Northville High School Aerospace Club

Project Rooni
Preliminary Design Review

10/28/2024

45700 Six Mile Rd, Northville, MI 48168

1.0 Team Summary Page

<table>
<tr><td colspan="4">Team Summary</td></tr>
<tr><td>Team:</td><td>Northville HS Aerospace Club
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https://nhsaerospace.github.io/</td></tr>
<tr><td>Mentor:</td><td>Andrew Brown
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<tr><td>Attend Huntsville:</td><td>Yes</td><td>PDR Hours:</td><td>558</td></tr>
<tr><td colspan="4">Launch Vehicle Summary</td></tr>
<tr><td>Motor selection:</td><td colspan="3">Full-scale primary: K1103X Full-scale secondary: K805G
Subscale primary: I300T Subscale secondary: I161W</td></tr>
<tr><td rowspan="3">Size/Mass:</td><td>Sustainer:</td><td colspan="2">48 in / 7.00 lbs</td></tr>
<tr><td>Payload:</td><td colspan="2">48 in / 3.419 lbs</td></tr>
<tr><td>Capsule:</td><td colspan="2">20.1 in / 4.027 lbs</td></tr>
<tr><td>Recovery System:</td><td colspan="3">Dual deploy with drogue parachute released at apogee, followed by the main parachute at a pre-programmed descent altitude. The recovery harness will include both Quicklinks and Kevlar.

Drogue: 18” elliptical parachute, deployed at apogee with backup at apogee + 2 seconds. 30 ft ⅜” tubular Kevlar harness.

Main: 78” elliptical parachute, deployed at 600 ft with backup at 550 ft during descent. 25 ft ⅜” tubular Kevlar harness.</td></tr>
<tr><td colspan="4">Payload Summary</td></tr>
<tr><td>Payload title:</td><td colspan="3">NHS Aerospace Sensor Module</td></tr>
<tr><td>Payload description:</td><td colspan="3">A STEMnaut flight capsule capable of collecting, transmitting and meaningfully interpreting telemetry including acceleration, velocity, altitude, and crew member orientations.</td></tr>
</table>

2.0 Changes Made Since Proposal

2.1 Changes Made to Vehicle Criteria

The level of detail of the launch vehicle was dramatically improved between the proposal and PDR. While the fundamental design has not changed much, minor changes and additional details have been applied and supported with new justifications to optimize the design. The changes include:

- Detailed stability analysis and optimization for real-life flight conditions. The stability margin was optimized to provide a good balance between minimum stability with margin and overstability.
- The fins design has been optimized to meet the optimized target stability.
- The fin thickness was adjusted to meet the minimum fin flutter velocity derived requirement.
- Fabrication ready CAD documents have been produced to facility ordering and fabricating new material.
- A 50% subscale version of the flight vehicle has been designed, documented, and fiberglass has been ordered and received.
- The secondary motor has been changed from a K2050ST to a K805G to better align with the target parameters of the mission.

2.2 Changes Made to Recovery Criteria

The basics of the recovery system remain unchanged from the proposal to the PDR. As we had the summer to work on it, we felt it was fairly mature. The minor differences include:

- Performed detailed load analysis of the recovery chain. This added details to the components used and solidified our decisions.
- Performed detailed rates of descents and drift calculations.
- The drogue was reduced from 24” to 18” in order to increase margin on requirement 3.12.
- The backup altimeter was changed from a Perfectflite Stratologger CF to an Eggtimer Quantum. The Stratologger CF was not available from the manufacturer.

2.3 Changes Made to Payload Criteria

Several component and electronics changes were made as payload design was refined. and as sensor limitations were found. These include:

- The central control module will be an Adafruit Feather M0 RFM96, which combines a LoRa radio module with an Arduino compatible development board, consolidating our electronics.
- We will be using an Adafruit BNO085 orientation sensor to detect STEMnaut orientation and a separate accelerometer to detect acceleration, as the orientation experiences reduced quality at high Gs.
- Additional details and accommodations for construction using heat-set inserts were added to all payload components, as well as an increase in overall strength by reinforcing joint areas and mate surfaces.
- We increased the ballast holder size to be able to hold the appropriate amount of ballast, as estimated by our simulations.

2.4 Changes Made to Project Plan

Testing plans were added to ensure a consistent testing procedure. As various airframe, payload, and STEM engagement needs became clear, details were added to budget and accounting. Detail was also added to the schedule to more closely follow information presented by NASA meetings and derived requirements.

3.0 Vehicle Criteria

Following the design flow suggested in the proposal, edited to include derived requirements (Fig. 1), each part of the launch vehicles were analyzed to ensure optimal fit to our project per NASA requirements, derived requirements, and our budget.

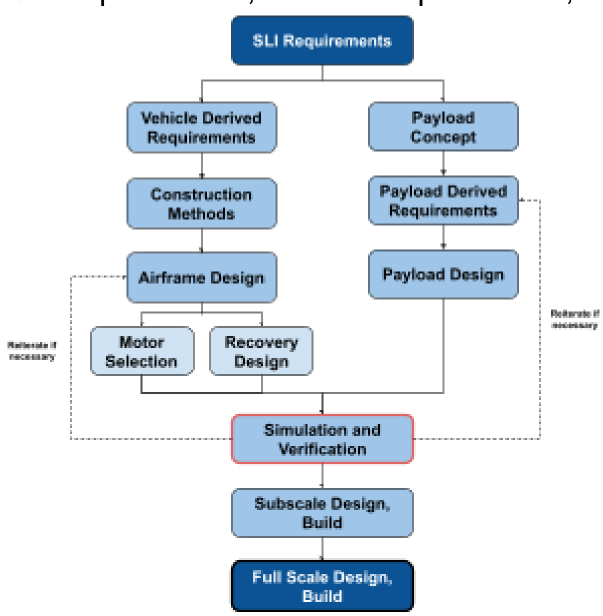


Fig. 1 - Design flow

3.1 Mission Statement

Our team aims to gain critical rocketry-related knowledge and inspire future generations of students by uniting curiosity, innovation, and entertainment through constructing high-powered rockets.

The following criteria will be used to determine if our project is a success:

- Design and construct a rocket that is structurally sound and stable through all aspects of flight.
- Successfully use a radio link to transmit and receive useful data payload data for analysis.
- Influence and inspire enough people to ensure the sustainability of both this club and the aerospace industry.
- Successfully complete all required NASA and derived aspects of the mission.
- Complete the project in a cost-effective manner.

3.2 Material, Construction and Design Selection

3.2.1 Full-Scale OpenRocket Model and CAD Model

The full-scale OpenRocket model includes all components that the launch vehicle needs to fly and recover safely. All components have a representative mass. More accurate masses will be provided after components have been ordered. The launch vehicle is 118 in. It includes the nose cone assembly with the tracker and payload, all recovery components like the parachutes, recovery hardware, avionics bay, and deployment charges. The model also includes the fin can with representative fillets to accurately simulate the final mass of the rocket. OpenRocket simulates the dry mass of the rocket to be 17 lbs.

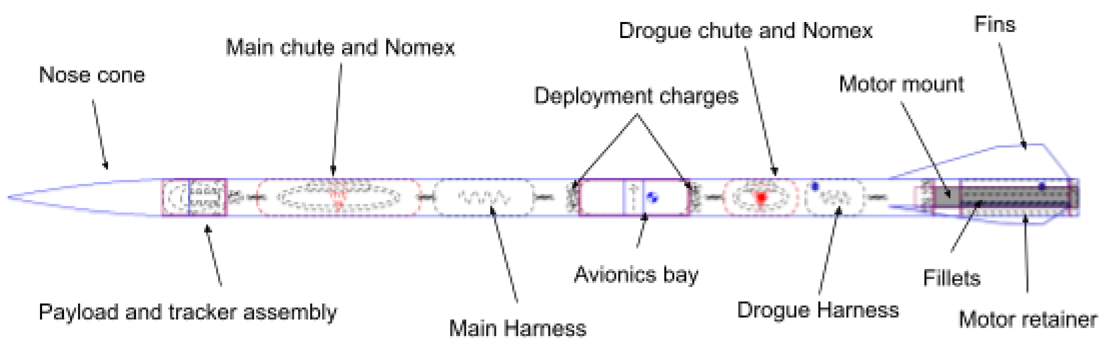


Fig. 2 - Full-scale OpenRocket model

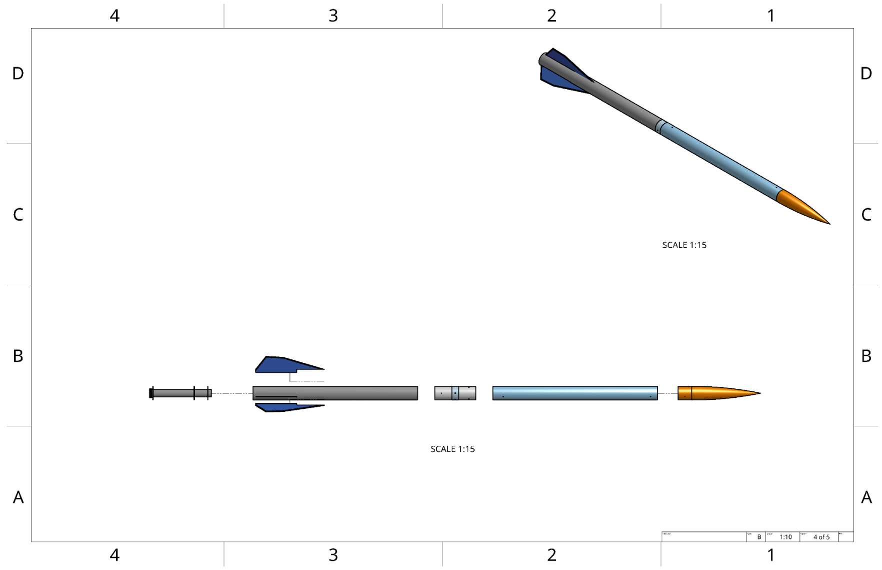


Fig. 3 - Integrated model

3.2.2 Airframe Material Selection

The material selection of the airframe determines several aspects of the overall project, including, but not limited to overall cost, robustness, performance, and final aesthetics. For this project, we consider the properties of four fairly common airframe material sets. These include conventional cardboard/plywood, phenolic, fiberglass, and carbon fiber. The main attributes used in this comparison are listed below.

Stiffness of Material -
The body tube supports all of the stress and strain of the weight during ascent. Therefore, it must be resistant to compression and tension as the airframe flexes. As the velocity of the rocket increases, the stress and strain on the fins also increases. Lower stiffness material can trigger a fin resonance such as fin flutter. Much of this can be overcome by using thicker material. However, thicker material leads to additional weight. The material used for the body tubes and fins should be as stiff as reasonably possible without sacrificing other parameters, such as cost or weight.

Impact Resistance -
Based on the descent criteria for this project, the rocket will descend at a fairly rapid rate. It is anticipated that there will be several hard landings prior to the launch in Huntsville. Therefore, it is desirable to have a material that can withstand several reasonably harsh landings, but within the SLI kinetic energy requirements.

Weight per Foot -
Most commercially available materials are only sourced for a fixed thickness. The relative amount of weight of the airframe determines how much lift is required to reach a specific altitude. If the airframe is excessively heavy, it will struggle to achieve our desired altitude with available motors. The goal is to obtain a material that is as light as possible that does not compromise in the overall strength.

Moisture Resistance -
This rocket will be launched at a minimum of two times prior to launching in Huntsville. Some of the launch sites are known for wet and often swampy areas. If moisture degrades the airframe, it will be difficult to get multiple, consistent flights out of the airframe. Having an airframe that maintains stable dimensions despite possible landing in water, swampy fields, or even snow is highly beneficial.

Ease of Construction -
The NHS Aerospace Club has experience constructing many types of materials and airframes from cardboard/plywood to fiberglass composite. However, based on the tight schedule of SLI, having a material that can be assembled quickly and easily is beneficial. The goal of our first year of participation is to use existing components rather than making our own fiberglass tubes, etc. Therefore, the ease of construction should be a factor, but not a dominant factor in selecting an airframe material.

Ease of Paint -
A very nice looking rocket with an automotive finish is really the goal of any major rocket build. While this is achievable with all materials considered, some are easier to achieve than others.

Cost per Foot -
Ultimately, the cost of the material will limit the material selection. More exotic materials will always be available, but cost will often drive what materials we can use. (LV-D-5).

Available Lengths -
While it is not a requirement, being able to obtain longer sizes of tubing is a benefit. Ideally, we would like materials four ft in length to avoid using unnecessary couplers.

The body tubes represent the largest portion of the airframe, and will guide the material selection process. The table below compares the materials considered and provides relative weighting of the metrics that are important to this project.

Table 1 - Airframe Material Selection Table

Metric	Material (Based on 4” Airframe)			
	LOC cardboard/ plywood fins	**Phenolic**	**Fiberglass**	**Carbon fiber**
Resistance to compression/tension	Poor	Moderate	Excellent	Excellent
Impact resistance	Poor	Moderate (Brittle)	Good	Good
Weight per foot (oz/ft)	4.1	5.1	8.7	8.1
Moisture resistance	Poor	Moderate	Excellent	Excellent
Ease of construction	Easy	Moderate	Moderate	Moderate
Ease of paint	Moderate	Moderate	Good	Good
Cost per foot ($)	$6.27	$9.35	$30.00	$69.68
Available lengths	34” pieces	30” pieces	Pieces up to 60”, cut by vendor	30” and 60”

Given the parameters in the table above, moisture resistance and resistance to compression and tension are probably the strongest drivers in our decision (LV-C-1, LV-C-2). This would suggest carbon fiber or filament-wound fiberglass, especially since they can also easily produce very nice-looking finished rockets without having to do major surface preparation. The benefit of weight in carbon fiber is minimal in comparison to the overall cost. Based on these tradeoffs, while fiberglass is not perfect, it is the best compromise of the available materials.

While not necessary, this decision highly suggests using fiberglass for the remainder of the airframe. This ensures compatibility with elements like couplers, centering rings, and motor mount tubes. While it is possible to mix plywood fins with a fiberglass body tube, we also selected fiberglass for the fins mainly due to the rigidity, stiffness, impact resistance, and paintability.

3.2.3 Body Tube Design Selection

The diameter of the body tube drives many performance aspects of the overall design. For simplicity, we chose a uniform body tube for the entire airframe (no transitions) between different diameters. This decision was based primarily on the level of experience of our team as well as the short design cycle. While a stepped diameter airframe may allow for certain performance benefits, we feel that we can achieve the required performance metrics with a simplistic, uniform diameter.

We settled on a 4” diameter airframe as a balance between practicality and performance. Based on design flow shown in Fig. 1, the airframe design is driven by requirements and the payload design. The diameter is dependent on the design of the payload. The initial payload concept design has a diameter of 3.740” including the methods to integrate the payload into the capsule (LV-C-8). Additionally, a 4” diameter is the smallest diameter that still allows easy access to internal components like the U-bolt attachment point on the forward centering ring which are used to connect the harness. This makes maintenance, inspection, and assembly more manageable. Using a 4” diameter also enables us to create a cost-effective 50% subscale model using commercially available materials which reduces our expenses. This diameter also provides ample space to safely pack a 6.5’ main parachute minimizing the risk of damage during ejection or failure to deploy due to overly tight packing.

While a 4” airframe represents the minimum diameter to meet our needs, a 6” airframe could have also been used. However, this would have added no real benefit while dramatically increasing the cost and weight of the project. The 6” airframe would have also resulted in a much lower altitude, possibly below the minimum allowable altitude while using K impulse motors.

Determining the length of the rocket is a compromise of balancing stability (both understable and overstable), how the mass is balanced across the entire airframe, and how the length of the rocket interacts with the balancing effect of the fins. We chose a very conservative stability target of 3.0 caliber when designing the airframe. This is a healthy margin above the minimum required stability of 2.0 caliber (Requirement 2.13). A small amount of weathercocking is acceptable; however, instability in the event of a shift in mass would be catastrophic. In addition, we wanted to select body tube sizes in 1 ft increments to allow us to purchase tube lengths pre-cut.

We settled on 4’ body tubes for both the booster and payload tubes. This places the avionics bay close to the center of mass and ensures ample space for all recovery elements without having to be aggressive with packing. Including the nose cone, the rocket is 9.8’ long with a resulting stability of 3.07 caliber (LV-D-1). These dimensions result in an aspect ratio of almost 30:1. While higher than what was presented in the Advanced Rocketry Workshop slides, this is consistent with other commercially available kits with a known track record of performance.

An optimization was performed with the airframe length to quantify weathercocking vs airframe length. To perform this analysis, we looked at the vertical orientation of the airframe through representative flight conditions in the presence of high winds. Vertical orientation was selected as the primary metric as this directly influences the rocket's stability, trajectory, and overall flight performance (LV-D-4).

The vertical orientation of a rocket, often referred to as pitch, helps determine its stability during flight. If a rocket is not properly orientated, it can experience aerodynamic forces that cause it to veer off course or in the worse case, start tumbling. Maintaining the correct vertical orientation ensures the rocket follows its intended flight path.

The amount of pitching is usually the worst in the first stages of the rocket launch. As the rocket leaves the launch rail, it is subjected to lateral aerodynamic forces which cause it to weathercock. The resistance to pitching is defined as stability. A small amount of weathercocking is acceptable, but larger amounts can veer the rocket well off optimum trajectory making recovery more difficult and possibly presenting a safety issue if the change in trajectory takes the rocket in an unexpected direction.

Below is a study where we compared vertical orientation through the ascent of the rocket to the length of payload tubes. The following parameters were held constant during all of the trials: fin design, booster tube length (4 ft), wind speed (20 mph, worst case per NAR flight safety condition), and the stability constant at 3.0. The stability was held constant by manually adjusting the center of gravity as the payload tube was adjusted.

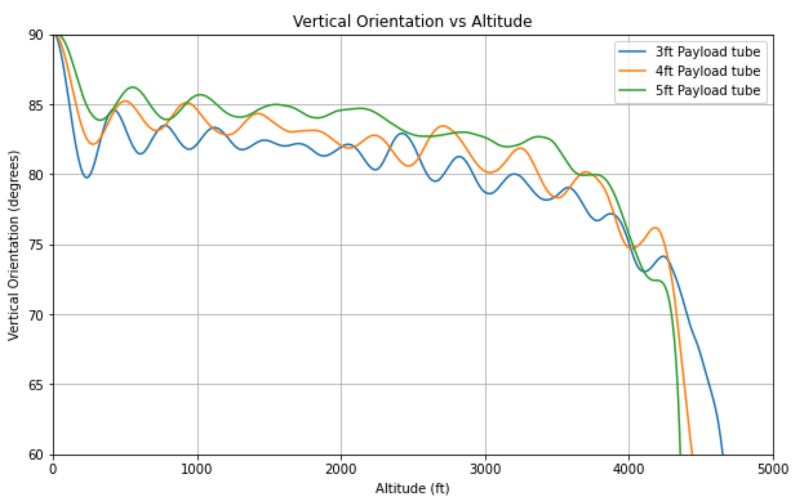


Fig. 4 - Vertical orientation vs altitude

We learned several important aspects from this analysis. Despite the stability margin being identical in all three cases, the vertical orientation had subtle differences as a function of the body tube length. In all cases, the rocket did weathercock immediately after leaving the launch rail. However, the amount of weathercocking was considerably worse for the shorter body tube than the longer ones. After the initial weathercocking, the restoring force of the fins resulted in a dampened oscillation. The magnitude and the frequency of the oscillation was also worse for the smaller body tube. While not a requirement, a straighter flight trajectory is always more desirable than an oscillating one.

To quantify the amount of weathercocking, a mean value was defined and calculated. We were interested in determining this value from immediately after the initial adjustment after the rocket left the rail to a more or less steady state value prior to motor burnout. The mean values for the vertical orientation of the rocket in the altitude range of 100 ft to 1000 ft is as follows:

Table 2 - Mean Vertical Orientation from 100 ft to 1000 ft at stability = 3.0 Caliber

Payload tube length (ft)	Mean vertical orientation
3	82.39°
4	84.17°
5	85.33°

Despite using a strong wind speed value of 20 mph, the weathercocking at a stability of 3.0 caliber is fairly low. However, vertical orientation values closer to 90° are preferred. A larger deviation in vertical orientation will result in the trajectory of the rocket changing with possible implications of:

- **Landing Site Violations**: a larger deviation from 90° will result in the rocket landing farther from the launch site. Mitigating this is important since we need the rocket to land in a 2500 ft radius as stated by requirement 3.11.
- **Safety**: Weathercocking could potentially send the rocket above spectator areas or above an area where people or property could be affected by a recovery failure.
- **Airframe Damage**: Excessive weathercocking will result in a larger than predicted horizontal velocity at apogee, potentially causing airframe damage such as zippering or damage to the drogue assembly.
- **Apogee Variation**: The apogee is inversely proportional to the vertical orientation of the rocket. As the vertical orientation gains a larger deviation from 90°, the apogee of the rocket will decrease (LV-D-4).

Based on the analysis above, there was a dramatic improvement going from a 3 ft payload tube (8.8 ft overall rocket) to a 4 ft payload tube (9.8 ft overall rocket). However, moving to a 5 ft (10.8 ft overall rocket) showed very minimal improvement at the expense of adding weight and increased drag, dramatically decreasing the altitude.

The component descriptions and specifications are shown in the figures and tables below. The general dimensions were based on Mach1 Rocketry fiberglass tubing. The fin slots will be cut to our specification by Mach1 Rocketry. However, all holes will be fabricated internally.

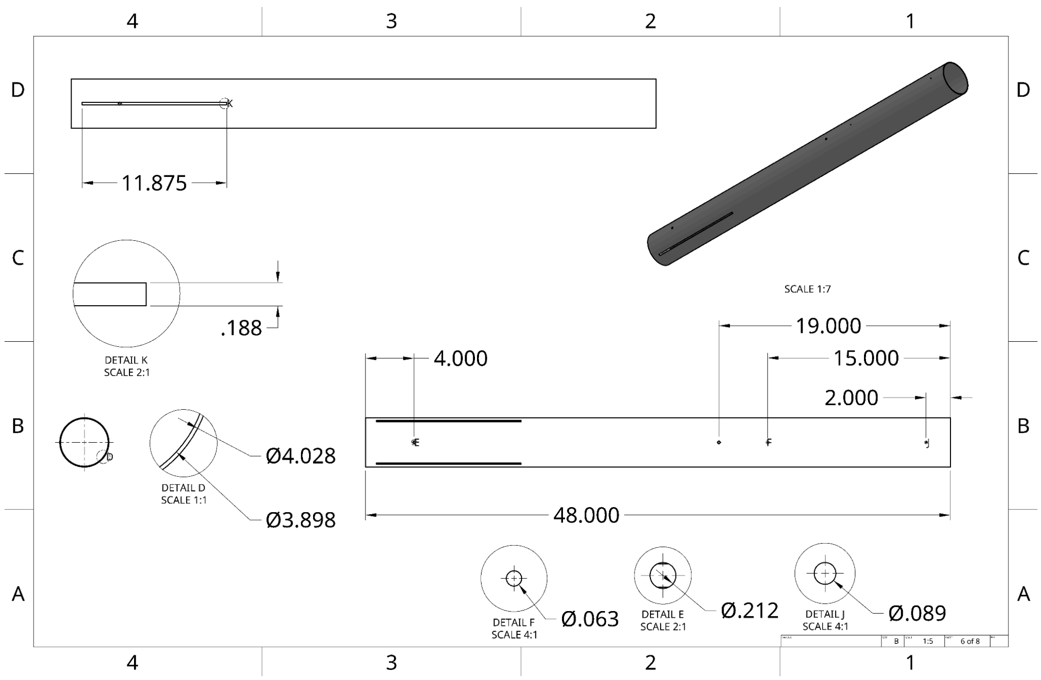


Fig. 5 - Booster tube drawing

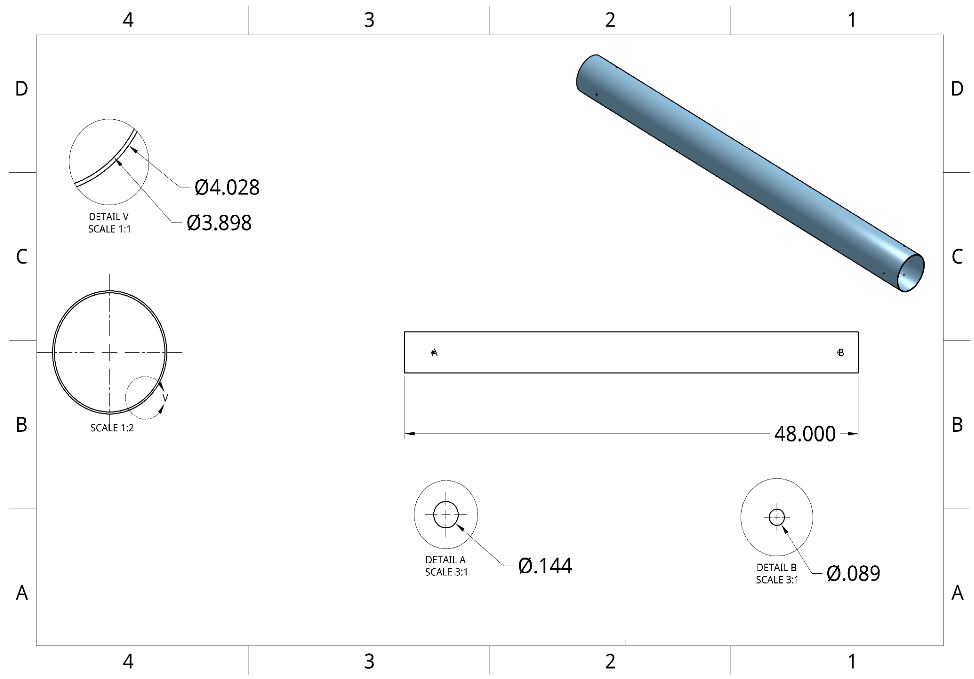


Fig. 6 - Payload tube drawing

Table 3 - Body Tube Parameters

Booster tube			Payload tube	
Parameter	**Value**		**Parameter**	**Value**
Material	FW fiberglass		Material	FW fiberglass
Length	48 in		Length	48 in
Outer diameter	4.028 in		Outer diameter	4.028 in
Inner diameter	3.898 in		Inner diameter	3.898 in
Number of slots	3			
Fin slot length	11.875 in			
Fin slot width	0.1875 in			

3.2.4 Motor Mount, Centering Ring, and Motor Retention

The motor mount diameter is selected to be a commercially available filament wound fiberglass tube. This is based on standard dimensions to accept a 54 mm motor case. A 54 mm motor mount tube gives us the widest range of possible motors ranging from small J's all the way through large K's, and even a small L for future flights.

Our proposed motor fits in an Aerotech 54/1706 case (LV-M-1), which is 15.77” long. However, we selected a larger motor mount length than necessary for the following reasons:

- **Broader Selection of Motors**: To avoid being constrained to one motor, we designed the motor mount to have extra space to accommodate different types of motors.
- **Access to Recovery Hardware**: The motor mount is supported by three centering identical rings. The forward centering ring assembly will be used to attach the Y-harness for the recovery assembly. To be able to access the U-bolts we elongated the motor mount length to allow a person with reasonable arm length to reach the recovery hard attachment points. This allows for a modular assembly, inspection, and cleaning of the Y-harness leader (LV-C-11).

The centering rings are used to adapt the body tube diameter down to the motor mount diameter while maintaining axial alignment. We are planning to use three centering rings to help constrain the motor mount to the body tube. The outer diameter of each of the centering rings is 3.898” which fits the inner diameter of the booster tube and the inner diameter of the centering rings is 2.228” which matches the outer diameter of the motor mount tube. The position of each centering ring is strategic. The aft centering ring adheres right below the bottom side of the fin slots while the middle centering ring adheres just above the fin slot gap which isolates the area between. We utilize that area to inject internal fillets to increase the strength of the bond between the fins, the motor mount, and body tube. In addition to maintaining axial alignment and stability of the motor mount, the forward centering ring serves an additional benefit of providing a hard attachment point for the recovery harness. Two U-bolts will provide redundant attachment points for the Y-harness.

For motor retention, we will use an aluminum screw cap motor retainer epoxied to the aft end of the motor mount. The screw cap offers a strong retention while being easy to remove. This satisfies requirement 2.22.5.

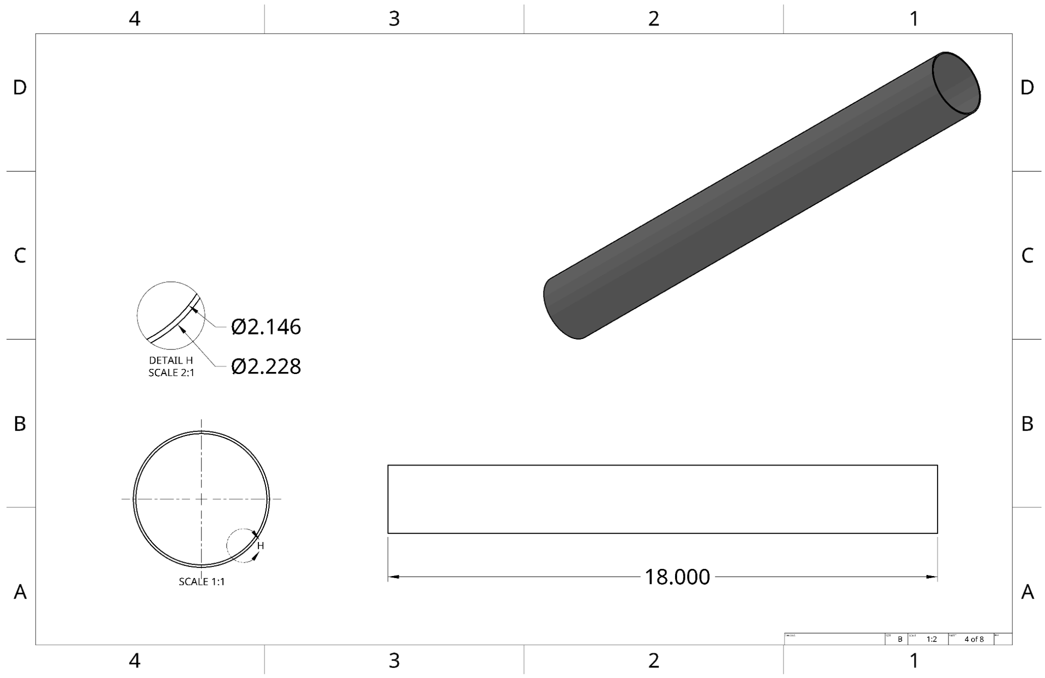


Fig. 7 - Motor mount drawing

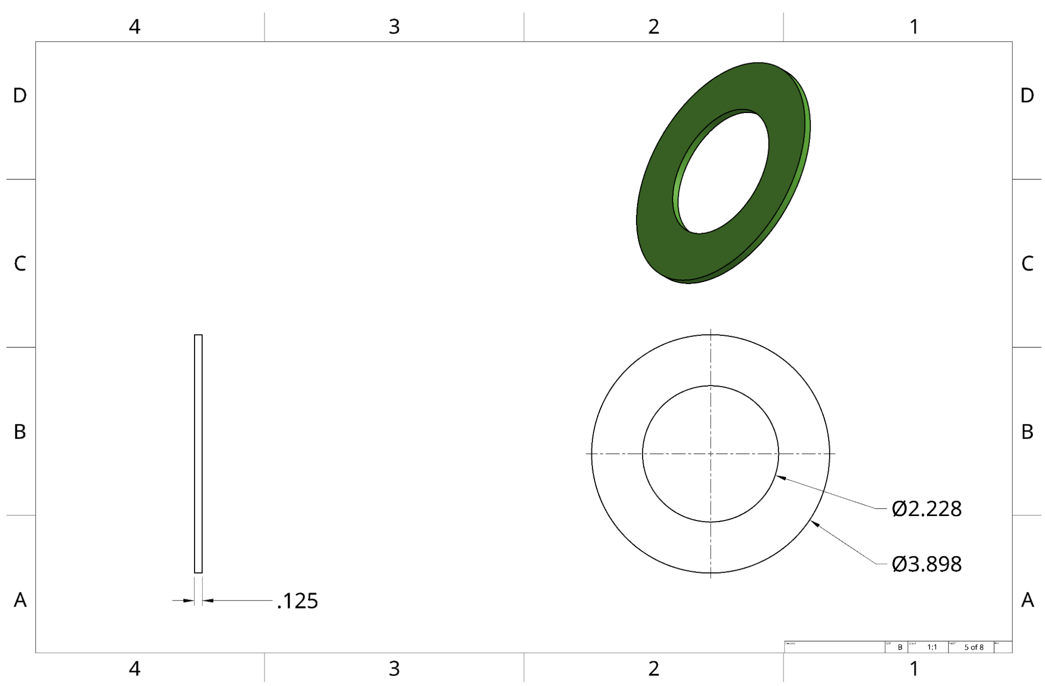


Fig. 8 - Aft and middle centering ring

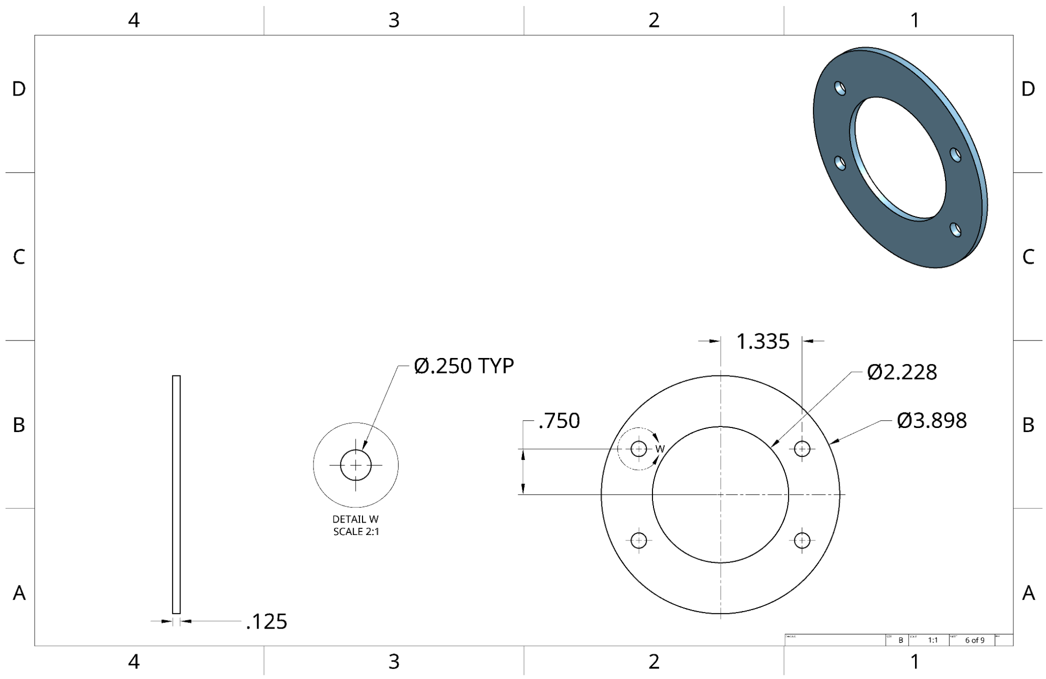


Fig. 9 - Front centering ring

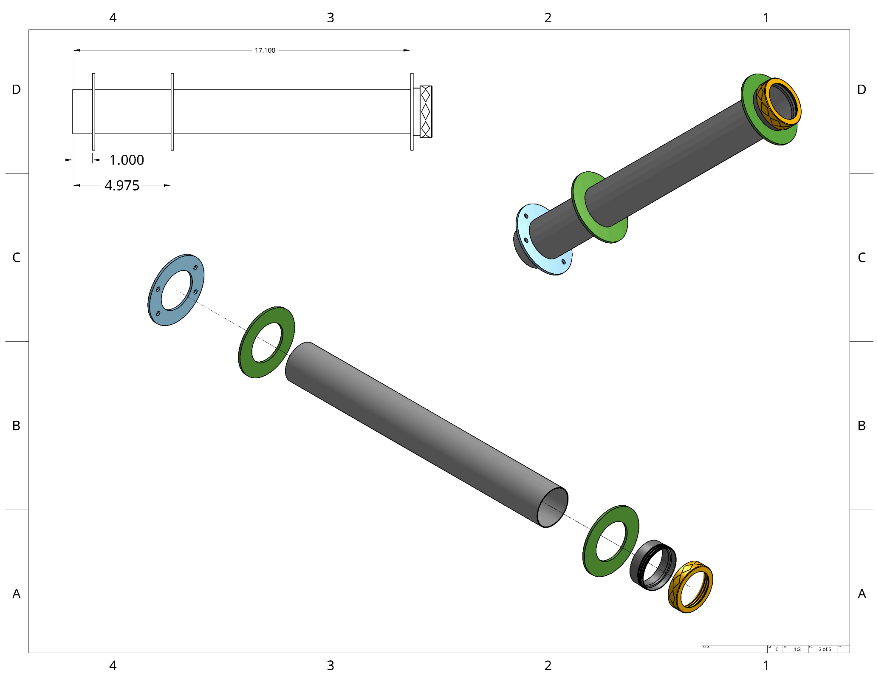


Fig. 10 - Motor mount assembly

Table 4 - Motor Mount and Centering Ring Parameters

Motor mount			Centering Rings	
Parameter	**Value**		**Parameter**	**Value**
Material	FW fiberglass		Material	G10 fiberglass
Length	18 in		Outer diameter	3.898 in
Outer diameter	2.228 in		Inner diameter	2.228 in
Inner diameter	2.146 in		Thickness	0.125 in

3.2.5 Avionics Coupler

The coupler is designed to house the avionics equipment and deployment charges for both the main and the drogue parachutes. The coupler is commercially available and designed to fit a 4" diameter airframe. With an outer diameter of 3.898", the coupler fits inside of the rocket allowing the deployment charges to sit entirely within the rocket and pressurize the body tubes to enable separation. It also includes holes for screws, shear pins, access holes for arming altimeters, and 3 ¼" vent holes to allow air to equilibrate with the outside to allow the barometric pressure sensors to function correctly.

The length of the coupler is 12" with 5" shoulders each going into the booster body tube section and the payload body tube. This leaves 2" for the switch band. The coupler must conform to both requirement 2.4.1 and 2.4.2 as the booster portion represents an "in-flight" separation point and the payload portion represents a "non-in-flight" separation point. With 2.4.1 being the more stringent (two airframe lengths and at least one body tube diameter in contact with the airframe), the dimensions exceed the requirement by a significant margin with a length of 2.5 times the diameter and and 1.25x times airframe diameter in contact with the body tube (2.5x if counting both ends, (LV-C-10). The coupler is fiberglass, which is fairly transparent for RF signals for the WiFi based altimeters (LV-C-7)

The coupler is secured to the payload tube with a series of screws (#6-32 x ½" stainless steel screws). The screws are threaded into the coupler with matching PEM nuts internal to the coupler. The screws allow the payload body tube to be disassembled from the coupler to provide access to recovery attachment points and ejection charge terminals and wells.

Shear pins (2-56, ¼" nylon screws) are used to keep the rocket assembly intact during the boost stage of the flight. The size and number of the shear pins are determined to prevent drag separation as well as a separation from an imbalance of pressure within the booster tube compared to the outside air. The shear pins are designed to shear at a very specific force that is reached during the apogee ejection charge event.

A coupler sleeve, or switch band, is used to reinforce the coupler, prevent the coupler from sliding farther into either tube than desired, and to provide a smooth transition between the coupler and the body tubes. The sleeve features ventilation holes to prevent pressure buildup which could interfere with the accuracy of the altimeter data and may cause premature deployment or late deployment. The coupler sleeve also includes holes to allow access to the switches that enable arming the altimeters (Requirement 3.6).

The bulkhead is a critical component, it holds all ejection change hardware and ensures proper function during flight. The two center holes accommodate a ¼” U-bolt (8896T94), which is used to connect the harness to other parts of the rocket. Adjacent to the U-bolt, the outer center holes are designed for two 13 inch stainless steel threaded rods, ¼-20 (98804A107) which pass through the coupler and secure the avionics sled inside the coupler tube. The bulkhead also features four 0.122” diameter holes for securing the charge wells. The avionics coupler contains the avionics sled which is fitted securely by the two threaded rods. Electrical feedthroughs are provided which connect the altimeters to the E-matches through the four 0.138” holes in the bulkhead, ensuring reliable ignition of the black powder during recovery events.

The front bulkhead connects to the harness containing the main parachute hardware and attached to the nose cone, while the aft bulkhead connects to the harness for the drogue parachute and links to the forward bulkhead in the motor mount, ensuring proper deployment of both parachutes during flight.

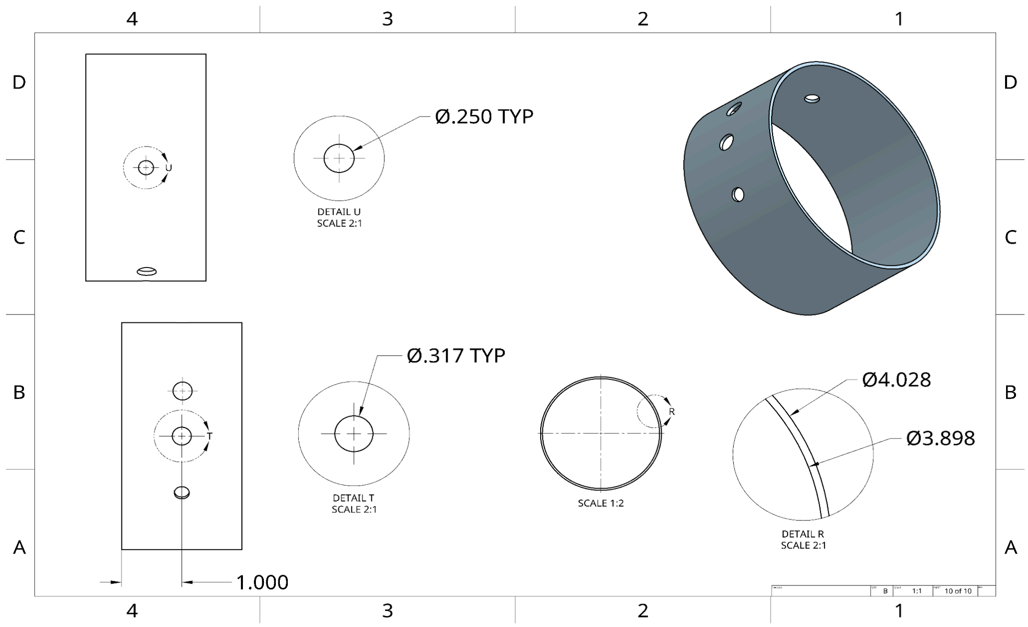


Fig. 11 - Coupler sleeve drawing

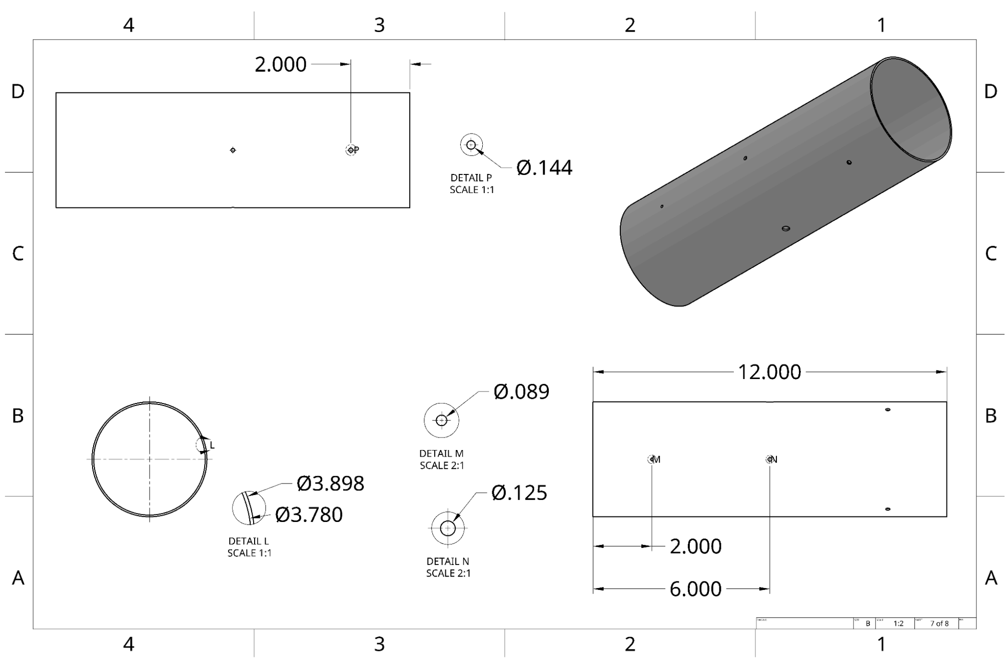


Fig. 12 - Avionics tube drawing

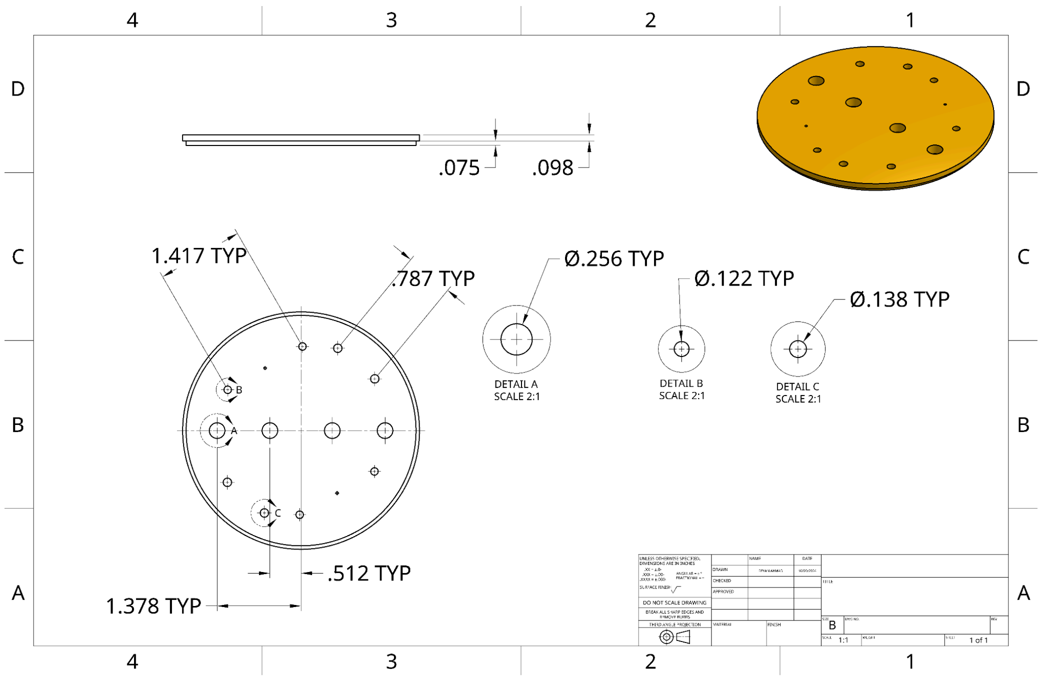


Fig. 13 - Avionics bulkhead drawing

Table 5 - Coupler/Avionics Bay Parameters

Coupler			Switch band	
Parameter	**Value**		**Parameter**	**Value**
Material	FW fiberglass		Material	FW fiberglass
Length	12 in		Length	2 in
Outer diameter	3.898 in		Outer diameter	4.028 in
Inner diameter	3.78 in		Inner diameter	3.898 in

3.2.6 Fins

The primary purpose of fins on a rocket is to provide a restoring aerodynamic force to maintain a desired velocity vector in the presence of any non-axial force such as wind or any asymmetry in the construction. The secondary purpose is simply to look good. This all comes at the expense of increased drag, additional parts, and fragility. To compare some of the major basic shapes of fins and their impact on the rocket, we performed a high level study of what we felt was important to look at in fin shape.

Table 6 - Fin Shape Study

Design choice	Effect	Suitability (y/n)
Elliptical	• Lowest induced drag due to smooth, rounded shape at subsonic speeds • Construction: More complex to design and build with fiberglass. • Impact resistance: Low risk of structural failure due to high-speed impact	Yes
Trapezoidal	• Moderate induced drag • Construction: is made of simple shapes and can be analyzed accurately • Impact resistance: low risk of structural failure due to high-speed impact depending on which trapezoidal shape selected • Aesthetically pleasing	Yes
Square	• High-induced drag especially at high subsonic speeds • Not optimal for performance • Construction: Easiest to design and build due to simple shape • Impact resistance: Low risk of structural failure due to high-speed impact • Not aesthetically pleasing at all.	No
Swept delta	• Low induced drag • High stability at supersonic speeds and usually utilized with high-speed rockets • Construction: more complex to design • Impact resistance: since these types of fins protrude out from the bottom of the booster tube, they are not suitable for high-speed landing at velocities up to 20 ft/s and have a high risk of structural failure.	No
Split fins	• Typically used to control roll and improve stability • More intricate to design and install • Impact resistance: moderate risk of structural failure due to high-speed impact	No

Based on the fact that the rocket will need to descend fairly quickly and we have little control over the surface that the rocket will impact on, we narrowed the focus to trapezoidal fins with a moderately large swept angle at the rear of the fin. This is shown below with an angle set at approximately 50°. As the rocket descends under the main parachute, the booster tube will be roughly vertical. By having the rear angle swept inward by 50°, the majority of the landing impact will be on the motor retainer and/or the body tube. This avoids impact where the vast majority of the force imparts a large moment force on the tip of the fin, possibly breaking a fin or damaging the root edge attachment or cracking a fillet (LV-C-9).

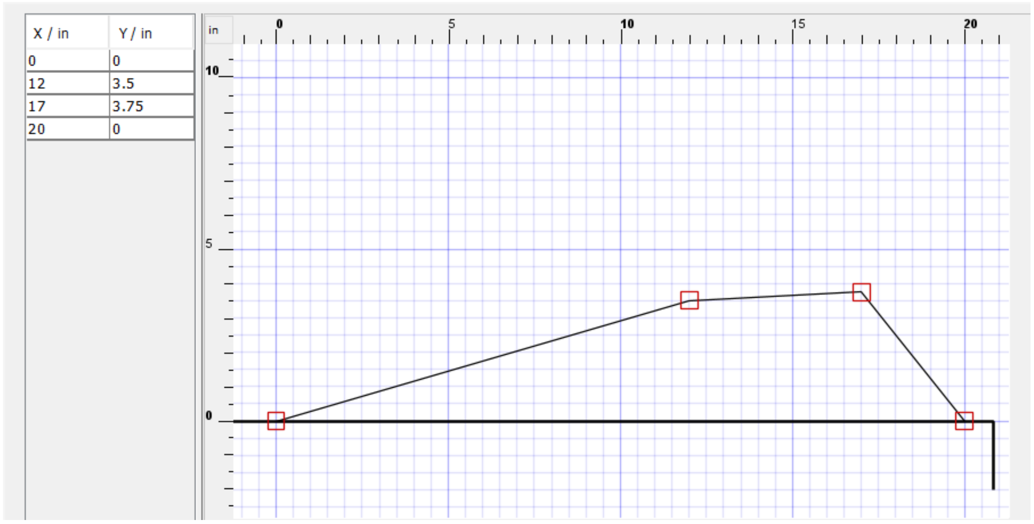


Fig. 14 - OpenRocket fin shape

Other considerations that went into this fin design include:

- Tapering on the rear of the fin to minimize fin damage from hard impacts.
- Long root cord to maximize bonding surface, root bonding from through the wall tabs, internal fillets, and external fillets.
- Ease of shape for fin beveling with a router table.
- Low fin height to fin length ratio leading to lower Cd.
- Overall aerodynamic efficiency for sub-Mach flight.
- Aesthetically pleasing design.

<u>Fin Height Analysis</u>

The fin design for the rocket incorporates several key design choices aimed at optimizing both performance and durability. The first element is the 20” fin root which provides a long contact area for attachment to the rocket body and the motor mount. This extended contact surface enhances the structural integrity of the fin, reducing the risk of damage or structural failures during flight. A larger bonding area distributes forces evenly across the surface, ensuring a stronger connection between the fin and the airframe. This design choice contributes to improved stability and overall structural robustness during the ascent, descent, and landing of the vehicle.

The design includes a rear fin angle of approximately 50°. This angle mitigates potential damage during landing. The fin geometry allows it to absorb and deflect landing forces more effectively. This design feature helps preserve the fin's structural integrity over multiple launches and landings.

As the primary purpose of the fins is to provide stability to the rocket, we first studied the impact of stability on the vertical orientation of the rocket through the duration of the flight. This helps determine what value of stability to actually target. Note that this is a similar analysis presented in the body tube length selection. In that case, we assumed a value of stability and varied the length of the airframe. In this case, we are actually determining what that stability should be.

A series of simulations were performed with representative fins, masses, and the body tube lengths determined in Section 3.2.3. For these simulations, the center of gravity, Cg, was varied to adjust the stability in the presence of 20 mph crosswinds.

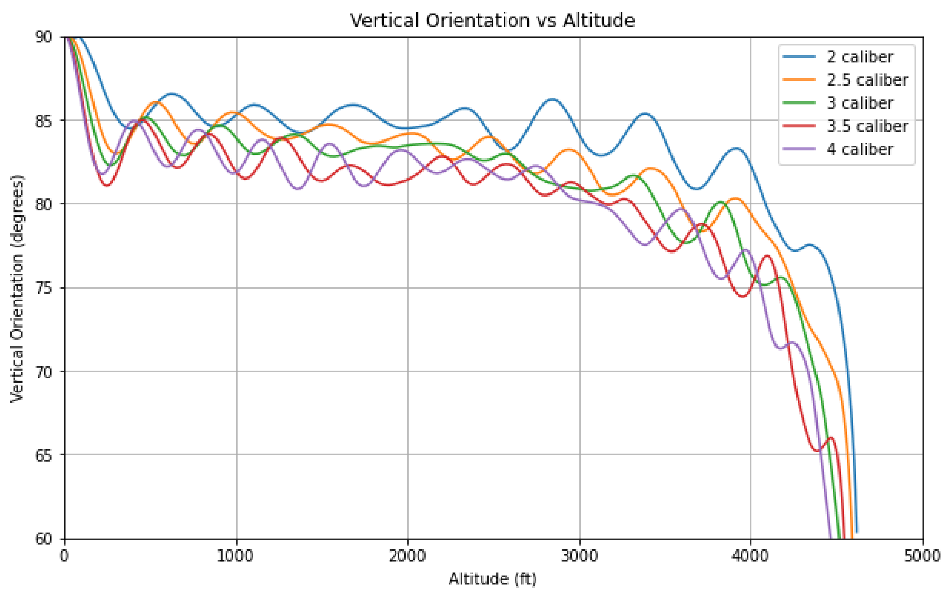


Fig. 15 - Vertical orientation vs rocket stability

The interpretation of the graph above can be difficult due to the dampened oscillations of the rocket during the ascent. It is often beneficial to look at the results as an average value over a specific range. The graph below shows the correlation between vertical orientation and static stability in an altitude range of 100 ft to 1000 ft.

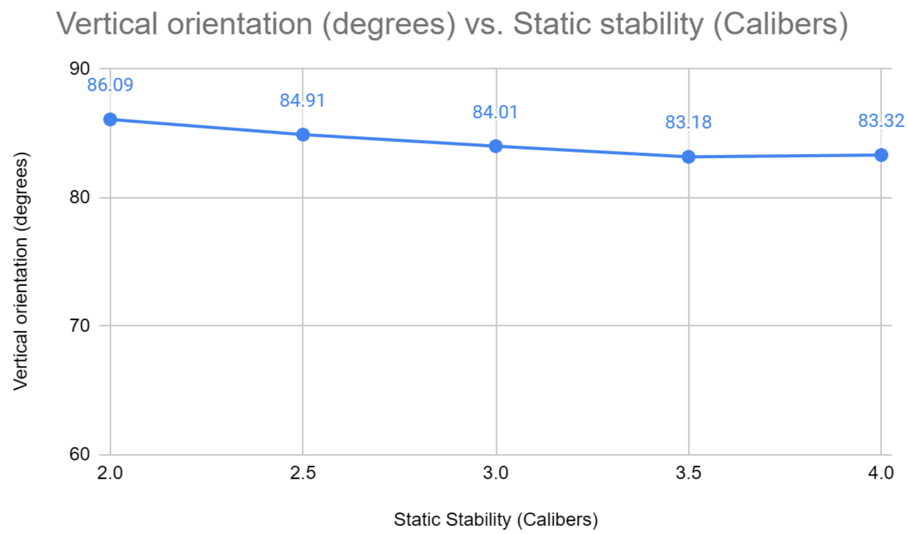


Fig. 16 - Average vertical orientation vs stability

Requirement 2.13 states that the minimum static stability needs to be at least 2.0 when the rocket exits the rail. Note that this is a minimum value. Our intention is to add adequate margin in the design to stay a safe distance above the minimum to allow for minor design changes, center of gravity changes, and errors in modeling. However, adding too much stability will result in excessive weathercocking and oscillations. As we went with a larger aspect body tube design (30:1), the design is fairly insensitive to overstability in the range of 2.0 - 3.5 caliber. Designing for a target static stability of 2.0 caliber leaves no margin and will not be considered. However, as shown in the graph above, the difference between a stability of 2.5 and 3.0 caliber is minimal with only a slight decrease in vertical orientation from 84.91 to 84.01. Similarly, the difference between 3.0 and 3.5 caliber remains small with vertical orientation changing from 84.01 to 83.18 degrees. The level of oscillation is also lower for values in the 2.0 to 3.0 caliber range. Based on this analysis, we will be pursuing a stability target of 3.0 caliber knowing that this gives adequate margin on either side of the design target (LV-D-1).

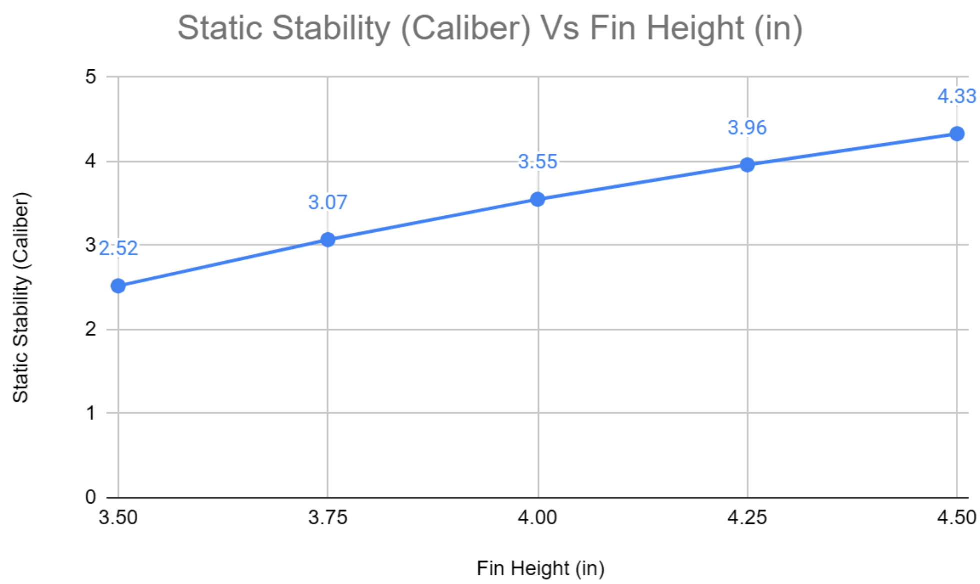


Fig. 17 - Static stability vs fin height

The graph above indicates the effect of fin height on the rocket's stability. A fin height of 3.75" provides a stability margin of 3.07 caliber. This falls within the recommended range for optimal stability. This configuration ensures that the rocket is stable enough to maintain a predictable flight path while avoiding risks associated with overstability like weathercocking. Overstability could occur with larger fin heights greater than 4.5" with a stability of 4.33 and may result in undesirable weathercocking, deviations in the flight path, or even a mission failure.

Conversely, a smaller fin height of 3.5" has a stability margin of 2.52 caliber and is on the lower end of the acceptable range. A stability margin closer to the minimum may reduce the rocket's ability to handle aerodynamic forces which could compromise flight performance or lead to mission failure. Further, as the design becomes more refined, there may be shifts in the center of gravity that would reduce our margin or even push the design to the point of non-compliance or even instability.

In this design, the 3.75" fin height centers the design within our target range. In addition, this provides a sleek, attractive design and satisfies our goal of being aesthetically pleasing.

Fin Thickness Study

Most fiberglass kits in the size range of interest utilize fin thicknesses ranging from ⅛" to ¼". This study investigates various flight aspects the fin thickness influences. One immediate concern with fin thickness is the impact on the overall altitude. A series of simulations were performed by varying the thickness of the fins and observing the impact on the total altitude with all other parameters held constant. Increasing the fin thickness had a marginal impact on the overall altitude. This result was slightly surprising, but not unexpected as the fins are very compact and do not change the drag significantly over the range of values considered. Most of the change in altitude may actually be from the increase in mass of thicker fins.

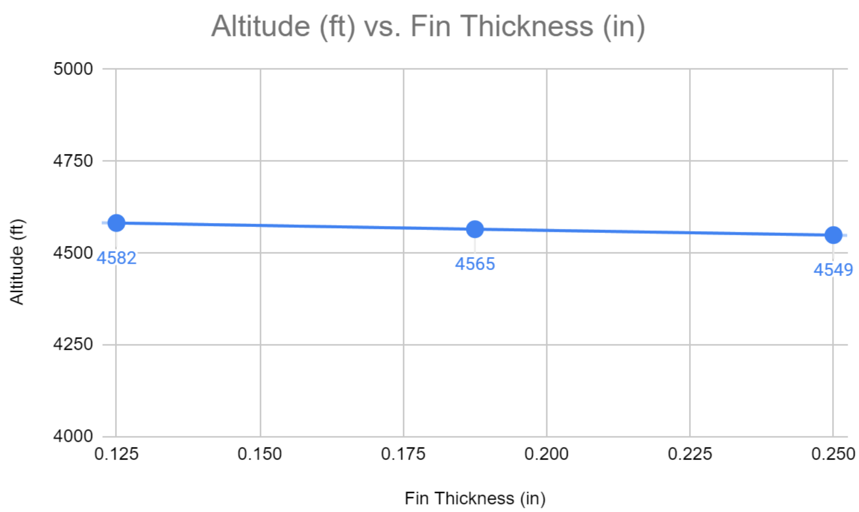


Fig. 18 - Altitude vs fin thickness

Fin flutter can be a catastrophic event if not recognized and mitigated properly. Fin flutter is an effect where the fins of a rocket experience rapid oscillatory motion. This usually occurs at high speeds where the airflow over the find creates fluctuating pressure distributions. To determine the impact of the fin thick on the flutter velocity, a series of calculations were run using a Python script written by John Bennet (**https://github.com/jkb-git/Fin-Flutter-Velocity-Calculator**). This code allows the user to input their specific fin design and launch conditions. The code will then calculate the approximate fin flutter velocity of the design. The author of this code does recognize that this is a simplistic analysis using many approximations, and he suggests using a 20% safety margin on any final calculation.

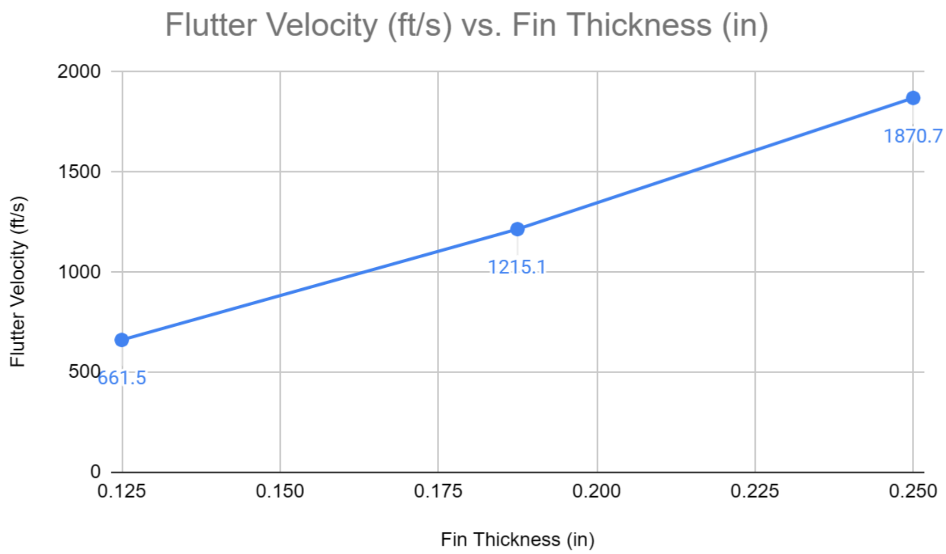


Fig. 19 - Flutter velocity vs fin thickness

The flutter velocity increases as the thickness increases due to the increased stiffness of the fin. The maximum simulated velocity of the launch vehicle on a K1103-X motor is 603 ft/s. A fin with a thickness of ⅛" provides a 9.7 % safety margin indicating that flight would be close to the flutter velocity and possibly triggering a rapid, unexpected disassembly (RUD). A fin thickness of ¼" provides a safety margin of 210.23%. Although it would be the safest choice to prevent structural damage or failure, a fin that thick is expensive compared to other fins. A fin thickness of 3/16" provides a safety margin of 101.5%, which is ideal since it is the most cost efficient thickness and it provides a relatively large margin of safety, ensuring that the fins do not receive any structural damage (LV-C-4).

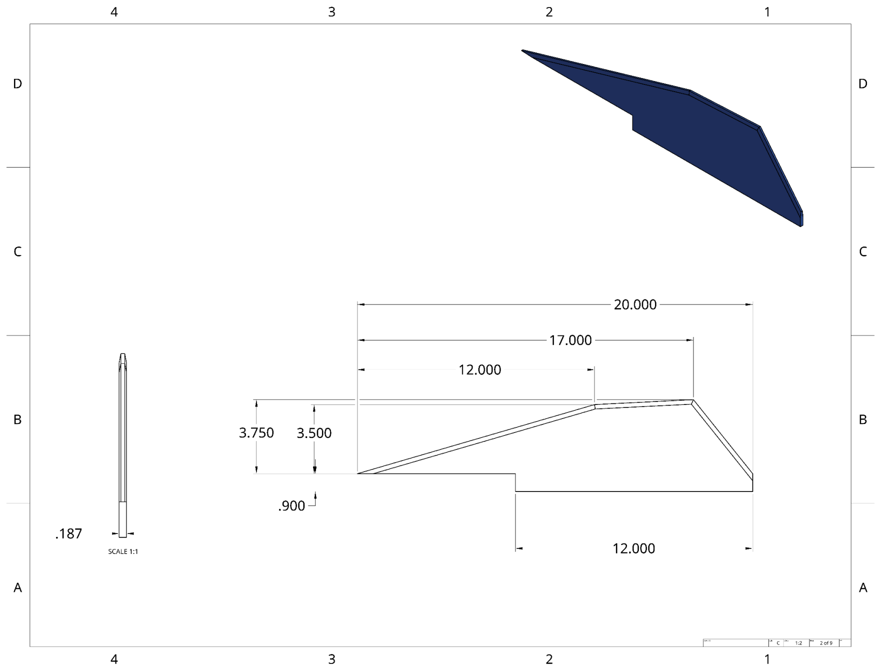


Fig. 20 - Fin drawing

Table 7 - Fin Parameters

Parameter	Value
Fin material	G10 fiberglass
Length	20 in
Max height	3.75 in
Thickness	0.187 in
Bevel angle	11.25°
Bevel distance	0.45 in
Fin tab length	12 in
Fin tab width	0.9 in

3.2.7 Nose Cone

We conducted a study to find the best nose cone in terms of drag coefficient and the effect it has on apogee. Using OpenRocket, we found the drag coefficient of each nose cone shape while keeping length (20 in), mass (1 lb) and wind speed (0 mph) constant in order to draw a fair comparison. We then ran simulations to find what the apogee would be if we used each nose cone. We did a brief study to understand what relative speed and performance each type of nose cone was optimum for.

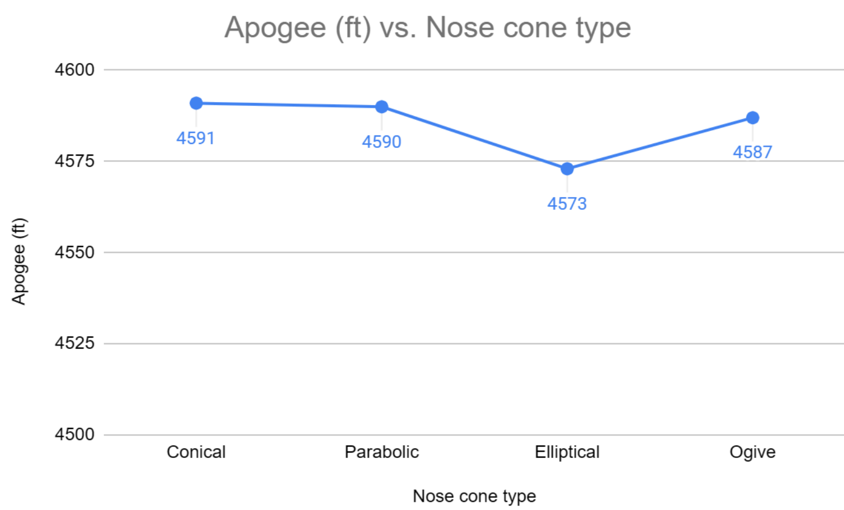


Fig. 21 - Apogee vs. nose cone type

Table 8. Nose Cone Comparison

Shape	Drag coefficient	Apogee (ft)	Availability	Best speeds
Conical	0.034	4591	Fiberglass	Transonic and supersonic
Parabolic	0.035	4590	Fabrication needed	Subsonic
Elliptical	0.041	4573	Fabrication needed	Subsonic
Ogive (5:1)	0.036	4587	Fiberglass	Transonic and supersonic

During the study, we found that the higher drag coefficient was, the more it would affect the apogee of the rocket negatively. In addition, we found that the elliptical nose cone had the highest drag coefficient and the lowest apogee, while a conical nose cone had the lowest drag coefficient and the highest apogee. The difference in altitude among the nose cones under consideration was very small suggesting that the overall shape of the nose cone was not a dominant factor in the performance of the rocket. While the best performing nose cone, the conical shape, resulted in an apogee of 4591 ft, the worst performing nose, the elliptical, resulted in an apogee of 4573 ft, or a difference of only 0.4%.

Fabricating a new nose cone is a possibility, but comes with a high degree of risk and resources. The two main options for fabricating a nose cone ourselves would be either filament wound fiberglass or additive manufacturing (3D printing). At this time, our team does not have the equipment or expertise to make a filament wound fiberglass nose cone. 3D printing a nose cone is an option given our current tools available. However, the structural integrity of the nose cone would have to be thoroughly tested as much of the strength of 3D printing is material, slicing, and tool specific. Either making a fiberglass nose cone or 3D printing a nose cone would require extensive testing. If the nose cone fails during ascent, the airframe would become unpredictable. This could result in either an unexpected disassembly, a large change of trajectory, or even a safety risk if the rocket or parts of the rocket fall or come down ballistically near spectators. This is not a risk we are comfortable assuming. For a very minimum penalty in Cd and altitude, we are opting for a commercially available fiberglass nose cone with a proven track record. The fiberglass material is RF transparent to allow the tracker and payload to transmit location and data without major attenuation (LV-C-7).

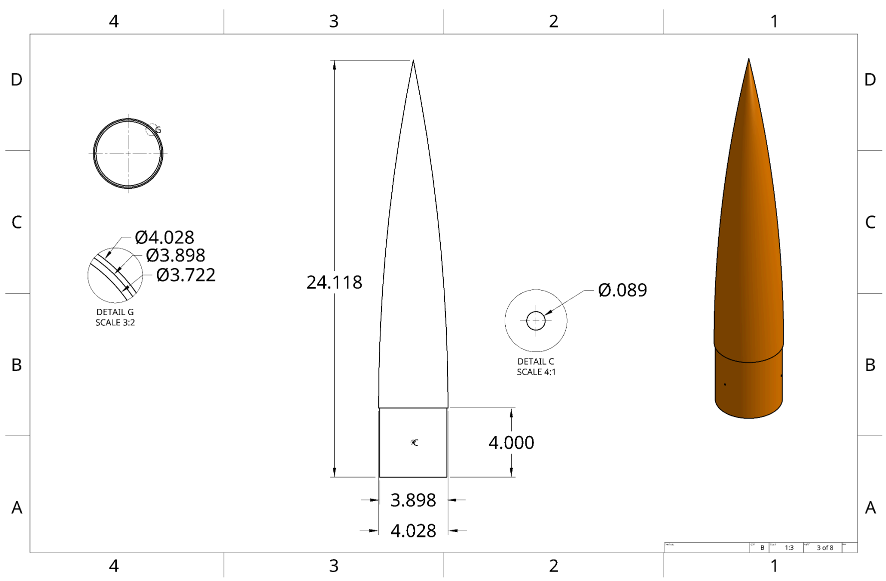


Fig. 22 - Nose cone drawing

Table 9 - Nose Cone Parameters

Parameters	Value
Length	20.118 in
Outer diameter	4.028 in
Nose cone shoulder length	7.000 in
Nose cone shoulder outer diameter	3.898 in
Nose cone shoulder inner diameter	3.78 in

3.2.8 Airframe Mass Estimate

The mass values of the airframe components are listed in the table below. Note that these are based on either manufacturer specified masses or masses calculated by density time volume in OpenRocket. A more accurate assessment of mass will be performed once components are delivered.

Table 10 - Preliminary Airframe Mass Estimates

Component	Mass (lbs)
Nose cone	1.00
Nose cone coupler	0.28
Payload tube	2.18
Booster tube	2.18
Motor mount	0.28
Centering rings	0.21
Coupler	0.48
Bulkhead	0.10
Trapezoidal fins	2.73
Total	**9.44**

3.2.9 Propulsion Design

For our full-scale rocket, we propose to use an Aerotech K1103X or an Aerotech K805G motor, leaning heavily towards the K1103X. Vehicle Requirements 2.14, 2.13, and 2.16 require a minimum thrust-to-weight ratio of 5.0:1.0, a minimum static stability margin of 2.0 caliber at the rail exit, and a 52 ft/s rail exit velocity. Several K-impulse motors were compared in our proposal, but limited to motors that fit in the Aerotech 54/1706 case or smaller (LV-M-1). After further analysis, we deemed the K1103X as the best choice for the primary motor selection and the K805G as the secondary choice. Technical information we based our choice upon is organized in the following table:

Table 11 - Motor details

Variables	Motor details	
Motor name	K1103X	K805G
Total impulse (Ns)	1789	1762
Thrust-to-weight ratio	12:1	9:1
Rail exit velocity (ft/s)	99.8	77.8
Rail exit stability (caliber)	3.12	2.96
Comments:	Easy to ignite, large flame, low amount of smoke.	Green flame, difficult to ignite

We concluded that the K1103X would be the best selection for our purposes. Upon simulation in OpenRocket, this motor allowed us to reliably reach our currently unofficial target altitude of 4500 ft and also met all of the minimum requirements for thrust-to-weight ratio, stability, and rail exit velocity; however, it requires the fuel grains to be glued to the liner, which will be done by the mentor.

As the relevant vehicle requirements were met, we are considering the K805G as our second option. Its overall numbers are slightly less than the K1103X; however, they still meet all requirements by NASA. The K1103X was chosen as first choice over the K805G due to the K805G's difficulty to ignite and its toxic barium chloride exhaust. Other motors considered in the proposal did not meet stability requirements or had unjustifiably high rail exit velocities.

3.3 Subscale Airframe Components

A 50% scaling factor was selected for the subscale vehicle demonstration. The 50% level allows us to build a 2”, or 54 mm, airframe with 38 mm motor mount in as close to an exact geometric scaling factor as possible. The 38 mm motor mount allows for a very wide variety of suitable motors ranging from small H’s to large I’s. All CAD models and component specifications are listed in Appendix C.

Not all components can be scaled equally and not all parameters scale. For example, as one goes smaller with a body tube size, a geometric scaling of 50% provides considerably smaller scaling of mass as mass is a volumetric effect. In addition, the tube sidewalls are thinner for smaller body tubes compounding the difference in mass. As a result, while most major aerodynamic parameters have been scaled by 50%, not all physical parameters are scaled correctly. Also, several components such as trackers, altimeters, batteries, etc do not scale at all. The proportion of the body tube lengths have been adjusted to set the Cg in the exact same relative position as the full scale.

Table 12 - Subscale Airframe Scaling Parameters

Parameter	Dimension	Geometric scaling factor	Mass scaling factor	Notes
Booster body tube	Diameter	50%	15%	• Length not exact to match Cg. • Mass does not scale exact (volume vs linear)
	Length	57%		
Payload body tube	Diameter	50%	14%	• Length not exact to match Cg. • Mass does not scale exact (volume vs linear).
	Length	43%		
Avionics coupler	Diameter	50%	18%	• Length larger than 50% to accommodate the avionics bay.
	Length	58%		
Motor mount	Diameter	70.4%	24%	• Motor mount diameter scaling is restricted due to availability of motors. • 38 mm motor mount selected as it provides the widest range of comparable motors to full scale.
	Length	67%		
Centering rings	Outer diameter	50%	19%	• As the motor mount is not a perfect scaling, the inner diameter is not as well. • Standard centering rings available from vendor are all ⅛”.
	Inner diameter	70.4%		
	Thickness	100%		
Fins	Overall shape	Identical shape, scaled 50%	11%	• Exterior shape is identical with uniform geometric scaling • Fin tabs could not be scaled uniformly due to motor mount restrictions.
	Fin tabs	Length scaled 50%, depth 33%		
	Fin thickness	50%		
Nose cone	Overall shape	Identical shape factor	38%	• Nose is identical in shape (5:1 ogive) with scaling for reduced diameter.
	Diameter	50%		
	Length	50%		

3.3.1 Subscale OpenRocket Model

An OpenRocket model of a 50% subscale was originally created using dimensions and masses from vendor supplied data and density values. During the PDR writing process, actual material was ordered and received allowing actual airframe component masses to be used. The following actual masses were used in the model:

- All fiberglass components
- Motor retainer
- Tracker assembly
- Both recovery harnesses
- Drogue and main parachutes
- Nomex blankets
- All quicklinks
- All forged eye bolts
- Assembled avionics bay with altimeters and hardware
- E-matches and charge holders

The following items were estimated masses based on volume and density of materials:

- Fillet epoxy
- Structural epoxy

The model does not include mass for primer, paint, or clearcoat. At this time, it is not clear if the subscale will be painted at the time of launching it due to schedule constraints.

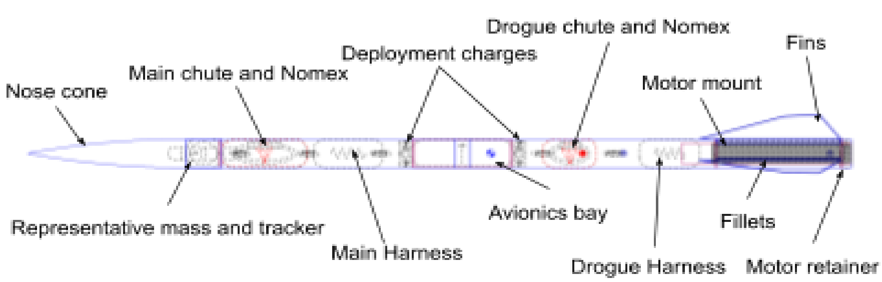


Fig. 23 - OpenRocket model-subscale

3.3.2 Material, Construction and Design Selection

In order to preserve similarity of the behavior of the subscale vs the full scale, we selected as close to a material set as possible, including using materials from the same vendor. The subscale will use Mach 1 fiberglass airframe components and identical construction methods, just simply scaled for size. There are minor differences in the recovery chain due to scaling restraints. These include:

- The leader connecting the booster to the drogue recovery harness will be epoxied to the motor mount using a high temperature epoxy. The leader will feed through the forward centering ring and be encapsulated with JB Weld.
- U-bolts are replaced with forged ¼-20 eyebolts (no bent eye bolts). There simply is no space available for U-bolts in the smaller airframe.
- Components such as quick links and Kevlar harness are reduced in size and load capacity.

The subscale will use the same altimeter bay components as the full scale with the exception of battery size as this is not subject to the three hour idle time requirement. A different altimeter sled will be used to accommodate the smaller airframe though.

3.3.3 Body Tube

The upper and lower body tubes are scaled 50% in diameter from the full scale. However, the lengths have been adjusted very slightly to compensate for shifts in the center of gravity. The tubes selected meet the specifications of Mach 1 Rocketry thin wall body tube fiberglass and are readily available. Due to hazards of fiberglass dust (See Section 7.2 Personnel Hazards), we are having these components cut to length and slotted by the vendor. The team will perform all drilling operations on the tubes.

3.3.4 Motor Mount, Centering Rings, and Motor Retention

The motor mount tube and centering rings are standard part numbers from Mach 1 Rocketry. Note that these components are not 50% scale, but rather selected due to motor sizes of commercially available motors. This imperfect scaling did shift the center of gravity, but provided no noticeable change to the aerodynamic properties of the overall airframe. The shift in center of gravity has been compensated by adjusting the lengths of the body tubes to shift the location of the altimeter bay. The motor is retained with a commercially available screw on aluminum motor retainer.

3.3.5 Avionics Coupler

The avionics coupler and switch band have been designed to accommodate redundant altimeters, switches, and batteries to replicate the functionality of the full-scale design. However, these components are not scaled and will be packed in the coupler very carefully.

3.3.6 Subscale Fin Design

The fins for the subscale design are scaled exactly 50% with the exception of the fin tabs. The fin tabs had to be adjusted to accommodate the non-perfect scaling of the motor mount. As a result, the fin tabs are only about 30% as deep as the full scale. This affects the mass distribution, but not the aerodynamic properties of the subscale. The mass distribution has been compensated by shifting the altimeter bay.

3.3.7 Subscale Nose Cone

The nose cone for the subscale airframe uses a 5:1 ogive fiberglass nose cone. This is an exact geometric scaling of the full-scale design. The tracker and representative scaled payload mass will be added to the nose cone, similar to the full-scale.

3.3.8 Subscale Airframe Mass Estimate

The components for the subscale airframe were delivered and weighed. Each component listed is from actual measured weight minus structural epoxy.

Table 13 - Preliminary Subscale Airframe Mass (Actual)

Component	Mass (lbs)
Nose cone	0.35
Payload tube	0.41
Booster tube	0.59
Motor mount	0.13
Centering rings	0.03
Coupler	0.15
Switch band	0.02
Bulkhead	0.07
Trapezoidal fins	0.30
Total	**2.05**

3.3.9 Propulsion Design

For our subscale rocket, we propose to use an Aerotech I300T or an Aerotech I161W motor, leaning towards the I300T. Technical information we based our choice upon is organized in the following table:

Table 14 - Motor Details

Variables	**Motor details**		**Full scale (K1103X)**
Motor name	I300T	I161W	K1103X
Total impulse (Ns)	426.5	328.7	1789
Thrust-to-weight	13:1	7:1	12:1
Rail exit velocity (ft/s)	91.7	64.4	99.8
Rail exit stability (caliber)	3.07	3.27	3.12
Comments:	Most similar to K1103X, altitude is a little on the high side	Very similar to K805G performance, much lower altitude for conservative flight.	Easy to ignite, large flame, low amount of smoke.

We concluded that the I300T would be optimal: a commercially available, Tripoli-certified reload for an Aerotech 38/480 motor casing. Upon simulation in OpenRocket, this motor allowed us to reliably reach our target subscale altitude of 3628 ft and also had very similar thrust to weight, rail exit velocity, and rail exit stability numbers. All numbers were within 9% of full scale.

To account for potential weather conditions and launchsite conditions, we also selected a backup subscale motor, an I161W, that achieves an apogee of approximately 2455 ft. Similar to the I300T, the I161W simulated a similar thrust to weight, rail exit velocity, and rail exit stability numbers. All numbers were within 45% of full scale.

4.0 Technical Design: Recovery System

Designing an effective recovery system for a rocket is crucial to ensuring the safe return of the launch vehicle. The primary goal of the recovery system is to minimize impact forces upon landing and ensure that the rocket and the payload are undamaged and reusable (Requirement 2.3).

The recovery concept of operations follows a standard dual deploy method with the drogue parachute being deployed at apogee and the main parachute deployed at a pre-programmed altitude on descent (currently at 600 ft, R-D-2). The charge wells for the drogue parachute are on the aft side of the avionics coupler bulkhead with a drogue separation point between the booster body tube and the coupler. The charge wells for the main parachute are on the forward side of the avionics coupler with a separation point between the nose cone and the payload body tube.

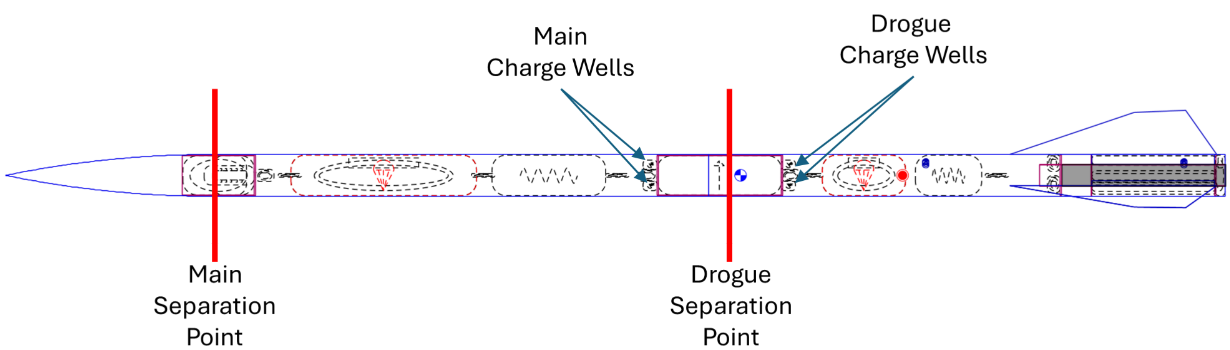


Fig. 24 - Identification of separation points and ejection charge locations.

4.1 High Level Descent Requirements

According to section 3 of the handbook, the requirements for rocket descent are 90 s from apogee to touchdown, electronically controlled deployment charges, main chute deployment greater than 500 ft above ground level, and an impact kinetic energy of less than 75 ft-lbs (Requirements 3.1, 3.3, 3.12). At this stage of the design, we will be aiming for an altitude of 4500 ft. This is halfway between the limits of 3500 ft and 5500 ft allowing for the most design flexibility between the PDR and CDR when an official altitude will be declared. The target for the drogue deployment is minimum velocity to prevent damage and comply with requirement 3.1.2. The target for the main deployment is 600 ft. This provides adequate margin for the main to deploy and inflate. It also allows the backup charge to be set at 500 ft and still comply with requirement 3.1.1.

The maximum landing velocity can be calculated from the maximum allowed impact KE. The heaviest separate section of the rocket is 7.00 lbs, and converting 75 ft-lbs to Joules, 7.00 lbs to kg, and substituting:

$$KE = \frac{1}{2}mv^2$$

$$101.7\,J = \frac{1}{2}(3.18)(v^2).$$

Solving for v:

$$v = \sqrt{\frac{2(101.7)}{3.18}} = 8.00\,m/s \approx 26.2\,ft/s.$$

The total descent time from apogee to landing is required to be less than 90 s. However, there are a number of unknown elements such as changes in barometric pressure, the presence of thermals, and wind. Therefore, derived requirement R-D-1 sets our maximum design descent time at 80 s. Allowing a 100 ft margin to main parachute deployment and a 18 ft/s main parachute descent velocity, we can calculate the time for and velocity of drogue descent:

- Main chute descent: 600 ft/17.9 ft/s = 33.3 s
- Drogue descent time: 80 s-33.3 s = 46.7 s
- Drogue descent velocity: v = d/t = (4500-600) ft/46.7 s = 83.5 ft/s.

To organize: in order to descend within the 80 s target, meet impact kinetic energy requirements from an apogee of 4500 ft, and have a margin for ideal main chute velocity, we need:

- 83.5 ft/s drogue descent velocity
- 600 ft main chute deploy
- 18.0 ft/s main chute descent velocity.

Note that these are target values for designing the recovery system. A detailed analysis of performance of the recovery system is presented in Section 6.2.4.

4.2 Component Selection

4.2.1 Parachute Selection

Parachute selection is an important part of successful recovery. It requires selecting between different types of parachutes and determining the size of the said parachute

$$D = \frac{1}{2}\rho V^2 S C_d$$

Table 15 - Parachute Drag Equation Variables

Variable	Definition
D	Drag produced (lbs)
ρ	Air pressure/ density (slug/ft^3)
S	Total reference area (ft^2)
C_d	Drag coefficient

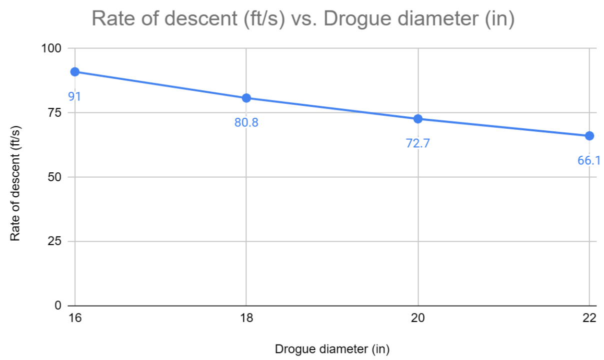
This equation is used to calculate the total drag produced by the parachute. The drag is dependent on the air pressure, the surface area of the parachute, and the coefficient of drag. Since air pressure is a variable that we cannot control, the best way to pick an efficient parachute is by choosing one with a high coefficient of drag and then refining the reference area to get optimum simulations. The table below shows the types of parachutes we researched and their advantages/disadvantages.

Table 16 - Types of Parachutes Considered

Parachute type	Advantages	Disadvantages
Parasheet	• Low cost • Simple to fold	• Inefficient, Cd of approximately 0.7. • Poor stability and usually oscillates.
Classic elliptical	• Good stability at lower speeds • Good efficiency, Cd of about 1.5-1.6 • Packs into a smaller volume	• Wobbles at high speeds. • Expensive. • Packing an irregular shape is more difficult than a flat parachute.
Cupped parabolic	• Only 4 shroud lines • Very robust to accidental high-speed deployment	• Low Cd of 0.8. • Much larger packing size compared to equivalent parachutes.
Cruciform	• Good high-speed stability • Simple design • Good for a high-speed drogue parachute	• Inefficient, CD of approximately 0.4. • Inaccurate models for OpenRocket.

The classic elliptical parachute has a high Cd of 1.5-1.6 which achieves ideal drag, with less parachute material and smaller packed volume; however, an elliptical parachute's asymmetrical shape causes an imbalance in the aerodynamic forces acting on the parachute, which in turn causes high-speed instability. It also causes air flow instabilities which can cause the parachute to pitch, roll, or yaw leading to unpredictable descent behavior.

High-speed instability can be fixed by incorporating a spill hole which is 15-20% of the diameter of the parachute. This reduces the pressure difference caused by the uneven air pressure on different parts of the canopy with a minimum impact on the effective parachute area. A spill hole allows some of the turbulent air under the canopy to escape and helps equalize the forces acting on the parachute, decreasing the oscillatory motion and resulting in a controlled descent. The plots below show the rate of descents for varying diameters for both the drogue and main parachutes.



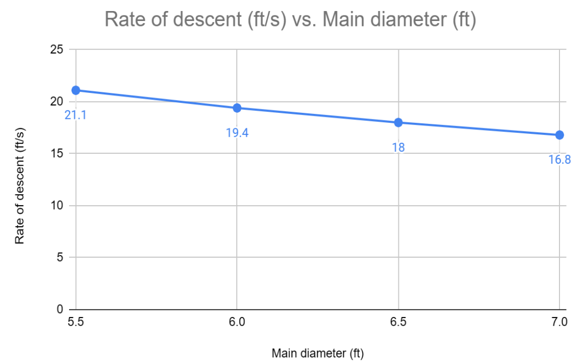


Fig. 25 - Drogue diameter vs rate of descent (left), Fig. 26. - Main diameter vs rate of descent (right)

The drogue parachute is selected to minimize the time the rocket spends in the air while slowing the descent rate enough for the main chute to safely deploy. The main chute is selected to reduce the rate of descent to a velocity that will not cause significant damage on landing while also meeting the 80 s derived requirement (R-D-1). Our simulations through an OpenRocket simulation have helped us determine that an 18 in drogue chute and a 6.5 ft main chute will slow down the rocket enough while also letting the rocket land in under 80 s (from apogee to touchdown).

4.2.2 Recovery Harness Selection

The recovery harness tethers the sections of the rocket together after separation allowing all units to descend as a unit. For high power rocketry, this is usually a long length of Kevlar or nylon. The drogue harness attaches to the booster and the coupler/payload tube/drogue parachute, while the main harness attaches between the coupler/payload tube and the nose cone/main parachute.

There are several key properties when selecting a harness set, namely:

- Strength - The harness absorbs all of the load from rapid deceleration at the drogue and main deployment events. In addition, it needs to absorb the load when these events do not go correctly.
- Wear Resistance - The harness often rubs against the opening of the body tube. In our case, this is a fiberglass airframe and the edge can be sharp or abrasive. The harness should have a high degree of wear resistance to avoid premature failure.
- Flame Resistance - The harness is exposed to the explosive charge generated by the black powder deployment charges. Over repeated use, this can degrade the material properties of the harness reducing its strength.

Both tubular nylon and Kevlar are commonly used in rocketry. However, for a given width material, tubular Kevlar offers an immense increase in harness strength allowing one to go with much thinner material. Kevlar also has considerably better wear and flame resistance. Nylon melts at about 520° F where Kevlar is heat resistant to well above 800° F. In addition, Kevlar does not melt or combust. From a wear perspective, Kevlar offers considerably higher wear resistance than nylon allowing repeated use for many flights and would meet derived requirements R-C-3.

The required length of a harness is an often debated aspect of rocketry. There are no hard requirements other than “long enough.” However, there are several rational trends to follow. Having too long of a recovery harness means excess weight and precious packing space. It also increases the potential of a tangled recovery with more material to unpack in the correct sequence.

The length of the harness needs to be long enough to allow the excess energy of the ejection charge to dissipate through the movement of the separated sections. If the length is too short, the separated sections will fully extend the harness with enough momentum to create a sudden shock on the components, possibly inducing a failure at one of the attachment points. By having a long harness, the separated sections have time to lose and dissipate some of the energy.

Another reason to have a longer recovery harness is to prevent zippering from an unintended high speed deployment. If the deployment occurs at a high velocity, the separated rocket has a higher chance of slowing down as individual pieces prior to the harness fully extending.

For our project, we are selecting 30 ft and 25 ft Kevlar harnesses for the drogue and main harness, respectively. This is approximately 3:1 and 2.5:1 harness length to rocket length ratio. The material is ⅜” tubular Kevlar with a rated strength of 3600 lbs. More detail on the recovery chain load analysis will be presented later in Section 4.4.

While the ⅜” tubular Kevlar has a load strength of 3600 lbs, the ends where the quick links connect to require a loop that needs to match or exceed the strength of just the Kevlar cord. The loops are stitched with a series of knots using 100 lbs test Kevlar line. Each knot then represents approximately 100 lbs. There is some degradation due to the abrupt bending of the material. To add margin, a minimum of 40 knots (~4000 lbs equivalent) are used.

4.2.3 Recovery Hardware Selection

The recovery harness is only as good as the components used to connect it to the airframe. The entire recovery chain is exposed to burning black powder. This is a highly corrosive environment. For the recovery chain, we used corrosion resistant materials whenever possible. While it is not the strongest steel available, 316 stainless steel provides one of the better levels of corrosion resistance with adequate tensile properties.

For all of the hard point attachments to the airframe, we selected a ¼-20 U-bolt with backing plate (McMaster-Carr part number 8896T94). Many of the components used have failure strengths specified by their manufacturers. However, the U-bolt used for our rocket did not have a manufacturer supplied failure strength. Due to this, the failure strength of the U-bolt needed to be calculated. The U-bolt has two main failure modes, namely the tensile strength of the bolt and the shear strength of the threads. Ultimately, the weaker of these two failure modes determine the ultimate strength.

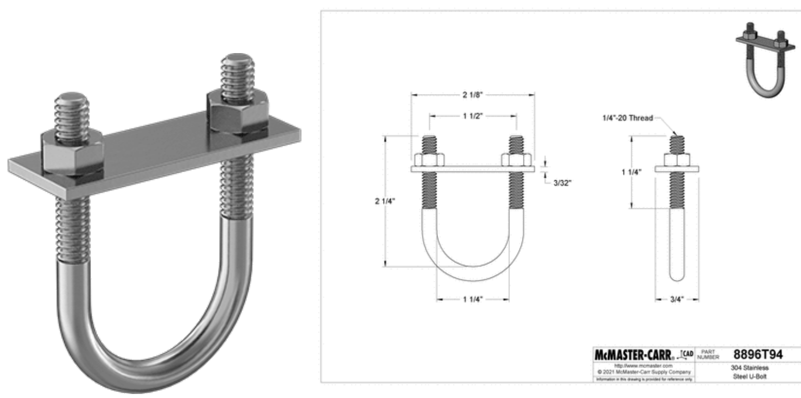


Fig. 27 - U-bolt selected for all hardpoint attachments to the airframe

The tensile strength of 316 stainless steel is 84100 psi. The bolt tensile stress area in square inches for ¼ - 20 size bolt is 0.0318 in^2 taking into account the interior dimensions of the threads. Using the bolt tensile stress area, we multiplied it by the tensile strength of 316 stainless steel, 84100 psi resulting in a failure of 2674.4 Ibs failure strength for a single bolt. As this is a U-bolt, we multiplied the number by two as there are two sets of threads in parallel, resulting in 5348.8 Ibs of force required for tensile failure.

The next part of calculating the failure strength of the U-bolt is to calculate the thread engagement failure strength. The shear strength of 316 stainless steel is approximately 42100 psi. The bolt thread stripping area per inch was determined to be 0.368 in^2

(Industrial Fastener Institute). Using these values, the bolt thread shear strength per inch would be 15492.8 lbs/in. The threads are engaged by a 0.22 in long matching ¼-20 bolt, also made from 316 stainless steel. This would provide 3408.4 lbs of thread shear strength. As the U-bolt uses two threaded portions in parallel, the net shear strength provided by the U-bolt would be 6816.8 lbs. Since we have two failure modes, the overall failure strength would be the weaker of the two, or 5349 lbs.

Using a U-bolt over an eye bolt of similar size provides significantly higher strength. With the threads being the weakest element of the connection, an eye bolt with a single threaded region would have to be approximately ½”-13 bolt size representing close to a doubling of mass.

Connecting the harness to a U-bolt requires some form of removable linkage to allow for cleaning and serviceability of not only the harness, but also the body tubes between flights. Quicklinks will be used for this. The quicklink selected is McMaster-Carr part number 8947t27 which is a 5/16” 316 stainless steel quick link with a rated continuous use failure strength of 2400 lbs with 4:1 safety margin. For the purposes of this report, we are converting the continuous use failure strength to peak failure by multiplying by the safety margin. This results in a value of 9600 lbs.

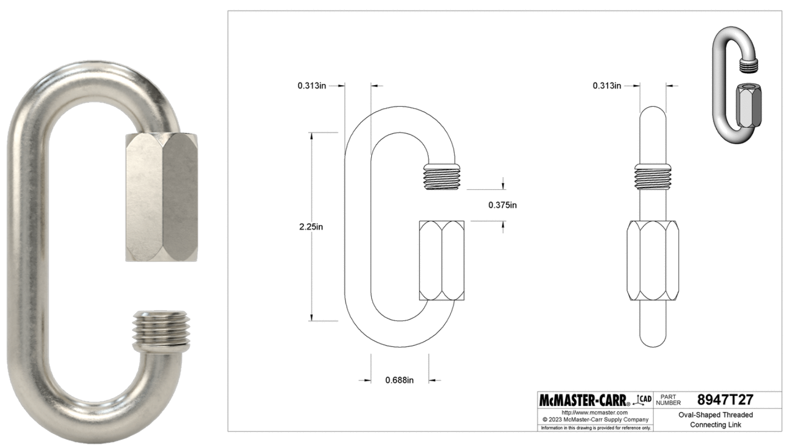


Fig. 28 - Quicklink selected for all Kevlar to U-bolt attachment points

The hardware that couples the drogue harness to the main harness through the coupler is a pair of threaded rods. Similar to the U-bolts, we are using ¼-20 hardware (McMaster-Carr part number 98804A107). This is subjected to the same failure modes of tensile failure (2674.4 lbs per rod) and thread shear failure (3408.4 lbs per rod). As the weakest point of failure is the tensile failure, and there are two rods in parallel, the threaded rod assembly would have a net failure strength of 5349 lbs.

4.3 Recovery Attachment

The recovery harness has to attach to the booster assembly in a safe and reliable manner. This is done through a leader section that connects to the fin can on one end and goes out of the top of the body tube on the other end where it attaches to the recovery harness. The leader may be permanently attached to the fin can or have the ability to be removed for serviceability. It should be noted that this leader also rubs against the upper edge of the body tube during the recovery stage and may show wear over time as fiberglass is abrasive. It should be inspected prior to all launches.

There are two main types of leaders, a single point harness leader, and a Y-harness leader. The single point simply is a single length of Kevlar attaching to the fin can. The Y-harness is a double piece of Kevlar with two attachment points on the fin can with a stitched connection at the top. This offers redundancy for both the leader and the fin can attachment point.

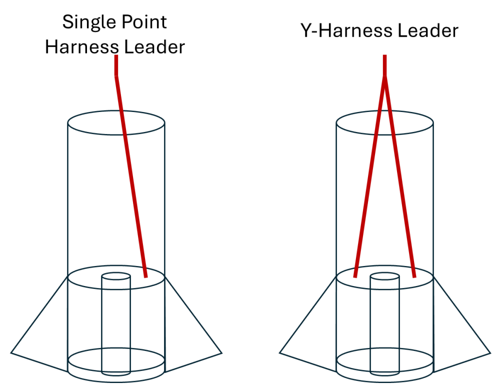
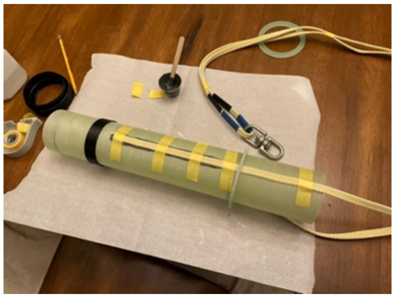
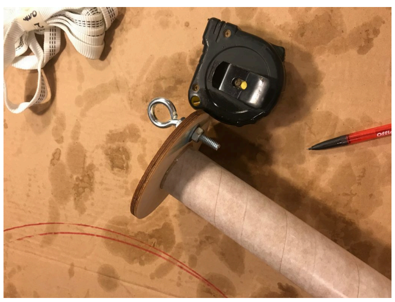


Fig. 29 - Single point vs Y-harness leader attachment

While the Y-harness has additional material and weight, it is preferable for an attachment method to mitigate attachment failure as well as the edge of the body tube rubbing against the harness (R-D-6).

Table 17 - Comparison of Harness Leader Attachment Methods

Method	Advantages	Disadvantages
Epoxy Leader to Motor Mount 	• Lightweight • Simple installation • Strong bond with high-quality, temperature resistant epoxy • Good for smaller diameters • Distributes the forces across the entire fin can assembly	• Permanent attachment • Requires precise application • Failure strength is not quantifiable as every application of epoxy differs.
Eyebolt in Forward Centering Ring 	• Removable for maintenance • Provides a central attachment point	• Adds weight • Load strength is lower than u-bolt. • Does not distribute the force across the centering ring as well
U-Bolt in Forward Centering Ring 	• Extremely durable and secure • Allows for the attachment of a Y-harness • Allows for easy attachment and removal of the harness	• Adds weight • Involves another centering ring on the motor mount with no other purpose other than act as a placeholder for the u-bolt

The ideal recovery attachment for the subscale would be the epoxy leader to motor mount as reaching into the subscale model is physically impossible due to its 2 inch airframe diameter. The forces produced by the subscale model are weaker hence do not require a separate centering ring to act as the force distributor.

The ideal recovery attachment for the full-scale model would be the U-bolts attached to the forward centering ring. U-bolts attached to the forward centering help distribute the forces across the centering ring and the motor mount. They have a higher load strength than eye bolts and allow for easy attachment and removal for the harness.

4.4 Recovery Load Analysis

The recovery chain refers to the entire recovery system from the attachment of the harness to the lower body tube all the way to the attachment to the nose cone. Ultimately, this system will absorb the entire load of the recovery. Based on the deceleration calculations in Section 6.2.4, the airframe does not actually see excessive amounts of force for a nominal recovery with individual force components in the range of 20 lbs. However, the recovery system is generally designed for the worst case when things go wrong such as a late deployment, a deployment under failsafe, or some other unexpected event. A margin factor of 100 - 150x is a reasonable safety factor for a less than favorable deployment. This may damage the airframe, but it at least holds everything together and prevents items from falling in a ballistic manner. R-C-2 requires a minimum 100:1 safety factor, or 2000 lbs shock load assuming the calculations are correct. However, the calculations use a number of approximations with a potentially large uncertainty. As a result, our recovery chain has been designed for an estimated load capacity of >3500 lbs (150x).

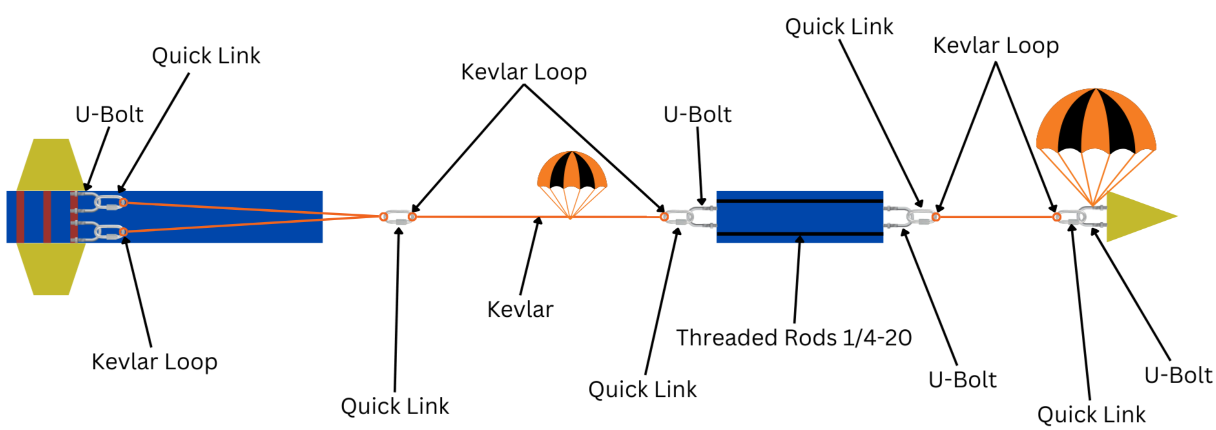


Fig. 30 - Components within the recovery chain

Table 18 - Recovery Chain Load Analysis

Component	Vendor	Part Number	Individual failure strength	Combined failure strength
U-bolt (x2)	McMaster-Carr	8896T94	5349 lbs	10698 lbs
Quick link (x2)	McMaster-Carr	8947T27	9600 lbs	19200 lbs
Tubular Kevlar loop (x2)	Custom		3600 lbs	7200 lbs
Kevlar Leader (x2)	Wildman Rocketry	Kevlar, ⅜ inch	3600 lbs	7200 lbs
Kevlar loop	Custom		3600 lbs	7200 lbs
Quick link	McMaster-Carr	8947T27	9600 lbs	9600 lbs
Kevlar	Wildman Rocketry	Kevlar, ⅜ inch	3600 lbs	3600 lbs
Kevlar loop	Custom		3600 lbs	3600 lbs
Quick link	McMaster-Carr	8947T27	9600 lbs	9600 lbs
U-bolt	McMaster-Carr	8896T94	5349 lbs	5349 lbs
Threaded rods (¼-20, Stainless)	McMaster-Carr	98804A107	2674 lbs	5348 lbs
U-bolt	McMaster-Carr	8896T94	5349 lbs	5349 lbs
Quick link	McMaster-Carr	8947T27	9600 lbs	9600 lbs
Kevlar loop	Custom		3600 lbs	3600 lbs
Kevlar harness	Wildman Rocketry	Kevlar, ⅜ inch	3600 lbs	3600 lbs
Kevlar loop	Custom		3600 lbs	3600 lbs
Quick link	McMaster-Carr	8947T27	9600 lbs	9600 lbs
U-bolt	McMaster-Carr	8896T94	5349 lbs	5349 lbs

The table above lists the load capacities of the individual components listed from the bottom of the airframe to the top. The elements not included in this are the fiberglass centering ring and bulkhead strengths. While this is a critical component, we do not have the capability to calculate these values. However, the components selected are standard parts for airframes of this size and have a track record of being flown successfully. As shown in the table, the weakest element in the recovery chain is the ⅜” tubular Kevlar.

4.5 Avionics Design

4.5.1 Altimeter Selection

The avionics bay for our rocket will be utilizing two commercially available altimeters. To choose between a wide variety of altimeters, we have conducted our research to decide which altimeters will be best for our purposes. This search consisted of looking at a wide variety of features to determine if there was a large benefit of using a more full-featured altimeter.

Table 19 - Altimeter Broad Feature Analysis

Manufacturer	Altimeters	Cost	Extra features
Eggtimer Rocketry	Quantum	$40	• Arming/disarming safety feature: 4 4-digit safety code is required to arm/disarm the altimeter. • Failsafe feature: If free fall is detected after drogue deployment, a failsafe feature is implemented where the main parachute will be deployed to attempt to save the rocket. • Remote ground testing from 100 ft away.
	Proton	$85	• Arming/disarming can be done from over 100 ft away. • 40 sample per second data collection
Missile Works	RRC2+	$54.95	• Audible altimeter readings via a beeper
	RRC3+	$79.95	• Impervious to Lithium battery discharge
Featherweight Altimeters	Blue raven	$175	• Dedicated software for altimeter • Contains an Accelerometer and gyroscope
Perfect Flite	StratoLoggerCF	$69.95	• Audle reporting of data through a beeper • 20 samples per second data connections • Resistant to false triggers from wind gusts
Altus Metrum	Easy Mini	$80	• Small and compact
Silicdyne	Fluctus	$339	• Dedicated flight analysis software • On-Board GPS • Contains Accelerometers, Barometers, and GyroMeter for tilt measurement

Many of the altimeters in the table above offer many features that, while interesting, exceed our use case for this project with a dramatic increase in costs. For example, we really only need an altimeter with the following features:

- Dual channel deployment

- Datalogging
- Ability to ground test easily, preferably triggered wirelessly
- Configurable

However, there are other features that would be highly desirable such as a wireless interface for remote configuration and a failsafe mode. The table below focuses on altimeters that offer most, if not all of these features.

Table 20 - Altimeter Feature Down-Selection

Feature	Altimeter			
	Eggtimer Quantum	**MissileWorks RRC2+**	**Featherweight Blue Raven**	**Perfectflite Strattologger CF**
Configurable	802.11 with app	DIP switch	Bluetooth with app	USB
Datalogging	Yes	No	Yes	Yes
Ground testing	Wireless, 100 ft	Shop vacuum to trigger events	Wireless, 25 ft	Shop vacuum to trigger events
Secondary arming	Wireless	N/A	Wireless	N/A
Failsafe mode	Yes	No	No	No
Fully assembled	No	Yes	Yes	Yes
Cost	$40	$55	$175	$65
Availability	Yes	Yes	Yes	Questionable

The Eggtimer Quantum meets all of the desired features at the lowest cost point. The downside of the Eggtimer Quantum is that it requires some electronics assembly. While this does add time to the project, the cost savings compensate for the difference. Several team members have experience assembling surface mount circuit boards and this is not determined to be a risk. In addition, the assembly will be inspected by the team mentor and tested in a vacuum chamber. It will also be flown in the subscale test with redundancy.

One major aspect of the Eggtimer Quantum that should not be overlooked is the failsafe mode. When failsafe mode is enabled, the flight computer will fire the main deployment charge if it detects a condition where the rocket is past apogee and it has reached an unsafe velocity, presumably due to drogue deployment failure. If this happened, it would probably result in a zippering of the airframe, breaking the 90-second apogee to touchdown rule, and drifting outside of the allowable range. However, it would prevent a ballistic recovery, possibly preventing injury, death, or destruction of property.

The Eggtimer Quantum complies with requirements 2.22.8 and 2.22.9 for frequency and power. The Eggtimer Quantum uses a WiFi signal in the 2.4 GHz range, which does not violate our requirements for frequency. This altimeter also has a maximum power of 24 mW which is far less than the maximum transmitter power of 250 mW, making the Eggtimer a legal choice for our rocket. The altimeter uses a FCC wireless module certified under FCC ID: 2ADUIESP-12.

In our proposal, we originally proposed using one Eggtimer Quantum and one Perfectflite Stratologger CF. However, it appears that the Stratologger CF is largely out of production with little to no availability. We have been monitoring the out of stock notice for many months and emails to Perfectflite are unanswered regarding restock inquiries. At this point, we are planning to go forward with two Eggtimer Quantum altimeters. While this does not provide alternate algorithms, the Eggtimer Quantum has proven to be a reliable altimeter.

4.5.2 Power Switch Selection

The table below shows the selection matrix for the power switches inside the avionics bay

Table 21 - Selection Matrix - Power Switches

	Switches				
Features	**Rotary**	**Push-Button**	**Magnetic**	**Screw**	**Pull-Pin**
Activation method	Turn knob to select on/off	Press button for on/off	Magnet proximity to sensor	Tighten screw to complete circuit	Remove pin to actuate microswitch
Reliability	High	Medium	Low	High	Medium
Durability	High	Medium	Medium	High	Medium
Size/Weight	Moderate	Compact	Compact	Compact	Medium
Vibration Resistance	Medium	Medium	High	High	Low

The screw switch has been selected for use in the avionics bay due to its high reliability, durability and resistance to vibration, which align with the requirements of SLI.

- Activation Method: The screw switch completes the circuit when the screw is tightened, providing a secure and deliberate means of power activation.

- Reliability: With a high reliability rating, the screw switch ensures consistent performance in the avionics bay, which is critical during launch and recovery operations.
- Durability: This switch is highly durable, making it capable of withstanding mechanical stresses encountered in high-impact and high-vibration environments.
- Vibration Resistance: The screw switch's design offers high resistance to vibrations, minimizing the risk of unintentional deactivation during launch or in flight turbulence.
- Size and weight: Although compact, the screw switch has sufficient structural integrity to support both stability and ease of integration within the bay's layout.

4.5.3 Battery Selection

The Eggtimer Quantum consumes approximately 80 mA of current, mainly due to the WiFi module. Once assembled, we will measure the current of our units to verify. To achieve sufficient powered-on time, we propose using a 450 mAh 2S LiPo battery pack. This 450 mAh of capacity gives us approximately 5.6 hours of life. However, given launch conditions, we may reduce capacity, testing to verify success before implementation in the avionics bay. This exceeds requirement 2.6 of having greater than three hour life in the launch configuration. The LiPo battery pack will be clearly marked and protected in accordance with requirement 2.21.

An alkaline battery was considered, but rejected due to lack of reliable recharging technology and low max discharging rate (1 C vs 50 C on the LiPo).

4.5.4 Recovery Schematics

The figure above shows the proposed avionics bay electrical schematic. It includes the components as follows:

- Commercially available barometric altimeters that are designed specifically for high-power rocketry.
- Fully redundant, parallel systems which utilize different brands of flight computers. Each has an independent power source and mechanical switch.
- The altimeters are armed via a screw switch which is capable of being armed through the airframe and remains in a locked, vibration-resistant state.
- Each battery is sufficient for at least 5 hours of operation

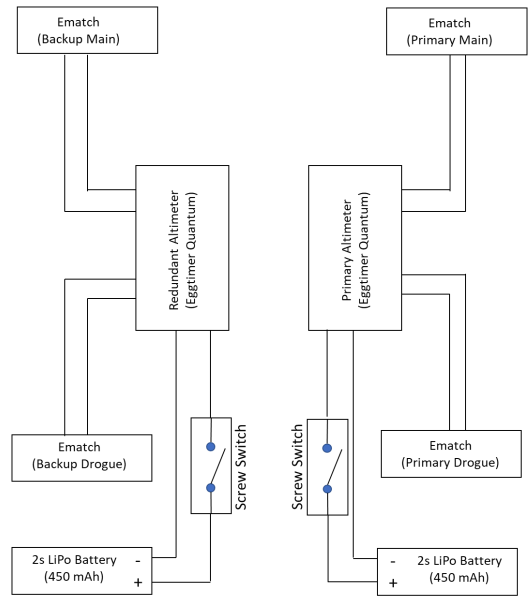


Fig. 31 - Altimeter bay connection diagram

4.5.5 Avionics Sled Design

At the time of submitting the PDR, the altimeter is an early work in progress with no CAD to show. However, concepts are moving forward and CAD models of a 3D printed altimeter sled will be one of the first priorities after the PDR is submitted. Concepts that are known at this time are:

- The sled will be housed between the coupler bulkheads, secured with ¼”-20 stainless threaded rods.
- The altimeter sled will be made from a toughened PLA with a small amount of TPU to make it more impact resistant.
- The altimeter sled will consist of two pockets to accommodate the Eggtimer Quantum altimeters. Each altimeter will be secured to the sled with 4-40 stainless screws threaded into brass heat-set inserts in the PLA sled.
- Batteries (2S LiPo 450 mAh cells) will be secured in pockets on the sled with red covers labeled “LiPo - Flammable.”
- Wires from the altimeters to the bulkheads will be twisted pairs, 22 AWG stranded wires with silicone insulation to provide EM immunity and vibration resistance.
- All wires to hardpoint connections will have strain relief. All wire lengths greater than 2” will be secured to the sled using cable ties.
- The screw switches will have a cover that allows a screwdriver access, but prevents the screw from being allowed to be backed out of the switch PCB.

A complete design will be presented at CDR.

4.6 Rocket Tracking and Telemetry

We researched a multitude of options for GPS tracking units, The table below includes all the options we considered while deciding.

Table 22 - Commercially Available GPS Trackers

Tracking unit	Cost	Features
Featherweight GPS	$165.00	• 10 GPS solutions per second • Vertical and horizontal velocity tracking • Reports positions up to 262,467 ft altitude and up to Mach 1.45 • Easy integration with an app • Live tracking
Eggtimer Mini GPS Tracker	$100.00	• 1 GPS solution per second • Vertical and horizontal tracking • Reports position up to 31,680 ft • Live tracking • Kit that requires assembly • No cell phone integration required • No acknowledgement on positions or packet recovery • Subject to tracker getting jammed with congestion.
Apogee Simple GPS Tracker	$475.84	• Live tracking • Stand-alone system (no cell phone integration) • Reports positions up to 31,680 ft
Fluctus	$339.00	• Vertical and horizontal tracking • Up to ±200G for accurate speed measurement • Measures altitudes up to 65,000 ft • The gyrometer measures the rotation of the rocket • Weighs 23 grams • Live tracking • Easy integration with the app
Multitronix Kate-3	$1525.00	• 5 GPS solutions per second • 50G accelerometer is recorded at 100 readings/sec • 3-axis gyroscope recorded at 100 readings/sec at up to 2000 degrees/sec • Live tracking
Marco Polo	$265.00	• Tracking up to 10,560 ft away • No live tracking • Can only be used as a backup tracker

While all of these trackers do satisfy requirement 3.13 with the exception of the Marco Polo (does not transmit actual location, only direction), the overall cost is high and varied. Ultimately, the decision comes down to what equipment our mentor has and will lend us. This allows the club to focus funds in other areas. To track the position and altitude of our rocket during flight, we will be using the Featherweight GPS tracker. After researching a variety of GPS units, we found that the Featherweight GPS tracker would most accurately provide us with our rocket's telemetry due to its tracking frequency of 10 GPS solutions per second and extensive range. It also effortlessly integrates with a phone application, allowing us to track our rocket in real-time and review its data immediately. We may add a Marco Polo for redundancy if determined necessary as our mentor also has one that can be loaned to the club and adds minimal weight.

The Featherweight GPS tracker manual specifies a 1S LiPo battery to supply 4.1 V to power the unit. The battery consumes an average of 86 mA of current under normal operation. The recommended battery of 400 mAh will provide approximately 4.5 hours of operation. The testing plan details a battery time analysis to check that this is valid under real-world conditions. If a larger battery is required, stepping up to an 850 mAh battery does remain an option.

The Featherweight GPS tracker meets requirements 2.22.8 and 2.22.9 by limiting transmission to 50 mW and uses a robust tracker/receiver unique addressing and handshake protocol.

4.7 Shear Pins

Shear pins are used to hold the airframe together and prevent unintended separation. They are designed to break, or shear, at a specific force. Shear pins are necessary between all points of separation of the airframe (Requirement 3.9).

As the launch vehicle ascends after launch, the motor will fairly quickly burn out and the airframe will decelerate as it approaches apogee. During this deceleration phase, there is more drag on the lower booster than on the upper portion of the airframe. This can lead to more drag force applied to the lower portion than the upper and induce drag separation. After burnout, the rocket decelerates at about 59 ft/s^2. A very simplistic calculation of a 7 lbs upper portion of the airframe and assuming all of the drag comes from the lower portion of the body tube (very pessimistic approximation), then the upper portion would require about 13 lbs of force holding the airframe together.

Another aspect to consider is the pressure change of the airframe cavities. Assuming the airframe is sealed, the internal cavity of the airframe will reach equilibrium while sitting on the launch pad at ground level. Once the rocket is launched though, the outside air pressure will decrease as the altitude increases. There is about a 2 psi difference in air pressure between ground level and 4500 ft. This difference in pressure generates a force on the bulkhead. This is about 27 lbf for both the drogue and the main cavity (similar volumes, same diameter).

For the booster to the coupler (drogue separation point), we would therefore require about 40 lbs of force to prevent unintended separation. As this is safety and mission critical, we are factoring in a minimum 2:1 safety factor. A 2-56 nylon shear pin will shear between 31 and 34 lbs of shear force depending on manufacturing tolerances. To exceed the 80 lbs (40 lbs plus 2:1 safety factor), we would require a minimum of 3x 2-56 shear pins.

For the nose cone, this also is subject to pressure differences and drag separation. However, the mass of the nose cone is considerably less than the entire upper body tube assembly. As a result, this only requires about 30 lbs of resistance. However, the larger concern is the force generated when the drogue is deployed at apogee. If the ejection charge is too large, and the lower harness reaches its full extent too fast or if the drogue deploys at a higher velocity than planned, the momentum of the nose can generate a considerably higher force to be restrained. This would result in the main parachute being deployed at apogee, which is highly undesirable and breaks about a dozen requirements. Common practice is to take the weight of the nose cone and multiply it by a safety factor. Our mentor suggested 100:1 plus the 30 lbs due to pressure and drag differences. The nose cone weighs 1.0 lbs, so this would make the required shear force to be about 130 lbs. A nylon 4-40 shear pin has a range of 50-54 lbs to shear depending on manufacturing tolerances. Therefore, we are planning to use 3x 4-40 nylon shear pins to restrict the nose to the payload tube.

4.8 Ejection Charge Sizing

E-matches controlled by the altimeters will be used to ignite the black powder deployment charges. To ensure separation while minimizing stress to airframe components, the type and amount of black powder used will need to be optimized through calculation and ground testing.

We will be using FFFFg, or 4Fg, black powder for our deployment charges. Black “powder” is granular, and its grade is determined by the size of the grains; the more F’s there are, the smaller the grain size. The speed at which the black powder burns is determined by the surface area to volume ratio, essentially the grain size. 4Fg will be used as it combusts quickly enough that separation is not affected by vent holes in our airframe. It also burns quickly converting from solid to gas, reducing the risk of flaming particles flying about.

Basic physics and chemistry equations can be used to approximate the needed black powder amount. Force can be calculated based on pressure, P, and area, A. Using the equation F=PA, the predefined cross-sectional area of our airframe will allow us to isolate and determine P. Ideal gas law and the chemical equation for the combustion of black powder will allow us to back-calculate the moles (and thus the mass) of black powder needed.

The nose cone will be coupled together using three 4-40 nylon shear pins, and the booster coupled using three 2-56 shear pins. Assuming the maximum value of tolerance and only the shear strength of the shear pins, the nose cone will require 163.53 lbs of force to separate and the booster 101.64 lbs. To ensure separation, we will add 20%: 196.24 lbs, and 121.97 lbs, respectively.

On our 4 in the airframe, $A \approx 4\pi$ in^2, using F=PA, the pressure needed to separate the nose from the payload tube is 15.62 psi and the coupler from the booster is 9.71 psi. Converting that to atmospheres and substituting into PV=nRT, we get for the nose cone:
$1.06V = n(0.08206)T$

And for the booster:
$0.66V = n(0.08206)T$

We are solving for *n*, moles of gas, thus:
$n_{nose} = \frac{1.06V}{0.08206T}$ and $n_{booster} = \frac{0.66V}{0.08206T}$

The volume of our payload section is approximately 7.93 L and the volume of our booster is 6.62 L. Depending on its composition, black powder burns at ~1200°-1350° Celsius. Taking a middle of 1250° C for T, we get the payload:
$n_{nose} = \frac{1.06(7.93)}{(0.08206)(1523.15)}$

And for the booster:
$n_{booster} = \frac{0.66(6.62)}{(0.08206)(1523.15)}$

These calculations give us the moles of gas needed to create our specified pressure:
$n_{nose} = 0.0673\,moles$ and $n_{booster} = 0.0350\,moles.$

A simplified chemical equation for the combustion of black powder is:
$2KNO_3 + 3C + S \rightarrow K_2S_{(s)} + 3CO_{2\,(g)} + N_{2\,(g)}$.[†]

Using stoichiometry, we can calculate the mass of black powder needed; the ratio of moles of gas to moles of reactants is 5:6:

For the nose cone:
5:6=0.0673:x
x=(0.101 moles black powder)*45.0 g/mol = 4.55 g

For the booster:
5:6=0.0350:y
y=(0.0524 moles black powder)*45.0 g/mol = 2.36 g

† : The reaction for the combustion of black powder is complex with many products, said products change based on the reaction environment. However, this seems to be an accepted simplification of the reaction, which should be good enough for our uses.

All values are rounded to the nearest tenth, due to massing precision constraints.

While in theory, our calculations are relatively accurate for the minimum force to separate a static rocket, these calculations are merely a starting point. Additional margins will be added to ensure separation at altitude and in the presence of other forces acting on the separation points.

The secondary tool used to verify our calculations was a spreadsheet from Speedmotion Rockets (**http://speedmotionrockets.com/Spreadsheets.html**). This tool includes additional effects that were not included in our hand calculations to present a more realistic scenario: it includes pressure differences within the airframe due to the change in barometric pressure launch to apogee, and force to overcome friction and separate the airframe. As a result, some of these numbers will vary slightly from our initial calculations, but are used to verify that we are close to equivalent.

According to the spreadsheet, the bare minimum mass of black powder needed is 3.3 g for drogue parachute ejection and 2.1 g for main parachute ejection. Tables showing data from the spreadsheet can be found in Appendix A Tables 1 and 2. Adding 20% for margin, drogue calculates to 4.0 g and main to 2.5 g. This is close to our hand calculations, 4.6 g and 2.4 g, indicating that we have a good starting point. After optimizing as much as possible using calculations and online resources, we will conduct ground testing to verify our calculations and ensure successful parachute deployment.

For the backup altimeter, an additional 20% margin will be applied to ensure separation if the primary charge fails. If the primary charge is successful, then the backup charge will fire into an open tube with no detrimental effect.

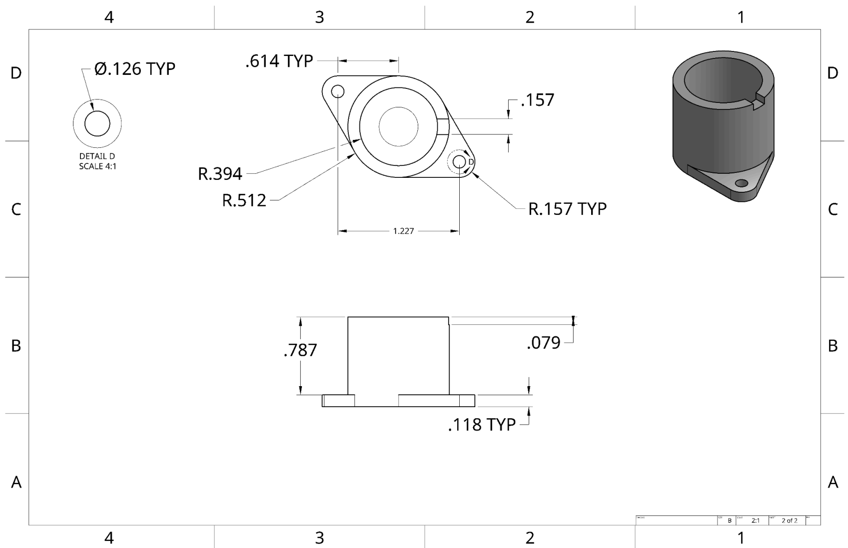


Fig. 32 - Deployment charge well drawing

A 3D printed charge well will be used to hold the recovery charges. Since the charge well will hold approximately 5 cc's of black powder and FFFFg powder packs at approximately 1 cc/gram, the charge well will safely hold the calculated 3.96 g and 2.46 g of black powder for drogue ejection and main parachute ejection, respectively. The E-match is installed with the head in the middle of the well, filled with a premeasured mass of black powder, then the remaining space will be filled with fire resistant cellulose insulation. The well is then sealed with electrical tape to contain its contents. To ensure optimal packing, the height of the charge well may be modified for the main parachute charge.

4.9 Subscale Recovery System

4.9.1 Overview

This section includes the analysis of all components inside the subscale modeland summarizes avionics, tracking, and includes calculations for subscale ejection charges.

4.9.2 Avionics

The avionics system for the subscale model will follow a similar configuration to that of the full-scale rocket. It will utilize the same schematic and components with the exception of a smaller battery. The subscale does not require a battery with a minimum three hour idle time, and a smaller battery will be used. The event deployment sequence will mirror the full-scale setup, using the same altimeter settings. The primary drogue chute charge will be set to deploy at apogee, the secondary drogue charge will fire at apogee plus 2 s. The primary main chute charge will fire at 600 ft and the secondary charge will fire at 550 ft.

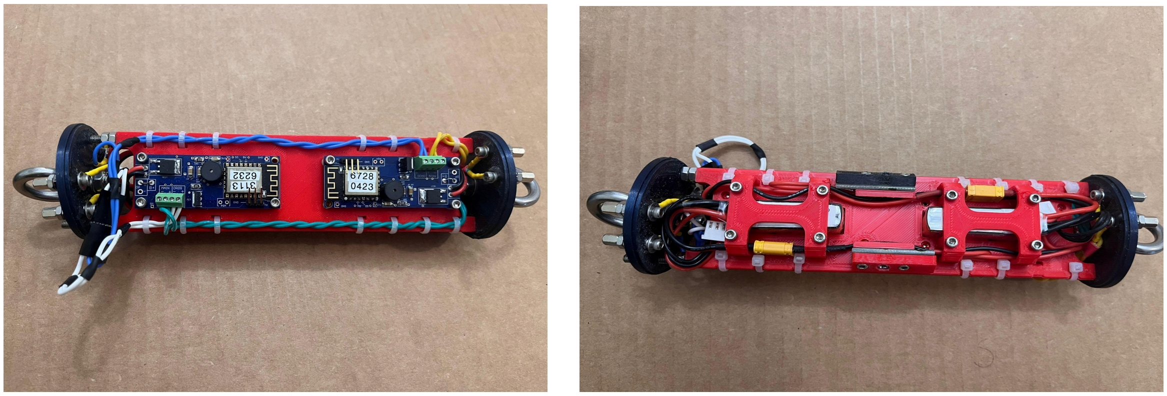


Fig. 33 - Subscale altimeter bay

The primary difference is that the altimeter sled will be downsized to accommodate the smaller space constraints. Specifically, the sled will be designed to fit inside a 2-inch diameter, 7 inch long coupler.

4.9.3 Rocket Tracking and Telemetry

The tracking and telemetry for the subscale will use the same tracker module as the full-scale airframe, namely, the Featherweight GPS Tracker. The tracker will be mounted in the nose cone in a similar manner as the full-scale.

4.9.4 Ejection Charge Sizing

Ejection charges for the subscale rocket were calculated using the same methods discussed in Section 4.8. Hand calculation notes can be found in Appendix B.

According to the spreadsheet, the bare minimum mass of black powder needed is 1.0 g for drogue parachute ejection and 0.4 g for main parachute ejection. Tables showing data from the spreadsheet can be found in Appendix A, Tables 3 and 4. Adding 20% for margin, main calculates to 1.2 g and drogue to 0.4 g. This is fairly close to our hand calculations, 0.6 g and 0.2 g, indicating that we have a good starting point for ground testing. After optimizing as much as possible using calculations and online resources, we will conduct ground testing to verify our calculations and ensure successful parachute deployment.

For the backup altimeter, an additional 20% margin will be applied to ensure separation if the primary charge fails. If the primary charge is successful, then the backup charge will fire into an open tube with no detrimental effect.

5.0 Technical Design: Payload Criteria

For our payload, we will be designing and constructing a scaled-back version of the college payload. Instead of recording and transmitting on a 2-M radio band to NASA, telemetry will be transmitted to a laptop on-site. Similar to the college/university mission, our objective as a first-year high school team will be to launch and safely recover a STEMnaut capsule holding four STEMnauts while recording telemetry data, namely max Gs, max velocity, altitude, descent rate, and chute status. We will code an application that, depending on the stage of the launch, ascent, apogee, or descent, will transmit different data important to that stage. We will, however, not be separating the capsule and will not be transmitting on the 2M band specified by NASA, but keeping the capsule in the rocket nose cone and transmitting to a computer on the ground.

5.1 Payload Objectives

The general objective of the payload will be to transmit telemetry and interpret it in a meaningful way. The specific goal will be to transmit acceleration, velocity, altitude, and STEMnaut orientation, receive the data, and display relevant data based upon the stage of launch. A critical part of the payload will be the detection of launch, apogee, descent, and ground impact. Using altimeter data and a central control module, we will detect each of these stages and using a wireless transmitter, transmit data based on what stage of flight the rocket is in:

Ascent: max G, max velocity
Apogee: maximum altitude
Descent: decent rate, chute status based on descent rate
Throughout: STEMnaut orientation

The capsule will be contained in the nose cone along with the GPS transmitter. We concluded this would be optimal to prevent any possible problems that could occur during parachute deployment if the payload were contained in the payload tube and something were to go wrong.

Successful detection of each of these stages, and continuous, accurate display of relevant data will concur a successful experiment. In order to ensure the best chances of success, we will follow a design process detailed in the flowchart below. This gives us a solid plan to follow instead of blindly iterating failures.

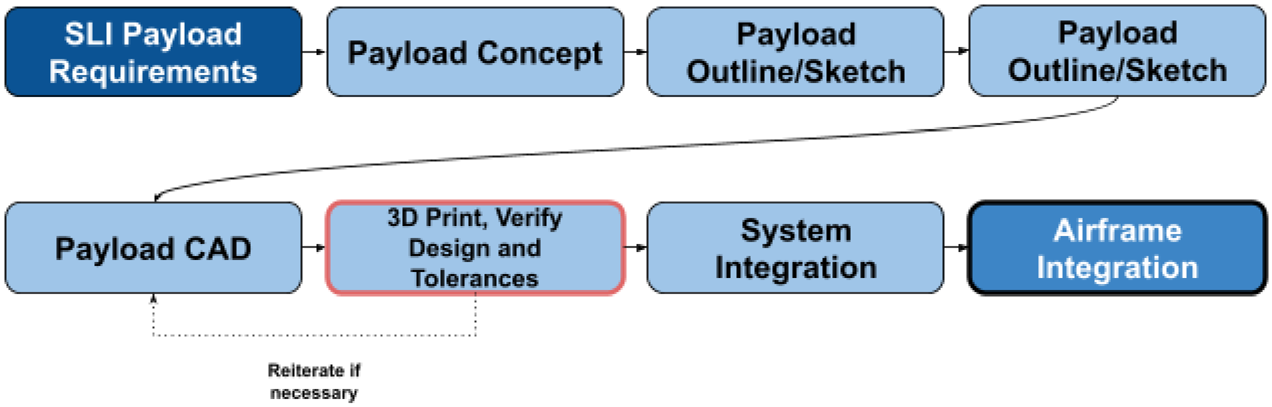


Fig. 34 - Design process for payload

5.2 Component Selection

For each component, at least two alternatives were considered and consolidated after research of other available alternatives. Our control module selection was significant in our sensor selection decisions, where we decided that keeping electronics within the Adafruit ecosystem would be optimal. This allows for compatibility between sensors as well as a common interface.

5.2.1 Control Module

For the central control module, we propose to use an Adafruit Feather M0 RFM96. It integrates a LoRa radio module with an Arduino IDE compatible microcontroller, reducing the need to purchase and consider the integration of any more external sensors than necessary. Furthermore, based on our electronic lead's familiarity with the platform, a large community, and abundant community resources, we chose a microcontroller with Arduino compatibility.

The RFM96 operates on a license-free 434 MHz band. Most GPS tracking units operate in the 915 MHz band (Featherweight, SimpleGPS, and Eggtimer). Using the 434 MHz band allows us to operate with less chance of interfering with other systems. However, this does come with a very minor range penalty. Initial estimates show that this system provides more than adequate range (P-D-2)

The LoRa radio module has a power output of +5 to +20 dBm, which is up to 100 mW. This is allowable under FCC part 15 and complies with requirement 2.22.8 (less than

250 mW). In order to comply with requirement 2.22.9 and mitigate interference, the transmitting and receiving modules will use unique address and handshaking. Unique addresses to the transmitting and receiving modules will ensure that the broadcast transmission will, ideally, only be processed by our modules. Handshaking ensures that the transmission will be minimized to only what is necessary, as an acknowledgement (ACK) signal will be sent from the receiving module to the transmitting module. If an acknowledgement is not received, the transmitter will retry a predetermined number of times over a brief timeout period. If communication still fails, then the transmitter will automatically stop until communication from the base station is restarted. This prevents excessive transmission and decreasing chances of interference.

Two alternatives were considered for the central control module: a Raspberry Pi and an Arduino Nano. The Raspberry Pi was rejected, as we do not need significant processing power. Furthermore, using Linux on the Pi would be overkill for our purposes and would require a significantly larger battery to power the unit. The Arduino Nano was our top choice, before coming across the RFM96; the RFM96 is more advantageous as it combines a more powerful M0 Cortex processor and the radio module on the same board.

5.2.2 Sensor Selection

For our sensors, we also decided to use Adafruit modules as they offer high-quality libraries, making their products work together well. Furthermore, many Adafruit sensor boards use the STEMMA QT interface, making daisy-chaining easy. While other alternatives from many other brands were first considered, considering our main controller will be from Adafruit, and since Adafruit has high-quality libraries, we consolidated our sensors to Adafruit. This also makes troubleshooting easy and compatibility a non-issue.

To detect altitude and vertical velocity, we plan to use an Adafruit BMP390, which uses the newest pressure sensor chip from Bosch. To detect STEMnaut orientation, we plan to use an Adafruit BNO085 orientation sensor. For max acceleration, we plan to use an Adafruit ADXL345 triple-axis accelerometer.

5.2.3 Payload Battery Selection

A LiPo battery was selected for the payload power source. A LiPo battery provides one of the higher power to size/weight ratios, is rechargeable, and is compatible with other batteries and charging methods used within this project. The voltage requirements for the microcontroller unit has a regulator on the board and allows us to use a voltage source between 3.4 V and 9 V. This is easily satisfied by a 1S LiPo battery providing 4.1 V when fully charged, a nominal 3.7 V, and 3.5 V when discharged to 20% capacity.

Table 23 - Estimated Payload Current Requirements

Component	Current	Condition
Microcontroller/Radio	40 - 120 mA (50 mA avg)	40 mA receiving, 120 mA transmitting
BMP390	0.032 mA	
BNO085	7.5 mA	
ADXL345	0.14 mA	
Quiic OpenLog	6 - 23 mA (10 mA avg)	6 mA idle, 23 mA during writes to SD card
Total	**82.5 mA**	**Estimated**

Based on the estimated current draw of the components in the table above, a standard 1S 450 mAh will provide over 5 hours of battery life in nominal conditions, and should exceed the required three hour life in flight ready conditions (requirement 2.6, P-D-4, P-C-2). In addition, the program will have the feature to shut down the radio transmission (still receiving), the sensors, and the data logging features remotely which will save considerable power if necessary. The battery life will be tested thoroughly as test FS-P-3.

5.3 Mechanical Component Design

All payload components were created using Autodesk Inventor Professional, then imported into Onshape for working drawings, editing, and collaboration. For modularity, ease of parts replacement, and ease of access, all parts are designed to be screwed together using 4-40 screws. Heat-set inserts will be used to ensure structural integrity of mating surfaces (P-D-6). Furthermore, a variable mass component to be used for ballast is also integrated into the payload/tracker assembly.

In order to determine the best material to 3D print our payload components, we researched various filaments; the filaments and their properties are organized into the table below:

Table 24 - 3D printer filament material analysis

Metric	3D Printer Filament					
	PLA (bambu Lab PLA basic)	**Polycarbonate (Bambu lab polycarbonate)**	**PLA with enhancement additives (Creality Hyper Series PLA)**	**ABS (Bambulab ABS)**	**PETG (Bambu Lab PETG basic)**	**CF Composite PLA (Creality Hyper Series PLA Carbon Fiber)**
Tensile strength (psi)	5076	7977	7687	4786	4641	N/A
Impact strength (ft-lb/in)	12	17	4.2	19	25	2
Flexural modulus (gPa)	2.8	2.3	2.5	1.8	1.7	3.6
Max print speed (in/s)	12	12	24	12	8	12
Density (slug/ft^3)	2.4	2.3	2.4	2.0	2.4	N/A
Cost per pound ($)	$10.45	$18.17	$14.99	$10.45	$10.45	$15.57

Payload components will be 3D printed using Creality Hyper Series PLA filament. It appears, among the filaments we compared, to be the best balanced in terms of tensile strength, flexural modulus, print speed, and cost. All material properties are directly from each manufacturer's website. The data, however, are not justified. Consequently, some of the data in the table are inconsistent; impact strength was not considered significantly due to significantly varied data from manufacturers. Furthermore, the failure mode for 3D printed components is typically layer adhesion, which is machine, print speed, and temperature dependent. To verify the structural integrity of the filament chosen and our print settings, we will carry out destructive testing. This will allow us to verify our payload components comply with P-D-3 and P-D-6.

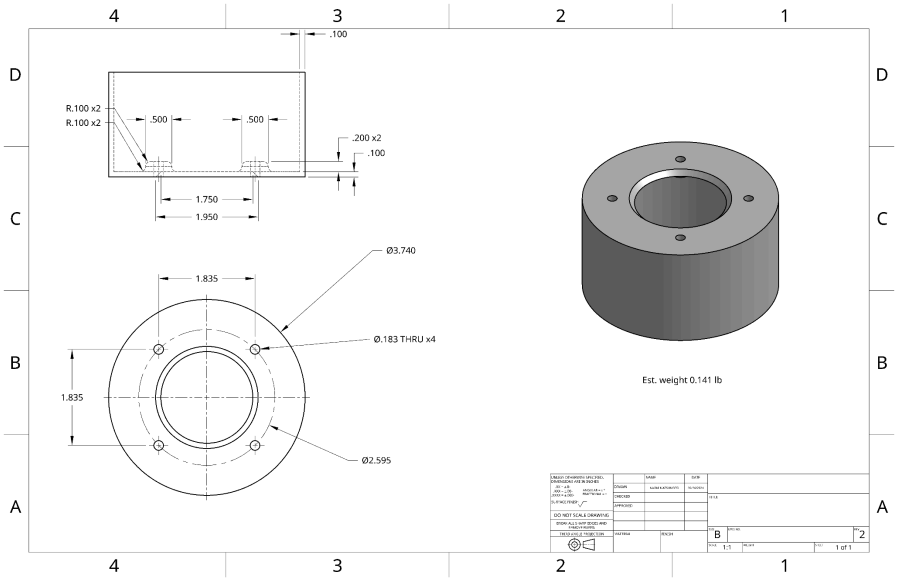


Fig. 35 - Main payload mount

The main mount will be epoxied into the nose cone coupler to act as the base for the screwed-in, modular tracker/payload assembly. To allow for addition of ballast mass, the central hole supports the addition of the ballast holder (figure below, [Fig 36](#)), to be clamped between the tracker/payload mount plate and the main mount.

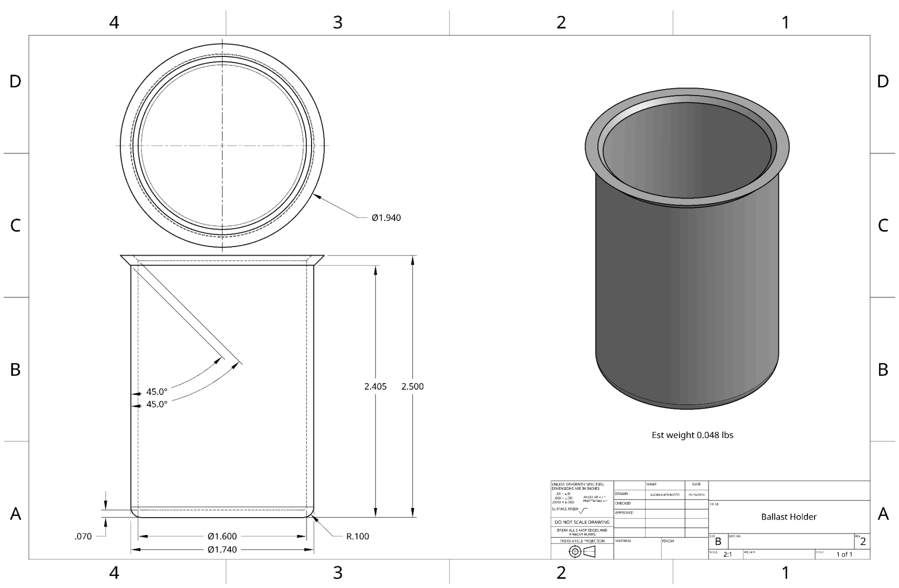


Fig. 36 - Ballast holder

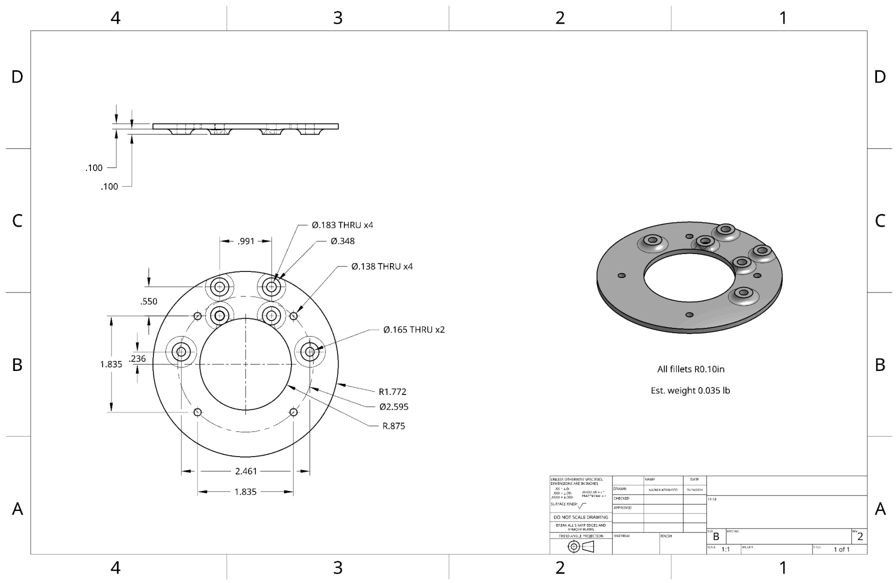


Fig. 37 - Tracker/payload mount plate

The payload and tracker will be mounted onto this main mount plate, to allow nearly full construction of the assembly before insertion into the nose cone coupler. This mount plate also clamps the ballast holder into place (see Fig. 40 for full assembly).

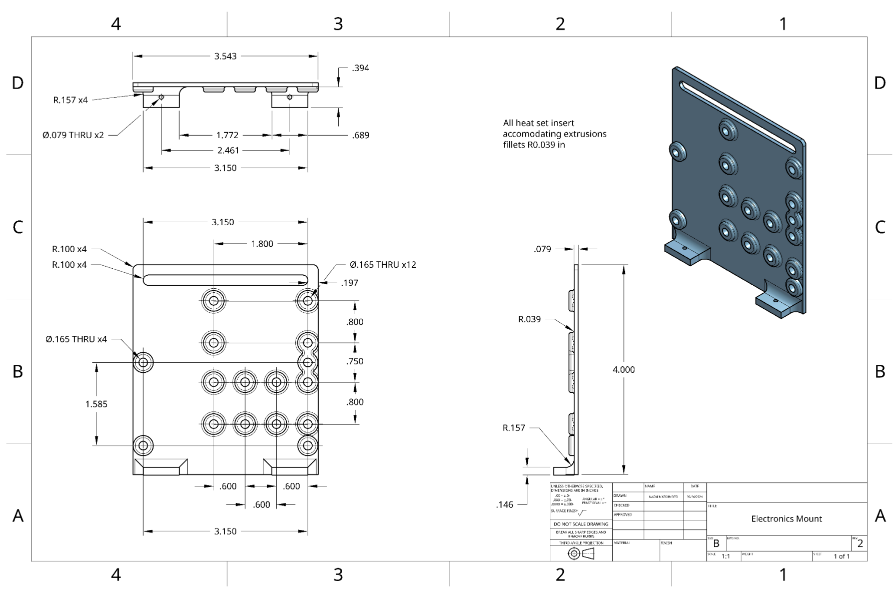


Fig. 38 - Payload electronics mount

The electronics mount plate will act as the backbone for the payload, where all electronics and the cockpit will be attached. The mount then screws into the tracker/payload mount place (Fig. 37). Holes to fit heat-set inserts are spaced to accommodate the Adafruit RFM96 and several STEMMA QT form factor sensor boards, as well as a mount for the cockpit. The slot at the top will be used for cable routing.

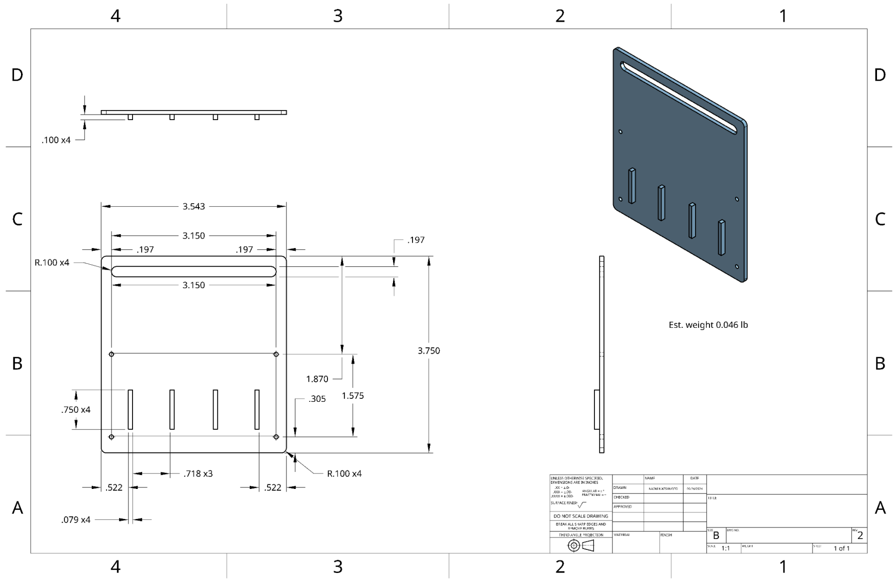


Fig. 39 - Payload cockpit mount

The cockpit will be built upon this mount plate, which will be screwed into the electronics mount. The four rectangular extrusions will be used to mount the STEMnauts into place, while the rest of the cockpit will be built freely upon the blank plate.

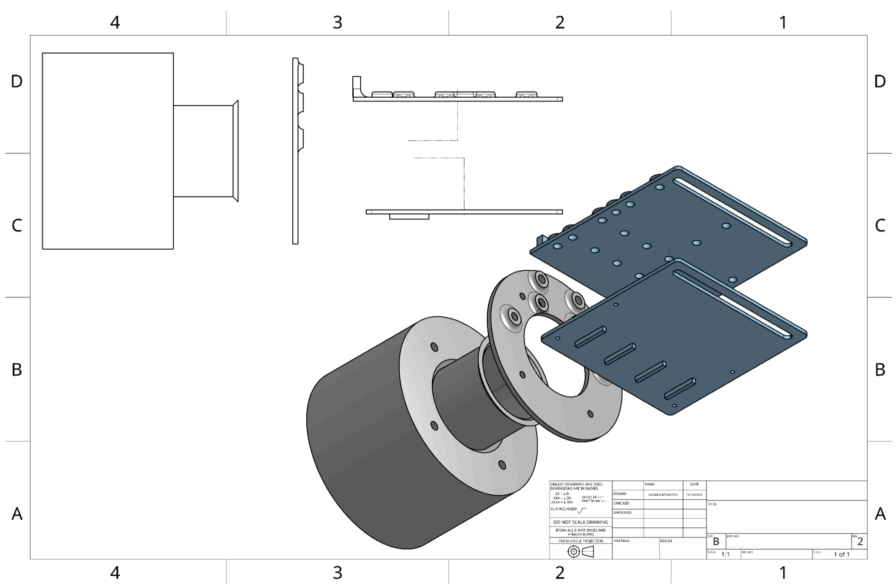


Fig. 40 - Payload assembly exploded view

Table 24 - Payload Component Estimated Masses

Part	CAD estimated mass (lbs)
Mount	0.14
Mount plate	0.035
Electronics mount	0.058
Cockpit	0.046
Ballast holder	0.048

5.4 Electrical Component Design

As stated in section 5.2, our payload electronics will be managed by the Adafruit Feather M0 RFM96 with an integrated Arduino microcontroller. The components being managed includes the Adafruit BMP390 pressure sensor, the Adafruit BNO085 orientation sensor, the SparkFun Qwiic OpenLog data logger, and the LiPo 1S 450 mAh battery. These components will be connected as seen in Fig. 41.

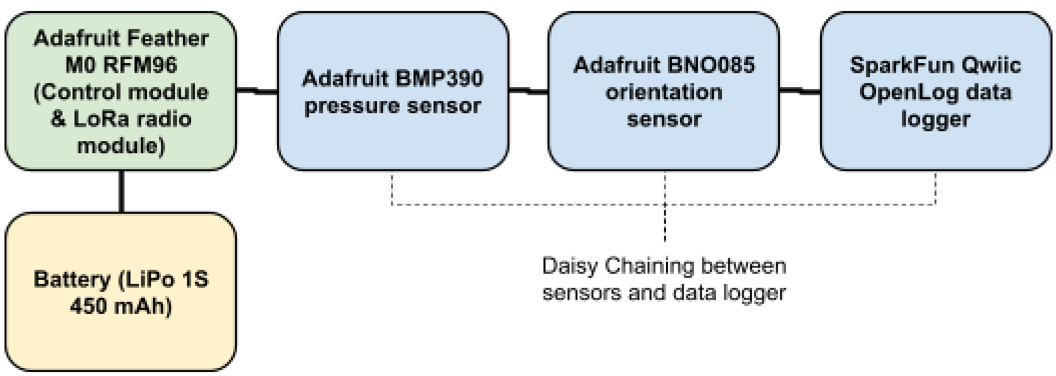


Fig. 41 - Payload electronics connection diagram

Each of our sensors will be connected to the Adafruit Feather M0 RFM96 via daisy-chaining. The power from the battery is connected to the 2 pin JST-PH battery port on the Adafruit feather board. To measure, record, and transmit our rocket telemetry data, our software logic will follow the flowchart as documented in Fig. 42.

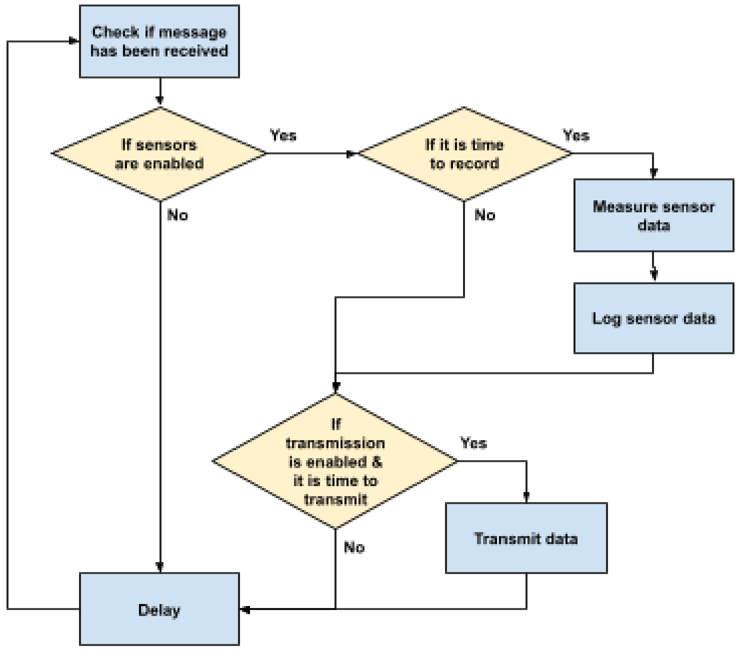


Fig. 42 - Payload programming logic flowchart

Before performing any sensor measurements or data transmissions, our control module will use its LoRa radio module (with client configuration) to check for any messages from its corresponding radio with server configuration. The client and server have unique two-byte identifiers, ensuring that they will only communicate to the IDs that they are configured to communicate with. Potential messages include enabling and disabling sensors, as well as enabling and disabling data transmission. When sensors are enabled, sensor data will be measured and logged on a set time interval (P-D-4). Data will only be transmitted if both sensors and transmission are enabled (P-D-5). Like data logging, transmissions will occur over a set interval. Once the rocket flight is complete, data measurements and transmissions can be disabled remotely (P-D-1).

5.5 Airframe Integration

The main mount (Fig. 35) will be epoxied into the nose cone coupler to act as the base for the screwed-in, modular tracker/payload assembly. For ease of assembly and parts replacement, the payload and tracker will be assembled on the mount plate (Fig. 37) before being screwed into the main mount. All screw interfaces will utilize heat-set inserts to optimize strength (P-D-3, P-D-6), instead of screwing straight into 3D printed plastic. Each part has also been created to optimize contact area, allowing better load distribution under high G conditions.

Our preliminary interfaces are detailed in Fig. 43. All forces will ultimately be handled by the epoxied joint between the nose cone coupler, main mount, and the support ring for positioning the main mount. A cross section detailing these joints is below:

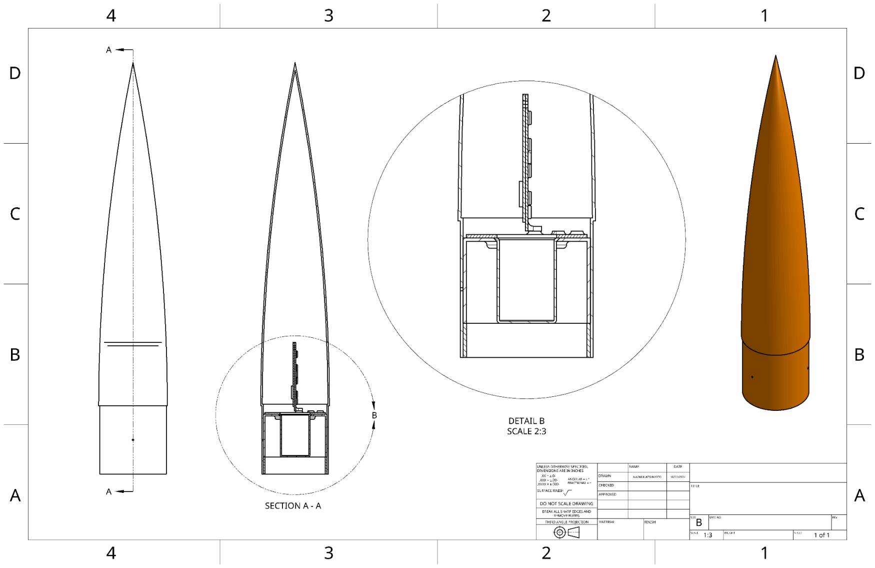


Fig. 43 - Nose cone cross section

6.0 Vehicle Mission Performance

6.1 Overview

This section details our process of design validation through simulation. This includes kinematic testing (altitude, acceleration, and ascent velocity), descent characteristics, and impact kinetic energy for both full-scale and subscale vehicles. Through these simulations and calculations, we attempted to verify that we have met the flight performance requirements. We made every attempt to make our analysis as realistic as possible given the tools available. Subsequent analyses will utilize physical testing of the subscale and comparing physical measurement to simulation, then extending lessons learned to the full-scale airframe.

6.2 Full Scale Mission Performance

The full-scale flight profile follows a conventional dual deploy flight profile. Using the fast burning K1103X, the motor burns out at about 1.7 s then coasts to an apogee at a little over 4500 ft at 16.7 s (LV-D-3). The rocket then descends under drogue with a main deployment at 600 ft. The total time of apogee to landing is approximately 80 s (R-D-1).

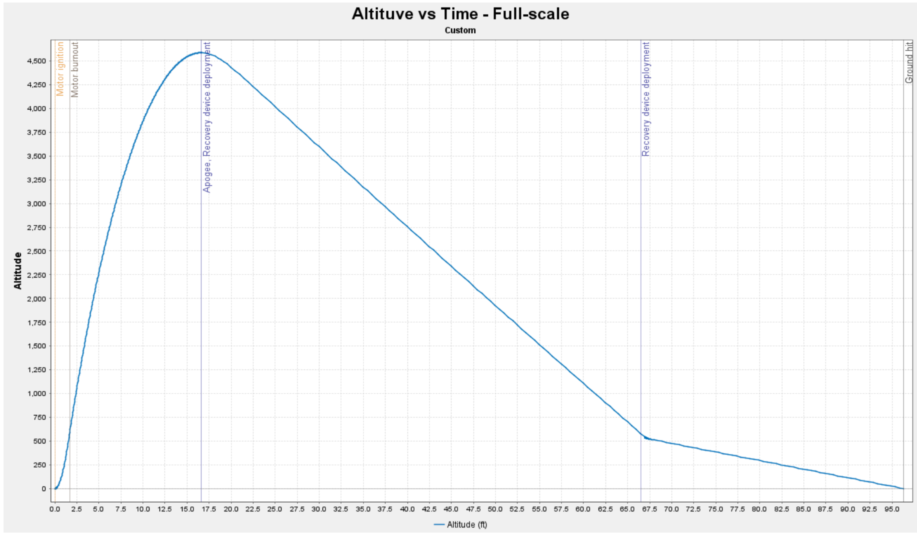


Fig. 44 - Full scale flight profile

6.2.1 Kinematics

Altitude

Requirement 2.1 states that teams achieve an apogee between 3500 - 5500 ft above ground level. Our full-scale design is optimized to target an altitude range of 4000 to 4600 ft, providing a comfortable margin within this requirement for adjustments between design and fabrication. This range allows us to utilize the full capabilities of the motor selected while reaching a consistent target altitude.

OpenRocket was utilized to simulate the rocket's altitude under varying wind speeds, with key atmospheric parameters set to their default values. The standard deviation for wind speed was kept constant at 0.0224, defining the variability of wind speed from the set value. Additionally, turbulence intensity was set at the default 10%. These settings provide a controlled, yet realistic representation of wind conditions allowing for accurate simulation of the rocket's performance at different wind speeds.

The analysis was performed using multiple simulations to understand the variations of the wind speed standard deviation. As the wind will not be constant during the ascent, this adds a random variable to help understand the possible range of values. All simulations are shown with the primary motor selection, an Aerotech K1103X, as well as the secondary motor selection, an Aerotech K805G.

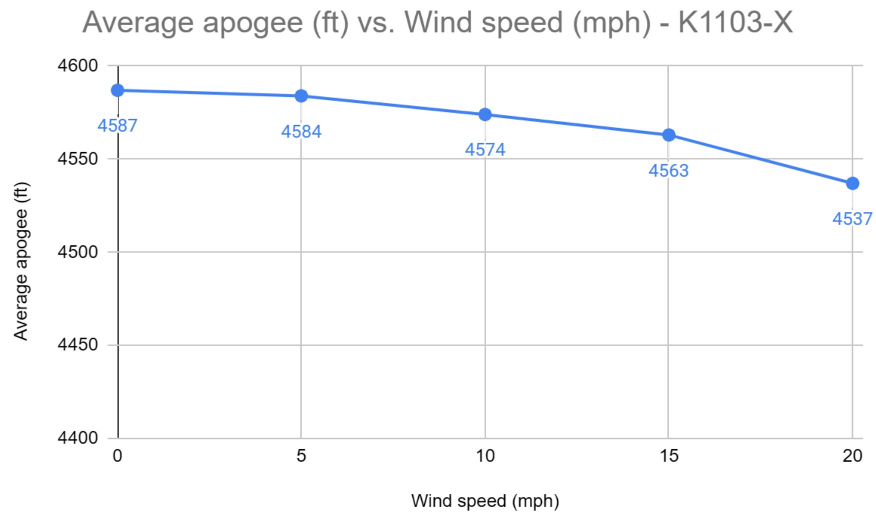


Fig. 45 - Average apogee vs wind speed

Table 25 - Full-Scale Simulated Altitude vs Wind for Aerotech K1103X-P

Wind speed	Altitude 1 (ft)	Altitude 2 (ft)	Altitude 3 (ft)	Average altitude (ft)
0	4587			4587
5	4585	4582	4584	4584
10	4573	4577	4572	4574
15	4565	4564	4559	4563
20	4529	4537	4546	4537

The table above represents the average apogee over 3 trials using the primary motor (Aerotech K1103X-P) for different wind speeds. Since all our simulations are performed in OpenRocket, there is always some when translating from simulation to the real world. Wind speed has an inverse relationship with apogee. As wind speed increases, average apogee decreases due to minor changes in the trajectory of the rocket upwind. A wind speed of 0 mph represents perfect launch conditions, and OpenRocket simulates our vehicle to reach 4587 ft. The worst conditions where a rocket could safely be flown is with a wind speed of 20 mph where our rocket simulates to an average apogee of 4537ft. A range of approximately 50 ft shows that our rocket is relatively resistant to wind speed differences during the ascent portion of the flight.

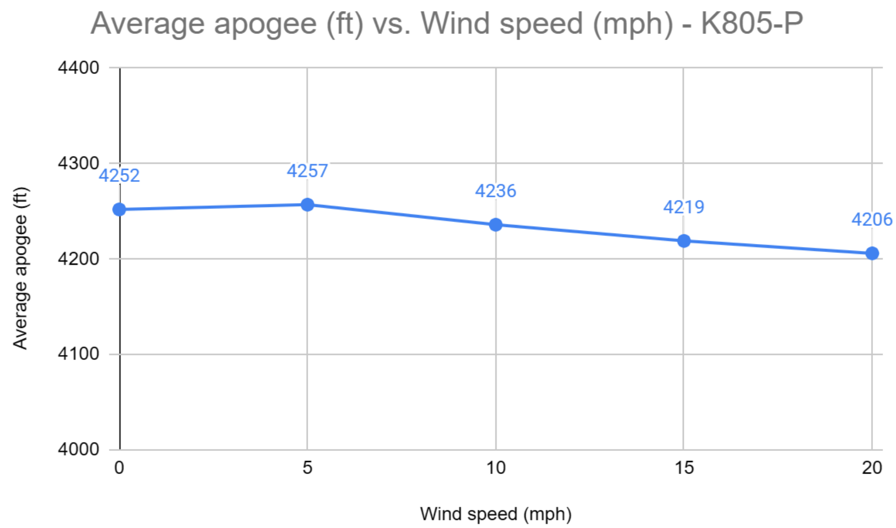


Fig. 46 - Average apogee vs wind speed - K805-P

Table 26 - Full-Scale Simulated Altitude vs Wind for Aerotech K805G

Wind speed	Altitude 1 (ft)	Altitude 2 (ft)	Altitude 3 (ft)	Average apogee (ft)
0 mph	4252			4252
5 mph	4257	4258	4257	4257
10 mph	4237	4235	4236	4236
15 mph	4219	4221	4217	4219
20 mph	4208	4206	4203	4206

The table above represents the average velocity using the secondary motor (Aerotech K805G) for different wind speeds. Since the motor has a lower total impulse of 1762 N, it produces a lower altitude. A wind speed of 0 mph provides an average apogee of 4252 ft and a wind speed of 20 mph provides an average apogee of 4206 N. Again the range of apogee is approximately 50 ft. This verifies that the apogee of our launch vehicle is relatively resistant to wind speed.

Maximum Acceleration

Maximum acceleration is primarily dependent on the thrust produced by the rocket motor. Maximum acceleration occurs during the maximum thrust produced by the motor during flight. Below are two thrust vs acceleration graphs showing the acceleration faced by the rocket while the motor is burning.

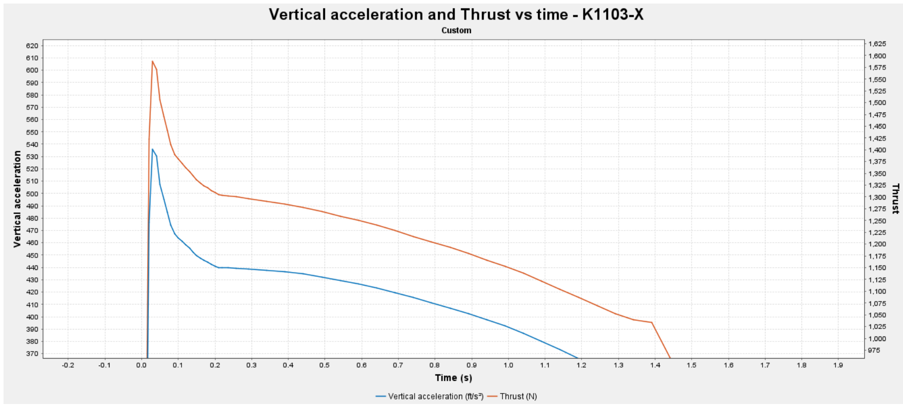


Fig. 47 - Vertical acceleration and thrust vs time - K1103X

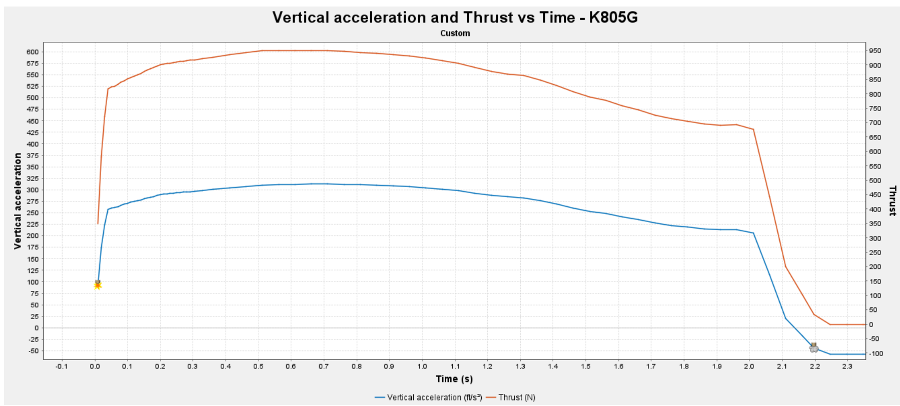


Fig. 48 - Vertical acceleration and thrust vs time - K805G

Table 27 - Maximum Thrust and Acceleration vs Time - Full-Scale

Motor	Maximum thrust (N)	Maximum acceleration (ft/s^2)	G-force value
K1103-X	1588	536	17
K805G	951	313	10

The table above shows the data comparing the time at which maximum acceleration, maximum thrust are faced by the full-scale rocket for both our primary (K1103X) and secondary motor (K805G).

The peak force exerted by the motor is measured in Newtons (N). The K1103X generates a higher maximum thrust (1588 N) compared to the K805G (951 N). The K805G has a slower burn rate with a lower total impulse. Hence, it reaches its maximum thrust later than the K1103X providing a more gradual acceleration. The K1103X motor provides a stronger, quicker burst of thrust resulting in a higher acceleration over a short period of time. This helps provide a higher rail velocity which will result in less weathercocking and more stability off of the pad.

The rocket experiences significant G-forces during its ascent, especially at a maximum acceleration. For instance, when using the K1103X motor, the rocket reaches a peak G-force of 17 G's, driven by a maximum acceleration of 536 ft/s^2 and a gravitational acceleration of 32 ft/s^2. In contrast, with the K805G motor, the rocket faces a peak G-force of 10 G's, driven by a maximum acceleration of 313 ft/s^2 and a gravitational acceleration of 32 ft/s^2.

Velocity

The velocity during the ascent phase of the rocket was simulated and shown in the plots below. Requirement 2.22.6 states that the launch vehicle must not exceed Mach 1 during flight, while Requirement 2.17 mandates a minimum rail exit velocity of 52 ft/s for the full-scale vehicle.

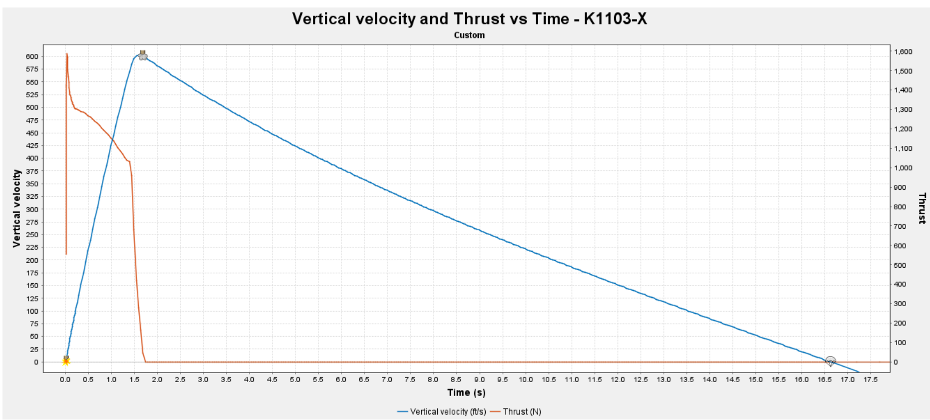


Fig. 49 - Vertical velocity and thrust vs time - K1103-X

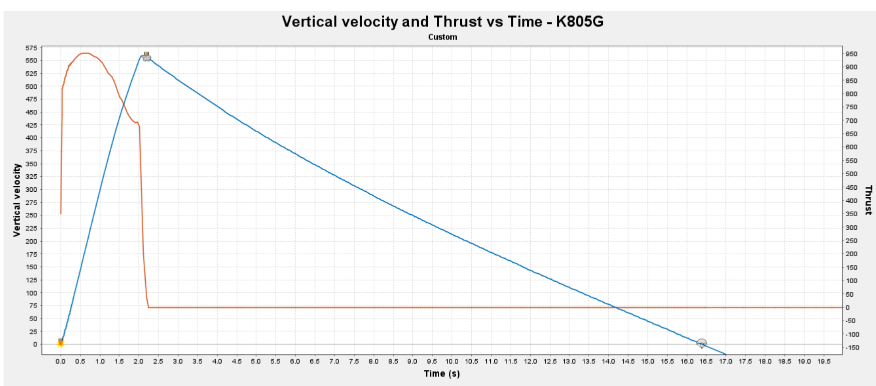


Fig. 50 - Vertical velocity and thrust vs time - K805G

Table 28 - Full-Scale Ascent Velocity

Motor	Rail exit velocity (ft/s)	Maximum velocity (ft/s)	Mach number	Time for maximum velocity (s)
K1103X	99.8	603	0.543	1.69
K805G	77.8	559	0.503	2.11

OpenRocket simulations show that the K1103X motor achieves a maximum velocity of 603 ft/s (Mach 0.543), while the K805G reaches 559 ft/s (Mach 0.503), both comfortably within the Mach 1 limit of requirement 2.22.6. The rail exit velocities of 99.8% for the K1103X and 77.8 ft/s for the K805G exceed the 52 ft/s minimum rail exit velocity as mandated by requirement 2.17 by 91.9% and 49.6% respectively.

The K1103X delivers a very high peak thrust at the beginning of the burn (1588 N), meaning it can accelerate the rocket quicker. As a result the rocket reaches a higher speed (603 ft/s) in a shorter time (1.69 s). The rapid thrust delivery allows the rocket to gain speed quickly, pushing it to a higher maximum velocity over a shorter period.

The K805G motor produces a more consistent, longer thrust period with a lower peak thrust (951N) than the K1103X, resulting in a slower acceleration. Since the rocket does not accelerate as quickly, it takes longer to reach its maximum velocity (559 ft/s) and requires more time (2.11 seconds) to achieve it.

6.2.2 Full-Scale Stability

Static Stability Measure

Static stability is defined as the tendency of a vehicle, after an external disturbance, to return to the undisturbed condition. Static margin or the margin of stability is used to describe the directional stability of a rocket.

$$S.M. = \frac{\overline{X_{CP}} - \overline{X_{CG}}}{Body\ diameter}$$

Table 29 - Definition of Variables for Static Stability

Variable	Definition
CP	Center of pressure (in)
CG	Center of gravity (in)

Understability

The CP of a rocket must be aft of the CG of a rocket. A major reason is that the rocket needs to be capable of handling aerodynamic forces without tilting. Since the aerodynamic forces act usually around the center of pressure, it might cause the rocket to tilt and change its angle of attack. This leads to the change of the flight path of the rocket from linear to rotational and eventually leads to the rocket tumbling.

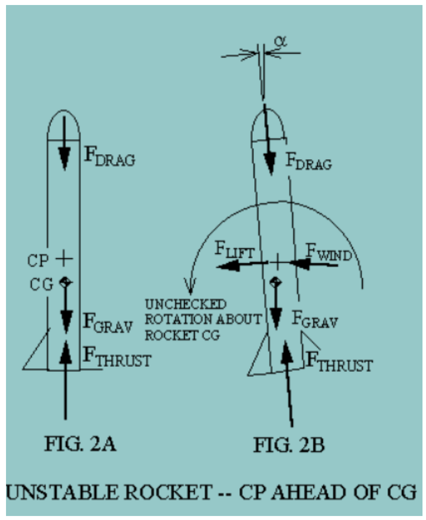


Fig. 51 - Stability definitions

Overstability is usually defined as having two or more body diameters worth of distance between the CG and the CP. Overstable rockets are usually weathercock, meaning the rocket leans more into the wind. Overstable rockets tend to slightly arc into the wind which reduces its max apogee. Overstability usually occurs with a stability margin of above 3.0 caliber.

Table 30 - Stability Parameters for Full Scale Design

Motor	Stability (caliber)	CG (in)	CP (in)
K1103X	3.08	70.77	83.17
K805G	2.98	71.16	83.17

OpenRocket calculates the static stability of a rocket. Our rocket design has a stability margin of 3.08 caliber with the primary motor configuration (K1103X) and a 2.98 caliber with the secondary motor configuration (K805G). A more detailed analysis of the vertical orientation and flight profile vs stability is shown in Sections 3.2.3 and Section 3.2.6.

Static Stability at Rail Exit

According to requirement 2.14, the launch vehicle must maintain a minimum static stability margin of 2.0 at the point of rail exit. While the above section calculates that static stability prior to launch, this section focuses on what is happening as the front rail button exits the launch rail. The graphs below plot the CG and CP locations of the rocket for both our primary (K1103X) and secondary (K805G) motors as the rocket exits the launch rail.

To establish the altitude at which the front rail button exits the launch rod, we utilized the following parameters:

Table 31 - Rail Exit Parameters - Full-Scale

Parameter	Value
Height of front rail button from bottom of rocket	2.42 ft
Length of launch rail	10 ft

The distance the front rail button travels along the rail can be calculated by:

$$D_{bottom\ to\ rail\ exit} = Length\ of\ launch\ rail\ -\ height\ of\ front\ rail\ button$$

$$D_{bottom\ to\ rail\ exit} = 10ft\ -\ 2.42\ ft\ =\ 7.58ft$$

Using OpenRocket's ability to graph locations of CG and CP over altitude and using a Python script to analyze the exact locations of CG and CP we evaluated that at an altitude of 7.58 ft, the CG and CP locations are as follows:

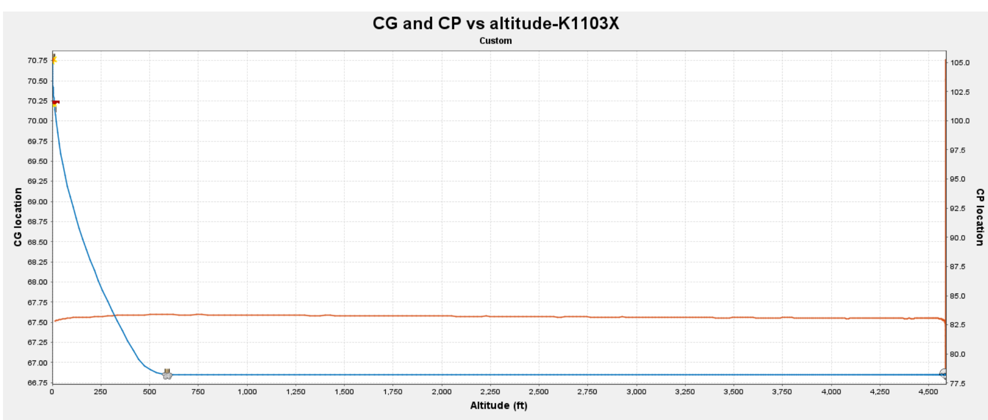


Fig. 52 - CG and CP vs altitude - K1103X

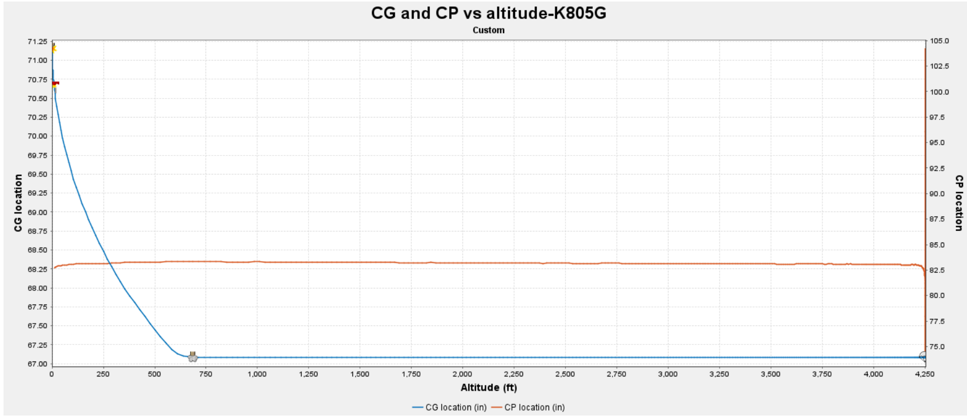


Fig. 53 - CG and CP vs altitude - K805G

Table 32 - CG and CP Locations - Full-Scale

Motor	CG location (in)	CP location (in)
K1103X	70.283	82.834
K805G	70.714	82.641

Using the formula to calculate static stability, we can calculate the stability at the point of rail exit. The body diameter for the full-scale vehicle is 4.028 in.

$$S.M. = \frac{\overline{X}_{CP} - \overline{X}_{CG}}{Body\ diameter}$$

$$S.M._{K1103X} = \frac{82.834 - 70.283}{4.028} = 3.12\ caliber$$

$$S.M._{K805G} = \frac{82.641 - 70.714}{4.028} = 2.96\ caliber$$

The launch vehicle in both motor configurations meets the minimum stability margin of 2.0 calibers at the point of rail exit.

6.2.3 Full-Scale Thrust-to-Weight

The thrust-to-weight ratio (T:W) is a key parameter in rocket design, as it determines whether a rocket can successfully overcome gravity and begin its ascent. As per requirement 2.15, the minimum T:W ratio is 5:1.

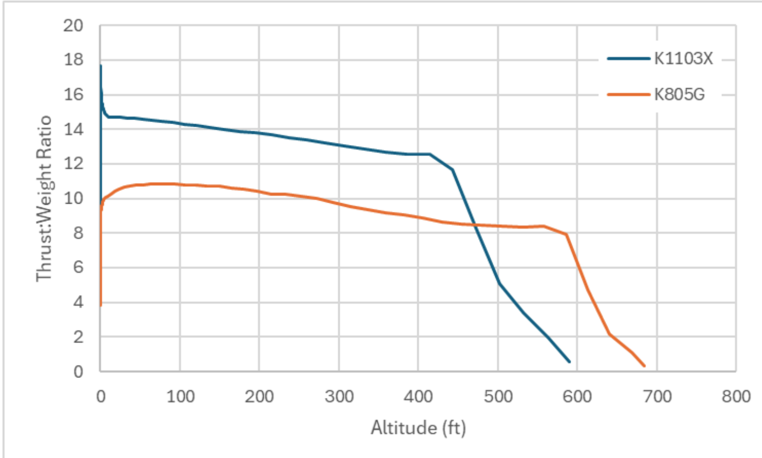


Fig. 54 - Thrust to weight ratio - full-scale

There are a few ways to calculate the thrust-to-weight ratio. The most simplistic method is to take the average thrust of the motor across the burn time and divide by the take-off weight of the rocket. Using the simplistic method, the T:W ratio is 12:1 for the K1103X and 9:1 for the K805G. However, this really does not paint an accurate picture of where the thrust-to-weight ratio is actually important. The thrust-to-weight ratio is primarily relevant during the first phase of the rocket's flight where the rocket is gaining speed and stability. During this phase, both the thrust and the mass are varying. Once the rocket reaches a stable velocity and altitude, which is typically during the later stages of motor burn, the T:W ratio becomes less critical. At this point, the rocket's momentum takes over and the thrust from the motor gradually decreases as the burn phase ends.

The thrust-to-weight ratio of both the primary and secondary motors exceeds the 5:1 T:W of requirement 2.15 at liftoff and through the early phase of the flight. The K1103X achieves an initial T:W ratio of approximately 18:1 at liftoff, which gradually decreases until 600 ft where the T:W ratio drops below 5:1 as the motor burns near completion. Similarly, the K805G motor starts with a T:W ratio of 11:1 at liftoff where it drops below the 5:1 as the motor burns off. In both cases, the motors provide sufficient thrust to achieve stable flight, maintaining a T:W ratio above the required 5:1 until the motor burns off, after which the rocket relies on momentum and aerodynamic stability for continued ascent.

6.2.4 Full-Scale Descent Characteristics

Descent time

Requirement 3.12 states that the descent time of the full-scale launch vehicle is limited to 90 seconds from apogee to touchdown. This is a combination of the descent time of the drogue and the descent time of the main parachute. This was modeled with

OpenRocket. It is acknowledged that this is not the most accurate modeling as there is a non-zero amount of time between the ejection charge and the parachute completely inflating. This is especially true for the larger main parachute that may take 3-5 s to fully deploy and inflate. This analysis also does not include the effects of thermals altering the descent rate.

Table 33 - Full-Scale Descent Times for the K1103X

Wind speed (mph)	Drogue to main (s)	Main to ground (s)	Apogee to ground (s)
0	49.82	29.87	79.69
5	49.84	29.62	79.46
10	49.92	29.07	78.99
15	49.48	30.32	79.80
20	49.57	29.78	79.35

Based on our analysis of descent times and the effect of varying wind speeds, all trials confirm that we are comfortably within the 90 second limit (from apogee to ground hit) limit specified by requirement 3.12. At a wind speed of 20 mph, the total descent time from apogee to touchdown is 79.35 seconds, which provides a 10% buffer against the limit. The full-scale vehicle remains under the drogue chute for an average of 49.73 seconds and under the main parachute for 29.73 second which make up for an average descent time of 79.46 seconds.

Drift Calculations

A critical parameter in recovering a rocket after a flight is the amount of drift. The requirement 3.11 states that the recovery radius must be less than 2500 ft. The flysheet requires a very simplistic calculation that does not take into account weathercocking or nosing over at apogee of the rocket. To get a better understanding, we performed an analysis in OpenRocket that analyzes the total drift of the rocket vs the wind speed taking into account both the ascent as well as the descent. All analysis assumes that the drogue is deployed at apogee and the main is deployed at 600 ft (primary altimeter system). This analysis was performed assuming a 10 ft launch rail (1515) that is in the vertical orientation. This analysis was only performed using the primary motor (K1103X).

Basic Drift Calculations - K1103X

The basic drift calculations were performed using the method suggested for use on the flysheet. This method consists of assuming a perfect vertical flight trajectory, then multiplying the descent time by the wind speed. This produces a simplistic case where the effects of weathercocking, nosing over at apogee, variable wind speed, turbulence, and thermals.

$$\Delta x = V_{wind\ speed} * T_{avg\ apogee\ to\ ground}$$

Table 34 -.Basic drift calculations

Wind speed (mph)	Wind speed (ft/s)	Average Descent Time (apogee to ground) (s)	Drift (ft)
0	0	79.46	0
5	7.33		582.44
10	14.67		1165.68
15	22		1748.12
20	29.33		2330.56

Utilizing only the distance equation, we were able to estimate the drift of the full scale launch vehicle. The worst condition for launch, 20 mph (29.33 ft/s), causes a drift of approximately 2330.56 ft which stays within the requirement 3.11 which is a margin of 6.7%.

To perform a more accurate analysis of drift conditions, the complete flight profile in the presence of wind and turbulence was used. Simulations were set up with standard flight conditions and a perfectly vertical 10 ft 1515 rod. The side profile of the worst case orientation with a constant wind vector is shown in the simulations and tables below.

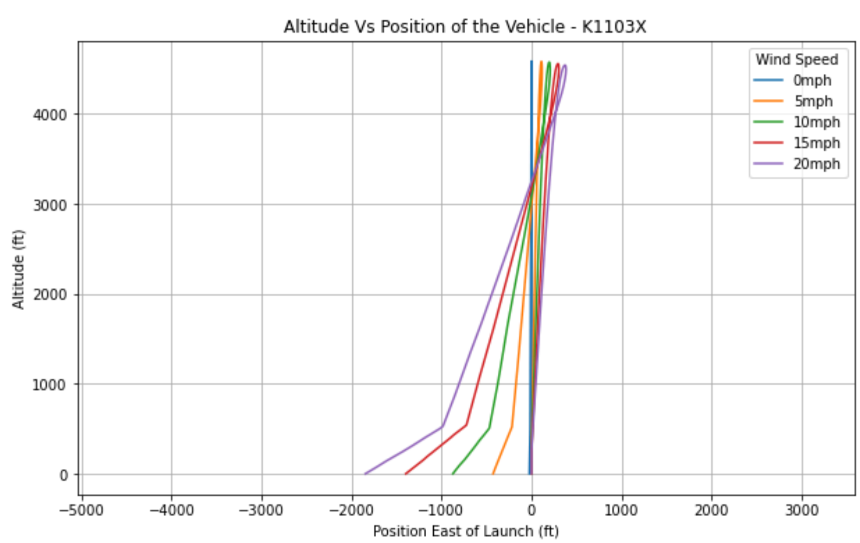


Fig. 55 - Drift plot - K1103X

Table 35 - K1103X Drift Values for OpenRocket Drift Model

Condition	Position from launch pad (ft)
0 mph	23.89
5 mph	426.85
10 mph	874.34
15 mph	1396.51
20 mph	1845.52

According to OpenRocket, simulations show that our rocket even in the worst condition of 20 mph lands comfortably within the limit of 2500 ft with a 26.2% safety margin. The main difference between the more accurate analysis and the simplistic analysis is primarily due to OpenRocket including the rocket weathercocking and nosing over into the wind. These effects are not included in the simple descent time multiplied by wind speed calculations.

Basic drift calculations-K805G

These calculations are done without using actual position data from OpenRocket. They utilize the formula shown for the primary motor above. We are only going to be doing the worst case calculation for drift for the secondary motor.

20 mph (29.33 ft/s)

$$\Delta x = 29.33\,ft/s \; * \; 75.81s = 2223.51\,ft$$

Utilizing only the distance equation, we were able to estimate the drift of the full scale launch vehicle. In the worst condition for launch, which is 20 mph (29.33 ft/s) , causes a drift of approximately 2223.51 ft which stays within the requirement 3.11 with a margin of 11.1%.

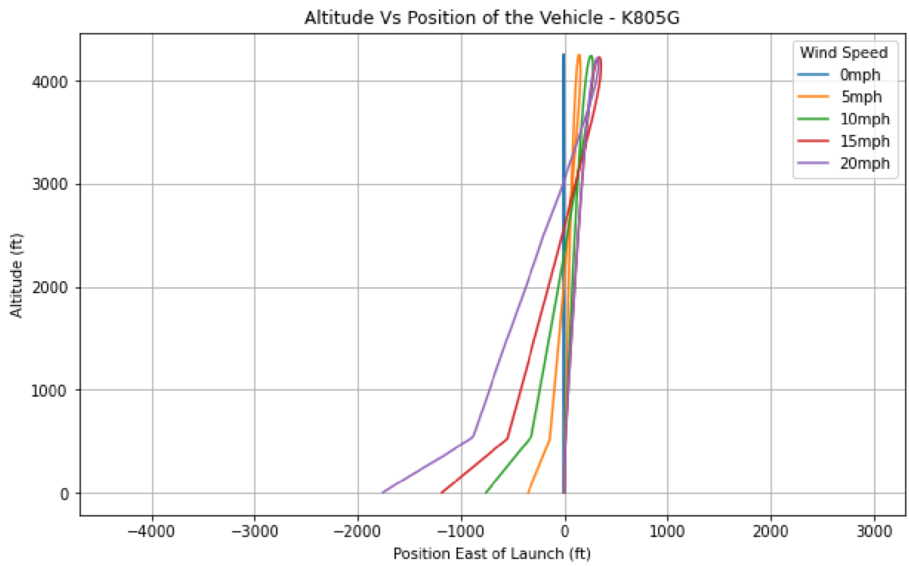


Fig. 56 - Drift plot - K805G

Table 36 - K805G Drift Values for OpenRocket Drift Model

Condition	Position from launch pad (ft)
0 mph	5.69
5 mph	348.70
10 mph	757.38
15 mph	1185.06
20 mph	1757.46

Descent Velocities

Descent velocities determine how far the airframe will drift, the shock from relative velocity changes, and how much force the airframe hits the ground with. Dual deploy offers the flexibility of tailoring the drogue and main descent velocities to meet our goals.

Drogue to Main Velocity

The velocity between drogue deployment (typically near or at apogee) and main chute deployment is critical since it affects the overall descent rate and the forces exerted on the recovery system. Understanding these velocities is key to ensuring that the recovery components are properly designed to handle the dynamic stresses during descent.

Through simulations conducted with OpenRocket, we have analyzed the total velocity at various stages of the flight, allowing us to capture both vertical and horizontal velocity components.

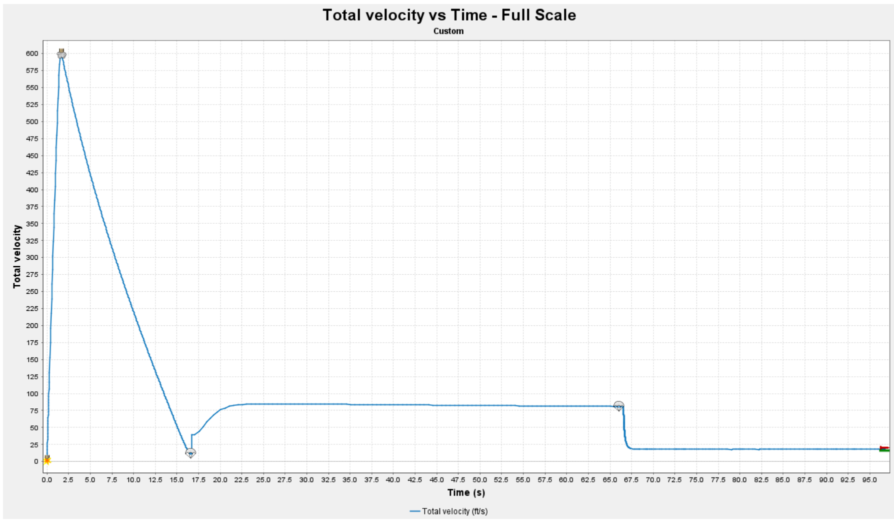


Fig. 57 - Total velocity vs time - full-scale

Based on OpenRocket simulations, the total velocity when the drogue is deployed at apogee is 11.19 ft/s. As this occurs at apogee where the vertical velocity is zero, the entire velocity vector is horizontal due to the rocket nosing over. The rocket reaches the drogue terminal velocity of 85 ft/s approximately 8.4 s after deployment.

Force on Recovery System : Drogue Deployment

Using the velocity data obtained from OpenRocket simulations, we can calculate the deceleration that the rocket faces after unfurling by using the following formula

$$a = \frac{\Delta V}{\Delta T} = \left| \frac{V_{t\ under\ drogue} - V_{drogue\ deployment}}{T_{apogee} - T_{inflation\ of\ drogue}} \right|$$

The drogue usually takes around 2 to 3 seconds from apogee to fully inflate and start decelerating the rocket. For our calculations we will be utilizing 2 seconds as ΔT. Terminal velocity under drogue as mentioned earlier is 85 ft/s and the velocity at deployment is 11.19 ft/s.

$$a = \frac{\Delta V}{\Delta T} = \left| \frac{85\ ft/s - 11.19\ ft/s}{2s} \right| = 36.91\ ft/s^2$$

Total acceleration is calculated by adding the gravitational acceleration simulated by OpenRocket. OpenRocket simulates gravitational acceleration to 32 ft/s^2.

$$A_{total} = a_{deceleration} + a_{gravitational\ acceleration}$$

$$A_{total} = 36.91\ ft/s^2 + 32\ ft/s^2 = 68.91\ ft/s^2$$

Force Calculation Booster Tube

Table 37 - Mass Under Drogue Parachute

Airframe Section	Total Mass (lbs)	Total mass conversion (slugs)
Booster section	7.4	0.23
Payload tube + nose cone assembly	10	0.311

The force exerted by ejection on to the different sections of the rockets can be calculated by using Newton's second law.

$$Force = mass_{section} * total\ acceleration$$

Table 38 - Force Calculations Under Drogue Parachute

Section	Mass (slugs)	Total acceleration (ft/s^2)	Force (lbf)
Booster section	0.2	68.91	15.84
Payload tube assembly	0.311		21.43

Kinetic energy under drogue

The rocket's kinetic energy reaches its peak at terminal velocity during descent under the drogue chute, which for the full-scale vehicle has been simulated through OpenRocket to be 85 ft/s.

Kinetic energy can be calculated by using the following equation

$$KE = \frac{1}{2}mv^2$$

Table 39 - Kinetic energy under drogue.

Section	Mass (slugs)	Terminal velocity (ft/s)	Kinetic energy (ft/lbf)
Payload tube assembly	0.311	85	1123.5
Booster tube assembly	0.23		830.9

Kinetic energy during descent under the drogue is critical since it directly affects the forces that need to be managed by the recovery system. High kinetic energy translates to greater stress on components like the drogue parachute, shock highers, and attachment points. If the recovery system fails to properly slow down the rocket, the impact forces on landing will be much higher, leading to potential damage or even total failure of the rocket.

Main to Ground Velocity

Using the velocity data obtained from OpenRocket simulations, we can calculate the deceleration that the rocket faces after the main chute unfurls using the same formula mentioned above. The main chute usually takes around 3 to 5 seconds to fully inflate and start accelerating the vehicle. Based on various launch observations and input from our team mentor for a deployment and inflation time for a 78" parachute, we will be utilizing 3 seconds as ΔT. The terminal velocity under the main chute is 18 ft/s and the velocity at deployment is 80.8 ft/s

$$a = \frac{\Delta V}{\Delta T} = \left|\frac{18\,ft/s - 80.8\,ft/s}{3s}\right| = 20.93\,ft/s^2$$

Total Acceleration

Using OpenRocket, the gravitational acceleration under the main is simulated to be 32 ft/s^2.

$$A_{total} = 20.93\,ft/s^2 + 32\,ft/s^2 = 52.93\,ft/s^2$$

Force Calculation on Rocket Sections

Table 40 - Mass Under Main Parachute

Component	Mass (lbs)	Mass (slugs)
Nose cone assembly	4.027	0.125
Payload assembly	3.419	0.106
Booster assembly	7.4	0.23

Force Calculations Under Main

Table 41 - Force Calculations Under Main Parachute

Section	Mass (slugs)	Total acceleration (ft/s^2)	Force (lbf)
Nose cone assembly	0.125	52.93	6.62
Payload tube assembly	0.106		5.61
Booster section	0.23		12.17

Kinetic Energy Under Main Chute

The rocket's kinetic energy under main parachute descent reaches its peak at terminal velocity. The simulated terminal velocity is 18 ft/s.

Table 42 - Kinetic Energy Under Main Parachute

Section	Mass (slugs)	Terminal velocity (ft/s)	Kinetic energy (ft/lbf)
Nose cone assembly	0.125	18.0	20.25
Payload tube assembly	0.106		17.14
Booster tube assembly	0.23		37.26

Based on these preliminary calculations, we can conclude that none of the full scale rocket sections will exceed the maximum impact kinetic energy specified by NASA. In addition, the forces calculated on the recovery harness *for a nominal recovery* are significantly less than the 3600 lbf design strength. However, the recovery harness is not sized for nominal, but rather for a worst case recovery. Once the rocket is built, recalculations with the actual mass of the rocket will be performed to confirm it still meets requirement 3.3.

6.3 Subscale Mission Performance

The geometry of the subscale rocket design was meant to be as close to 50% as possible. See Section 3.3 for a discussion on what could be scaled effectively and what could not. In general, the overall shape, CP, CG, and hence stability was kept as close as possible to make the subscale truly representative of the full-scale. In addition, motors were selected to provide similar numbers for parameters such as rail exit velocity, similar acceleration, and thrust-to-weight ratio.

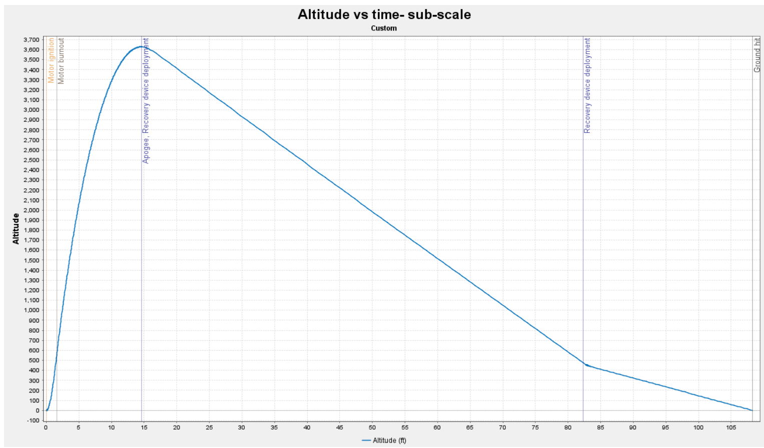


Fig. 58 - Altitude vs time - subscale

6.3.1 Subscale Kinematics

Subscale Altitude

The subscale altitude is not exactly a 50% scale as the motors selected do not have an exact 50% scale thrust. Similar to the full-scale simulations, we set standard deviation of the wind speed to 0.0224 and turbulence intensity at 10% to keep simulations consistent and realistic.

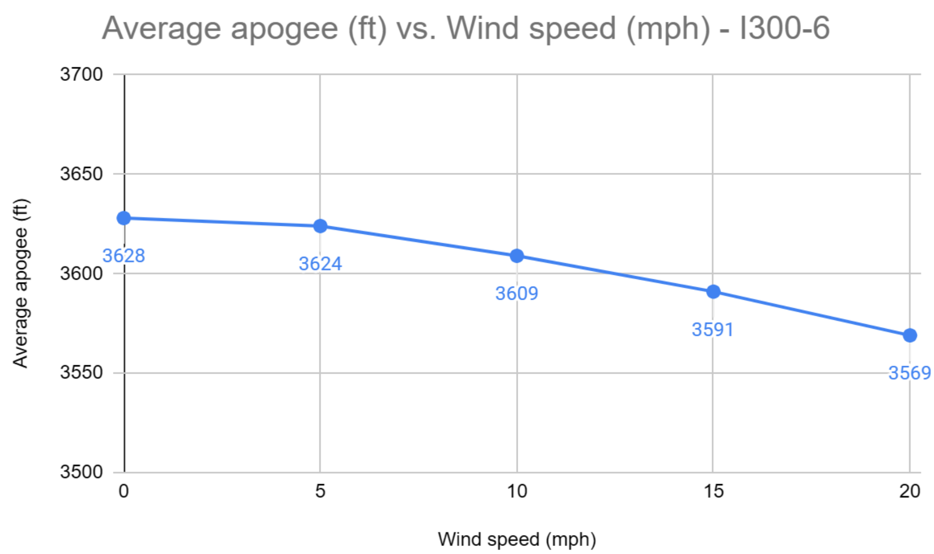


Fig. 59 - Subscale average apogee vs wind speed - I300T

Table 43 - Subscale Simulated Altitude vs Wind for Aerotech I300T

Wind speed	Altitude 1 (ft)	Altitude 2 (ft)	Altitude 3 (ft)	Average apogee (ft)
0 mph	3628			3628
5 mph	3623	3624	3624	3624
10 mph	3610	3611	3607	3609
15 mph	3589	3595	3590	3591
20 mph	3574	3563	3570	3569

The table above shows the average apogee of the subscale model with the primary motor, the Aerotech I300T. A wind speed of 0 mph provides an apogee of 3628 ft and a wind speed of 20 mph provides an apogee of 3528 ft. The range is still approximately 60 ft which shows that our subscale model mimics the flight characteristics of the full-scale model in terms of altitude variation vs weathercocking in the presence of large variation of wind speed.

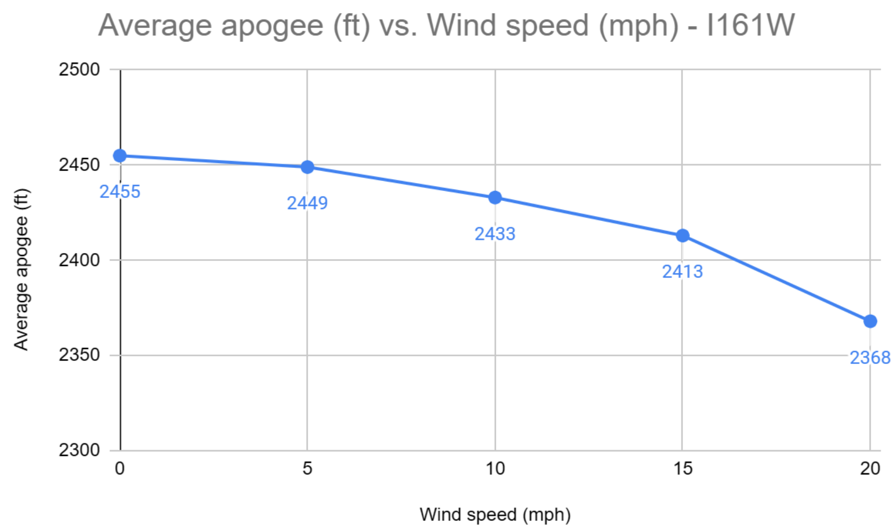


Fig. 60 - Subscale average apogee vs wind speed - I161W

Table 44 - Subscale Simulated Altitude vs Wind for Aerotech I161W

Wind speed	**Altitude 1 (ft)**	**Altitude 2 (ft)**	**Altitude 3 (ft)**	**Average altitude (ft)**
0 mph	2455			2455
5 mph	2449	2450	2449	2449
10 mph	2432	2436	2432	2433
15 mph	2417	2413	2409	2413
20 mph	2370	2364	2369	2368

The table above shows the average apogee of the subscale model utilizing the secondary motor, an Aerotech I161W. A wind speed of 0 mph simulates an average apogee of 2455 ft and a wind speed of 20 mph simulates an average apogee of 2368 ft. The secondary motor will be selected for flight if the flight and field conditions require a lower altitude flight.

Maximum Acceleration

Maximum acceleration is primarily dependent on the thrust produced by the rocket motor. Maximum acceleration occurs during the maximum thrust produced by the motor during flight. Below are two thrust vs acceleration graphs showing the acceleration faced by the rocket while the motor is burning.

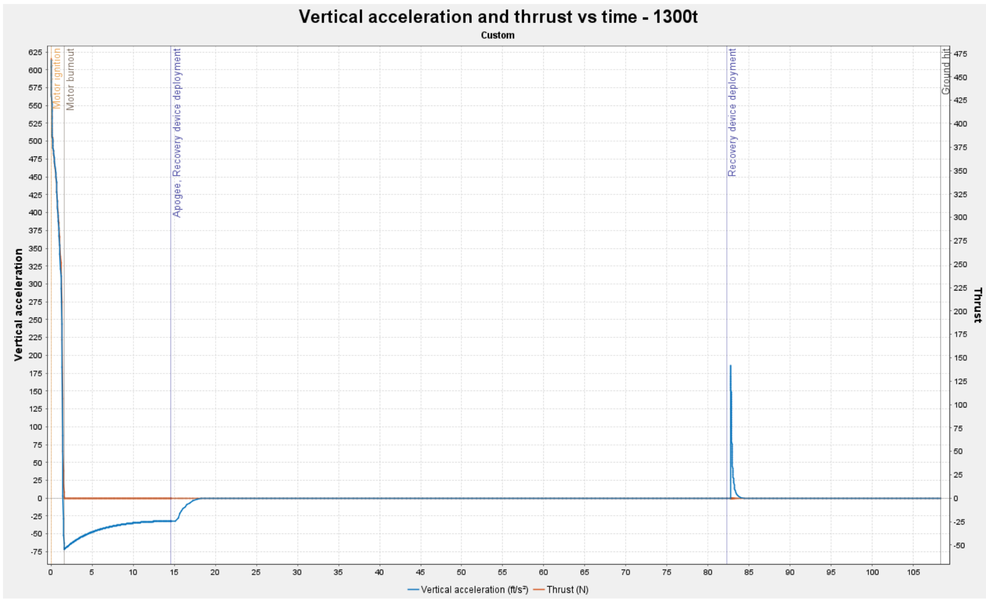


Fig. 61 - Vertical acceleration and thrust vs time - I300T

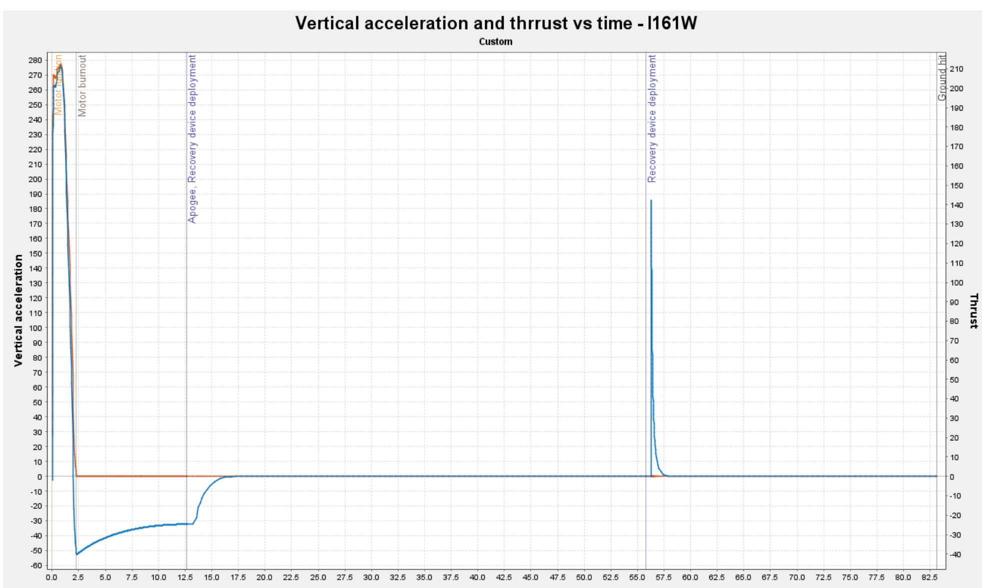


Fig. 62 - Vertical acceleration and thrust vs time - I161W

Table 45. Maximum thrust and acceleration vs time - subscale

Motor	Maximum thrust (N)	Maximum acceleration (ft/s^2)	G-force value
I300T	469.4	613.2	19
I161W	212.32	275.5	8

The table above shows the data comparing the time at which maximum acceleration, maximum thrust are faced by the subscale rocket for both our primary (I300T) and secondary motor (I161W).

The peak force exerted by the motor is measured in Newtons (N). The I300T generates a higher maximum thrust (469.4 N) compared to the I161W (212.32 N). The I161W has a slower burn rate with a lower total impulse. Hence, it reaches its maximum thrust later than the I300T providing a more gradual acceleration. The I300T motor provides a stronger, quicker burst of thrust resulting in a higher acceleration over a short period of time. This helps provide a higher rail velocity which will result in less weathercocking and more stability off of the pad.

The rocket experiences significant G-forces during its accent, especially at a maximum acceleration. For instance, when using the I300T motor, the rocket reaches a peak G-force of 19 G's, driven by a maximum acceleration of 613 ft/s^2 and a gravitational acceleration of 32 ft/s^2. In contrast, with the I161W motor, the rocket faces a peak G-force of 8 G's, driven by a maximum acceleration of 275 ft/s^2 and a gravitational acceleration of 32 ft/s^2.

Velocity

The graphs and tables below illustrate the rail exit velocity and maximum velocity for the subscale model

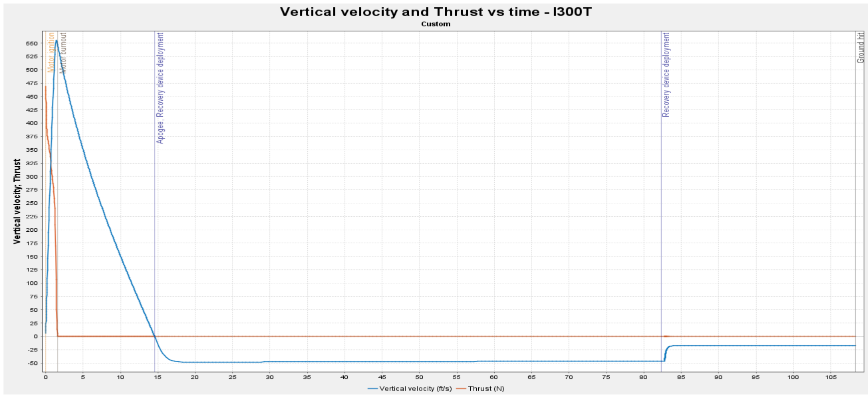


Fig. 63 - Vertical velocity and thrust vs time - I300T

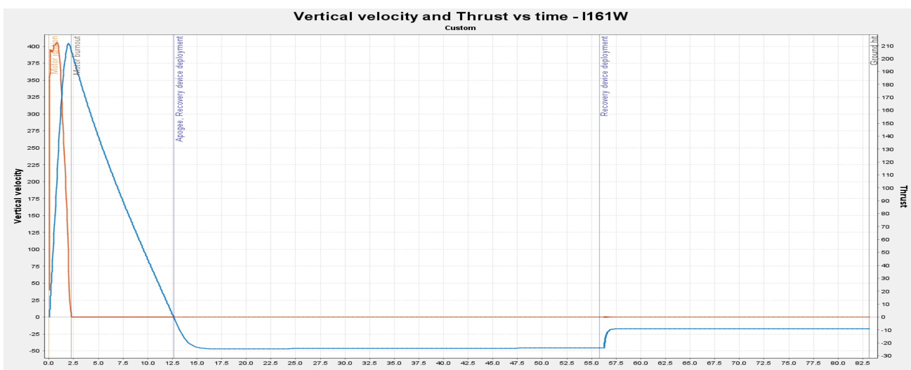


Fig. 64 - Vertical velocity and thrust vs time - I161W

Table 46 - Full-Scale Ascent Velocity

Motor	Rail exit velocity (ft/s)	Maximum velocity (ft/s)	Mach number	Time for maximum velocity (s)
I300T	91.7	555	0.499	1.43
I161W	64.4	404	0.363	1.95

OpenRocket simulations show that the I300T motor achieves a maximum velocity of 555 ft/s (Mach 0.499), while the I161W reaches 404 ft/s (Mach 0.363), both comfortably within the Mach 1 limit of requirement 2.22.6. The rail exit velocities of 91.7 ft/s for the I300T and 64.4 ft/s for the I161W exceed the 52 ft/s minimum rail exit velocity as mandated by requirement 2.17 by 76.3% and 23.8% respectively

The I300T delivers a peak thrust at the beginning of the burn (469 N), meaning it can accelerate the rocket quicker. As a result the rocket reaches a higher speed (555 ft/s) in a shorter time (1.43 s). The rapid thrust delivery allows the rocket to gain speed quickly, pushing it to a higher maximum velocity over a shorter period.

The I161W motor produces a more consistent, longer thrust period with a lower peak thrust (212 N) than the I300T, resulting in a slower acceleration. Since the rocket doesn't accelerate as quickly, it takes longer to reach its maximum velocity (404 ft/s) and requires more time (1.95 seconds) to achieve it.

6.3.2 Subscale Stability

The stability margin of a rocket is a relative and not absolute value; thus, for our subscale vehicle we are aiming for a stability margin of above 2.0 caliber. This is the same value required for the full-scale vehicle.

Table 47 - Stability Parameters for Full Scale Design

Motor	Stability (caliber)	CG (in)	CP (in)
I300T	3.07	32.407	39.254
I161W	3.27	31.957	39.254

OpenRocket calculates the static stability of a rocket. Our subscale rocket design has a stability margin of 3.07 caliber with the primary motor configuration (I300T) and a stability margin of 3.27 caliber with the secondary motor configuration (I161W). The effects of this margin have been simulated in Sections 3.2.3 Body Tube Design Selection and 3.2.6 Fins, proving the ability of our rocket to withstand the effects of aerodynamic forces.

Static Stability at Rail Exit

According to requirement 2.14, the launch vehicle must maintain a minimum stability margin of 2.0 at the point of rail exit. The graphs below plot the CG and CP locations of the rocket for both our primary (I300T) and secondary (I161W) motors as the rocket exits the launch rail.

To establish the altitude at which the front rail button exits the launch rod, we utilized the following parameters:

Table 48 - Rail Exit Parameters - Full-Scale

Parameter	Value
Height of front rail button from bottom of rocket	1.34 ft
Length of launch rail	8 ft

The distance the front rail button travels along the rail can be calculated by:

$$D_{bottom\ to\ rail\ exit} = Length\ of\ launch\ rail\ -\ height\ of\ front\ rail\ button$$

$$D_{bottom\ to\ rail\ exit} = 8ft\ -\ 1.34\ ft\ =\ 6.66\ ft$$

Using OpenRocket's ability to graph locations of CG and CP over altitude and using a python script to analyze the exact locations of CG and CP we evaluated that at an altitude of 6.66 ft, the CG and CP locations are as follows:

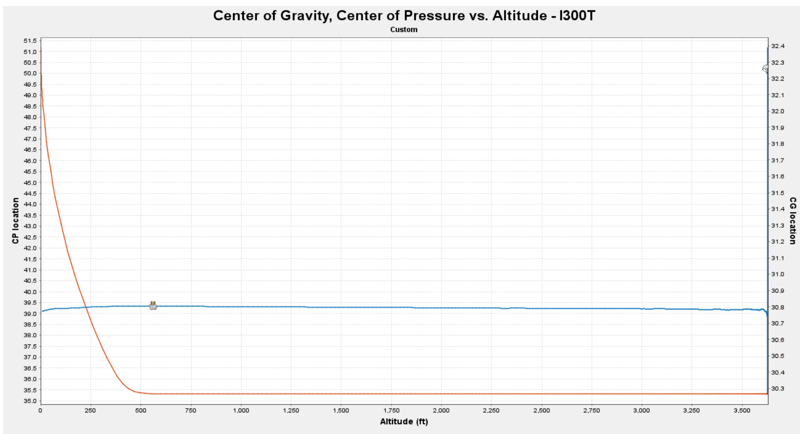


Fig. 65 - CG and CP vs altitude - I300T

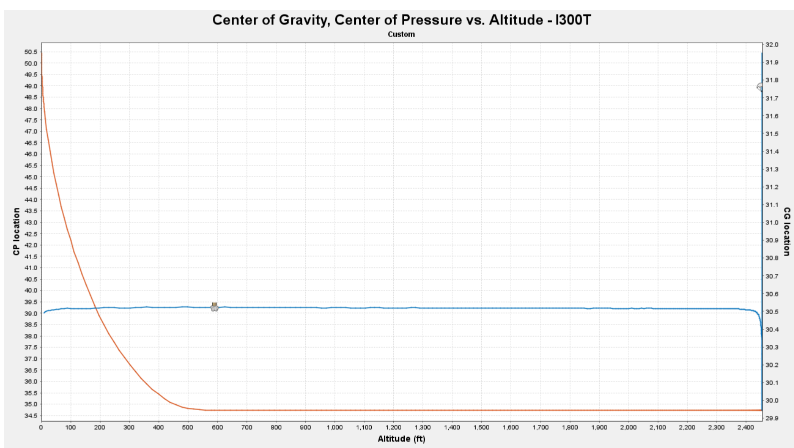


Fig. 66 - CG and CP vs altitude - I161W

Table 49 - CG and CP Locations - Full-Scale

Motor	CG location (in)	CP location (in)
I300T	32.125	39.09
I161W	31.69	39.016

Using the formula to calculate static stability, we can calculate the stability at the point of rail exit. The body diameter for the subscale vehicle is 2.228 inches.

$$S.M. = \frac{\overline{X}_{CP} - \overline{X}_{CG}}{Body\ diameter}$$

$$S.M._{I300T} = \frac{39.09 - 32.125}{2.228} = 3.13\ caliber$$

$$S.M._{I161W} = \frac{39.016 - 31.69}{2.228} = 3.29\ caliber$$

The launch vehicle in both motor configurations meets the minimum stability margin of 2.0 calibers at the point of rail exit as well as being below our upper end of stability from derived requirement LV-D-1. In addition, these values are consistent with the full-scale design.

6.3.3 Subscale Thrust-to-Weight Ratio

The thrust-to-weight (T:W) ratio for the subscale model is designed to approximate 50% of the full-scale rocket's performance. For the full-scale vehicle, the primary motor achieves a T:W ratio of 18:1, while the secondary motor reaches 11:1.

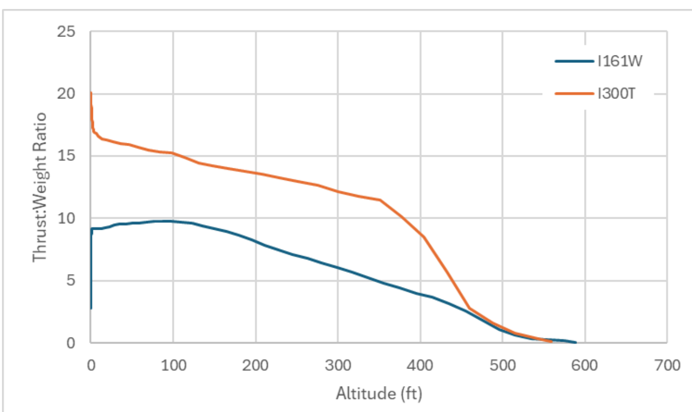


Fig. 67 - Thrust-to-weight ratio - subscale

Using the same method to calculate thrust-to-weight ratio as in 6.2.3 Full-Scale Thrust-to-Weight, the thrust-to-weight ratio for the subscale vehicle is approximately the same as the full-scale. The I300T motor achieves an initial T:W ratio of approximately 16:1 and the I161W motor achieves an initial T:W ratio of 9:1. The motors provide sufficient thrust to achieve stable flight. Using average values of thrust and full take-off weight, the thrust-to-weight ratio is 13:1 for the I300T and 7:1 for the I161W.

6.3.4 Subscale Descent Characteristics

Descent time

This analysis is done with the same processes for the full-scale vehicle. The main subscale parachute takes approximately 2-3 s to fully deploy and inflate. This analysis also does not include the effects of thermals altering the descent rate.

Table 50 - Full-Scale Descent Times for the I300T

Wind speed (mph)	Drogue to main (s)	Main to ground (s)	Apogee to ground (s)
0	67.68	26.03	93.71
5	67.18	27.11	94.29
10	67.3	26.22	93.52
15	66.95	26.56	93.51
20	66.39	26.83	93.22

At a wind speed of 20 mph, the total descent time from apogee to touchdown is 93.22 seconds. The subscale vehicle remains under the drogue chute for an average of 67.1 seconds and under the main parachute for 26.55 seconds which make up for an average descent time of 93.65 seconds. While this is above the limit of 90 s for the full-scale (requirement 3.12), there is no requirement for the subscale and liberty was taken for a gentle recovery using existing parachute sizes that we have available.

Drift

Similar to the full-scale, the drift of the subscale was calculated using a simplistic descent time multiplied by wind speed as well as a more detailed approach factoring in weathercocking. Unlike the full-scale, the subscale is not subject to the maximum recovery radius of 2500 ft (requirement 3.11). Due to increasing the descent time above to use existing parachutes, the calculated drift of the subscale will naturally be larger. As the fields we intend to fly at have much larger available space, and we do not plan to fly in 20 mph winds. This should not be a problem.

Basic Drift Calculations - I300T

The basic drift calculations were performed using the method suggested for use on the flysheet. This method consists of assuming a perfect vertical flight trajectory, then multiplying the descent time by the wind speed. This produces a simplistic case where the effects of weathercocking, nosing over at apogee, variable wind speed, turbulence, and thermals.

$$\Delta x = V_{wind\ speed} * T_{avg\ apogee\ to\ ground}$$

Table 51 -.Basic Drift Calculations-Subscale

Wind speed (mph)	Wind speed (ft/s)	Descent Time (apogee to ground) (s)	Drift (ft)
0	0	93.65	0
5	7.33		686.45
10	14.67		1373.84
15	22		2060.3
20	29.33		2746.75

Utilizing only the distance equation, we were able to estimate the drift of the full scale launch vehicle. The worst condition for launch, 20 mph (29.33 ft/s), causes a drift of approximately 2746.45 ft.

To get a better understanding, we performed an analysis in OpenRocket that analyzes the total drift of the rocket vs the wind speed taking into account both the ascent as well as the descent. All analysis assumes that the drogue is deployed at apogee and the main is deployed at 600 ft (primary altimeter system). This analysis was performed assuming a 8 ft launch rail (1010) that is in the vertical orientation. This analysis was performed with both the primary and secondary motors, the I300T and the I161W.

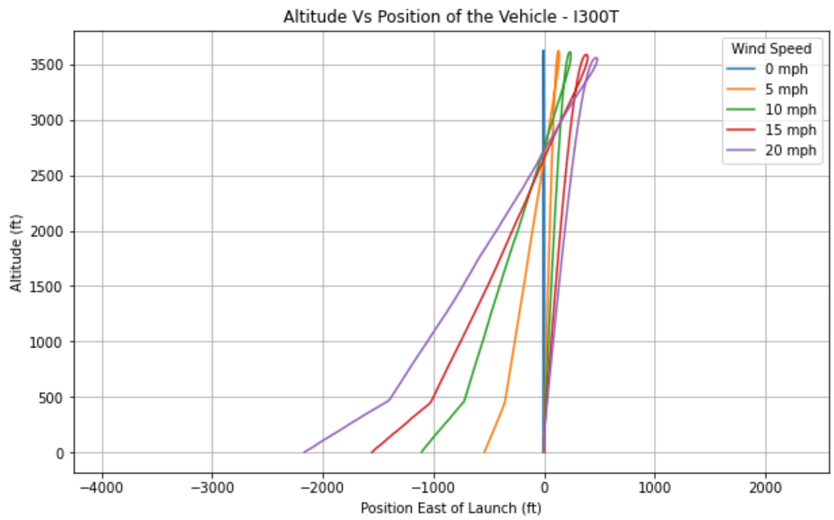


Fig. 68 - Drift plot - I300T

Table 52 - I300T Drift Values (Flight Profile)

Condition	Position from launch pad (ft)
0 mph	4
5 mph	539
10 mph	1106
15 mph	1556
20 mph	2167

Our worst case scenario with our high thrust I300T motor indicates a position at 2167 ft. These scenarios present a worst case, as no rail tilt has been used to reduce the radius from the launch pad.

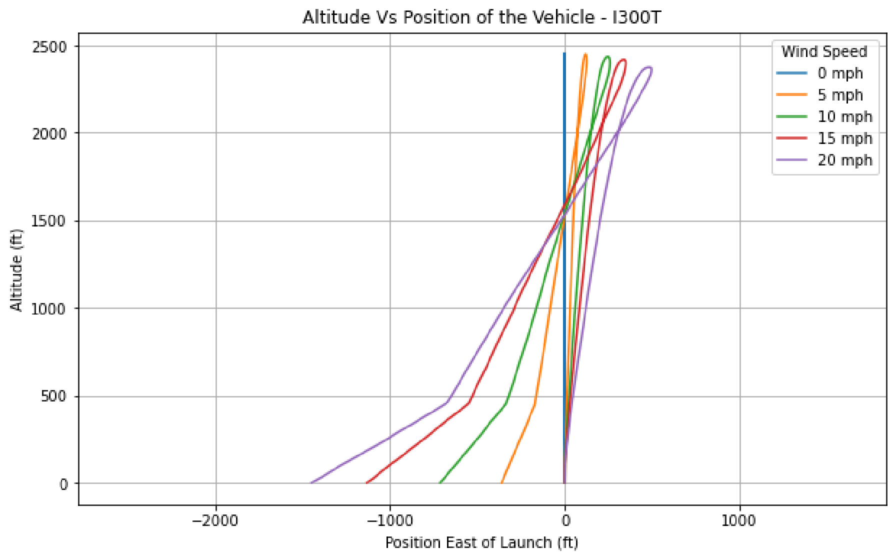


Fig. 69 - Drift plot - I161W

Table 53 - I161W Drift Values (Flight Profile)

Condition	Position from launch pad (ft)
0 mph	2.49
5 mph	361.72
10 mph	713.45
15 mph	1131.25
20 mph	1448.26

Our decreased power I161W motor provides a lower altitude, and thus less horizontal drift. Our worst case scenario with this configuration had a radius of 1448.26 ft.

<u>Descent Velocities</u>
Descent velocities determine how far the airframe will drift, the shock from relative velocity changes, and how much force the airframe hits the ground with. Dual deploy offers the flexibility of tailoring the drogue and main descent velocities to meet our goals.

<u>Drogue to Main Velocity</u>
The velocity between drogue deployment (typically near or at apogee) and main parachute deployment is critical since it affects the overall descent rate and the forces exerted on the recovery system. Understanding these velocities is key to ensuring that

the recovery components are properly designed to handle the dynamic stresses during descent.

Through simulations conducted with OpenRocket, we have analyzed the total velocity at various stages of the flight, allowing us to capture both vertical and horizontal velocity components.

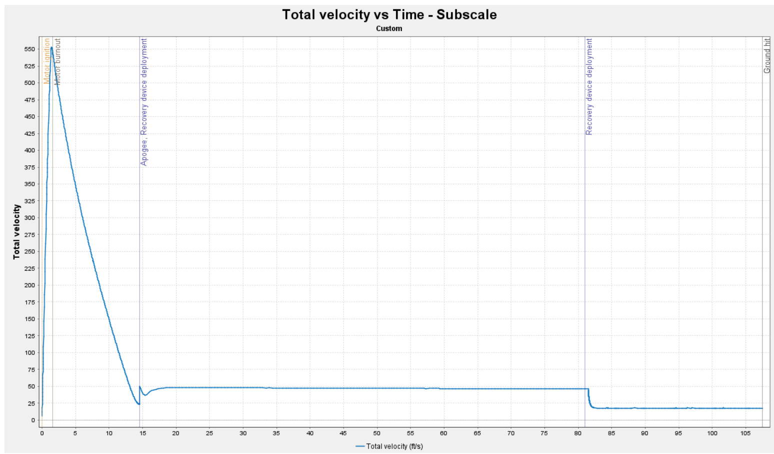


Fig. 70 - Total velocity vs time - full-scale

Based on OpenRocket simulations, the total velocity when the drogue is deployed at apogee is 21.48 ft/s. As this occurs at apogee where the vertical velocity is zero, the entire velocity vector is horizontal due to the rocket nosing over. The rocket reaches the drogue terminal velocity of 46.1 ft/s after deployment.

Force on Recovery System : Drogue Deployment - Subscale

Using the velocity data obtained from OpenRocket simulations, we can calculate the deceleration that the rocket faces after unfurling by using the following formula

$$a = \frac{\Delta V}{\Delta T} = \left| \frac{V_{t\ under\ drogue} - V_{drogue\ deployment}}{T_{apogee} - T_{inflation\ of\ drogue}} \right|$$

The drogue usually takes around 2 to 3 seconds from apogee to fully inflate and start decelerating the rocket. For our calculations we will be utilizing 2 seconds as ΔT. Terminal velocity under drogue as mentioned earlier is 46.1 ft/s and the velocity at deployment is 21.48 ft/s.

$$a = \frac{\Delta V}{\Delta T} = \left| \frac{46.1\ ft/s - 21.48\ ft/s}{1s} \right| = 24.62\ ft/s^2$$

Total acceleration is calculated by adding the gravitational acceleration simulated by OpenRocket. OpenRocket simulates gravitational acceleration to 32 ft/s^2.

$$A_{total} = a_{deceleration} + a_{gravitational\ acceleration}$$

$$A_{total} = 24.62\ ft/s^2 + 32\ ft/s^2 = 56.62\ ft/s^2$$

Force calculation booster tube

Table 54 - Mass Under Drogue Parachute

Airframe Section	Total Mass (lbs)	Total mass conversion (slugs)
Booster section	1.25	0.04
Payload tube + nose cone assembly	2.85	0.09

The force exerted by ejection on to the different sections of the rockets can be calculated by using Newton's second law:

$$Force = mass_{section} * total\ acceleration$$

Table 55 - Force Calculations Under Drogue

Section	Mass (slugs)	Total acceleration (ft/s^2)	Force (lbf)
Booster section	0.04	56.62	2.26
Payload tube assembly	0.09		5.09

Kinetic Energy Under Drogue

The rocket's kinetic energy reaches its peak at terminal velocity during descent under the drogue chute, which for the full-scale vehicle has been simulated through OpenRocket to be 46.1 ft/s.

Kinetic energy can be calculated by using the following equation

$$KE = \frac{1}{2}mv^2$$

Table 56 - Kinetic Energy Under Drogue.

Section	Mass (slugs)	Terminal velocity (ft/s)	Kinetic energy (ft/lbf)
Payload tube assembly	0.04	46.1	42.5
Booster tube assembly	0.09		85.6

Main to Ground Velocity

Using the velocity data obtained from OpenRocket simulations, we can calculate the deceleration that the rocket faces after the main chute unfurls using the same formula mentioned above. The main chute usually takes around 2 to 3 seconds to fully inflate and start accelerating the vehicle. Based on various launch observations and input from our team mentor for a deployment and inflation time for a 36" parachute, we will be utilizing 2 seconds as ΔT. The terminal velocity under the main chute is 17.5 ft/s and the velocity at deployment is 46.1 ft/s

$$a = \frac{\Delta V}{\Delta T} = \left| \frac{17.5\,ft/s - 46.1\,ft/s}{2s} \right| = 14.3\,ft/s^2$$

Total Acceleration

Using OpenRocket, the gravitational acceleration under the main is simulated to be 32 ft/s^2.

$$A_{total} = 14.3\,ft/s^2 + 32\,ft/s^2 = 46.3\,ft/s^2$$

Force Calculation on Rocket Sections

Table 57 - Mass Under Main Parachute

Component	Mass (lbs)	Mass (slugs)
Nose cone assembly	1.422	0.044
Payload assembly	1.132	0.035
Booster assembly	1.25	0.038

Force Calculations under main

Table 58 - Force Calculations Under Main Parachute

Section	Mass (slugs)	Total acceleration (ft/s^2)	Force (lbf)
Nose cone assembly	0.044	46.3	2.04
Payload tube assembly	0.035		1.62
Booster section	0.038		1.76

Kinetic Energy Under Main Chute

The subscale rocket's kinetic energy under main parachute descent reaches its peak at terminal velocity. The simulated terminal velocity is 17.5 ft/s.

Table 59 - Kinetic Energy Under Main Parachute

Section	Mass (slugs)	Terminal velocity (ft/s)	Kinetic energy (ft/lbf)
Nose cone assembly	0.044	17.5	6.74
Payload tube assembly	0.035		5.36
Booster tube assembly	0.038		5.82

Based on these preliminary calculations, we can conclude that none of the subscale rocket sections will exceed the maximum impact kinetic energy specified by NASA. Once the rocket is built, recalculations with the actual mass of the rocket will be performed to confirm it is still within NASA's specs.

6.4 Summary

To consolidate the information, a table with the relevant metrics is shown below with the corresponding requirements. This is included for both primary and backup motors for both the full-scale and subscale rockets.

Table 60 - Summary of Performance Parameters

Metric	Full-scale K1103X	Full-scale K805G	Subscale I300T	Subscale I161W	Requirement
Altitude (ft)	4587	4252	3628	2455	2.1: Between 3500 and 5500 ft Apogee
Stability Margin (cal)	3.12	2.96	3.07	3.27	2.13: Min 2.0 at Rail Exit
Thrust:Weight Ratio	12:1	9:1	13:1	7:1	2.14: Min 5:1
Peak Acceleration (ft/s^2)	536	313	613.2	275.5	No Requirement
Rail Exit Velocity (ft/s)	99.8	77.8	91.7	64.4	2.16: Min 52 ft/s
Peak Velocity (ft/s)	603	559	555	404	2.22.6: Max Mach 1 (1125 ft/s)
Capsule KE at Landing (ft-lbf)	20.3	20.3	6.7	6.7	3.3: Max KE at Landing of 75 ft-lbf
Coupler/Payload Tube KE at Landing (ft-lbf)	17.1	17.1	5.4	5.4	3.3: Max KE at Landing of 75 ft-lbf
Booster KE at Landing (ft-lbf)	37.26	37.26	5.8	5.8	3.3: Max KE at Landing of 75 ft-lbf
Recovery Radius at 20 mph wind (ft)	2331	2224	2747	1448	3.11: Max Radius of 2500 ft
Descent Time (s)	79.7	75.8	93.7	70.8	3.12: Max 90 s

7.0 Safety

This section begins our safety personnel and FMEA analysis. This is not complete at the time of the PDR. The team learned critical information during the safety webinar that was held later in the process of preparing the PDR. At this time, most of the hazards, causes, effects, and mitigations are written with moderate confidence. However, we acknowledge that we are struggling with some of the verification columns and will revisit this prior to CDR.

7.1 Hazard Definitions

These tables define the probability ratings and severity ratings for each hazard type, to serve as a standard for rating our defined hazards.

Table 61 - Hazard Probability Classification

Definition	Hazard probability	Value
Improbable	Less than 2%	1
Rare	Between 2% and 10%	2
Unlikely	Between 10% and 15%	3
Occasional	Between 15% and 40%	4
Probable	Greater than 40%	5

Table 62 - Definitions of Hazard and Failure Severity

Description	Value	Effect on personnel	Effect on launch vehicle	Effect on environment	Effect on mission success
Negligible	1	Minor scratch, cut, or burn	Minor cosmetic damage	Minor to negligible	Negligible effect to success
Minor	2	Minor injury that requires immediate first aid	Major cosmetic damage that does not affect airframe performance	Easy clean up, minimal harm	Expected, minor effect with minimal setback
Moderate	3	Injury that requires medical attention	Minor damage that requires fixing for optimal airframe performance	Proper clean up required to mitigate environmental damage	Unexpected, but still fixable setback that requires project reworking
Severe	4	Injury that requires immediate, significant medical attention and/or intervention	Major damage to the airframe where repair is required for airframe integrity	Damage to the environment unless addressed as soon as possible	Unexpected, significant setback that jeopardizes project completion; will require significant or complete project reworking if at all fixable
Catastrophic	5	Significant bodily injury or death	Loss of part of or all of the airframe	EPA intervention required	Project failure and/or disqualification

7.2 Personnel Hazards

Table 63 - Table of Personal Hazards

Hazard	Cause	Effect	Likelihood (before)	Severity (before)	Mitigation	Likelihood (after)	Severity (after)	Verification
Direct contact with edges of fiberglass	Handling fiberglass	Skin irritation, minor cuts, and possible infection	5	1	• Eliminate sharp edges by taping when possible. • Wear protective gloves and clothing. • Have a first aid kit available at all times should an incident arise.	1	1	• Team will create a safety contract agreement. • SOP for fiberglass handling will be written. • Verify first aid kit is present and stocked prior to each build session.
Exposure to airborne particulates	Sanding fiberglass	Possible respiratory complications like coughing, wheezing, and soreness in the nose and throat. Long-term effects include complications such as dermatitis	5	3	• Wet sand when possible to eliminate dust becoming airborne. • Work in areas with adequate ventilation including air filtration. • Wear a respirator or a dust mask • Dispose of all extra dust formed into a closed-off container to prevent it from being airborne	1	1	• Team will create a safety contract agreement. • SOP for fiberglass sanding will be written. • Each build session begins with respirator inspection and filter verification. • Check for the air purifier vent turned on.
	Mixing epoxy using additives	Respiratory complications, silicosis	5	1	• Minimize the possibility of additives becoming airborne by keeping additives confined. • Wear a particulate mask/respirator to prevent inhalation.	3	1	• Team will create a safety contract agreement. • Will create SOP for using epoxy. • Check for an air purifier. • Check respirator filters at the start of all build sessions.

	Sanding body filler, primer, paint, or clear coat layers.	Respiratory irritation and complications.	5	1	• Wet sand when possible to reduce the amount of dust generated and regularly clean the workspace and equipment to prevent the accumulation of hazardous materials • Wear a respirator at all times while working with surface fillers and primers • Work in a well-ventilated area or outside	1	1	• Team will create a safety contract agreement. • Will create SOP for • All machining to be worked in pairs. • Verify first aid kit is present and stocked prior to each build session.
	Applying filler, spray paint, or clearcoat where paint has been been oversprated (particulate)	Eye and respiratory irritation, and long-term detrimental effects to the cardiovascular systems.	5	1	• Minimize overspray and regularly maintain and clean equipment. • Wear a respirator at all times while working with paint and clear coat. • Work in a well-ventilated area or outside	3	1	• Team will create a safety contract agreement. • Will create SoP for using the drill press. • All machining to be worked in pairs. • Verify first aid kit is present and stocked prior to each build session.
Exposure to toxic fumes	Cleaning fiberglass with solvents	Headaches, nausea, unconsciousn ess, skin irritation, permanent eye damage.	5	2	• Work in a well-ventilated area or work outside. • Wear gloves and a respirator at all times while handling solvents	2	1	• Team will create a safety contract agreement. • SOP for fiberglass handling will be written. • Check for the air purifier vent turned on.
	Working with epoxy resins	Respiratory injury, allergic reactions, and possible asphyxiation.	5	2	• Use the least hazardous type of epoxy that performs the desired functions • Minimize quantity of epoxy in use at a given time. • Wear a respirator at all times and work in a well-ventilated area.	3	1	• Team will create a safety contract agreement. • Will create SOP for using epoxy. • Check for the air purifier and fan turned on. • Check respirator filters at the start of all build sessions.
	Using solvent based surface fillers such as Bondo.	Eye and respiratory irritation, detrimental	5	1	• Reduce risk by using an appropriate amount of Bondo and other solvent-dissolved surface fillers • Wear a respirator at all times. • Work in a well-ventilated area.	2	1	• Team will create a safety contract agreement. • Will create SOP for using the drill press. • All machining to be worked in

		effects on the nervous system, and reproductive harm.						pairs. ● Verify first aid kit is present and stocked prior to each build session.
	Applying aerosolized primer, paint, or clearcoat	Eye and respiratory irritation, long-term detrimental effects to the nervous, cardiovascular, and reproductive systems.	5	1	● Prevent exposure by using less toxic, Low Volatile Organic compounds paint and clear coats when possible ● Work in a well-ventilated area or outside ● Wear a respirator at all times while working with paint and clear coat. ● Wear safety glasses.	3	1	● Team will create a safety contract agreement. ● Will create SOP for using clear coat and paint. ● Check for an air purifier. ● Check respirator filters at the start of all build sessions.
	Heating flux (soldering)	Inflammation of the nose, eye, throat, and long-term effects like asthma and dermatitis.	5	1	● Eliminate risk by working in a well-ventilated area or under a fume extraction system to prevent inhalation of fumes. ● Reduce the effects of exposure by avoiding prolonged exposure and using a flux with low volatility or less harmful substances. ● Store solder in a sealed container and away from direct contact to reduce the risk of accidental exposure or spillage	2	1	● Team will create a safety contract agreement. ● Will create SOP for soldering electronic components ● All soldering is done under supervision. ● Verify that proper ventilation is in place. Verify everyone is using proper PPE.
	HF release from mishandling of lithium batteries	Lung damage.	1	4	● Eliminate the risk of exposure to HF gas by handling batteries according to manufacturer instructions and avoid any actions that could lead to leakage or overheating. ● Use proper containment and disposal methods for damaged or defective batteries to prevent the release of hazardous gasses ● Reduce the effects of exposure by working in a well-ventilated area. If the battery leaks or emits gas, evacuate the area immediately and utilize chemical-resistant gloves and goggles at all times	1	1	● Team will create a safety contract agreement. ● Will create SOP for handling of batteries. ● Verify first aid kit is present and stocked prior to each build session.

			5	1	• Regularly inspect the lithium batteries for damage and store them in a cool, dry place away from flammable materials.			
Direct skin contact with toxic chemical	Working with epoxy	Development of irritation and allergic contact dermatitis.	5	1	• Maintain safe working distance when working with epoxies, and use appropriately sized applicators when possible. • Wear nitrile gloves while working with epoxy. • If epoxy gets on the skin, immediately clean the contact area with isopropyl alcohol.	2	1	• Team will create a safety contract agreement. • Will create SOP for using epoxy. • Maintain stock levels of isopropyl alcohol for cleaning epoxy from skin.
	Altering epoxy using additives	Skin irritation	5	1	• Wear protective gloves • Wear protective clothing/apron	2	1	• Team will create a safety contract agreement. • Will create SOP for using epoxy. • Check for an air purifier. • Check respirator filters at the start of all build sessions.
	Using solvent based surface fillers such as Bondo.	Skin and eye irritation,, detrimental effects on the nervous system, and reproductive harm.	5	1	• Reduce risk by using an appropriate amount of Bondo and other solvent-dissolved surface fillers • Wear protective nitrile gloves • Wear protective clothing and eye protection.	2	1	• Team will create a safety contract agreement. • Will create SOP for using the drill press. • All machining to be worked in pairs. • Verify first aid kit is present and stocked prior to each build session.
	Applying spray filler, paint, or clearcoat.	Skin and eye irritation, and long-term detrimental effects to the nervous, cardiovascular, and reproductive systems.	5	1	• Prevent exposure by using less toxic, Low Volatile Organic compounds paint and clear coats when possible • Wear nitrile gloves. • Wear protective clothing and eye protection.	2	1	• Team will create a safety contract agreement. • Will create SOP for using clear coat and paint. • Check for an air purifier. • Check respirator filters at the start of all build sessions.

	Skin contact with solder and flux	Skin rashes and long-term effects like dermatitis.	5	1	• Wear gloves to avoid direct skin contact with flux. • Reduce the effects of exposure by avoiding prolonged exposure and using a flux with low volatility or less harmful substances. • Store solder in a sealed container and away from direct contact to reduce the risk of accidental exposure or spillage	2	1	• Team will create a safety contract agreement. • Will create SOP for soldering electronic components • All soldering is done under supervision. • Verify that proper ventilation is in place. Verify everyone is using proper PPE.
	HF contact from mishandling of lithium batteries	Skin burns, damage to calcified organs.	1	4	• Eliminate the risk of exposure to HF gas by handling batteries according to manufacturer instructions and avoid any actions that could lead to leakage or overheating. • Use proper containment and disposal methods for damaged or defective batteries to prevent the release of hazardous gasses • Reduce the effects of exposure by working in a well-ventilated area. If the battery leaks or emits gas, evacuate the area immediately and utilize chemical-resistant gloves and goggles at all times • Regularly inspect the lithium batteries for damage and store them in a cool, dry place away from flammable materials.	1	1	• Team will create a safety contract agreement. • Will create SOP for handling of batteries. • Verify first aid kit is present and stocked prior to each build session.
Loss of breathable oxygen	Working with epoxy resins	Possible asphyxiation.	1	5	• Use the least hazardous type of epoxy that performs the desired functions • Use only small quantities of resin at a time. • Work in large room or outdoor space.	1	1	• Team will create a safety contract agreement. • Will create SOP for using epoxy. • Check for the air purifier and fan turned on. • Check respirator filters at the start of all build sessions.
Exposure to highly flammable gasses	Use of aerosolized paint and clearcoat	High risk of ignition from a spark or heat source causing first/second/third degree	5	4	• Eliminate risk by avoiding the use of aerosolized paint and clearcoat near open flames, sparks, or any heat sources • Work outside, in a well-ventilated area, or use ventilation systems that safely disperse flammable gasses. • Prevent build-up of flammable gasses by storing aerosolized paint and clearcoat cans in cool, well-ventilated areas and follow all	5	1	• Team will create a safety contract agreement. • Will create SOP for exposure to highly flammable gasses • Verify first aid kit is present and stocked prior to each build session.

		burns and injury			guidelines for handling and disposal			
Exposure to high temperatures	Thermal runaway exothermic reactions from epoxy curing	Burns, the container melting, and possible exposure of skin and/or wounds to hot, uncured epoxy.	3	1	• Mix the appropriate amount of epoxy when in use. • Apply epoxy in thin layers, especially in large cavities, and ensure the working area is well-ventilated • To prevent heat buildup, transfer epoxy from the mixing container to a wide shallow container to increase surface area.	3	1	• Team will create a safety contract agreement. • Will create SOP for using epoxy. • Check for the air purifier and fan turned on. • Check respirator filters at the start of all build sessions.
	Soldering electrical components	First/second/third-degree burns	5	4	• Eliminate risk by using a soldering iron with temperature control and holding the soldering rod by the insulated handle at all times • Work in a well-ventilated area and wear heat-resistant gloves, wear proper PPE at all times • Prevent accidents by keeping the soldering iron in a designated stand and make sure to turn it off and wait for the soldering iron to cool before changing tips.	5	1	• Team will create a safety contract agreement. • Will create SOP for soldering. • Verify first aid kit is present and stocked prior to each build session.
	Handling the hot end of a 3D printer	First/second/third-degree burns	2	2	• Avoid touching the hot end of a 3d printer • Ensure that the 3D printer is turned off and unplugged before approaching and use heat-resistant gloves or wait a sufficient amount of time before lifting hot components	2	1	• Team will create a safety contract agreement. • Will create SOP for using a 3D printer. • Wait five minutes after using before touching hot-end • Verify first aid kit is present and stocked prior to each build session.
	Premature motor ignition	First/second/third-degree burns	1	4	• Motor components are stored unassembled in ESD-safe packaging. • The motor is only assembled immediately before launch. • Ignitor leads are shorted until ready to hook up to ignition leads. • Check all electronic equipment including the	1		

					electronic igniters. ● Verify ignitor leads are un-energized before connecting to the ignitor. ● Standard NAR/Tripoli protocol is to be followed by waiting at least 60 seconds before approaching the launch vehicle. ● In the case of a misfire, wait to approach the rocket for clear range and only under the permission of LCO.			
	Premature black powder ignition	First/second/third-degree burns	1	4	● Only allow authorized personnel to handle any flammable or potentially explosive materials and ensure safety protocols are followed. ● Safe distance of 20 ft while conducting ground tests. ● Wear protective PPE.	1	1	● Team will create a safety contract agreement. ● Will create SOP for premature ignition during ground test
Contact with a sharp, spinning edge	Use of a drill press	Cuts, hair removal, and abrasion, loss of extremities	1	4	● Eliminate risk by securing the workpiece with clamps or a vise before starting the machine, and make sure that the drill bit is functioning as intended. ● Reduce risk by utilizing protective barriers or guards on the drill press, wearing appropriate PPE ● Prevent accidents by keeping hands, loose clothing, and long hair away from drill bits, and turn off the drill press before making any adjustments.	1	1	● Team will create a safety contract agreement. ● Will create SOP for using the drill press. ● All machining to be worked in pairs. ● Verify first aid kit is present and stocked prior to each build session.
	Use of a router table	Cuts and abrasion, loss of extremities	1	5	● Use jigs and push-blocks to feed material with hands away from the cutter. ● Work in pairs with one observer checking for hand positions.	1	1	● Team will create a safety contract agreement. ● SOP for contact with a sharp spinning edge ● Ensure that sharp spinning edge is out of reach for general usage
Exposure to intense sound	Use of a router table	Hearing loss	5	2	● Maintain a safe distance from the machinery when in operation. ● Use sound-dampening materials to reduce sound produced and wear proper hearing protection while operating such machines.	5	1	● Team will create a safety contract agreement. ● SOP for exposure to intense sound ● Ensure each team member has earmuffs and earbuds at launch

	Use of a dual-action polisher	Hearing loss	5	1	• Wear appropriate ear protection while working with a dual-action polisher • Maintain a firm grip on the polisher and use it at the recommended speed settings. • Keep all lose clothing, and hair away from the dual action polisher at all times	5	1	• Team will create a safety contract agreement. • Will create SOP for using the dual-action polisher. • All machining to be worked in pairs. • Verify first aid kit is present and stocked prior to each build session.
	Premature motor ignition	Hearing loss	1	2	• Motor components are stored unassembled in ESD-safe packaging. • The motor is only assembled immediately before launch. • Ignitor leads are shorted until ready to hook up to ignition leads. • Check all electronic equipment including the electronic igniters. • Verify ignitor leads are un-energized before connecting to the ignitor. • Standard NAR/Tripoli protocol is to be followed by waiting at least 60 seconds before approaching the launch vehicle. • In the case of a misfire, wait to approach the rocket for clear range and only under the permission of LCO.	1	1	
	Premature ignition during ground test	Hearing loss	1	4	• Only allow authorized personnel to handle any flammable or potentially explosive materials and ensure safety protocols are followed. • Safe distance of 20 ft while conducting ground tests. • Wear protective PPE.	1	1	• Team will create a safety contract agreement. • Will create SOP for premature ignition during ground test
	Static electricity ignition of black powder	Hearing loss	1	4	• Only allow authorized personnel to handle any flammable or potentially explosive materials and ensure safety protocols are followed. • Use twisted pairs for leads to e-matches to prevent magnetic field coupling from other electronic devices.	1	1	• Team will create a safety contract agreement. • Will create SOP for static electricity ignition • Ensure that we are working in properly grounded environment to ensure static discharge does not happen

Exposure to fast-moving mechanical components	Working with a 3D printer	Impact injury and trauma	1	1	• Ensure that all moving components are properly enclosed or guarded. Avoid reaching in or attempting to adjust the printer when in operation • Maintain a safe distance and ensure that the printer is equipped with emergency stop buttons.	1	1	• Team will create a safety contract agreement. • Will create SOP for using a 3D printer. • Verify first aid kit is present and stocked prior to each build session.
	Use of a vinyl cutter	Physical injury, minor cuts	1	1	• Eliminate risk from sharp moving blades by ensuring that the machine's safety guards are functional and in the proper place. • Maintain a safe working distance while the machine is in operation • Always turn off and unplug the machine when making adjustments or removing vinyl.	1	1	• Team will create a safety contract agreement. • Will create SOP for using the vinyl cutter. • All machining to be worked in pairs. • Verify first aid kit is present and stocked prior to each build session.
Contact with the sharp edge of a blade	Use of hobby knives, utility knives, and scissors	Cuts and infection	5	2	• Eliminate risk by using safety features like retractable blades or blade guards, ensure the tools are in good condition, and avoid using excessive force • Use cutting tools on stable, non-slip surfaces and wear protective gloves designed to resist cuts and avoid distractions. • Store knives and scissors in a safe container and cover the blades when not in use.	2	1	• Team will create a safety contract agreement. • Will create SOP for using knives and scissors. • Verify first aid kit is present and stocked prior to each build session.
Exposure to fast-moving polishing wheel	Use of a dual-action polisher	Clothes and hair being caught and polishing compounds entering the eyes, causing physical injury.	5	1	• Maintain a firm grip on the polisher and use it at the recommended speed settings. • Keep all lose clothing, and hair away from the dual action polisher at all times	3	1	• Team will create a safety contract agreement. • Will create SOP for using the dual-action polisher. • All machining to be worked in pairs. • Verify first aid kit is present and stocked prior to each build session.
Exposure to metal shrapnel	Trimming or cutting electrical components	Eye injury, skin injury	3	1	• Eliminate risk by using the appropriate tools such as precision cutters and wearing protective safety goggles at all times • Perform cutting operations in a controlled environment where debris can be contained	1	1	• Team will create a safety contract agreement. • Will create SOP for handling electronics • All soldering/trimming of metal

			2	5	and cleaned up ● Prevent the generation of metal shrapnel by securing the electrical components before trimming to minimize the risk of accidental debris.			components will be done under supervision ● Verify first aid kit is present and stocked prior to each build session.
Severe Impact from Falling Objects	Parachute deployment failure	Severe impact injury	2	5	● Redundant altimeters and ejection charges ● Ground testing ● Angle launch vehicle away from personnel/spectators. ● Enable failsafe mode on the flight computer to deploy the main if it detects no drogue separation.	1	1	● Team will create a safety contract agreement. ● Will create SOP for launching the rocket. ● Proper checklists will be followed for rocket launch ● Verify first aid kit is present and stocked prior to each launch.
	Parachute tangle of failure to inflate	Severe impact injury	2	4	● Angle launch vehicle away from personnel/spectators. ● Ensure shroud lines are not obstructed. ● Verify that the Nomex material does not interfere with parachute deployment ● Rehearse rocket preparation before conducting a launch and make sure that team members are well-versed in recovery processes.	1	4	
	Failure of rocket components to stay tethered.	Severe impact injury	1	5	● Design for adequate recovery load margin ● Ensure all connection points are secured and functional without damage ● Follow a checklist to minimize mistakes	1	5	
	Trajectory change from excessive weathercockin g or instability	Severe impact injury	1	5	● Design for adequate stability ● Follow NAR safe distance requirements ● Angle launch rods away from spectators.	1	5	
	Fin failure in flight	Severe impact injury	1	3	● Use best practices for assembly (clean epoxy surfaces, adequate filletting, material selection, etc.). ● Design fin structures to push the fin flutter velocity above operating range plus margin. ● Perform margin analysis to avoid fin flutter velocities.	1	3	

7.3 Failure Modes and Analysis

7.3.1 Vehicle Structure FMEA

Table 64 - Table of Vehicle Structure FMEA

Failure Mode	Cause	Effect	Likelihood (before)	Severity (before)	Mitigation	Likelihood (after)	Severity (after)	Verification
Premature motor ignition	Electrostatic discharge	Premature or unprompted launch of rocket, motor ignition before being put in rocket, and/or loss of a potential launch	1	4	• Motor components are stored unassembled in ESD-safe packaging. • The motor is only assembled immediately before launch. • Ignitor leads are shorted until ready to hook up to ignition leads.	1	4	• Proper checklists will be followed for all construction • Wear safety glasses • All launches will be following NAR and local club rules.
	Faulty wiring or connectors				• Follow NAR requirement of arming altimeter with the rocket vertical, prior to insertion of ignitor. • Check all electronic equipment including the electronic igniters. • Verify ignitor leads are un-energized before connecting to the ignitor.	1	1	• Proper checklists will be followed for all construction • Contact the wires and check for sparks
	Delayed ignition after initial ignition attempt.				• Standard NAR/Tripoli protocol is to be followed by waiting at least 60 seconds before approaching the launch vehicle. • Wait to approach the rocket for clear range and only under the permission of LCO.	1	1	• Proper installation of the igniter • Selection of a propellant which is known to ignite easily.
Trajectory	Winds or drift	Impact incident	1	5	• Identify trajectory and stand	1	5	• A ground check checklist will be followed

change	due to early parachute deployment	resulting in severe airframe stress and/or failure			clear of the landing path. ● Use a GPS tracker for recovery ● Follow Standard NAR protocols.			● Ensure mentor and/or appropriately certified personnel is overseeing procedures
Structural failure in air.	Fin failure	Impact incident resulting in severe airframe stress and/or failure	1	5	● Use best practices for assembly (clean epoxy surfaces, adequate filletting, material selection, etc.). ● Perform margin analysis to avoid fin flutter velocities.	1	5	● A ground check checklist will be followed ● Make sure each component is structurally sound during build and conduct random, frequent checks.
Motor failure	Motor overpressurization	Loss of airframe and/or booster assembly through metal shrapnel, rapid unscheduled disassembly of the airframe resulting in airframe loss	1	5	● Make sure that the motor has been assembled according to the manufacturer's descriptions. ● Incorporate pressure relief systems like vent holes to prevent damage to other components	1	5	● A ground check checklist will be followed ● Motors will only be handled by a mentor and a headcount will be conducted before and after the rocket has been loaded onto the pad.
	Motor under pressurization	Inconsistent or failure of flight, resulting in unscheduled airframe stress or failure	1	3	● Select a motor with a history of proven starts ● Select an easily ignitable, low-oxidation propellant ● Check the simulation of motor internal pressures to ensure the motor design is pressurizing adequately. ● Ensure the ignitor and pressurization cap are correctly installed per motor instructions and verify that the ignitor is secured	1	3	● A ground check checklist will be followed ● Motors will only be handled by a mentor and a headcount will be conducted before and after the rocket has been loaded onto the pad.

7.3.2 Recovery FMEA

Table 65 - Table of Vehicle Recovery FMEA

Failure Mode	Cause	Effect	Likelihood (before)	Severity (before)	Mitigation	Likelihood (after)	Severity (after)	Verification
Black powder ignition	Static electricity ignition	Unprompted ejection of a parachute during launch, resulting in failure of recovery equipment	1	5	• Only allow authorized personnel to handle any flammable or potentially explosive materials and ensure safety protocols are followed. • Use twisted pairs for leads to e-matches to prevent magnetic field coupling from other electronic devices.	1	5	• A ground check checklist will be followed • Ensure mentor and/or appropriately certified personnel is overseeing pre-launch procedures
Black powder non-ignition	Failed electronic deployment, miscalculated ejection charges	Main and/or drogue parachute ejection failure	1	5	• Redundant altimeters and ejection charges • Ground testing • Angle launch vehicle away from personnel/spectators. • Enable failsafe mode on the flight computer to deploy the main if it detects no drogue separation.	1	1	• A ground check checklist will be followed • Ensure mentor and/or appropriately certified personnel is overseeing pre-launch procedures
Parachutes do not open after ejection	Improper folding of the parachute, tangled parachute, improper preparation	Main and/or drogue parachute ejection failure	1	3	• Ensure shroud lines are not obstructed. • Verify that the Nomex material does not interfere with parachute deployment • Rehearse rocket preparation before conducting a launch and make sure that team members are well-versed in recovery processes.	1	3	• A ground check checklist will be followed • Ensure mentor and/or appropriately certified personnel is overseeing pre-launch procedures • Double check parachute is properly folded

No separation events after planned ejection altitudes	Electronics turned off/not working, miscalculated ejection charges.	Main and/or drogue parachute ejection failure	1	5	• Ground test and make sure the black powder charges are sufficient enough to separate the rocket. • Verify no binding in the couplers. • Perform e-match conductivity checks and inspect all wiring. • Use a checklist with independent confirmation to ensure the altimeter is armed and all necessary steps are performed.	1	5	• A ground check checklist will be followed • Ensure mentor and/or appropriately certified personnel is overseeing pre-launch procedures
Ripped parachutes due to drag separation	Failure to anticipate aerodynamic forces	High G incident resulting in failure of recovery equipment	1	5	• Shear pin calculations are done correctly • Checklist to prevent forgetting installation of shear pins.	1	5	• A ground check checklist will be followed • Ensure mentor and/or appropriately certified personnel is overseeing pre-launch procedures
Recovery chain is open	Missing quicklinks, loose U-bolts, breakage of recovery chain	Pieces of the rocket falling untethered and possibly ballistic	2	5	• Verify installation of all U-bolts prior to launch. • Inspect harnesses for damage prior to launch • Verify installation of U-bolts. • Perform final check of the entire recovery chain prior to launch installation. • Practice rigging the recovery system.	1	5	

7.3.3 Payload FMEA

Table 66 - Table of Vehicle Payload FMEA

Failure Mode	Cause	Effect	Likelihood (before)	Severity (before)	Mitigation	Likelihood (after)	Severity (after)	Verification
Failure of mechanical components	Improper construction, improper load distribution design	Payload experiment failure	1	4	• Follow best practices for mechanical design • Load testing in CAD, use of oversized load-bearing surfaces and heat-set inserts	1	4	• Ensure a construction and adhesive use SOP is created and followed • Drop tests to ensure payload integrity
Failure/improper operation of electronic components	Improper electronics construction (soldering, circuit design), coding errors	Payload experiment failure	2	4	• Verify electronics operation prior to system and airframe integration	2	4	• Multiple tests before system integration, with only electronics • Multiple tests after system integration prior to airframe integration and payload flight testing • Physical drop tests to ensure electronics can handle ground impact
Airframe integration failure	Improper construction, improper load distribution design	Payload dislodged from nose cone; payload experiment failure	1	3	• Drop tests prior to payload flight testing • Load testing in CAD	1	3	• Ensure a construction and adhesive use SOP is created and followed • Make sure each component and joint is structurally sound during build and conduct random, frequent checks.
Runs out of battery	Lack of testing, uneducated/ unresearched battery selection, charging forgotten before use	Payload experiment failure	2	4	• Ensure proper battery selection in PDR • Calculate estimated battery life in battery selection	2	4	• Ensure a SOP is created for pre-launch payload preparation • Conduct tests to verify battery life
Inaccurate	Coding errors	Payload	2	3	• Multiple verifications of any	2	3	• Refer back to payload electronics flowchart to

clocking/ logging		experiment failure, payload accuracy jeopardized, data analysis requiring significant correction			written code by peers and/or mentor ● Electronics tests prior to system and airframe integration			ensure it is followed, verify prior to critical construction and integration steps

7.4 Environmental Risk Analysis

Table 67 - Table of Environmental Hazards

Hazard	Cause	Effect	Likelihood (before)	Severity (before)	Mitigation	Likelihood (after)	Severity (after)	Verification
Unsecured hazardous chemicals	LiPo battery rupture or explosion.	Harm to wildlife	1	4	● Purchase from a credible source. Test capabilities of the battery in a real life setting.	1	4	● Conduct ground testing to ensure failure during the mission does not happen ●
Waste from rocket build	Microparticles from sanding, materialistic waste	Pollutes environment	5	1	● Wet sand when possible ● Use disposable materials only as necessary or if it is optimal to build efficiency	5	1	● Create a cleaning SOP ● The team will be briefed on proper disposal of hazardous waste from build sessions ● Student team lead and safety officer will ensure team members are behaving responsibly
Expulsion of greenhouse gasses into the atmosphere	Transportation via a combustion engine powered vehicle.	Pollutes environment	5	1	● Optimize transportation by carpooling when realistic	5	1	● Communicate with team about possible transportation methods prior to travel
Launch vehicle	Drift, trajectory	Rocket lands	1	1	● Check weather before launch,	1	1	● The safety officer will consistently monitor

lands outside the designated launch area	change	where wildlife or fauna could be harmed			perform drift calculations, make sure rocket lands in a 2,500 ft radius.			weather prior to launch ● The team will comply with any RSO decisions at the launchsite
Structural failure	Improper construction	Critical structural failure	1	3	● Ensure all components are structurally sound ● Use best practices for assembly (clean epoxy surfaces, adequate filletting, material selection, etc.)	1	3	● The team will create SOP for critical construction steps
	Mid-flight CATO, fin flutter	Rocket debris scattered across the launch site, harming wildlife and contaminating crop soil.	1	3	● Ensure fin flutter does not occur ● Use a motor with proven reliability	1	3	● Perform fin flutter simulations before designing; check for damage before launch ● Our team will purchase a motor with a known, high reliability, from a reliable vendor
General waste	Using a 3D printer	Non-biodegra dable waste contributes to pollution	3	1	● Optimize prints ● Optimize as much as possible in software prior to printing	1	1	● Design better scaffolding. ● Use lower infill. ● Minimize number of reprints. ● Recycle print waste.
	General irresponsibility when managing waste; failure to properly dispose of waste	Unnecessary litter, potential release of hazardous waste into the environment	3	3	● Properly label and dispose of hazardous waste ● Ensure team properly disposes of general waste ● Clean all surfaces, characterize waste.	2	3	● The team will be briefed on proper disposal of hazardous waste from build sessions ● Student team lead and safety officer will ensure team members are behaving responsibly

7.5 Project Risk Analysis

Table 68 - Table of Project Risks

Failure Mode	Cause	Effect	Likelihood (before)	Severity (before)	Mitigation	Likelihood (after)	Severity (after)	Verification
Funds exhausted before project completion	Lack of fundraising, unanticipated costs, poor planning	Funds not available to make required purchases	4	5	• Improve project planning and cost estimation. • Perform additional fundraising activities. • Agree to self-fund unfunded travel costs.	3	1	• Across the project, consistently update and communicate budget across each team section
Deadlines missed	Major NASA milestone report - PDR, CDR, FFR, PLAR	Cannot proceed to next milestone or disqualified	2	5	• Improve project planning and time estimation. • Delegate tasks to spread resources across the project.	1	5	• Consistently update and communicate timing and calendar across each team section. • Have weekly check-ins on project progress.
	Subscale and/or full scale vehicle launch test deadlines missed	Cannot launch the rocket.	1	5	• Plan project with enough time to allow several potential launch dates	1	5	• Consistently update and refer to project plan to ensure all builds are completed on time
	Some members are overcommitted to other activities.	Cannot complete critical project steps	5	3	• Delegate tasks with redundant assignments to spread tasks.	2	2	• Consistently update and refer to project plan GANTT chart and workload distribution/progress spreadsheet • Ensure communication in and across each team section
	Some team members do not complete tasks	Cannot complete critical project steps	5	5	• Delegate tasks with redundant assignments • Provide open access to educator and mentor for additional technical support	5	2	• Ensure communication in and across each team section

	Weather delays launch	Cannot launch rocket	5	5	• Plan multiple potential launch dates	5	2	
Resources not available for build.	Shipments fail to arrive in a timely manner or are damaged.	Cannot complete assembly or launch test flights.	4	5	• Plan acquisition of long lead-time items. • Order components assuming delays when possible. • Pre-order rocket motors.	2	5	• Verify material requirements by checking acquisition plan vs project plan weekly.

8.0 Project Plan

8.1 Testing Plan

To gain confidence that the design, assembly, and final implementation will be sufficient, we determined several tests to be performed to validate components, subsystems, and final assembly. Note that some of these do overlap requirements and are placed here for completeness and to have test identification numbers assigned to them. At the time of PDR, this is a work in progress and it is expected that this list will evolve as we move forward to CDR and FRR. Two of the tests (parachute drag analysis) are currently listed as TBD. More research will be performed prior to CDR to understand the methods we can use to validate the parachute performance criteria.

Table 69 - Abbreviations for Test Number

Airframe			System	
Abbreviation	Meaning		Abbreviation	Meaning
SS	Launch Vehicle		A	Airframe
FS	Recovery		R	Recovery
			P	Payload
			S	Full System

Table 70 - Team Derived Tests

Test	Component	Description
SS-R-1	Altimeter 1	Test subscale altimeter 1 functional in bell jar under controlled conditions
SS-R-2	Altimeter 2	Test subscale altimeter 1 functional in bell jar under controlled conditions
SS-R-3	Altimeter 1 drogue deployment charges	Ground test subscale deployment drogue charge size and altimeter 1
SS-R-4	Altimeter 2 main deployment charges	Ground test subscale deployment main charge size and altimeter 1
SS-R-5	Cd test of subscale drogue parachute	TBD
SS-R-6	Cd test subscale main parachute	TBD
SS-A-1	Launch preparation rehearsal	Practice rigging subscale rocket in preparation for flight.
SS-A-2	Subscale flight test	Validate aerodynamics and stability of design. Verify Cd of airframe. Gain valuable team experience of preparing, launching, and recovering a high power rocket. Required for CDR
FS-R-1	Altimeter 1	Test full-scale altimeter 1 functional in bell jar under controlled conditions

FS-R-2	Altimeter 2	Test full-scale altimeter 1 functional in bell jar under controlled conditions
FS-R-3	Altimeter 1 drogue deployment charges	Ground test full-scale deployment drogue charge size and altimeter 1
FS-R-4	Altimeter 2 main deployment charges	Ground test full-scale deployment main charge size and altimeter 1
FS-R-5	Drag full-scale test drogue parachute	TBD
FS-R-6	Test idle on time of Altimeter 1	Test idle time for altimeter 1 for full charge to 20%.
FS-R-7	Test idle on time of Altimeter 2	Test idle time for altimeter 2 for full charge to 20%.
FS-P-1	Functionality test of payload (pre-integration)	Test functionality of the payload on lab bench
FS-P-2	Range test of payload (pre-integration)	Test the expected ground line-of-sight range of payload radio.
FS-P-3	Payload battery life verification	Test time for payload battery to decrease from full charge to 20%.
FS-P-3	Impact test of mechanical assembly	Drop test from 10 ft for safety margin
FS-P-4	Depressurization test	Put payload assembly inside a bell jar and test it to 24 inches of mercury
FS-A-1	Launch preparation rehearsal	Practice rigging the entire rocket in preparation for full-scale demonstration flight.
FS-A-1	Full-scale vehicle demonstration flight	Validate aerodynamics, stability, and assembly of full scale design. Verify Cd of airframe, altitude, descent velocities, time from apogee to landing, and recovery radius. Gain valuable team experience of preparing, launching, and recovering a high power rocket.
FS-S-1	Launch preparation rehearsal	Practice rigging the entire rocket in preparation for full-scale payload demonstration flight.
FS-S-2	Full-scale payload demonstration flight	Perform additional validation on the airframe plus perform functional test for the payload.

8.2 Derived Requirements

Table 71 - Abbreviations for Derived Requirements

System			Subsystem	
Abbreviation	Meaning		Abbreviation	Meaning
LV	Launch Vehicle		C	Component
R	Recovery		M	Motor
P	Payload		A	Assembly
			T	Test
			F	Flight
			D	Design

Table 72 - NHS Aerospace Launch Vehicle Derived Requirements

Req	Description	Justification
LV-C-1	All launch vehicle airframe components should be designed to withstand multiple flights and rigorous testing	Reusability is key to both the success and budget of the mission. Durability across multiple flights helps validate the design and reduces the need for frequent replacement and repairs
LV-C-2	All airframe components will be water and moisture resistance	Most launch flights have environments which could cause water damage to the launch vehicle and could compromise the structural integrity of the rocket.
LV-C-3	All launch vehicle components shall be designed with a safety factor of more than 15% from the minimum	A 15% safety factor ensures that all components can withstand unforeseen loads or stresses during flight. Improving overall reliability and reducing the risk of failure during the mission
LV-C-4	The launch vehicle design should be able to withstand fin flutter velocities > 1125 ft/s	Ensuring that the vehicles maximum speed does not exceed mach 1 or (1125 ft/s), to comply with both nasa's requirement and preserve the integrity of the rocket.
LV-C-5	All dimensions from the OpenRocket design should be accurately reflected in the ordered components, with a maximum tolerance of ± 0.1 inch.	The dimensions of the rockets are an important component for the accuracy and success of the mission
LV-C-6	All masses from the OpenRocket design should be accurately reflected in the components with a tolerance of 0.1 oz.	Accurate mass distribution is critical for stability and achieving the desired CG.
LV-C-7	Coupler and nose cone will be constructed of materials that do no strongly attenuate RF signals.	Reliable transmissions of RF signals from telemetry, tracking, payload and recovery is critical for mission success.
LV-C-8	Interior body tube diameter greater than 3.8"	Minimum outer diameter of payload is 3.8". This must fit within the airframe inner diameter.

LV-C-9	Aft fin taper >45°	Prevent fin damage for nominal landing (<45 ° booster tilt on landing).
LV-C-10	Coupler length > 2x (body tube dia) + (switch band length)	Ambiguous requirement 2.4.1 and 2.4.2 for coupler that satisfies both. Selecting more stringent of the two plus adding requirement of accommodating switch band.
LV-C-11	Distance from top of booster tube to forward centering ring < 3'	Required access for arms reach to harness leader hardpoint attachment for servicing and inspection.
LV-M-1	Largest motor to be used is in the 54/1706 case	Motor case is borrowed from a mentor. Mentor does not own 54/2560 cases.
LV-A-1	Components in contact with the motor mount require high-temp-epoxy.	Conventional epoxy weakens with temperature. Outside of the motor case can reach 200 C.
LV-D-1	Static Stability < 4.0	Required to meet vertical orientation (LVF-2) in presence of 20 mph crosswind.
LV-D-2	Dry weight (including payload) < 19.8 lbs	Using Aerotech 54/1706 case, largest motor, assume negligible Cd, 19.8 lbs dry weight is the heaviest that can be lifted to 4000 ft.
LV-D-3	Target altitude between 4000 ft and 5000 ft	Target the mid range of requirement 2.1 with enough margin to deal with unexpected design challenges.
LV-D-4	Vertical Flight Orientation > 80° through motor burnout	Have less than 100 ft of altitude variation due to weathercocking
LV-D-5	All parts of the launch vehicles should not exceed the limit of $2500	Reduce waste and make sure that all components bought are used properly. Minimize fund usage.

Table 73 - NHS Aerospace Recovery Derived Requirements

Req	Description	Justification
R-C-1	All simulated recovery components should match physical measurements to within 0.1 oz	Mass is important for KE and force calculations on the recovery systems and will affect the overall flight of the rocket.
R-C-2	Recovery load strength to have a minimum 100:1 safety margin from nominal deployment forces.	Safety margin suggested by mentor.
R-C-3	Non-protected components in the recovery chain will be made of Kevlar or other flame resistant material.	Exposed recovery components such as the recovery harness cannot be adequately protected from black powder ejection charges.
R-D-1	Apogee to landing time <80 seconds	Meet requirement 3.12 plus 10 s margin to account for uncontrollable environmental effects such as thermals and barometric pressure changes.
R-D-2	Main deployment altitude > 600 ft	Meet requirement 3.1.1 plus 100 ft (1-2s) for main to deploy and inflate.
R-D-3	Secondary deployment charge should fire > 550 ft.	Meet requirement 3.1.1 assuming primary charge fails.
R-D-4	Heat sensitive recovery components should have sufficient thermal protection	Requirement 3.1 requires a parachute be used to control descent from 500 ft to ground.

		Parachutes are typically made from nylon, which is heat sensitive and requires thermal protection from deployment charges
R-D-5	Kevlar should have abrasion protection when in contact with fiberglass edges during the recovery stage.	Fiberglass edges are highly abrasive. Safety and re-usability.
R-D-6	Drogue recovery harness should be attached to the booster using a Y-harness.	Add redundancy when feasible in the recovery chain.
R-D-7	The backup ejection charges will be +20% of the primary charges.	If the primary charges fail, an adequate safety margin is required to ensure airframe separation.
R-D-8	Altimeter failsafe mode will be enabled.	Should the drogue primary and back charges fail, we need to ensure that the rocket does not come down ballistic, even if this means violating 3.11 and 3.12.
R-T-1	Altimeters should pass the FS-R-1,2 tests	Require simulated depressurization and pressurization test as well as functionality of the deployment charge switches prior to use.

Table 74 - NHS Aerospace Payload Derived Requirements

Req	Description	Justification
P-D-1	The radio will be able to be turned on and off remotely	Should interference with other systems occur while loaded on the pad or after launch, we need to prevent our system from interfering with other systems.
P-D-2	Maximum transmission range on the ground must be greater than 2500 ft.	Payload transmissions need to be possible to the maximum possible altitude of the flight.
P-D-3	Payload to support pressurization/depressurization from 11 psi to 14 psi	The launch vehicle will go to a maximum of 5500 ft.
P-D-4	A failsafe for failed radio transmission, data logging, shall be added to the payload	If RF transmission fails, it is required to have a log of relevant flight data.
P-D-5	Radio transmission must automatically disable after 5 failed transmission attempts	This would ensure that if the radio signal were lost after launch, the radio signal would not interfere with other rocket transmissions
P-D-6	Structural components will be designed to handle >10x estimated shock loads.	Link to a test. FS-P-3
P-C-1	Free space transmission range must be greater than 5500 ft in altitude	Payload transmissions need to be greater than the maximum landing radius for ground level transmissions.
P-C-2	The battery must last longer than 3 hours when inside the rocket, outside with a temperature range 80F.	Requirement 2.6 states that the rocket must have 3 hours of standby life. This adds clarification to the battery life.
P-T-1	Provide a functional testing plan for all electronic components prior to each launch	Ensures all components work before each launch and are able to transmit accurate data.
P-A-1	All dimensions from the CAD model should	Keeping a tolerance of 0.1 inch will ensure that the payload can

	accurately reflect in iterations with a tolerance of 0.1 inch	fit inside the launch vehicle.
P-A-2	All wires making hard contact require strain relief	Without proper strain relief, wires could break during handling or launch, inhibiting data collection and transmission
P-A-3	STEMnauts shall be securely fastened to the cockpit area and should not shift beyond 0.5 in under nominal deployment loads.	Unrestrained STEMnauts present a hazard to other payload components during flight

8.3 NASA SLI Program Requirements

Table 75 - General Requirements

1.1 Students on the team will do 100% of the project, including design, construction, written reports, presentations, and flight preparation with the exception of assembling the motors and handling black powder or any variant of ejection charges, or preparing and installing electric matches (to be done by the team's mentor). Student team members shall only be a part of one team in any capacity. Teams will submit new work. Excessive use of past work will merit penalties	Students are doing all of the work under the guidance of an adult educator and mentor. No energetics have been used, but will rely on the mentor to perform all of the purchase, storage, and preparation of all energetics.
1.2 The team will provide and maintain a project plan to include, but not limited to the following items: project milestones, budget and community support, checklists, personnel assignments, STEM engagement events, and risks and mitigations	Project plan is created and a working document. Details of the project plan are found in section 8.0 Project Plan. This plan will be continuously updated as the project progresses.
1.3 Team members who will travel to the Huntsville Launch shall have fully completed registration in the NASA Gateway system before the roster deadline. Team members shall include: 1.3.1. Students actively engaged in the project throughout the entire year. 1.3.2. One mentor (see requirement 1.13). 1.3.3. No more than two adult educators	The adult educator has registered the team through the NASA Gateway system. Team roster preparation is in process. Team will have one TRA mentor and one adult educator.
1.4 Teams shall engage a minimum of 250 participants in Educational Direct Engagement STEM activities. These activities can be conducted in-person or virtually. To satisfy this requirement, all events shall occur between project acceptance and the FRR addendum due date. A template of the STEM Engagement Activity Report can be found on pages 86 – 89.	We completed one activity with 4 different classes under the same general course, being Intro to Engineering and Design. Our activity was building straw rockets from the NASA Educator Guide, and in total, we have completed Education Direct Engagement STEM activities with 120 students.
1.5. The team shall establish and maintain a social media presence to inform the public about team activities.	We have created social media platforms as follows Twitter: @NHSAerospace Facebook: @Northville High School Aerospace Club Instagram: @OfficialNHSAeropace Website: https://nhsaerospace.github.io We have been updating the platforms with fun facts about rocketry and regular updates about the team's progress across the project.
1.6. Teams shall email all deliverables to the NASA project management team by the deadline specified in the handbook for each milestone. In the event that a deliverable is too large to attach to an email, inclusion of a link to download the file will be sufficient. Late submissions of PDR, CDR, or FRR milestone documents will be accepted up to 72 hours after the submission deadline. Late	All deliverables have, and will continue to be submitted in a timely manner, meeting or exceeding deadlines.

submissions will incur an overall penalty. No PDR, CDR, or FRR milestone documents will be accepted beyond the 72-hour window. Teams that fail to submit the PDR, CDR, or FRR milestone documents will be eliminated from the project	
1.7. Teams who do not satisfactorily complete each milestone review (PDR, CDR, FRR) shall be provided action items needed to be completed following their review and shall be required to address action items in a delta review session. After the delta session, the NASA management panel shall meet to determine the teams' status in the program and the team shall be notified shortly thereafter	Reviews have not been conducted. However, every effort will be made to adequately respond to all assigned actions promptly as a result of a review.
1.8. All deliverables shall be in PDF format.	All documents, with exception of the team roster, will be submitted as pdf.
1.9. In every report, teams shall provide a table of contents including major sections and their respective subsections	Table of contents will be included on all reports.
1.10. In every report, the team shall include the page number at the bottom of the page.	Page numbers are included on the bottom of pages for all documents.
1.11. The team shall provide any computer equipment necessary to perform a video teleconference with the review panel. This includes, but is not limited to: a computer system, video camera, speaker telephone, and a sufficient Internet connection. Cellular phones should be used for speakerphone capability only as a last resort.	Video conference equipment to be provided by the school district.
1.12. All teams attending Launch Week shall be required to use the launch pads provided by Student Launch's launch services provider. No custom pads shall be permitted at the NASA Launch Complex. At launch, 8-foot 1010 rails and 12-foot 1515 rails will be provided. The launch rails will be canted 5 – 10 degrees away from the crowd on Launch Day. The exact cant will depend on Launch Day wind conditions.	Team will use NAR/NASA supplied launch equipment. As the rocket is greater than 20 lbs, we plan to use a 1515 rail.
1.13. Each team shall identify a "mentor." A mentor is defined as an adult who is included as a team member, who will be supporting the team (or multiple teams) throughout the project year, and may or may not be affiliated with the school, institution, or organization. The team mentor shall not be a student team member The mentor shall maintain a current certification, and be in good standing, through the National Association of Rocketry (NAR) or Tripoli Rocketry for the motor impulse of the launch vehicle and must have flown and successfully recovered (using electronic, staged recovery) a minimum of two flights in this or a higher impulse class, prior to PDR. The mentor is designated as the individual owner of the rocket for liability purposes and must travel with the team to Launch Week. One travel stipend will be provided per mentor regardless of the number of teams he or she supports. The stipend will only be provided if the team passes FRR and the team and mentor attend Launch Week in April	A mentor has been identified and accepted the role. The mentor is TRA L3/NAR L2 and has flown more than the required K and higher impulse flights with electronic recovery. The mentor will attend and assist with ground testing, subscale, vehicle demonstration, payload demonstration, and final flight in Huntsville.
1.14. Teams will track and report the number of hours spent working on each milestone.	The number of hours for each milestone are being tracked. The hours for the PDR are listed in section 1.0 Team Summary Page

Table 76 - Vehicle Requirements

2.1 The vehicle shall deliver the payload to an apogee altitude between 3,500 and 5,500 ft above ground level (AGL). Teams flying below 3,000 ft or above 6,000 ft on their competition launch will not be eligible for the Altitude Award.	The overall design and motor selection targeted approximately 4500 ft as the midpoint of the range (3.2.1 Full-Scale OpenRocket Model and CAD Model) and detailed simulations (6.2.1 Kinematics) show consistent modeling to support this. Actual performance will be demonstrated with the full scale demonstration flights.
2.2 Teams shall declare their target altitude goal at the CDR milestone. The declared target altitude shall be used to determine the team's altitude score.	Altitude will be declared at CDR
2.3 The launch vehicle shall be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.	The material set and overall design of the launch vehicle has been performed with reusability in mind (3.2 Material, Construction and Design Selection).
2.4. The launch vehicle shall have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute. 2.4.1. Coupler/airframe shoulders which are located at in-flight separation points shall be at least two airframe diameters in length. (One body diameter of surface contact with each airframe section.) 2.4.2. Coupler/airframe shoulders which are located at non-in-flight separation points shall be at least 1.5 airframe diameters in length. (0.75 body diameter of surface contact with each airframe section.) 2.4.3. Nosecone shoulders which are located at in-flight separation points shall be at least ½ body diameter in length.	The vehicle has 3 independent sections, all tethered together. The coupler is defined in section 3.2.4 Avionics Coupler. One end of the coupler has an in-flight separation, and one end is a non-in-flight separation point. Both 2.4.1 and 2.4.2 apply. The current coupler exceeds required length for both applicable rules. The nose cone shoulder is defined in section 3.2.5 Nose Cone. The shoulder extends well beyond the required ½ body tube minimum.
2.5 The launch vehicle shall be capable of being prepared for flight at the launch site within 2 hours of the time the Federal Aviation Administration flight waiver opens.	While this cannot be addressed at this time, there are dry-run preparation rehearsals in the project testing plan prior to each launch (8.1 Testing Plan).
2.6 The launch vehicle and payload shall be capable of remaining in launch-ready configuration on the pad for a minimum of 3 hours without losing the functionality of any critical on-board components, although the capability to withstand longer delays is highly encouraged.	Battery sizing has been calculated to provide adequate on time (Avionics - 4.5.3 Battery Selection, Tracker - 4.6 Rocket Tracking and Telemetry, and Payload - 5.2.3 Payload Battery Selection). In addition, tests are defined in the test plan to verify on time before functional test (8.1 Testing Plan).
2.7 The launch vehicle shall be capable of being launched by a standard 12-volt direct current firing system. The firing system will be provided by the NASA-designated launch services provider	All motors selected are TRA certified motors supplied with ignitors that are specified to function with 12 V launch controllers. However, we have no control over how effective the current sourcing capabilities are of the supplied launch controllers. Additional ignitors will be available should a misfire occur.
2.8 The launch vehicle shall require no external circuitry or special ground support equipment to initiate launch (other than what is provided by the launch services provider)	No additional ground support will be required to initiate launch.
2.9 The launch vehicle shall use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).	The motors selected as the primary and alternate for both subscale and full-scale flights are TRA certified, commercially available motors (Full Scale - 3.2.8 Propulsion Design, Subscale - 3.7.5 Propulsion Design).

2.9.1. Final motor choice shall be declared by the Preliminary Design Review (PDR) milestone. 2.9.2. Any motor change after PDR shall be approved by the NASA management team or NASA Range Safety Officer (RSO). Changes for the sole purpose of altitude adjustment shall not be approved. The only exception is teams switching to their secondary motor choice, provided the primary motor choice is unavailable due to a motor shortage	The subscale motors are in possession of the mentor. The primary full-scale motors have been on order for 10 weeks. We anticipate delivery in the next 4-6 weeks with plenty of time prior to the required time for the full-scale launch.
2.10 The launch vehicle shall be limited to a single motor propulsion system.	Both subscale and full-scale use single motor (no clusters or staging).
2.11 The total impulse provided by a High School or Middle School launch vehicle shall not exceed 2,560 Newton-seconds (K-class).	The total impulse of the full scale selected motors is less than 2560 N-s (3.2.8 Propulsion Design).
2.12 Pressure vessels on the vehicle must be approved by the RSO and shall meet the following criteria: 2.12.1. The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) will be 4:1 with supporting design documentation included in all milestone reviews. 2.12.2. Each pressure vessel shall include a pressure relief valve that sees the full pressure of the tank and is capable of withstanding the maximum pressure and flow rate of the tank. 2.12.3. The full pedigree of the tank shall be described, including the application for which the tank was designed and the history of the tank. This will include the number of pressure cycles put on the tank, the dates of pressurization/depressurization, and the name of the person or entity administering each pressure event	Not applicable. There are no intentional pressure vessels used.
2.13 The launch vehicle shall have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.	The current design has a static stability of approximately 3 at rail exit, exceeding the required value of 2.0 (6.2.2 Full-Scale Stability, 6.3.2 Subscale Stability)
2.14 The launch vehicle shall have a minimum thrust to weight ratio of 5.0 : 1.0.	The motors selected easily exceed the minimum thrust-to-weight ratio of 5:1 (Full Scale - 3.2.8 Propulsion Design, Subscale - 3.3.5 Propulsion Design). Full scale values are 12:1 and 9:1 for the primary and secondary motor selections.
2.15 Any structural protuberance on the rocket shall be located aft of the burnout center of gravity. Camera housings will be exempted, provided the team can show that the housing(s) causes minimal aerodynamic effect on the rocket's stability	There are no structural protuberances currently. May add a commercially available rocket camera shroud in the future. That will be made clear at CDR.
2.16 The launch vehicle shall accelerate to a minimum velocity of 52 fps at rail exit.	The design of the full-scale and subscale exceed 52 ft/s at rail exit. (Full-Scale - 6.2.1 Kinematics, Subscale - 6.3.1 Subscale Kinematics). The modeled exit velocity for the full-scale is 99.8 ft/s and the subscale is 80.2 ft/s. These numbers will be verified with altimeter data from launches.
2.17 All teams shall successfully launch and recover a subscale model of their rocket. Success of the subscale is at the sole discretion of the NASA review panel. The subscale flight may be conducted at any time between proposal award and the CDR submission deadline. Subscale flight data shall be reported in the CDR report and presentation at the CDR milestone. Subscales are required to use a minimum motor impulse class of E (Mid Power motor).	A 50% subscale has been designed and modeled. The aerodynamics and center of mass are as close to a 50% scaling as the full-scale as possible within the constraints that were available. Section 3.3 Subscale. The stability was designed to be as close as reasonably possible between the full-scale and the

2.17.1. The subscale model should resemble and perform as similarly as possible to the full-scale model; however, the full-scale will not be used as the subscale model. 2.17.2. The subscale model shall carry an altimeter capable of recording the model's apogee altitude. 2.17.3. The subscale rocket shall be a newly constructed rocket, designed and built specifically for this year's project. 2.17.4. Proof of a successful flight shall be supplied in the CDR report. 2.17.4.1. Altimeter flight profile graph(s) OR a quality video showing successful launch and recovery events as deemed by the NASA management panel are acceptable methods of proof. Altimeter flight profile graph(s) that are not complete (liftoff through landing) will not be accepted. 2.17.4.2. Quality pictures of the as landed configuration of all sections of the launch vehicle shall be included in the CDR report. This includes, but is not limited to: nosecone, recovery system, airframe, and booster. 2.17.5. The subscale rocket shall not exceed 75% of the dimensions (length and diameter) of your designed full-scale rocket. For example, if your full-scale rocket is a 4" diameter 100" length rocket, your subscale shall not exceed 3" diameter and 75" in length	subscale (6.3.2 Subscale Stability). The propulsion has been selected to roughly replicate the acceleration and rail velocity that the full-scale will experience (6.3.1 Subscale Kinematics) Components for the subscale have been ordered and a launch is planned in early December. Further requirements in this section will be reported after the launch at CDR.
2.18.1. Vehicle Demonstration Flight—All teams shall successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration. The rocket flown shall be the same rocket to be flown as their competition launch. The purpose of the Vehicle Demonstration Flight is to validate the launch vehicle's stability, structural integrity, recovery systems, and the team's ability to prepare the launch vehicle for flight. A successful flight is defined as a launch in which all hardware is functioning properly (drogue chute at apogee, main chute at the intended lower altitude, functioning tracking devices, etc.) The following criteria shall be met during the full-scale demonstration flight: 2.18.1.1. The vehicle and recovery system shall have functioned as designed. 2.18.1.2. The full-scale rocket shall be a newly constructed rocket, designed and built specifically for this year's project. 2.18.1.3. The payload does not have to be flown during the full-scale Vehicle Demonstration Flight. The following requirements still apply: 2.18.1.3.1. If the payload is not flown, mass simulators shall be used to simulate the payload mass. 2.18.1.3.2. The mass simulators shall be located in the same approximate location on the rocket as the missing payload mass. 2.18.1.4. If the payload changes the external surfaces of the rocket (such as camera housings or external probes) or manages the total energy of the vehicle, those systems will be active during the full-scale Vehicle Demonstration Flight. 2.18.1.5. Teams shall fly the competition launch motor for the Vehicle Demonstration Flight. The team may request a waiver for the use of an alternative motor in advance if the home launch field cannot support the full impulse of the competition launch motor or in other extenuating circumstances. 2.18.1.6. The vehicle will be flown in its fully ballasted configuration during the full-scale test flight. Fully ballasted refers to the maximum amount of ballast that will be flown during the competition launch flight. Additional ballast shall not be added without a re-flight of the full-scale launch vehicle. 2.18.1.7. After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components shall not be modified without the concurrence of the NASA management team or Range Safety Officer (RSO). 2.18.1.8. Proof of a successful flight shall be supplied in the FRR report.	Vehicle Demonstration Flight will be scheduled for Jan-Feb time frame. Motors are currently on order. Airframe components are waiting for results of subscale and feedback from PDR/CDR.

2.18.1.8.1. Altimeter flight profile data output with accompanying altitude and velocity versus time plots is required to meet this requirement. Altimeter flight profile graph(s) that are not complete (liftoff through landing) shall not be accepted. 2.18.1.8.2. Quality pictures of the as landed configuration of all sections of the launch vehicle shall be included in the FRR report. This includes, but is not limited to: nosecone, recovery system, airframe, and booster. 2.18.1.8.3. Raw altimeter data in.csv or.xlsx format. 2.18.1.9. Vehicle Demonstration flights shall be completed by the FRR submission deadline. No exceptions will be made. If the Student Launch office determines that a Vehicle Demonstration Re-flight is necessary, then an extension may be granted. THIS EXTENSION IS ONLY VALID FOR RE-FLIGHTS, NOT FIRST TIME FLIGHTS. Teams completing a required re-flight shall submit an FRR Addendum by the FRR Addendum deadline	
2.18.2 Payload Demonstration Flight—All teams shall successfully launch and recover their full-scale rocket containing the completed payload prior to the Payload Demonstration Flight deadline. The rocket flown shall be the same rocket to be flown as their competition launch. The purpose of the Payload Demonstration Flight is to prove the launch vehicle's ability to safely retain the constructed payload during flight and to show that all aspects of the payload perform as designed. A successful flight is defined as a launch in which the rocket experiences stable ascent and the payload is fully retained until it is deployed (if applicable) as designed. The following criteria shall be met during the Payload Demonstration Flight: 2.18.2.1. The payload shall be fully retained until the intended point of deployment (if applicable), all retention mechanisms shall function as designed, and the retention mechanism shall not sustain damage requiring repair. 2.18.2.2. The payload flown shall be the final, active version. 2.18.2.3. If the above criteria are met during the original Vehicle Demonstration Flight, occurring prior to the FRR deadline and the information is included in the FRR package, the additional flight and FRR Addendum are not required. 2.18.2.4. Payload Demonstration Flights shall be completed by the FRR Addendum deadline. NO EXTENSIONS WILL BE GRANTED	Payload Demonstration Flight has not occurred.
2.19 An FRR Addendum shall be required for any team completing a Payload Demonstration Flight or NASArequired Vehicle Demonstration Re-flight after the submission of the FRR Report. 2.19.1. Teams required to complete a Vehicle Demonstration Re-Flight and failing to submit the FRR Addendum by the deadline shall not be permitted to fly a final competition launch. 2.19.2. Teams who complete a Payload Demonstration Flight which is not fully successful may petition the NASA RSO for permission to fly the payload during launch week. Permission shall not be granted if the RSO or the Review Panel have any safety concerns	FRR has not occurred.
2.20 The team's name and Launch Day contact information shall be in or on the rocket airframe, as well as in or on any section of the vehicle that separates during flight and is not tethered to the main airframe. This information shall be included in a manner that allows the information to be retrieved without the need to open or separate the vehicle	Team contact information will be added to the airframe after paint. Information will be added with permanent adhesive vinyl.
2.21 All Lithium Polymer batteries shall be sufficiently protected from impact with the ground and will be brightly colored, clearly marked as a fire hazard, and easily distinguishable from other payload hardware.	LiPo batteries will comply with regulation. 3D printed housings will secure batteries and leave ample room for marking.

2.22.1. The launch vehicle shall not utilize forward firing motors. 2.22.2. The launch vehicle shall not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.) 2.22.3. The launch vehicle shall not utilize hybrid motors. 2.22.4. The launch vehicle shall not utilize a cluster of motors. 2.22.5. The launch vehicle shall not utilize friction fitting for motors. 2.22.6. The launch vehicle shall not exceed Mach 1 at any point during flight. 2.22.7. Vehicle ballast shall not exceed 10% of the total unballasted weight of the rocket, as it would sit on the pad (i.e., a rocket with an unballasted weight of 40 lbs. on the pad may contain a maximum of 4 lbs. of ballast). 2.22.8. Transmissions from on-board transmitters, which are active at any point prior to landing, shall not exceed 250 mW of power (per transmitter.) 2.22.9. Transmitters shall not create excessive interference. Teams shall utilize unique frequencies, handshake/passcode systems, or other means to mitigate interference caused to or received from other teams 2.22.10. Excessive and/or dense metal shall not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses	We are not planning on using any forward firing motors, motors with titanium sponge based propellant, hybrid motors, or clusters. Motor will be retained with an aluminum screw cap retainer (see section 3.2.3 Motor Mount, Centering Ring, and Motor Retention). The launch vehicle will stay below Mach 1 (current simulations are at Mach 0.54, see section 6.2.1 Kinematics). The current plans for ballast weight will be below 10% of vehicle mass. All transmitters are well under 250 mW (see sections 4.5.1 Altimeter Selection, 4.6 Rocket Tracking and Telemetry, and 5.2.1 Control Module) and comply with FCC part 15. Transmitters will abide by frequency allocation. In addition, we plan to use LoRaWAN network with unique addressing. The payload transmitter uses unique addressing, acknowledgements, and reliable handshake protocols. The launch vehicle does not contain excess metal other than hardware in the recovery chain and minor nuts/bolts.

Table 77 - Recovery System Requirements

3.1 The full-scale launch vehicle shall stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee, and a main parachute is deployed at a lower altitude. Tumble or streamer recovery from apogee to main parachute deployment is also permissible, provided that kinetic energy during drogue stage descent is reasonable, as deemed by the RSO. 3.1.1. The main parachute shall be deployed no lower than 500 ft. 3.1.2. The apogee event shall contain a delay of no more than 2 seconds. 3.1.3. Motor ejection is not a permissible form of primary or secondary deployment.	4.1 High Level Descent Requirements describes the main recovery plan. Drogue Primary = Apogee Drogue Backup = Apogee + 2 s Main Primary = 600 ft Main Backup = 500 ft
3.2 Each team shall perform a successful ground ejection test for all electronically initiated recovery events prior to the initial flights of the subscale and full-scale vehicles.	Ground testing will be performed prior to launch for both subscale and full-scale (Section 8.1 Testing Plan)
3.3 Each independent section of the launch vehicle shall have a maximum kinetic energy of 75 ft-lbf at landing.	The kinetic energy is simulated to be much less than 75 ft-lbf at landing (Section 6.2.4 Full-Scale Descent Characteristics)
3.4 The recovery system shall contain redundant, commercially available barometric altimeters that are specifically designed for initiation of rocketry recovery events. The term “altimeters” includes both simple altimeters and more sophisticated flight computers.	The recovery system design has full parallel, redundant systems of commercially available flight computers (Section 4.5.1 Altimeter Selection, 4.5.4 Recovery Schematics)
3.5 Each altimeter shall have a dedicated power supply, and all recovery electronics shall be powered by commercially available batteries.	Each altimeter has its own power switch and commercially available battery (Section 4.5.3 Battery

	Selection)
3.6 Each altimeter shall be armed by a dedicated mechanical arming switch that is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad	The current design plans to use two screw switches, accessible from the exterior of the airframe with a screwdriver (Section 4.5.2 Power Switch Selection)
3.7 Each arming switch shall be capable of being locked in the ON position for launch (i.e., cannot be disarmed due to flight forces).	The screw switch is locked in an on position by torquing the screw (Section 4.5.2 Power Switch Selection).
3.8 The recovery system, GPS and altimeters, and electrical circuits shall be completely independent of any payload electrical circuits.	Recovery, GPS, and payload are each on their own independent power supply.
3.9 Removable shear pins shall be used for both the main parachute compartment and the drogue parachute compartment	3x 2-56 and 3x 4-40 nylon shear pins will be used for the booster-to-coupler and payload tube to nose cone, respectively. Details are in Section 4.7 Shear Pins.
3.10 Bent eye bolts shall not be permitted in the recovery subsystem.	All recovery harness hard point attachments use ¼-20 U-bolts. No bent eyebolts are used in the entire recovery chain (Section 4.2.3 Recovery Hardware Selection)
3.11 The recovery area shall be limited to a 2,500 ft. radius from the launch pads.	The current recovery radius is less than 2500 ft at 20 MPH wind speed, calculated two different methods (Section 6.2.4 Full-Scale Descent Characteristics)
3.12 Descent time of the launch vehicle shall be limited to 90 seconds (apogee to touch down).	The descent time from apogee to touchdown is currently modeled at 80 s (Section 6.2.4 Full-Scale Descent Characteristics)
3.13 An electronic tracking device shall be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent section to a ground receiver. 3.13.1. Any rocket section or payload component, which lands untethered to the launch vehicle, shall contain an active electronic tracking device. 3.13.2. The electronic tracking device(s) shall be fully functional during the official competition launch.	All parts of the launch vehicle will be tethered. There will be a single GPS tracker and telemetry unit in the nose cone. The selected tracker device is a Featherweight GPS tracker (Section 4.6 Rocket Tracking and Telemetry)
3.14 The recovery system electronics shall not be adversely affected by any other on-board electronic devices during flight (from launch until landing). 3.14.1. The recovery system altimeters shall be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device. 3.14.2. The recovery system electronics shall be shielded from all on-board transmitting devices to avoid inadvertent excitation of the recovery system electronics. 3.14.3. The recovery system electronics shall be shielded from all on-board devices which may generate magnetic waves (such as generators, solenoid valves, and Tesla coils) to avoid inadvertent excitation of the recovery system. 3.14.4. The recovery system electronics shall be shielded from any other on-board devices which may adversely affect the proper operation of the recovery system electronics	The recovery system is housed in a separate avionics bay (the main coupler) and is isolated from the payload and tracking system (nose cone). While the altimeters are WiFi based, they have been thoroughly tested with 802.11 with unique ID's and arming codes. All leads to e-matches are tightly twisted reducing any possible flux coupling. The payload and tracking unit radios are low power and in an isolated chamber. There are no large magnetic field generators such as solenoids, generators, or Tesla coils present on the rocket.

Table 78 - Payload Experiment Requirements

4.1 High School/Middle School Division— Teams may design their own science or engineering experiment or may choose to complete the College/University Division mission stated below. Data from the science or engineering experiment will be collected, analyzed, and reported by the team following the scientific method.	Details of our High School payload can be found in Section 5.0 Technical Design: Payload Criteria. Data will be datalogged as well as sent via LoRa radio to a base station.
4.2 ULSI - Not applicable	N/A
4.3 ULSI - Not applicable	N/A
4.4 General Payload Requirements: 4.4.1. Black powder and/or similar energetics are only permitted for deployment of in-flight recovery systems. Energetics will not be permitted for any surface operations. 4.4.2. Teams shall abide by all FAA and NAR rules and regulations. 4.4.3. Any payload experiment element that is jettisoned during the recovery phase shall receive real time RSO permission prior to initiating the jettison event, unless exempted from the requirement by the RSO or NASA. 4.4.4. Unmanned aircraft system (UAS) payloads, if designed to be deployed during descent, shall be tethered to the vehicle with a remotely controlled release mechanism until the RSO has given permission to release the UAS. 4.4.5. Teams flying UASs shall abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft (Public Law 112-95 Section 336; see https://www.faa.gov/uas/faqs). 4.4.6. Any UAS weighing more than. 55 lbs. shall be registered with the FAA and the registration number marked on the vehicle	Black powder will only be used for deployment charges (handled by the mentor). The team will follow all applicable rules and regulations including, but not limited to BATF, FAA, NFPA, FCC, and local ordinances. In addition, the team will follow the NAR safety code as well as the Tripoli Unified Safety Code for all launches and preparation for launches. No experiments will be jettisoned from our airframe, and no UAV/UAS devices will be used.

Table 79 - Safety Requirements

5.1 Each team shall use a launch and safety checklist. The final checklists shall be included in the FRR report and used during the Launch Readiness Review (LRR) and any Launch Day operations.	The team will begin writing a launch and safety checklist. The completion of the list will gate the subscale demonstration launch and show continuous improvement through every launch up until LRR.
5.2 Each team shall identify a student safety officer who will be responsible for all items in Section 5.3	Naoki Matsumoto has been identified as our team's student safety officer.
5.3 The role and responsibilities of the safety officer shall include, but are not limited to: 5.3.1. Monitor team activities with an emphasis on safety during: 5.3.1.1. Design of vehicle and payload 5.3.1.2. Construction of vehicle and payload components 5.3.1.3. Assembly of vehicle and payload 5.3.1.4. Ground testing of vehicle and payload 5.3.1.5. Subscale launch test(s) 5.3.1.6. Full-scale launch test(s) 5.3.1.7. Competition Launch 5.3.1.8. Recovery activities 5.3.1.9. STEM Engagement Activities 5.3.2. Implement procedures developed by the team for construction, assembly, launch, and recovery activities. 5.3.3. Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and SDS/chemical inventory data. 5.3.4. Assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures	The role of the safety officer was defined in the proposal and copied into the PDR as Appendix C - Role of Student Team Safety Officer. The role includes all points under requirement 5.3.

5.4 During test flights, teams shall abide by the rules and guidance of the local rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch does not give explicit or implicit authority for teams to fly those vehicle configurations and/or payloads at other club launches. Teams shall communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.	At all launches, the team will follow the rules and guidance of the club and RSO. The RSO's decision on all matters is final and absolute.
5.5 Teams shall abide by all rules set forth by the FAA.	All flights will be conducted at NAR/TRA club fields with established FAA waivers. The waiver will be verified by the student team safety officer.

Table 80 - Final Flight Requirements

6.1 NASA Launch Complex 6.1.1. Teams are not permitted to show up at the NASA Launch Complex outside of launch day without permission from the NASA management team. 6.1.2. Teams shall complete and pass the Launch Readiness Review conducted during Launch Week. 6.1.3. The team mentor shall be present and oversee rocket preparation and launch activities. 6.1.4. The scoring altimeter shall be presented to the NASA scoring official upon recovery. The scoring altimeter shall be one of the altimeters used for recovery events. 6.1.5. Teams may launch only once. Any launch attempt resulting in the rocket exiting the launch pad, regardless of the success of the flight, will be considered a launch. Additional flights beyond the initial launch, will not be scored and will not be considered for awards	The team understands and will abide by the requirements for the NASA Launch Complex. The team mentor may have a commitment on the last day of the event. An alternative mentor, Richard Sharp, has been selected and agreed to serve as team mentor for this day. The team is familiar with this mentor and have flown with him before. This has been approved by John Eckhart.
6.2 Commercial Spaceport Launch Site - Not Applicable	N/A

8.4 Budget

The budget provided covers all aspects necessary to complete the project successfully, including income, Bill of Materials (BOM) for both full-scale and subscale, STEM engagement costs. We have also accounted for a set subsidy to provide to all team members attending Launch Week. The budget is categorized into several sections, including full-scale, subscale, consumables, PPE, STEM engagement, and travel. Each budget includes the individual item, quantity demanded, unit price, shipping, final cost, and total gross expenditures. We have received a Michigan Tax Exemption as a Non-Profit School, and as such, many items within the budget do not account for any taxes required. Some items, however, such as travel, are not applicable toward the tax exemption. A summarized table of total expenditures is in Appendix E.

8.4.1 Bill of Materials (BOM)

The BOM is categorized into full-scale and subscale line item budgets including individual components, quantity of units, and material vendors. Each BOM also includes the preliminary gross cost for each rocket. For many of the common, reusable items, they will be loaned by the NAR/TRA mentor to the team to reduce our first-year team cost. These include items like Kevlar recovery harnesses, parachutes, and expensive tracker modules that can be moved from airframe-to-airframe. Other items, such as screws, which are most often purchased in quantities far larger than needed for this project, have been donated by the team mentor. Compared to our proposal, our overall budget has increased by a slight margin due to updated prices of incoming orders and unprecedented shipping expenses, and will continue to be updated as the project continues. A detailed breakdown of the BOM is located in Appendix E.

8.4.2 STEM Engagement

The team's STEM Engagement activities' materials are subsidized by the school district and donated by the teacher educator. No current expenses are required, though we have included the gross expense for valuing purposes. A breakdown of expenses is located in Appendix E.

8.5 Funding

8.5.1 Funding Pathways

During the project timeline, the team will strive towards several approaches to generate funding for the necessary expenditures.

Team Fund: The team currently has approximately a total of $3,400 allocated for buying rocket components and funding the club's sustainability plans for future members. This fund includes funding from sponsorships, membership fees, and the team savings from previous years.

Fundraising Events: Organize bake sales and coordinate with local businesses (ie. Chipotle or Panera) to raise money for the build.

School Funding: Our team has submitted a proposal to the Northville Educational Foundation that supports materials for larger school district projects and requested a grant for stipends to cover travel expenses for the launch week in Alabama. The district often gives out grants to help supply projects otherwise difficult to produce in a school setting. The application process is newly open to student proposals this year.

Sponsorships: Approach local businesses or branches and request grants to fund the project. In return, we offer to promote the companies on our website, social media, team events, and on the rockets themselves. To date, we have received a sponsorship from Microchip Technology and several individual sponsorships.

8.5.2 Allocation of Funds

Project Materials: Materials and components needed to successfully build the two rockets and the payload, including all component materials, consumables, tools, PPE, motors, and electronics. Currently, most of our funding is allocated towards project materials.

Travel Expenses: The budget currently accounts for our educator's travel expenses, as well as a set stipend for team members, to participate in the Launch Week. We intend to fund a portion of the travel costs to ensure greater participation in Huntsville, AL.

Promotional Materials: Any funds necessary to showcase the project and the team, including banners, brochures, and presentation materials.

Contingency Fund: Continue to build a contingency fund to cover unexpected incidentals that may arise during the competition.

8.6 Timeline

In order to break down the project and have deadlines for important milestones, the team created a GANTT chart to ensure all work that needs to be completed is getting completed. The GANTT chart includes all important NASA deliverables and team deadlines. This will be used in conjunction with a work assignment spreadsheet to delegate appropriate tasks to appropriate people.

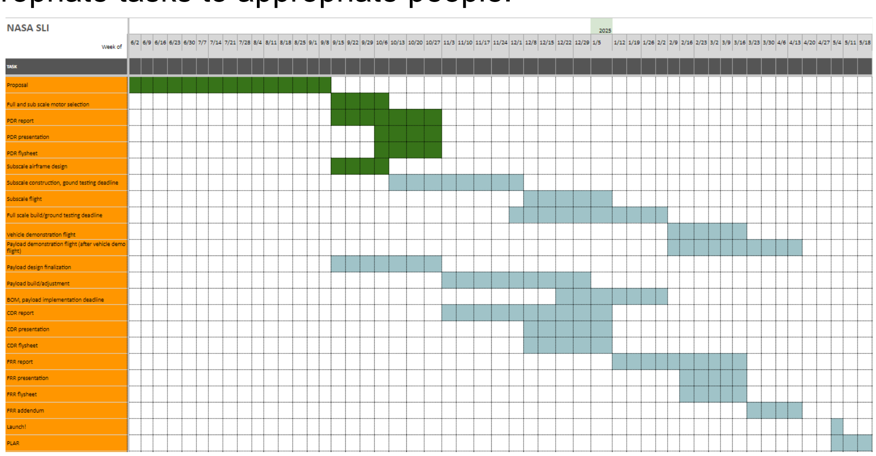


Fig. 71 - Gantt chart - timeline

Appendix A - Spreadsheet Deployment Charge Calculations

Table 81 - Full Scale Main Parachute Black Powder Calculations

Black powder: Drogue		
Rocket	SLI full-scale	
Body tube diameter	4	in
Body tube length	39	in
Ground level altitude	250	ft
Max altitude	4500	ft
Force to overcome friction	3	lbs
Screw size	4-40	
Number of screws	3	
Black powder weight	3.30	g
Calculated values		
Ground level pressure	14.56	psi
Max altitude pressure	12.46	psi
Ejection charge pressure	13.03	psi

Table 82 - Full-Scale Drogue Parachute Black Powder Calculations

Black powder: Main		
Rocket	SLI full-scale	
Body tube diameter	4	in
Body tube length	39	in
Ground level altitude	250	ft
Max altitude	4500	ft
Force to overcome friction	3	lbs
Screw size	2-56	
Number of screws	3	
Black powder weight	2.05	g
Calculated values		
Ground level pressure	14.56	psi
Max altitude pressure	12.46	psi
Ejection charge pressure	8.10	psi
Force on nose cone at max altitude	26.46	lbs
Min shear strength of screws	92.94	lbs
Max shear strength of screws	104.65	lbs
Ejection charge force at ground level	104.82	lbs
Ejection charge net force at max altitude	131.28	lbs
Good combination?	TRUE	

Table 83 - Sub-Scale Main Parachute Black Powder Calculations

Black powder: Drogue		
Rocket	SLI subscale	
Body tube diameter	2	in
Body tube length	19	in
Ground level altitude	250	ft
Max altitude	2550	ft
Force to overcome friction	3	lbs
Screw size	2-56	
Number of screws	3	
Black powder weight	1	g
Calculated values		
Ground level pressure	14.56	psi
Max altitude pressure	13.39	psi
Ejection charge pressure	32.45	psi
Force on nose cone at max altitude	3.69	lbs
Min shear strength of screws	92.94	lbs
Max shear strength of screws	104.65	lbs
Ejection charge force at ground level	104.95	lbs
Ejection charge net force at max altitude	108.63	lbs
Good combination?	TRUE	

Table 84 - Sub-Scale Drogue Parachute Black Powder Calculations

Black powder: Main		
Rocket	SLI Subscale	
Body tube diameter	2	in
Body tube length	19	in
Ground level altitude	250	ft
Max altitude	2550	ft
Force to overcome friction	3	lbs
Screw size	2-56	
Number of screws	1	
Black powder weight	0.35	g
Calculated values		
Ground level pressure	46.56	psi
Max altitude pressure	13.39	psi
Ejection charge pressure	11.36	psi
Force on nose cone at max altitude	3.68	lbs
Min shear strength of screws	30.98	lbs
Max shear strength of screws	36.88	lbs
Ejection charge force at ground level	38.68	lbs
Ejection charge net force at max altitude	42.37	lbs
Good combination?	TRUE	

Appendix B - Subscale Deployment Charge Hand Calculations

Shear Pins: Nose cone, three 2-56s; booster, one 2-56

Nose (drogue):

Body tube size: 13.5*pi
101.64 lbs
121.968 (20% margin)
Pressure: p=f/a 121.968/pi = 38.82 psi=2.64 atm
pv=nrt
2.64(0.69)=n(0.08206)(1523.15)
n= 0.015 mol blk powder/6*5 *45 g = 0.55 g

Booster (main):

Body tube size: 14*pi = 0.72L
33.88 lbs
40.656 (20% margin)
Pressure: f=pa 40.656/pi = 12.94 psi = 0.88 atm
pv=nrt
0.88(0.72)=n(0.08206)(1523.15)
n= 0.0051 mol blk powder/6*5*45 g = 0.19 g

Appendix C - Subscale CAD and Component Specification

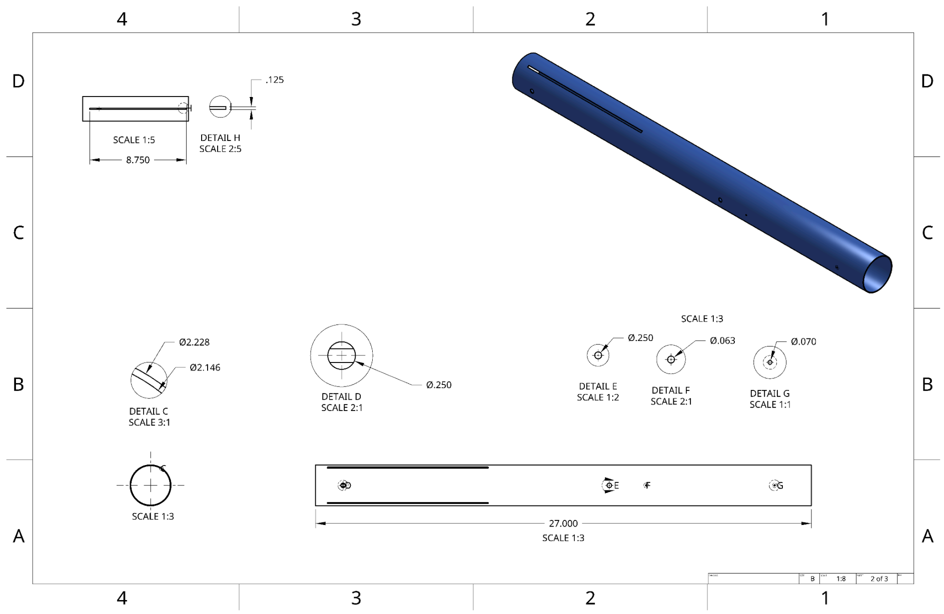


Fig. 72 - Subscale booster tube drawing

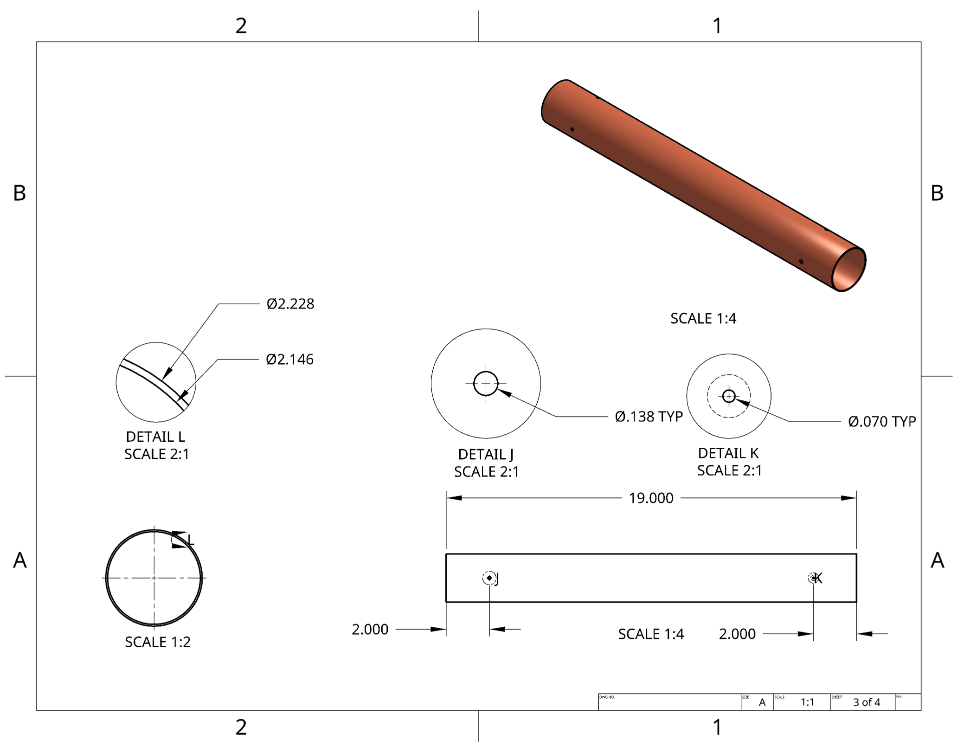


Fig. 73 - Subscale payload tube drawing

Table 85 - Body Tube Parameters

Booster tube			Payload tube	
Parameter	**Value**		**Parameter**	**Value**
Material	FW fiberglass		Material	FW fiberglass
Length	27 in		Length	19 in
Outer diameter	2.228 in		Outer diameter	2.228 in
Inner diameter	2.146 in		Inner diameter	2.146 in
Number of slots	3			
Fin slot length	8.85 in			
Fin slot width	0.125 in			

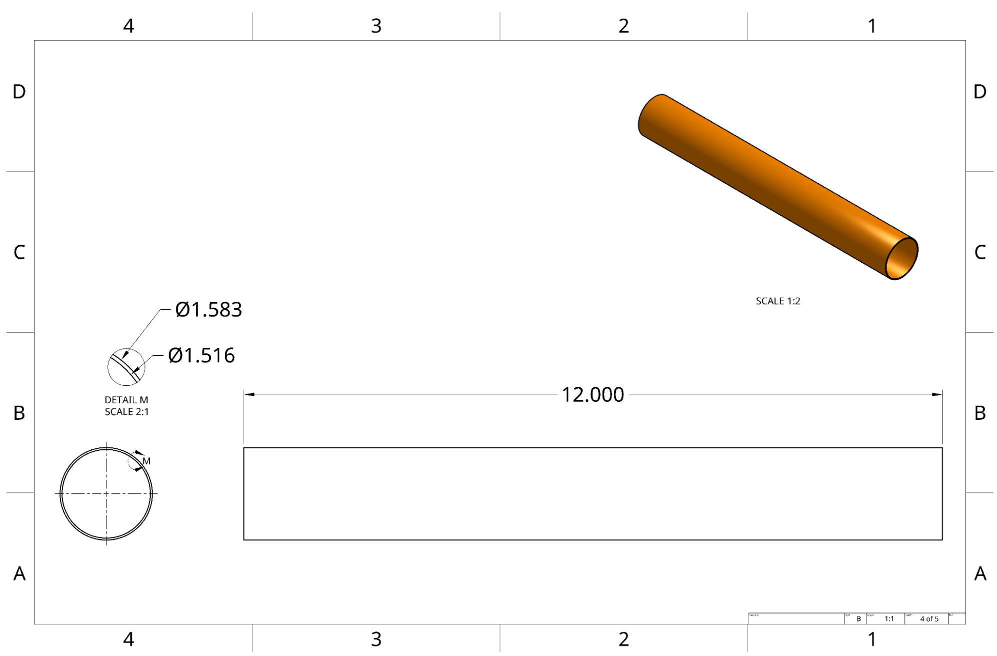


Fig. 74 - Motor mount tube

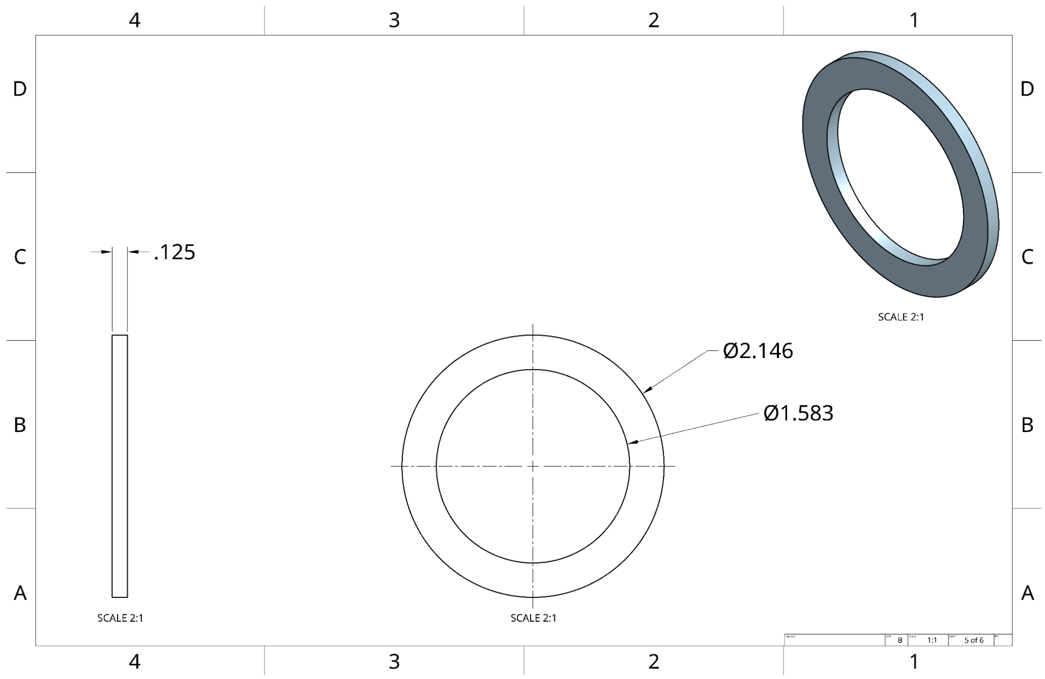


Fig. 75 - Forward centering ring

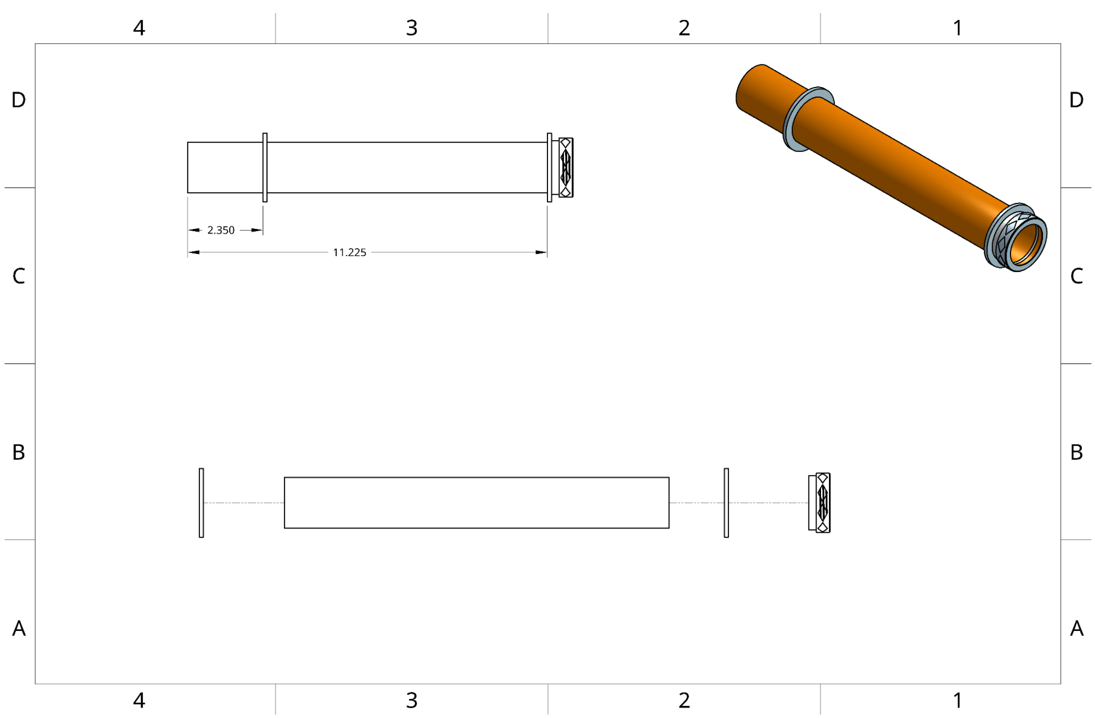


Fig. 76 - Motor mount assembly drawing

Table 86 - Motor Mount and Centering Ring Parameters

Parameter	Value
Motor mount material	FW fiberglass
Motor count length	12 in
Motor mount outer diameter	1.583 in
Motor mount inner diameter	1.516 in
Centering ring outer diameter	2.146 in
Centering ring iner diameter	1.583 in
Centering ring thickness	0.125 in

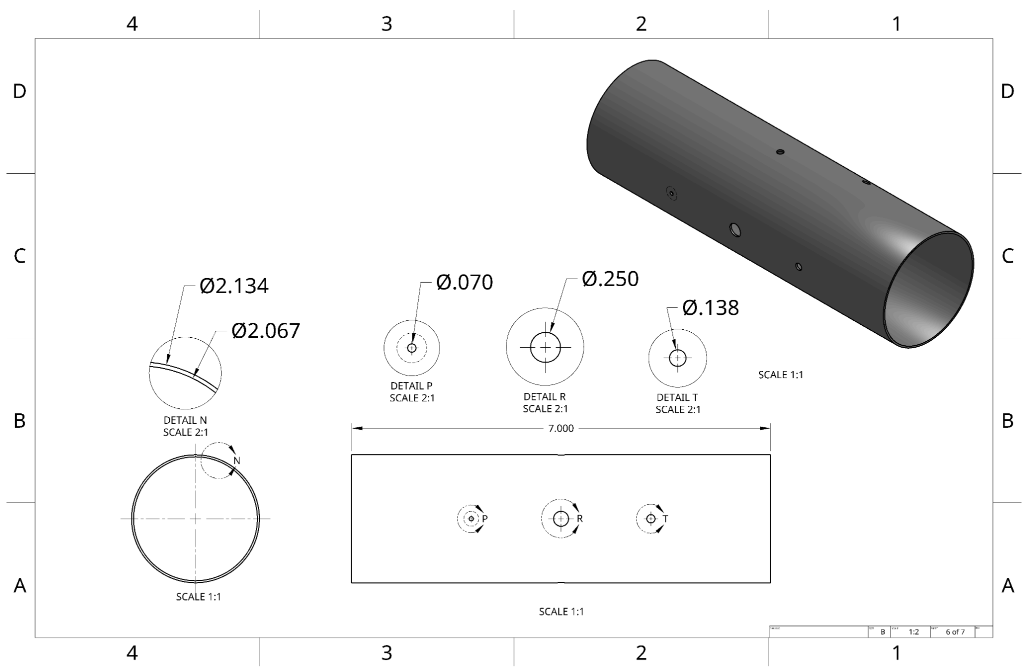


Fig. 77 - Subscale avionics coupler

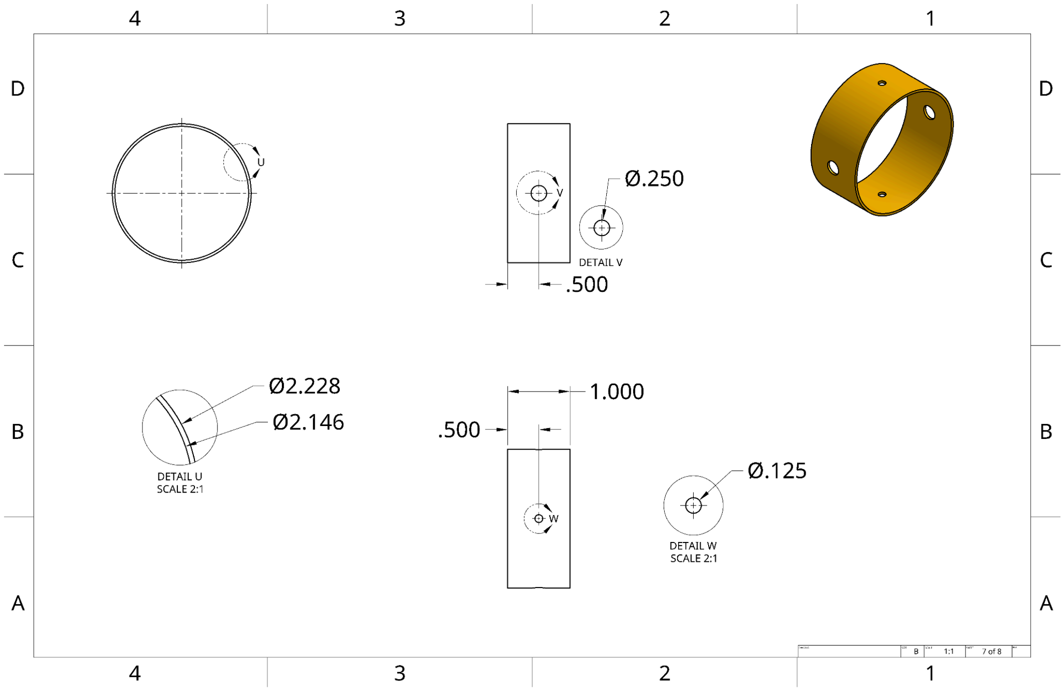


Fig. 78 - Coupler sleeve drawing

Table 87 - Subscale Coupler/Avionics Bay Parameters

Coupler			Switch band	
Parameter	**Value**		**Parameter**	**Value**
Material	FW fiberglass		Material	FW fiberglass
Length	7 in		Length	1 in
Outer diameter	2.134 in		Outer diameter	2.228 in
Inner diameter	2.146 in		Inner diameter	2.146 in

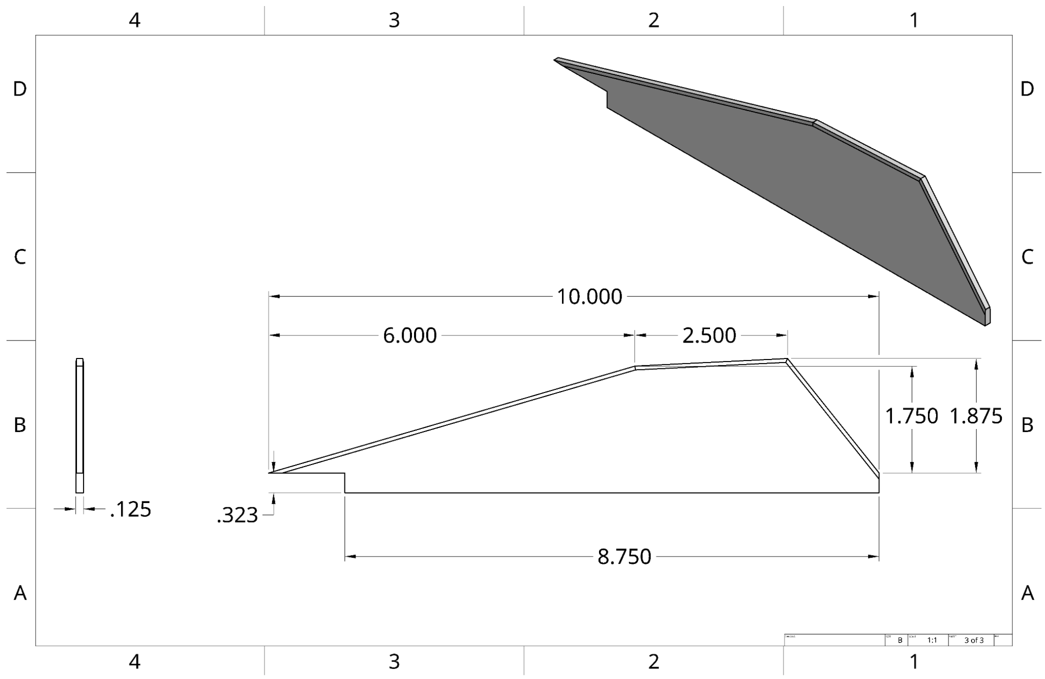


Fig. 79 - Subscale fin design

Table 88 - Fin Parameters

Parameter	Value
Material	G10 fiberglass
Length	10.255 in
Max height	2.125 in
Thickness	0.125 in
Bevel angle	11.25°
Bevel distance	0.45 in
Fin tab length	8.75 in
Fin tab width	0.323 in

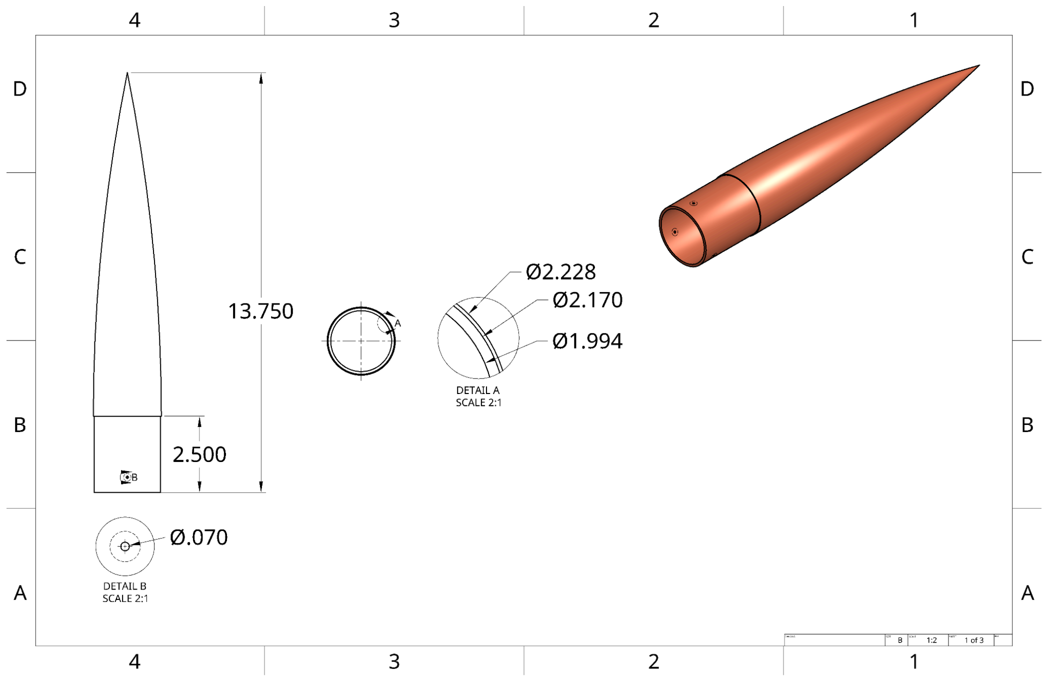


Fig. 80 - Nose cone drawing

Table 89 - Nose Cone Dimensions

Parameter	Size
Length	11.25 in
Outer diameter	2.228 in
Nose cone shoulder length	2.5 in
Nose cone shoulder outer diameter	2.17 in
Nose cone shoulder inner diameter	1.994 in

Appendix D - Role of Student Team Safety Officer

The safety officer is responsible for ensuring the safety of the team for the entire duration of the project. The role of safety officer has been appointed by the club, and the team members have direct contact through WhatsApp as well as group meetings. Responsibilities of the safety officer include:

1) Mitigation of potential hazards:
    a) Responsible for implementing protocols that help mitigate potential hazards.
    b) Maintaining the safety documentation for the team.
2) Attend every potentially hazardous step to ensure proper precautions are taken to mitigate risks. These responsibilities include:
    a) Making sure proper procedures are followed during build opportunities including all PPE equipment.
    b) Supervised launch vehicle and payload assembly and enforced proper procedures during all testing and launching days.
    c) Ground testing. NAR/TRA qualified mentors should be present for additional supervision and handling of all potentially explosive. flammable substances.
    d) Launch days
        i) Subscale launch testing: Ensure all safety measures are taken before/during/after launch and ensure all redundancy measures have been checked and are functional.
        ii) Full-scale launch testing: Ensure all safety measures are taken before/during/after launch and ensure all redundancy measures have been checked and are functional. Ensure the payload does not cause any structural strain on the rocket.
    e) Supervision of team on launch days
        i) Ensure the team follows all safety protocols for pre/post-launch
        ii) Ensure all redundancy equipment is operational
        iii) NAR/TRA certified mentor should be present and supervising the team in any step involving potential chemical/physical hazards
    f) Supervision of recovery activities
        i) Maintaining contact with the electronic recovery equipment in the rocket to track the trajectory and alert the team about any changes.
        ii) Enforce recovery safety protocols
        iii) Verify that all deployment charges are spent and electronics are disarmed before handling the rocket.
        iv) Supervise the disposal of spent propellant.
3) Hazard mitigation in STEM engagement
    a) Adult supervision while helping educate students.
    b) All members need to be accounted for at all times

Appendix E - Budget

Table 90 - Total breakdown of budget

Total budget				
Balance summary	Budget (2024-2025)		Actuals	Variance
Income	**3,399.91**		**3,494.91**	**-95.00**
Revenue (1000)	3,400		3,495	95
Sponsors (1100)	**1,510.00**		**1,510.00**	**0.00**
Administration: Microchip	1,000.00		$1,000.00	0.00
Administration: Ganesh Moorthy	500.00		$500.00	0.00
Administration: Andrew Brown	10.00		$10.00	0.00
Administration: Lauren Carr				0.00
Membership fees (1200)	**520.00**		**0.00**	**520.00**
Administration: Income	520.00		615.00	520.00
Fundraising (1300)	**0.00**		**0.00**	**0.00**
Administration: Income	0.00			0.00
Other (1400)	**1,369.91**		**$1,369.91**	**$1,369.91**
Administration: Previous surplus	1,369.91		$1,369.91	0.00
Expenses	**9,740.16**		**856.63**	**8,802.10**
Build (2000)	1,469.16		856.63	612.53
Rocket (2100)	**1,329.70**		**857**	**473**
Fullscale (2101)	1,113.60		641	473
Build: Booster	234.55		0	234.55
Build: Avionics Bay	83.87		0	83.87
Build: Payload	102.22		0	102.22
Build: Nose assembly	87.44		0	87.44
Build: Experimental payload	163.95		$163.95	0.00

Build: Recovery	0.00		0	0.00
Build: Energetics	441.58		476.58	-35.00
Subscale (2102)	216.10		216	-
Build: Booster	95.65		$95.65	0.00
Build: Avionics bay	29.75		29.75	0.00
Build: Payload	27.20		27.2	0.00
Build: Nose assembly	63.50		63.5	0.00
Build: Recovery	0.00		0	0.00
Build: Energetics	0.00		0	0.00
Miscellaneous (2200)	**139.46**		**0.00**	**139.46**
Consumables (2201)	62.58		-	63
Build: Consumables	62.58		0	62.58
Personal Protection Equipment (2202)	76.88		0	76.88
Administration: PPE	76.88		0	76.88
Stem Engagement (3000)	0.00		0	0
Supplies (3001)	0.00		0	0.00
Outreach: Supplies	0.00		0	0.00
Management (4000)	**8,271.00**		**81.43**	**8,189.57**
Travel (4001)	8,041.00		0	8,041.00
Administration: Mentor travel	841.00		0	841.00
Administration: Member travel	7,200.00		0.00	7,200.00
Other (4002)	230.00		81.43	148.57
Administration: Shipping	200.00		81.43	118.57
Administration: Launch fees	30.00		0.00	30.00
Net difference (surplus or deficit)	**-6,340.25**		**2,638.28**	**-8,897.10**

Table 91 - Full-Scale Bill of Material

Full Scale Bill of Materials									
System	Component	Vendor	Qty	Unit Cost	Shipping	Final Cost	Status	Details	Team Cost
Booster	54 mm Screw On Motor Retainer	Mach1Rocketry	1	$31.00		$31.00		15% vendor discount	$26.35
	54 mm FWFG Motor Mount, price per inch	Mach1Rocketry	18	$1.50		$27.00		15% vendor discount	$22.95
	54 mm to 98 mm G10 Fiberglass Centering Rings	Mach1Rocketry	3	$6.75		$20.25		15% vendor discount	$17.21
	3/16" G10 Fiberglass Custom Fin Set	Mach1Rocketry	1	$50.00		$50.00		15% vendor discount	$50.00
	U-bolt, Stainless, 1/4-20, 1-1/4" (8896T94)	McMaster-Carr	2	$5.47		$10.94			$10.94
	1515 Rail Buttons	Railbuttons	2	$0.75	$0.00	$1.50	Received	Donated by Mentor	$0.00
	PEM nuts, Stainless, #10-24 (96439A450)	McMaster-Carr	2	$0.50	$0.00	$0.99	Received	Donated by Mentor, rounding error	$0.00
	98 mm FWFG Body Tube, Price per foot.	Mach1Rocketry	4	$30.00		$120.00		15% vendor discount	$102.00
	Custom Fin Slotting	Mach1Rocketry	3	$2.00		$6.00		15% vendor discount	$5.10
Avionics Bay	98 mm FWFG Coupler, 12" length	Mach1Rocketry	12	$3.00		$36.00		15% vendor discount	$30.60
	98 mm G10 Stepped Bulkhead	Mach1Rocketry	2	$14.00		$28.00		15% vendor discount	$23.80
	98 mm FWFG Switch Band, 1" length	Mach1Rocketry	1	$3.50		$3.50			$3.50
	Threaded Rod, 1/4-20, Stainless, 13" (98804A107)	McMaster-Carr	2	$4.66		$9.32		15% vendor discount	$7.92
	Nylon Lock Nut, 1/4-20, Stainless (91831A029)	McMaster-Carr	2	$0.13	$0.00	$0.25	Received	Donated by Mentor, rounding error	$0.00
	Knurled Nut, 1/4-20 (92741A160)	McMaster-Carr	2	$1.00	$0.00	$2.00	Received	Donated by Mentor	$0.00
	Eggtimer Quantum	Eggtimer Rocketry	1	$40.00	$0.00	$40.00	Received	Loaned by Mentor	$0.00
	Perfectflite Stratologger CF	Perfectflite	1	$64.95	$0.00	$64.95	Received	Loaned by Mentor	$0.00
	Screw Switch	Missileworks	2	$3.00		$6.00			$6.00
	#8-32 Stainless PEM Nuts (96439A360)	McMaster-Carr	3	$0.37		$1.10		rounding error	$1.10
	U-bolt, Stainless, 1/4-20, 1-1/4" (8896T94)	McMaster-Carr	2	$5.47		$10.94			$10.94
	2S 450 mAh LiPo Battery	Amazon	2	$10.00	$0.00	$20.00	Received	Loaned by Mentor	$0.00
Rocket Payload Assembly	98 mm FWFG Body Tube, Price per foot.	Mach1Rocketry	4	$30.00		$120.00		15% vendor discount	$102.00
	#8-32 Stainless Truss Head Screws	McMaster-Carr	3	$0.07		$0.22		rounding error	$0.22
Nose Assembly	98 mm Nose Cone, FWFG, 5:1 cone, coupler, bulkhead	Mach1Rocketry	1	$90.00		$90.00		15% vendor discount	$76.50
	#8-32 Stainless PEM Nuts (96439A360)	McMaster-Carr	3	$0.37	$0.00	$1.10	Received	Donated by Mentor, rounding error	$0.00
	#8-32 Stainless Truss Head Screws	McMaster-Carr	3	$0.07	$0.00	$0.22	Received	Donated by Mentor, rounding error	$0.00
	U-bolt, Stainless, 1/4-20, 1-1/4" (8896T94)	McMaster-Carr	2	$5.47		$10.94			$10.94
	Featherweight GPS Tracker Module	Featherweight	1	$165.00	$0.00	$165.00	Received	Loaned by Mentor	$0.00
Experimental Payload	STEMMA QT / Qwiic JST SH 4-Pin Cable - 50mm Long	Adafruit	5	$0.95	$0.00	$4.75	Ordered		$4.75
	STEMMA QT / Qwiic JST SH 4-pin to Male Headers Cable	Adafruit	1	$0.95	$0.00	$0.95	Ordered		$0.95
	Adafruit Feather M0 RFM96 LoRa Radio	Adafruit	3	$34.95	$21.43	$104.85	Ordered		$104.85
	Adafruit 9-DOF Orientation IMU Fusion Breakout	Adafruit	1	$24.95	$0.00	$24.95	Ordered		$24.95
	ADXL345 - Triple-Axis Accelerometer	Adafruit	1	$17.50	$0.00	$17.50	Ordered		$17.50
	BMP390 Barometric Sensor Board	Adafruit	1	$10.95	$0.00	$10.95	Ordered		$10.95
Recovery	Quicklinks, Stainless, 5/16". (8947T27)	McMaster-Carr	5	$5.00	$0.00	$25.00	Received	Loan from Mentor	$0.00
	Quicklink, Stainless, 1/4"	McMaster-Carr	1	$2.00	$0.00	$2.00	Received	Loan from Mentor	$0.00
	Drogue Harness, 3/8" Tubular Kevlar, Stitched Loop, 30 ft	Custom	1	$46.00	$0.00	$46.00	Received	Loan from Mentor	$0.00
	Main Harness, 3/8" Tubular Kevlar, Stitched Loop, 25 ft	Custom	1	$33.00	$0.00	$33.00	Received	Loan from Mentor	$0.00
	Drogue Parachute (add specs)	Custom	1	$79.23	$0.00	$79.23	Ordered	Loan from Mentor	$0.00
	Main Parachute (add specs)	Custom	1	$200.00	$0.00	$200.00	Ordered	Loan from Mentor	$0.00
	Drogue Nomex Blanket	Custom	1	$9.00	$0.00	$9.00	Received	Donated by Mentor	$0.00
	Main Nomex Blanket	Custom	1	$19.00	$0.00	$19.00	Received	Donated by Mentor	$0.00
Energetics	Aerotech K1103X-P Reload Kit	buyrocketmotors	3	$183.99	$35.00	$551.97	Ordered	20% vendor discount, + HAZMAT fee	$441.58
	Aerotech 54/1706 Motor Case	Wildman Hobbies	1	$186.29	$0.00	$186.29	Received	Loan from Mentor	$0.00
	Goex ffffG Black Powder, per gram	Chris' Rocket Supplies	100	$0.07	$0.00	$6.61	Received	Donated from Mentor, rounding error	$0.00
	Firewire Electronic Match	MJG Technologies	20	$0.71	$0.00	$14.20	Received	Donated from Mentor	$0.00
					Gross Total:	*$2,213.47*		*Team Cost Total:*	*$1,113.60*

Table 92 - Full-Scale Bill of Material

Sub-Scale Bill of Materials

System	Component	Vendor	Qty	Unit Cost	Shipping	Final Cost	Status	Details	Team Cost
Booster	38 mm Screw On Motor Retainer	Mach1Rocketry	1	$27.00	$0.00	$27.00	Ordered	15% vendor discount	$22.95
	38 mm FWFG Motor Mount, price per inch	Mach1Rocketry	12	$1.25	$0.00	$15.00	Ordered	15% vendor discount	$12.75
	38 mm to 54 mm G10 Fiberglass Centering Rings	Mach1Rocketry	2	$4.50	$0.00	$9.00	Ordered	15% vendor discount	$7.65
	3/32" G10 Fiberglass Custom Fin Set	Mach1Rocketry	1	$20.00	$25.00	$20.00	Ordered	15% vendor discount	$20.00
	1010 Rail Buttons	Railbuttons.com	2	$0.75	$0.00	$1.50	Received	Donated by Mentor	$0.00
	PEM nuts, Stainless, #10-24 (96439A450)	McMaster-Carr	2	$0.50	$0.00	$0.99	Received	Donated by Mentor, rounding error	$0.00
	54 mm FWFG Body Tube, 27"	Mach1Rocketry	2	$16.00	$0.00	$32.00	Ordered	15% vendor discount	$27.20
	Custom Fin Slotting	Mach1Rocketry	3	$2.00	$0.00	$6.00	Ordered	15% vendor discount	$5.10
Avionics Bay	54 mm FWFG Coupler, 7" length	Mach1Rocketry	7	$2.00	$0.00	$14.00	Ordered	15% vendor discount	$11.90
	54 mm G10 Stepped Bulkhead	Mach1Rocketry	2	$9.50	$0.00	$19.00	Ordered	15% vendor discount	$16.15
	54 mm FWFG Switch Band, 1" length	Mach1Rocketry	1	$2.00	$0.00	$2.00	Ordered	15% vendor discount	$1.70
	Threaded Rod, M4, Stainless, 8" Length (90024A222)	McMaster-Carr	1	$3.37	$0.00	$3.37	Received	Donated by Member	$0.00
	Nylon Lock Nut, M4, Stainless (93625A150)	McMaster-Carr	2	$0.08	$0.00	$0.16	Received	Donated by Mentor	$0.00
	Knurled Nut, M4, Stainless	Amazon	2	$0.92	$0.00	$1.84	Received	Donated by Mentor	$0.00
	Eggtimer Quantum	Eggtimer Rocketry	2	$40.00	$0.00	$80.00	Received	Loaned by Mentor	$0.00
	Screw Switch	Missileworks	2	$3.00	$0.00	$6.00	Received	Loaned by Mentor	$0.00
	#6-32 Stainless PEM Nuts (96439A230)	McMaster-Carr	3	$0.23	$0.00	$0.69	Received	Donated by Mentor	$0.00
	Forged Eye Bolt, M4, Stainless	Amazon	2	$1.14	$0.00	$2.27	Received	Donated by Mentor, rounding error	$0.00
Payload Assembly	54 mm FWFG Body Tube, 19"	Mach1Rocketry	2	$16.00	$0.00	$32.00	Ordered	15% vendor discount	$27.20
	#6-32 Stainless Truss Head Screws	McMaster-Carr	3	$0.07	$0.00	$0.22	Received	Donated by Mentor, rounding error	$0.00
Nose Assembly	54 mm Nose Cone, FWFG, 5:1 cone, coupler, bulkhea	Mach1Rocketry	1	$63.50	$0.00	$63.50	Ordered	15% Discount	$63.50
	Forged Eye Bolt, M4, Stainless	Amazon	1	$1.14	$0.00	$1.14	Received	Donated by Mentor	$0.00
	Featherweight GPS Tracker Module	Featherweight	1	$165.00	$0.00	$165.00	Received	Loaned by Mentor	$0.00
	3D Printed Tracker Mount	Custom	1		$0.00	$0.00	Received	Donated by Mentor	$0.00
	4-40 3/8" Stainless Screws	McMaster-Carr	4	$0.06	$0.00	$0.23	Received	Donated by Mentor, rounding error	$0.00
Recovery	Quicklink, Stainless, 1/4"	Amazon	4	$2.40	$0.00	$9.60	Received	Loan from Mentor	$0.00
	Quicklink, Stainless, M3	Amazon	1	$0.64	$0.00	$0.64	Received	Loan from Mentor	$0.00
	Drogue Harness, 1/4" Tubular Kevlar, Stitched Loop, 2	Custom	1		$0.00	$0.00	Received	Loan from Mentor	$0.00
	Main Harness, 1/4" Tubular Kevlar, Stitched Loop, 15	Custom	1		$0.00	$0.00	Received	Loan from Mentor	$0.00
	Drogue Parachute (15" 0.707 Elliptical)	Custom	1	$59.26	$0.00	$59.26	Ordered	Loan from Mentor	$0.00
	Main Parachute (32" 0.707 Elliptical)	Custom	1	$105.18	$0.00	$105.18	Ordered	Loan from Mentor	$0.00
	Drogue Nomex Blanket	Custom	1		$0.00	$0.00	Received	Loan from Mentor	$0.00
	Main Nomex Blanket	Custom	1		$0.00	$0.00	Received	Loan from Mentor	$0.00
Energetics	Aerotech I Reload Kit	Wildman Hobbies	1	$65.00	$0.00	$65.00	Received	Donated from Mentor	$0.00
	Aerotech 38/XXX Motor Case	Wildman Hobbies	1		$0.00	$0.00	Received	Loan from Mentor	$0.00
	Goex ffffG Black Powder, per gram	Chris' Rocket Supplies	15	$0.07	$0.00	$0.99	Received	Donated from Mentor, rounding error	$0.00
	Firewire Electronic Match	MJG Technologies	8	$0.71	$0.00	$5.68	Received	Donated from Mentor	$0.00
				Totals:		*$749.26*			*$216.10*

Table 93- Personal Protection Equipment - Bill of Materials (BOM)

Item	Source	Link	Quantity	Price	Total
Nitrile Gloves (400 Pack)	Costco	Link	1	$27.99	$27.99
Leather Work Gloves	Walmart	Link	2	$2.97	$5.94
Safety Glasses Z87.1	Walmart	Link	9	$2.24	$20.16
N95 Respirator Mask	Home Depot	Link	4	$1.97	$7.88
Ear Plug (3-Pack)	Walmart	Link	3	$4.97	$14.91
			Total		$76.88

Table 94 - Consumables - Bill of Materials (BOM)

SLI Sub-Scale and Full-Scale Consumables

Component	Vendor	Qty	Unit Cost	Final Cost	Status	Team Cost
Proline 4500Q (pint) *	Wildman Hobbies	1	$39.00	$39.00	Donated by Mentor	$0.00
JB Weld (10 oz) *	Amazon	1	$17.98	$17.98	Donated by Mentor	$0.00
West System 105/206 (32 oz) *	Amazon	1	$105.86	$105.86	Donated by Mentor	$0.00
West System 404, High Density Filler *	Amazon	1	$51.26	$51.26	Donated by Mentor	$0.00
West System 406, Colloidal Silica *	Amazon	1	$19.21	$19.21	Donated by Mentor	$0.00
Dupli-Color Filler Primer	JB Tools	1	$7.74	$7.74		$7.74
Dupli-Color Sandable Primer	JB Tools	2	$6.81	$13.62		$13.62
Dupli-Color Base Coat Paint	JB Tools	3	$6.87	$20.61		$20.61
Dupli-Color High Temperature Gloss Clear Coat	JB Tools	3	$6.87	$20.61		$20.61
			Total:	$295.89		$62.58

Table 95 - STEM Engagement - Bill of Materials (BOM)

Expenses Per Engagement Class

Ms. Cullen (Simran)

Item	Qty	Unit Cost	Final Cost

Ms. Macdonald (Hollyn)

Item	Qty	Unit Cost	Final Cost

IED (Simran)

Item	Qty	Unit Cost	Final Cost

Ms. Horvath (Arjun) - 77 Students

Item	Qty	Unit Cost	Final Cost
Paper	150	$0.01	$1.50
Tape	5	$7.05	$35.25
Scissors	15	$3.47	$52.05
Ruler	15	$1.00	$15.00
Dowel	12	$0.33	$3.96
Eye Protection	10	$7.98	$79.80
Rocket BP	100	$0.24	$24.00
			$211.56

Physics (Arjun) - 155 Students (TBD)

Item	Qty	Unit Cost	Final Cost