMasterCarr	1x 10pk 2-56 brass threaded inserts	$12.10
	2/4/2016	Wildman Rocketry	Cesaroni Pro38 5-grain casing	$58.95
	2/4/2016	Plastic Materials Inc.	Additional tooling board, PVA mold release	$245.81
	2/6/2016	Fry's Electronics	Female spade connectors for 22-20ga wire	$2.49

	2/6/2016	Harbor Freight Tools	Flourescent tube light, plastic sheeting	$25.98
	2/11/2016	Plastic Materials Inc.	Sealant tape, hard primer, vacuum seal	$137.76
	2/24/2016	Home Depot	1/4" male NPT quick disconnect to male 1/4" coupler	$1.94
	2/22/2016	Home Depot	1/4"/ 3/8" NPT coupler set	$5.00
	2/24/2016	Hobby People	2x .0625"x4"x24" balsa sheet	$4.98
	3/3/2016	Home Depot	Sandpaper	$22.65
		Harbor Freight Tools	2x HVLP spray gun	$30.00
	3/3/2016	Home Depot	Sandpaper	$19.52
		Wildman Rocketry	2x Cesaroni I-216-CL Pro38 5-grain rocket motor reloads	$110.00
	3/21/2016	West Marine	Sealant tape	$17.43
	3/21/2016	Home Depot	1/4" eyebolt	$2.47
	3/23/2016	West Marine	Sealant tape	$34.86
	3/24/2016	West Marine	Sealant tape	$17.43
	3/24/2016	Southbay Industrial Hardware	5/16-18 x 1" bolt	$1.46
	3/25/2016	Home Depot	String	$2.69
	3/26/2016	Home Depot	Flat black spray paint	$4.22
	3/30/2016	Apogee Rockets	38mm tail motor retention plate	$9.95

Appendix H3: Rocket Mass Budget (at CDR)

System Total (g)	Component	Units	Mass (g)
Mass	Nosecone	1	91.00
3404.30	1/4-28 Eyebolt	1	25.00
	Shearpins	4	0.00
	Fore Tube	1	287.00
	Drougue Chute	1	70.00
	Shock Cord	1	20.00
	Ejection Ring	1	8.00
	Charge cap+charge	1	4.4
	Egg Module	1	180.00
	CF/Balsa Bulkhead	1	25.00
	Charge cap+charge	1	4.4
	Launch Lug	2	8.00
	Coupler Tube	1	124.00
	Ebay electronics	1	373.00
	Altimeter	1	18.10
	Charge cap+charge	1	4.4
	Aft Body tube	1	520
	Shock Cord	1	20.00
	Main Chute	1	574.00
	Camera cap+back piece+ring	1	30
	Camera	1	74.00
	Camera CF bulked	1	25.00
	Eyebolt	1	47.00
	ABS Bulkhead	1	53.00
	Rivets	8	8.00
	Centering Ring	1	20.00
	Fins	4	70.00
	Tailcone	1	50.00
	End cap	1	45.00
	Al Plate	1	25.00

Appendix H4: Final Integration Schedule (as-built)

Tues 3/29, 9am-5pm

- ~~Vacuum fin side 2~~ Epoxy spot fill fin side 1
- ~~Epoxy spot fill fin side 2~~
- Cut & square tail cone
- ~~Cut, square,~~ and sand shoulder on nose cone
- Drill nose cone shear pin holes
- Drill tail cone removable rivet holes Removable rivets fitted, good to go
- Sand tail cone centering ring to size

Tues 3/29, 6pm-EOD

- Epoxy camera assembly (WS op)
- Mount nose cone bulkhead and eyebolt (WS op)

Wed 3/30

- Sand 220-2000 fins, clear coat side 1
- Fin #1 mount (Rocketpoxy op)
- Battery mounting!

Thurs 3/31

- Fin clear coat side 2
- Fin 1 clear coat
- Drill camera hole
- Heat shrink open holes in body tube (double sided tape in the toolbag)
- Fairing buildup on tail cone for tight fit
- Fin #2 mount (Rocketpoxy op)

Fri 4/1

- Fin #3 mount (AM)
- Fin #4 mount (PM)
- Cut tail motor retention plate
- Interior fin fillet 1 (PM)

Sat 4/2

- Mount rail button 1 (locate holes on straight line…laser level in the toolbag…1 on CG) (WS op)
- Interior fin fillet 2
- Paint front tube (metallic silver coat 1)
- Mount 2nd aft tube centering ring (epoxy op)

Sun 4/3

- Lens material mount camera hole
- Sand tail cone shoulder to fit
- Collect tail retention plate from Trent
- Drill tail retention plate holes in tail centering ring & assemble
- Mount tail cone centering ring

Mon 4/4

- Reinforce fillets 1
- Plug rivet holes w/Bondo
- Reinforce fillets 2
- Mount rail button 2 (on CG)
- Fairing fill for nose cone shoulder step
- Fairing fill for tail cone shoulder step
- Print nose cone tip/cut tip from backup nose cone and epoxy on
- Clean camera lens

Tues 4/5

- Sand front tube
- Re-apply tail cone shoulder
- FRR

Wed 4/6

- Wood fill front & rear tube
- Prime rear & front tube

Thurs 4/7

- Sand front & rear tube
- Apply decals & clear coat to front and rear tube
- Ebay wiring & continuity check
- Sand & paint tail cone shoulder
- Sand & paint nose cone shoulder
- Re-finish exposed portion of nose cone (even out the clear coat)

Fri 4/8

- Develop launch day checklists and procedures
- ~~Egg module drop test~~

Appendix I: Detailed Anomaly Analysis

Appendix I1. Drogue Deployment Failure

At apogee, the nosecone did not separate from the fore tube, which was the primary cause of the damage that prevented the rocket from being flown a second time. What follows is the detailed analysis of determining what went wrong.

By looking at the altimeter readout and inspecting the ejection charge after recovery, it was determined that the drogue ejection charge was activated and went off at apogee (see Figure 33 below). The charge went off, but either the nosecone pinched in the body tube or the charge was insufficiently sized. Since the payload deployment was able to separate the nose cone from the body tube, it seems less likely that it pinched and more likely that to nosecone was not pushed out all the way by the charge due to insufficient force.

Figure 33: Expended drogue ejection charge after launch

The carbon fiber nosecone was not manufactured by the time of ejection testing on March 12, so a 3D-printed ABS backup article was used. The testing was successful, but the testing was never repeated for the flight article. There are two changes that are the most likely culprits for causing the failure. First, the bulkhead in the flight article was located farther toward the tip, creating an increased volume for pressurization than that of the backup. This can be seen below in Figure 34 below. Second, the friction fit was tighter than for the backup. Both of these factors mean that more force, and therefore a larger charge, should have been used to successfully separate the nosecone.

Figure 34 Nosecone as flown; Backup nosecone as tested

Appendix I2. Failure Force Estimation

There are two key events in failure that are of particular interest for force estimation. These are the zippering of the fore tube and the breaching of the aft coupler bulkhead. These calculations are necessarily rough, as there were spikes in the data due to other highly transient flight events such as ejection charge activation and component separation that made direct analysis impossible at several key moments.

For the zippering of the fore tube, the force was estimated using the instantaneous drag force of the drogue chute at the moment it fully deployed. At this moment, it was assumed that the drogue chute was traveling at the same rate of the rocket. For this calculation, the drag equation was used. Using the density of air at 900 feet and the parachute parameters as given by the data sheet [7], the drag force is estimated to be

$$F_D = \frac{1}{2}\rho u^2 C_D A = \frac{1}{2}\left(1.175\frac{kg}{m^3}\right)\left(101.3\frac{m}{s}\right)^2 (1.5)(0.203\ m^2) = \mathbf{1835.8\ N}$$

To calculate the pressure on the wall of the body tube, this force was assumed to act on a rectangle formed by the thickness of the body tube (0.00125m) and the width of the shock cord (0.0058m). The pressure was therefore

$$P = \frac{F}{A} = \frac{1835.8\ N}{(0.00123m)(0.0058m)} = \mathbf{2.49 \times 10^8 Pa}$$

The force decreased as the rocket slowed, but this high load at the moment of drogue opening while the rocket was going straight down shows why the tube zippered as it did.

To calculate the force needed to pull the aft coupler eyebolt through the bulkhead, an impulse calculation was used. The initial velocity was assumed to be the last reliable velocity measurement before ejection charge firing (u = 101.3m/s at t = 27.9s), and the final velocity was taken to be the velocity immediately before the spike caused by the bulkhead (u = 60m/s at t = 29.25s). The break was assumed to occur instantaneously, and the time of load transfer was assumed to be the time taken for the rocket to descend the length of the shock cord at its assumed velocity. Assuming that the parachute was halfway along the length of the 10ft. (3.05m) shock cord, this time was 0.015s. The mass of the front section was used. From the impulse equation,

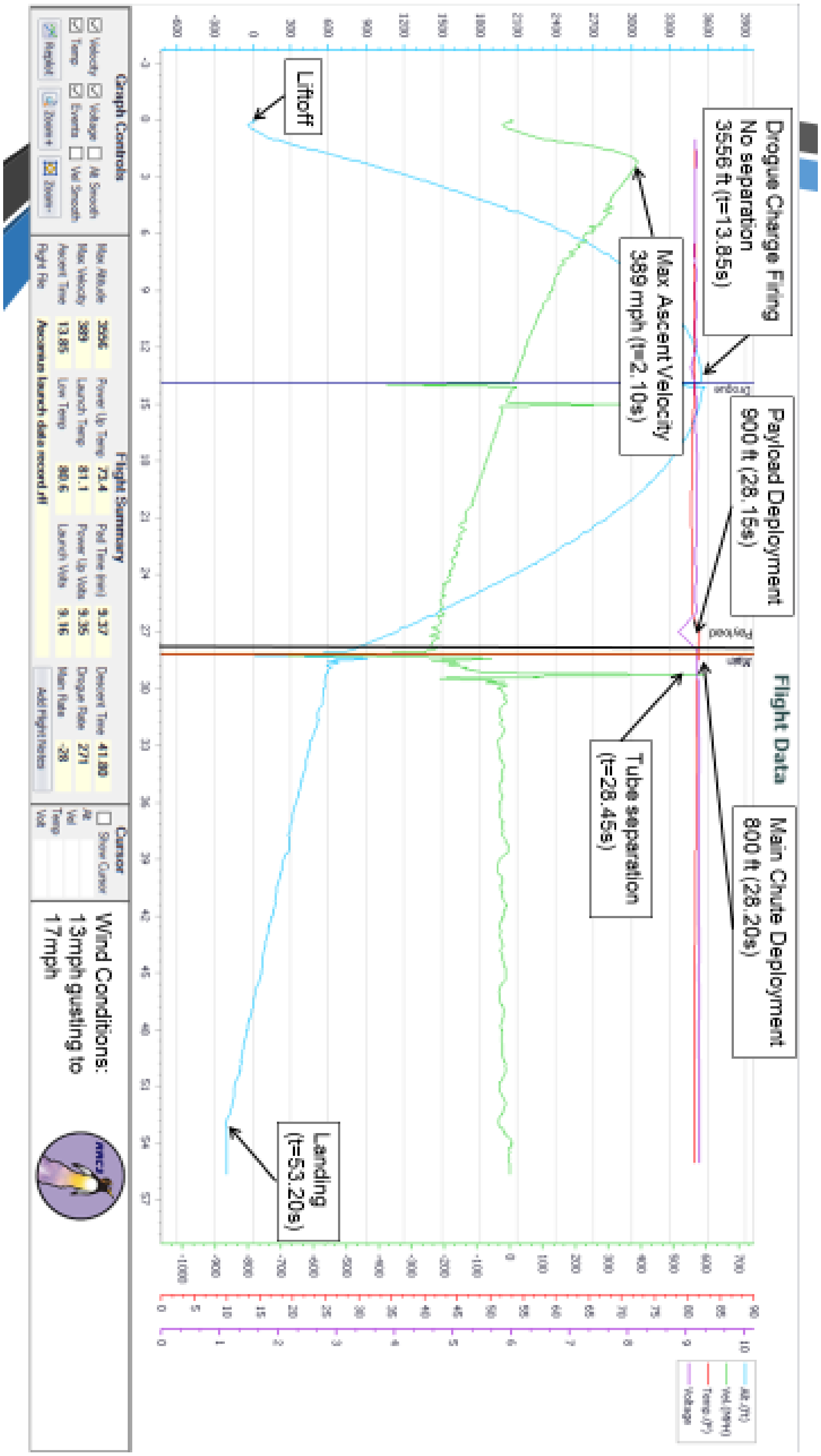
$$F = m\frac{\Delta v}{\Delta t} = 1.12kg\frac{\left(101.3\frac{m}{s} - 60.0\frac{m}{s}\right)}{(0.015s)} = 3083.7\ N$$

Using the area of the nut face using the SolidWorks part, the pressure was found to be

$$P = \frac{3083.7\ N}{6.532 \times 10^{-5} m^2} = 47\ MPa$$

While this is slightly below the nominal bending rupture stress for plywood (60 MPa) [8], the load transfer likely occurred over an even shorter time than was estimated, and the load transfer was sudden rather than static.

Appendix I3: Altimeter Flight Data



Appendix J: Launch Day Checklists

Appendix J1: Electronics Bay Launch Preparation

1. No leads to ejection charges connected to terminal blocks. ☐☐
2. New, unused battery securely mounted to electronics sled (3x zip ties). ☐☐
3. Battery connection good. ☐☐
4. Quick connect for main parachute connected to matching terminal block (side of ebay with 1 ejection cap mounted). ☐☐
5. Sled rails in coupler, rotary switch lined up with port hole labeled 'S' (scored with vertical line on exterior of coupler band), with no obstructions. ☐☐
6. Sled nuts secured on aft bulkhead. ☐☐
7. Main chute terminal block leads secure and fully connected. ☐☐
8. Switch can be activated through static port hole with 3/32 flatblade screwdriver. ☐☐
9. Fore bulkhead base nuts mounted. ☐☐
10. Drogue and payload terminal blocks connections secure & complete. ☐☐
11. Fore bulkhead mounted tight & flush with coupler. ☐☐
12. Electronics bay assembly has no play. ☐☐
13. Edge of fore bulkhead sealed with masking tape. ☐☐

Signed:

	Ray Colquhoun, Assembly Engineer	Joshua Solberg, Mission Assurance Engineer
Flight 1		
Flight 2		

Appendix J2: Fore End Launch Preparation

1. Shock cord routed, in order:
    1. drogue parachute (lock connection point with knot approximately 8" from base of nose cone) ☐☐
    2. drogue chute protector ☐☐
    3. egg ring ☐☐
    4. payload chute protector ☐☐
    5. fore bulkhead ☐☐
2. Shock cord tied securely to nose cone bulkhead. ☐☐
3. Shock cord tied to fore end of ebay (has 2 terminal blocks labeled "D" w/black tape and "A" w/orange tape). ☐☐
4. Payload (orange, "A") ejection cap wires connected to terminal block. ☐☐
5. Drogue (black, "D") ejection cap wires connected to terminal block. ☐☐
6. Drogue and Payload ejection wires good continuity – long tone, 10 sec pause, 5 short beeps ☐☐
7. Ebay inserted into front tube, hole marks aligned. ☐☐
8. Ebay secured to front tube (removable rivets). ☐☐
9. Payload ejection charge (0.51g) packed and mounted according to checklist **A1**. ☐☐
10. Payload chute protector packed, covering all area of payload exposed to ejection charge. ☐☐
11. Egg wrapped & secured in Payload Module ☐☐
12. Payload Module & Payload chute mounted & secured (masking tape). ☐☐
13. Drogue parachute packed according to checklist **A2.** ☐☐
14. Drogue chute protector and drogue chute packed in nose cone. ☐☐
15. Drogue ejection charge (0.34g) packed and mounted according to checklist **A1**. ☐☐
16. Nose cone connected to front tube. ☐☐

Signed:

	Ray Colquhoun, Assembly Engineer	Joshua Solberg, Mission Assurance Engineer
Flight 1		
Flight 2		

Appendix J3: Aft End Launch Preparation

1. Shock cord routed, in order:
    1. Camera platform ☐☐
    2. Main parachute (secure connection point approximately halfway along exposed length of shock cord) ☐☐
    3. Main chute protector☐☐
2. Shock cord tied to ebay. ☐☐
3. Shock cord tied to aft end bulkhead. ☐☐
4. GoPro secured to camera backing. ☐☐
5. GoPro powered on and connected with assigned smartphone app. ☐☐
6. Camera platform assembly mounted and secured to ring (masking tape). ☐ ☐
7. Main parachute packed according to checklist **A2**. ☐☐
8. Main chute protector packed. ☐☐
9. Main ejection charge (0.66g) packed according to checklist **A1**. ☐☐
10. Coupler and front tube secured to aft tube (shear pins). ☐☐
11. Tail cone secured to aft tube (align the hole nearest the shoulder edge w/ hole opposite #4 on aft centering ring). ☐☐

Signed:

	Ray Colquhoun, Assembly Engineer	Joshua Solberg, Mission Assurance Engineer
Flight 1		
Flight 2		

Appendix J4: Motor Insertion & Retention

1. Delay charge removed from motor reload & stored appropriately. ☐☐
2. Motor casing inserted until full stop against engine block, then backed out 2 inches. ☐☐
3. Motor reload inserted & threaded **into casing only**. ☐☐
4. Casing & motor assembly inserted to physical stop, threaded 3 turns or to stop to adapter. ☐☐
5. Tail motor retention plate secured evenly over reload. ☐☐

Signed:

	Ray Colquhoun, Assembly Engineer	Joshua Solberg, Mission Assurance Engineer
Flight 1		
Flight 2		

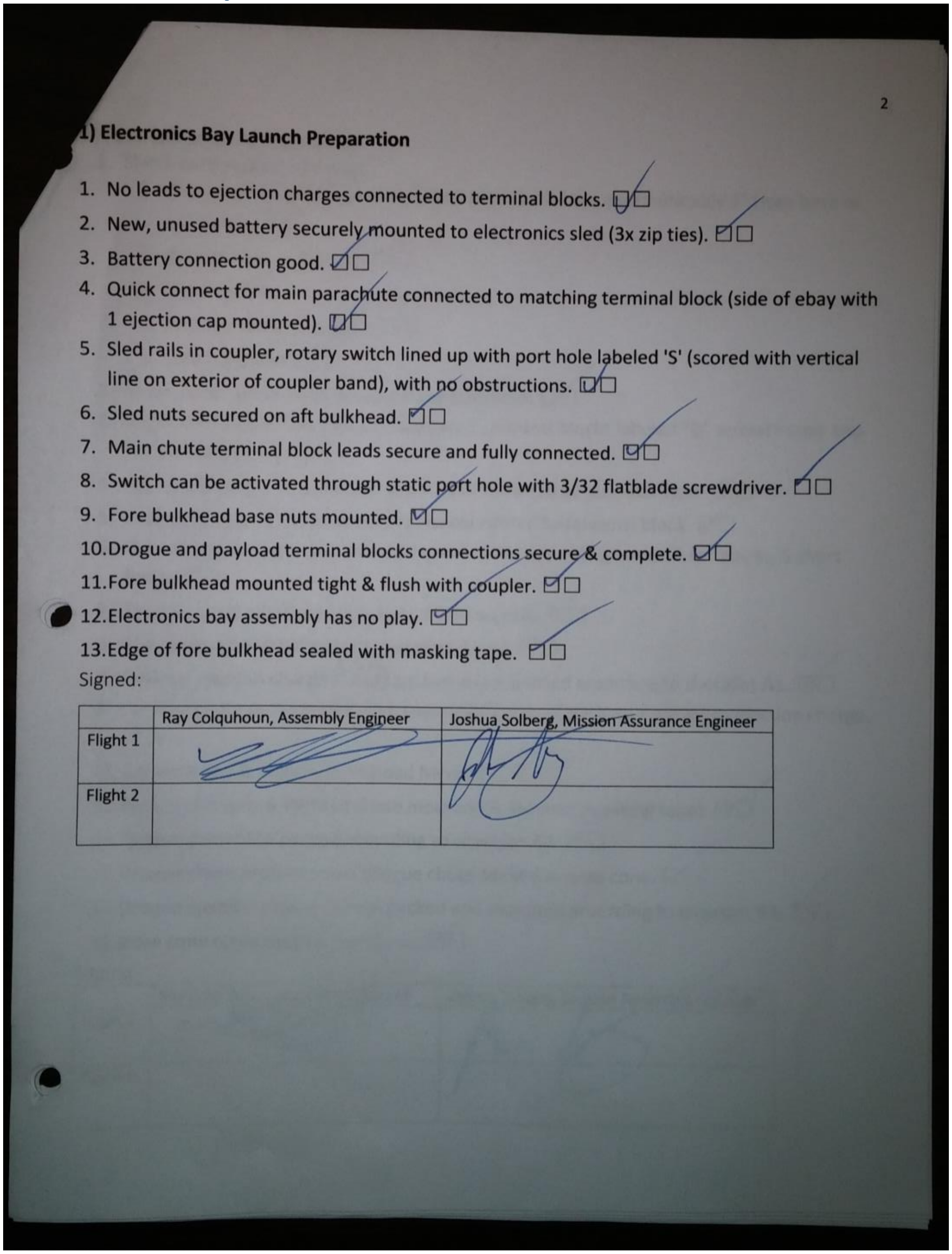
Appendix J5: Launch Pad Preparation

1. Launch card submitted and RSO approved. ☐ ☐
2. Rocket mounted on launch rail. ☐ ☐
3. Motor igniter inserted. ☐ ☐
4. Motor cap replaced with igniter threaded through. ☐ ☐
5. Igniter continuity good. ☐ ☐
6. Altimeter on - long tone, 10 sec silence, 7 short beeps. ☐ ☐
7. All team members at least 500ft away from launch rail. ☐ ☐
8. (After launch) Ejected payload tracked. ☐ ☐

Signed:

	Ray Colquhoun, Assembly Engineer	Joshua Solberg, Mission Assurance Engineer
Flight 1		
Flight 2		

Appendix J6: Launch Day Checklist Evidence



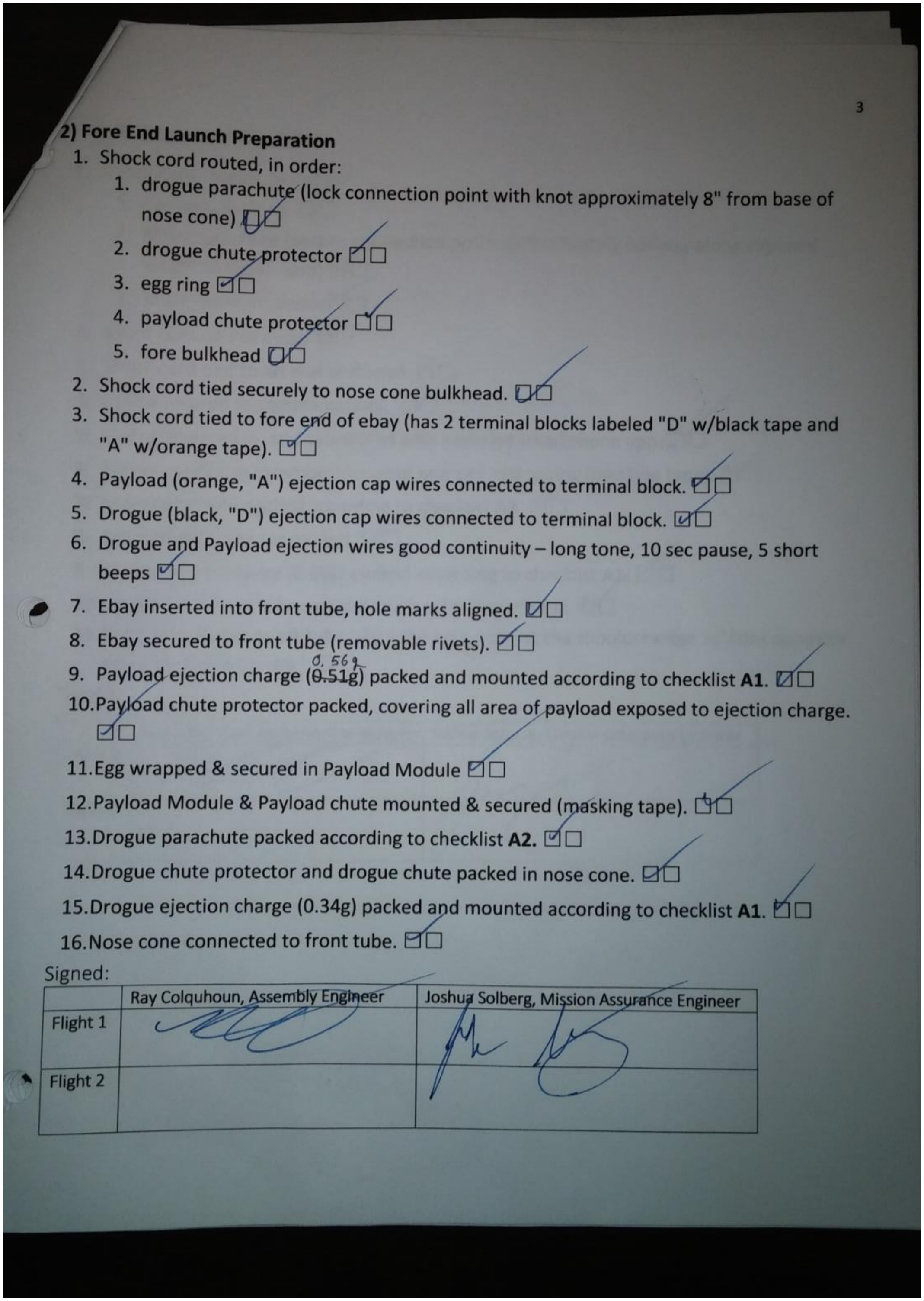
2

1) Electronics Bay Launch Preparation

1. No leads to ejection charges connected to terminal blocks. ☑☐
2. New, unused battery securely mounted to electronics sled (3x zip ties). ☑☐
3. Battery connection good. ☑☐
4. Quick connect for main parachute connected to matching terminal block (side of ebay with 1 ejection cap mounted). ☑☐
5. Sled rails in coupler, rotary switch lined up with port hole labeled 'S' (scored with vertical line on exterior of coupler band), with no obstructions. ☑☐
6. Sled nuts secured on aft bulkhead. ☑☐
7. Main chute terminal block leads secure and fully connected. ☑☐
8. Switch can be activated through static port hole with 3/32 flatblade screwdriver. ☑☐
9. Fore bulkhead base nuts mounted. ☑☐
10. Drogue and payload terminal blocks connections secure & complete. ☑☐
11. Fore bulkhead mounted tight & flush with coupler. ☑☐
12. Electronics bay assembly has no play. ☑☐
13. Edge of fore bulkhead sealed with masking tape. ☑☐

Signed:

	Ray Colquhoun, Assembly Engineer	Joshua Solberg, Mission Assurance Engineer
Flight 1	[signature]	[signature]
Flight 2		



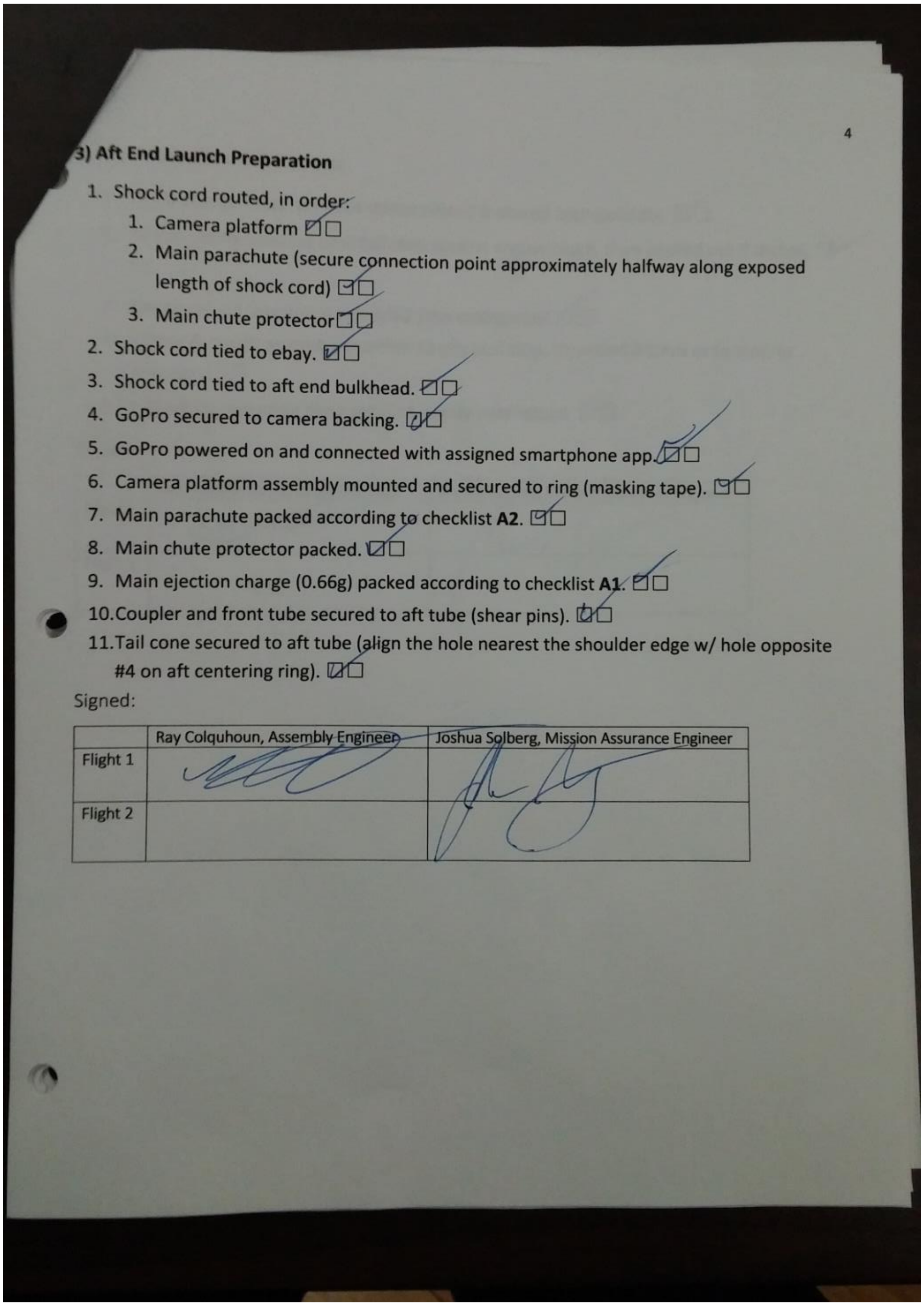
3

2) Fore End Launch Preparation

1. Shock cord routed, in order:
   1. drogue parachute (lock connection point with knot approximately 8" from base of nose cone) ☑☐
   2. drogue chute protector ☑☐
   3. egg ring ☑☐
   4. payload chute protector ☑☐
   5. fore bulkhead ☑☐
2. Shock cord tied securely to nose cone bulkhead. ☑☐
3. Shock cord tied to fore end of ebay (has 2 terminal blocks labeled "D" w/black tape and "A" w/orange tape). ☑☐
4. Payload (orange, "A") ejection cap wires connected to terminal block. ☑☐
5. Drogue (black, "D") ejection cap wires connected to terminal block. ☑☐
6. Drogue and Payload ejection wires good continuity – long tone, 10 sec pause, 5 short beeps ☑☐
7. Ebay inserted into front tube, hole marks aligned. ☑☐
8. Ebay secured to front tube (removable rivets). ☑☐
9. Payload ejection charge (~~0.51g~~ 0.56g) packed and mounted according to checklist **A1**. ☑☐
10. Payload chute protector packed, covering all area of payload exposed to ejection charge. ☑☐
11. Egg wrapped & secured in Payload Module ☑☐
12. Payload Module & Payload chute mounted & secured (masking tape). ☑☐
13. Drogue parachute packed according to checklist **A2**. ☑☐
14. Drogue chute protector and drogue chute packed in nose cone. ☑☐
15. Drogue ejection charge (0.34g) packed and mounted according to checklist **A1**. ☑☐
16. Nose cone connected to front tube. ☑☐

Signed:

	Ray Colquhoun, Assembly Engineer	Joshua Solberg, Mission Assurance Engineer
Flight 1	[signature]	[signature]
Flight 2		



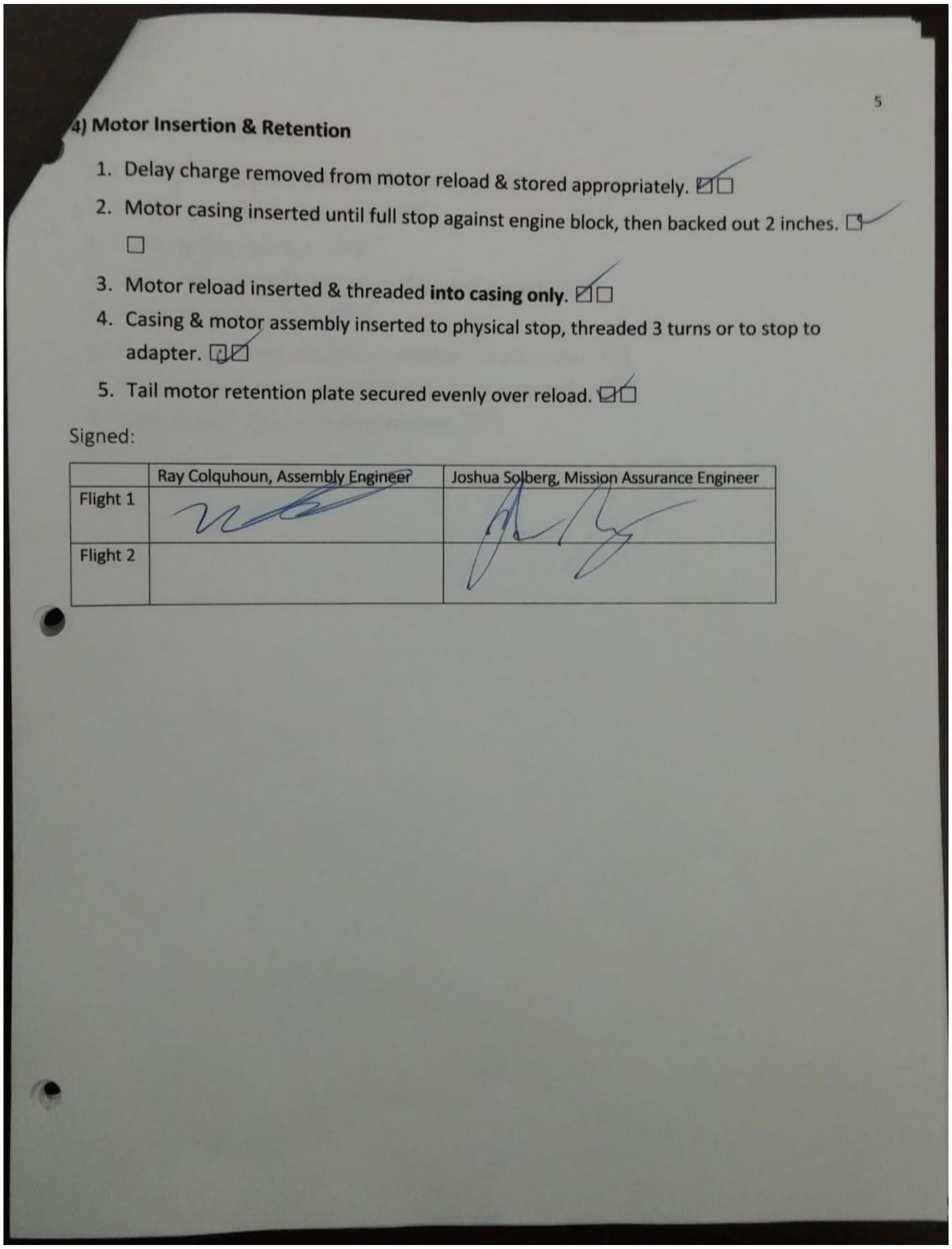
4

3) Aft End Launch Preparation

1. Shock cord routed, in order:
   1. Camera platform ☑☐
   2. Main parachute (secure connection point approximately halfway along exposed length of shock cord) ☑☐
   3. Main chute protector ☑☐
2. Shock cord tied to ebay. ☑☐
3. Shock cord tied to aft end bulkhead. ☑☐
4. GoPro secured to camera backing. ☑☐
5. GoPro powered on and connected with assigned smartphone app. ☑☐
6. Camera platform assembly mounted and secured to ring (masking tape). ☑☐
7. Main parachute packed according to checklist **A2**. ☑☐
8. Main chute protector packed. ☑☐
9. Main ejection charge (0.66g) packed according to checklist **A1**. ☑☐
10. Coupler and front tube secured to aft tube (shear pins). ☑☐
11. Tail cone secured to aft tube (align the hole nearest the shoulder edge w/ hole opposite #4 on aft centering ring). ☑☐

Signed:

	Ray Colquhoun, Assembly Engineer	Joshua Solberg, Mission Assurance Engineer
Flight 1	[signature]	[signature]
Flight 2		



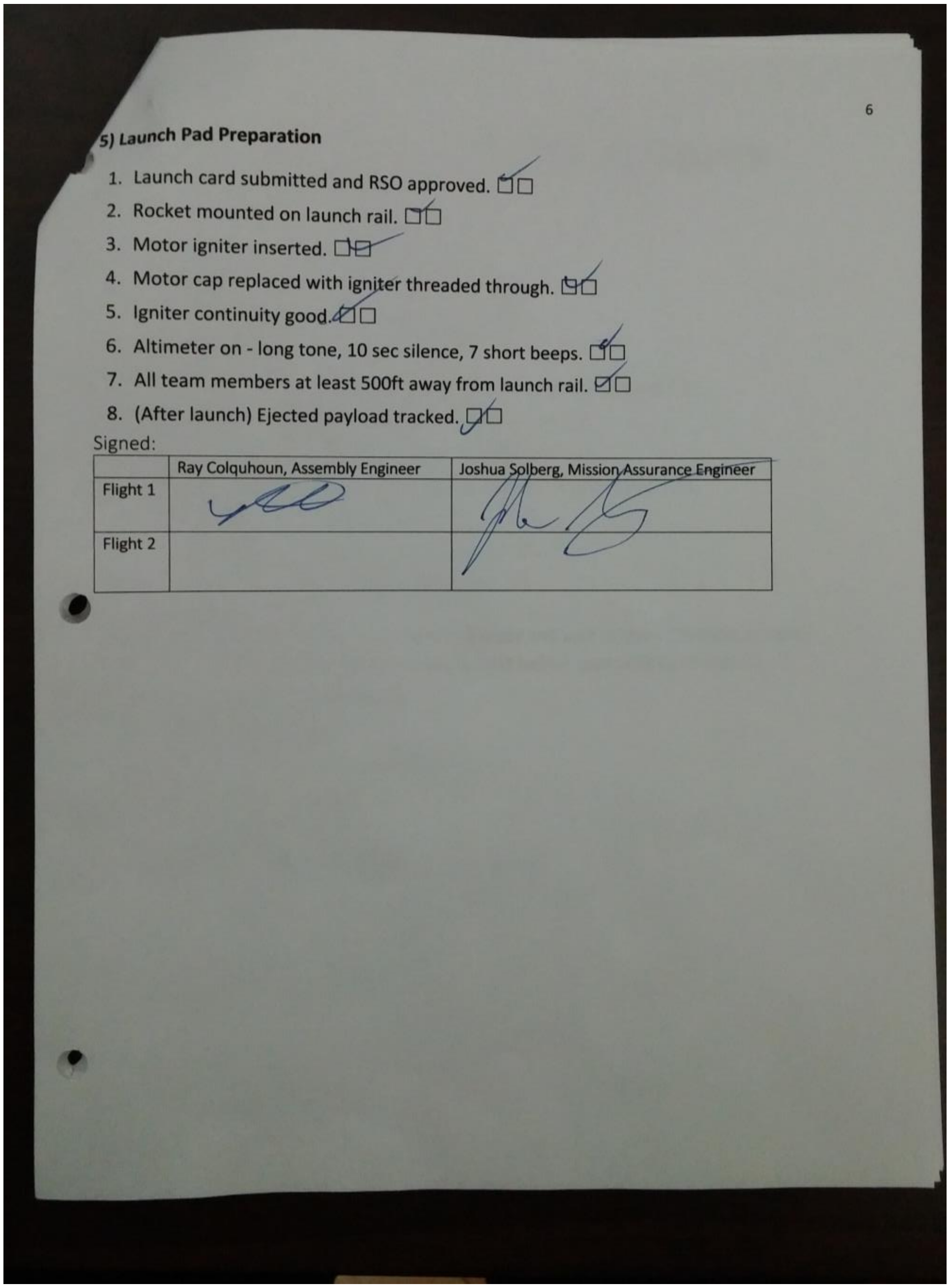
5

4) Motor Insertion & Retention

1. Delay charge removed from motor reload & stored appropriately. ☐☐
2. Motor casing inserted until full stop against engine block, then backed out 2 inches. ☐ ☐
3. Motor reload inserted & threaded **into casing only**. ☐☐
4. Casing & motor assembly inserted to physical stop, threaded 3 turns or to stop to adapter. ☐☐
5. Tail motor retention plate secured evenly over reload. ☐☐

Signed:

	Ray Colquhoun, Assembly Engineer	Joshua Solberg, Mission Assurance Engineer
Flight 1		
Flight 2		



6

5) Launch Pad Preparation

1. Launch card submitted and RSO approved. ☐☐
2. Rocket mounted on launch rail. ☐☐
3. Motor igniter inserted. ☐☐
4. Motor cap replaced with igniter threaded through. ☐☐
5. Igniter continuity good. ☐☐
6. Altimeter on - long tone, 10 sec silence, 7 short beeps. ☐☐
7. All team members at least 500ft away from launch rail. ☐☐
8. (After launch) Ejected payload tracked. ☐☐

Signed:

	Ray Colquhoun, Assembly Engineer	Joshua Solberg, Mission Assurance Engineer
Flight 1		
Flight 2		

Appendix J7: AUXILIARY PROCEDURES

J7.1 Ejection Charge Packing

1. Pour measured black powder charge into cut finger of nitrile glove.
2. Place head of e-match into bag, ensuring it is contact with black powder.
3. Pull the black powder into the bottom of the glove tip, while pulling up against the e-match. Twist the glove around the e-match TIGHTLY in order to ensure good contact between e-match and powder charge.
4. Electrical tape the bag closed around e-match as tightly as possible. Color coding is: **Black for drogue**, **red for main**, **orange for payload**
5. Masking tape e-match into ejection cap, ensuring head of e-match is in contact with bottom of cap.
6. Connect e-match to terminal block or testing leads as appropriate. Secure to ejection cap with masking tape.

J7.2 Parachute Packing Procedure

1. Take top of parachute in hand and let hang evenly.
2. Spread parachute evenly, with equal numbers of folds on either side of the central axis.
3. Z-fold the parachute leads into the interior of the chute.
4. Fold the wings of the parachute inwards in thirds, then again in order to make the radial profile as narrow as possible.
5. Fold the parachute from the top to the bottom in thirds.
6. Tighten the radial profile of the parachute as necessary.
7. Wrap two lengths of shock cord around the parachute central axis.
8. Coil excess shock cord and wrap around itself 1-2x to prevent interference & guarantee deployment.
9. Sprinkle baby powder on to parachute exterior to help deployment.

J7.3 Altimeter-Computer Connection

1. Make sure that USB connection & altimeter are powered OFF. Have mDACS software open.
2. Connect altimeter & USB to computer.
3. Check which COM port is active.
4. Click 'Host Connect' in the software.
5. Turn on the USB connection.
6. Turn on the altimeter.

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