Project Elijah

Preliminary Design Review

Cedarville Student Launch 2024-2025

Cedarville University
251 N. Main St.
Cedarville, OH 45314

October 28, 2024

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Acronym	Full Name
AGL	Above Ground Level
AB	Airbrakes Subsystem
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
APCP	Ammonium Perchlorate Composite Propellant
APRS	Automatic Packet Reporting System
CAD	Computer Aided Design
CDR	Critical Design Review
CE	Chief Engineer
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulation
CG	Center of Gravity
CNC	Computer Numerical Control
CP	Center of Pressure
CPR	Close Proximity Recovery
CSL	Cedarville Student Launch
CSO	Chief Safety Officer
DAC	Digital-to-Analog Converter
ECE	Electrical and Computer Engineer
EES	Engineering Equation Solver
EPL	Engineering Project Laboratory
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FCC	Federal Communications Commission
FMEA	Failure Modes and Effect Analysis
FRR	Flight Readiness Review
FSK	Frequency-Shift Keying
GLOW	Gross Lift-Off Weight
GPS	Global Positioning System
HART	Highway Addressable Remote Transducer
HPR	High Power Rocketry
HPRSC	High Power Rocketry Safety Code
I^2C	Inter-Integrated Circuit
I^2S	Inter-Integrated Circuit Sound
IDE	Integrated Development Environment
LiPo	Lithium-Ion Polymer
LO	Launch Officer
LRR	Launch Readiness Review
MGA	Mass Growth Allowance
MPCP	Mass Properties Control Plan

MSDS	Material Safety Data Sheet
MVP	Minimum Viable Product
NAR	National Association of Rocketry
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Agency
Ni-Cd	Nickel–Cadmium
NOAA	National Oceanic and Atmospheric Administration
NSL	NASA Student Launch
NTE	Not To Exceed
OD	Outer Diameter
OSHA	Occupational Safety and Health Administration
PCB	Printed Circuit Board
PDF	Payload Demonstration Flight
PDF	Portable Document Format
PDR	Preliminary Design Review
PETG	Polyethylene Terephthalate Glycol
PID	Proportional-Integral-Derivative
PLA	Polylactic Acid
PLAR	Post-Launch Assessment Review
PM	Project Manager
PPE	Personal Protective Equipment
PTT	Push-to-Talk
QC	Quality Control
RPN	Risk Priority Number
RSO	Range Safety Officer
RTC	Real-Time Clock
SDS	Safety Data Sheet
SL	Student Launch
SLP	Sea Level Pressure
SO	Safety Officer
SPI	Serial Peripheral Interface
SRB	Safety Review Board
STEM	Science, Technology, Engineering, and Mathematics
TBD	To Be Determined
TRA	Tripoli Rocketry Association
UAS	Unmanned Aircraft System
USLI	University Student Launch Initiative
VDF	Vehicle Demonstration Flight
WBS	Work Breakdown Structure
WSR	Wright Stuff Rocketeers

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1. Summary of PDR Report

1.1. Team Summary

Team Name	Cedarville Student Launch (CSL)
Team Address	251 N. Main St, Cedarville, OH 45314
Team Email	custudentlaunch@cedarville.edu
Team Mentor Information	Dave Combs davecombs@earthlink.net (937) 248 – 9726 NAR #86830, High HPR Level 2
Hours Spent on PDR	532
Launch Plan	CSL intends to launch at local NAR chapter during given launch window of April 5th – May 4th.
Team Social Medias	Instagram / X: custudentlaunch Website: https://cedarville-universitys-student-launch.webflow.io/

1.2. Launch Vehicle Summary

Target Apogee	4100 [ft]
Motor Choices (Primary & Secondary)	Aerotech K1000T-P Aerotech K1800ST-P
Vehicle Length	103 [in]
Body Tube O.D.	4.024 [in]
Expected Weight at Launch	29.2 [lbf]
Fore Section Length/Weight	9.257 [lbf]
Avionics Bay Section Length/Weight	2.848 [lbf]
Aft Section Length/Weight	8.641 [lbf]
Recovery System	Dual deployment: Drogue at apogee/Main at 600’

1.3. Payload Summary

The primary payload will be a STEMnaut flight capsule housed in the rocket’s fore section and remain contained in the airframe from launch to descent. The capsule will safely retain four STEMnauts as well as contain equipment necessary to transmit, via radio frequency, relevant rocket and STEMnaut landing site data to a receiver at the launch site.

2. Changes made since Proposal

2.1. Changes Made to Vehicle Criteria

2.1.1. Mechanical Changes

There have been several mechanical changes to the launch vehicle since the proposal. The tail cone has been redesigned due to size constraints. Instead of a machined aluminum, ceramic coating, and Polyethylene Terephthalate Glycol (PETG) assembly, the tail cone will now be a roll bent aluminum sheet construction with flanges and tabs to retain the motor casing and for fastening to the thrust structure. In addition, the tail cone's ogive shape has been changed to a conical geometry.

The overall length of the rocket was increased by a total of 10 inches, where the added length was split between the booster and main parachute airframe sections. The purpose of this change was to better accommodate the airbrakes being significantly longer than planned since early kinematic analysis yielded a fairly compact brake mechanism, but the leading airbrake design needed more space in the airframe to fit all the motion components.

2.1.2. Electrical Changes

The electrical modifications to the secondary payload (airbrakes) which were made from the proposal to the PDR are as follows. First, the electronics bay includes three barometers, not two. This alteration allows for a decision algorithm which is within the airbrakes (AB) system that requires either one or three sensors. The algorithm calculates the average of the three sensors and deletes the outlier of the three. Second, the Raspberry Pi will not only run from a Simulink program. It will be coded in the Arduino IDE using C++, which will implement a Simulink program. And finally, the electronics bay will be relocated from the bottom of the secondary payload to the top.

2.2. Electrical Changes Made to Payload Criteria

CSL changed the initial plans to use the FC-303 radio transmitter to the *Baofeng* UV-5R radio transmitter. After further investigation, it was discovered that this transmitter did not support the two-meter band as initially thought. External flash memory was also included to increase the reliability of flight data writing. No mechanical changes were made.

2.3. Changes Made to Project Plan

Major changes to the project plan involved changing the testing and validation plan. Specific deadlines for test flights and validations were decided and put in CSL's project timetable. Due to time constraints and lack of information that would be learned from specific tests, the initially proposed static fire test and wind tunnel test have been cancelled. These changes can be seen in the Project Plan section.

CSL also updated its budget with a new system classification "flight consumables" and with more specific line items and prices. The Science, Technology, Engineering, and Mathematics, (STEM)

Engagement and Electronics/Payload sections have been most impacted by this. These changes can be seen in the Project Plan section.

The target vehicle apogee has also been changed from 4300 feet to 4100 feet. As mass estimates of CSL rocket subsystems matured, the rocket was simulated to fly lower than initially predicted. To demonstrate the effectiveness of the secondary payload (the airbrakes), CSL lowered the target apogee to compensate for the reduction in maximum simulated apogee.

3. Vehicle Criteria

3.1. Mission Statement and Success Criteria

Project Elijah's mission is to safely fly a STEMnaut flight capsule to a desired apogee and after landing, and to transmit the capsule and landing site data to a designated receiver. CSL will also establish knowledge bases that can be passed on to future teams through Project Elijah. Mission success involves the launch vehicle adhering to all criteria outlined by the 2025 SL Competition and CSL's internal standards, and properly performing in flight, landing, data transmission, and flight survivability.

CSL's current solution to completing mission objectives involves a launch vehicle using a dual-bay parachute deployment system to ensure safe landing, containing an enclosed STEM craft for safe STEMnaut flight and reliable data transmission, and housing an airbrake system to ensure control of apogee. Handbooks containing standardized information on safety, STEM engagement, and general rocketry design will be compiled to ensure future CSL members have reliable and helpful guidelines when they take on the National Aeronautics and Space Administration (NASA) USLI competition.

3.2. General Launch Vehicle Overview

From the outset of the competition year, CSL was interested in developing an advanced airbrake system to meet the target altitude in a variety of launch conditions. The launch vehicle carrying the primary and secondary payload thus needed to be able to 1) far exceed the target apogee so that the airbrakes could bring the rocket down to the target altitude and 2) be small and light enough to use inexpensive Class II motors so that CSL could be approved for the maximum amount of test launches to validate the airbrake control system.

To meet these design objectives, CSL developed a design featuring a drag-reducing tail cone, a high-efficiency nose cone, and a slender aspect ratio. The first iteration of this design is shown in Figure 3.2.1.

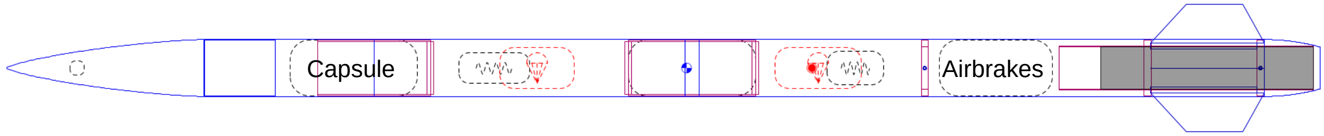

Figure 3.2.1. *OpenRocket simulation schematic for the first iteration of the launch vehicle.*

At the preliminary design phase, the fundamental component arrangement of the design shown in Figure 3.2.1 has not changed dramatically. However, after careful consideration of maturing mass properties according to the procedures outlined in section 3.11, a minor redesign was deemed necessary. Figure 3.2.2 shows the leading design, which features a lengthened booster tube to accommodate a longer-than-anticipated airbrakes assembly and a conical-profiled tail cone instead of an ogival-profiled one. The relevant data and design rationale for these changes is discussed in detail in sections 3.8 and 3.10, and Table 3.2.1 summarizes the performance differences between the two designs.

Table 3.2.1. *Basic geometry and performance differences between the two designs.*

	1st Iteration	2nd Iteration
Vehicle Mass [lb]	27.70	28.80
Static Stability [cal]	2.21	2.22
Length [in]	93	103
Predicted Apogee [ft] (evaluated on a K1000T-P motor)	4883	4553

The leading design of the Project Elijah launch vehicle is 103 inches (8.58 feet) long, with a maximum airframe diameter of 4.024 inches. It is composed of four main airframe components, descending from apogee in three tethered sections with two in-flight separation points as indicated in Figure 3.2.2. As per competition requirements, the design features dual-bay deployment with a drogue parachute in the aftmost parachute compartment in the booster section and with a main parachute being housed in its own compartment behind the primary payload.

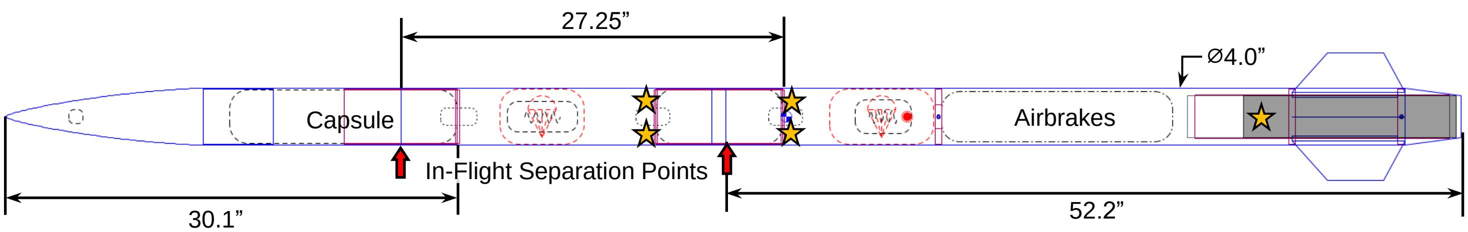

Figure 3.2.2. *OpenRocket simulation schematic of the leading design of the full-scale launch vehicle describing the dimensions of the three tethered sections of the rocket as well as the in-flight separation points. Star icons indicate the location of energetic matter in the rocket. The primary payload (capsule) and secondary payload (airbrakes) are shown in their places in the airframe.*

As a means of ensuring element-level compatibility across the entire rocket, the leading launch vehicle design has been fully modelled in SOLIDWORKS. At the time of this preliminary design review, this model is dimensionally accurate but lacks complete fastener representation, some electronic components, the recovery devices, and all energetic matter in the rocket. As the project develops, these features will be fully represented. Figure 3.2.3 shows the three in-flight-separable sections of the rocket in flight configuration as well as their primary subsystems. Engineering drawings of each individual subsystem are featured subsequently in sections 3.3 – 3.11.

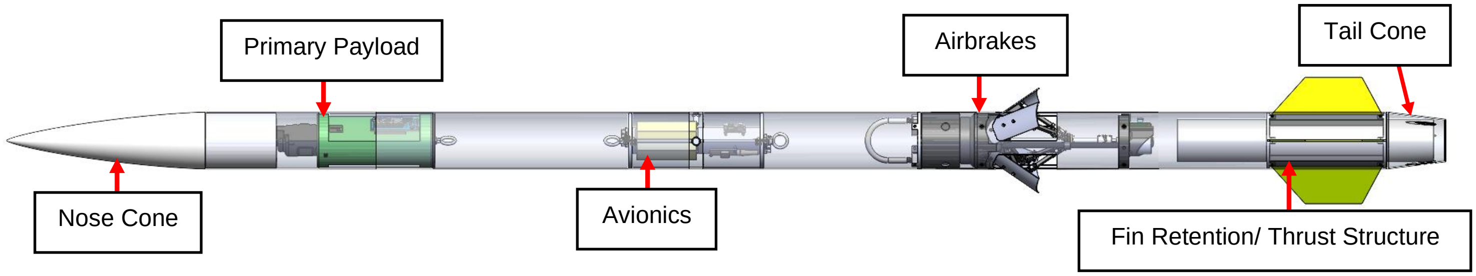

Figure 3.2.3. *PDR-level SOLIDWORKS assembly of the full-scale launch vehicle and its subsystems. The airbrakes are shown here in a deployed position.*

3.3. Airframe Material

The CSL team performed a trade study to determine the best material for the airframe of the rocket. The materials considered were blue tube, carbon fiber, and fiberglass. They were used to determine the correct material, properties of strength, durability, weight, and cost were compared to best fit CSL's needs.

3.3.1. Blue Tube

The CSL trade study explored using a shatterproof alternative phenolic known as Blue Tube, a high-density, high-strength paper material easily cut and shaped to meet CSL's requirements. Blue Tube offers strength like fully cured phenolic tubes and have significantly higher impact resistance. One of its key benefits is that it doesn't require additional reinforcement, like epoxy or fiberglass wrapping, making it suitable for high-power rocketry straight from the manufacturer. Its thin outer layer also makes sanding and painting easier compared to phenolic tubes.

However, Blue Tube is more expensive than both paper and phenolic tubes. Despite the higher cost, it is often worth it because paper and phenolic tubes tend to shatter easily, given their brittle properties. Still, Blue Tube is not as strong as phenolic and may be prone to damage during the recovery stage from the shock cord zippering. Additionally, its density increases the overall weight of the assembly, which can significantly affect CSL's target altitude. According to a study by Always Ready Rocketry, as shown in Figure 3.3.1, Blue Tube has an average breaking load of 1,549 [lbf] and a peak stress of 5,076 [psi]. This data is essential for evaluating the material's reliability and the rocket's overall safety.

3/12/2009

Sample ID:	BlueTube.mss	Test Date:	3/11/2009
Method:	Tube Compression (Simple Servo).msm	Operator:	MTS

Sample Results:
Specimen Results:

Specimen #	Specimen Comment	Inner Diameter in	Outer Diameter in	Platen Separation in	Area in^2	Modulus ksi	Load At Yield lbf
1		3.002	3.128	9.00000	0.60662	559.60219	2974.13082
2		3.002	3.128	9.00000	0.60662	607.10291	3211.11207
3		3.002	3.128	9.00000	0.60662	574.09091	3052.63859
Mean		3.002	3.128	9.00000	0.60662	580.26534	**3079.29383**
Std. Dev.		0.000	0.000	0.00000	0.00000	24.34486	120.71828

Specimen #	Stress At Yield MPa	Peak Load lbf	Peak Stress psi	Energy To Peak ft*lbf	Break Load lbf	Elongation at Peak in	
1	33.80322	2974.13082	4902.72798	14.11096	1504.89966	0.11156	
2	36.49669	3211.11207	5293.38147	20.93077	1607.34466	0.13095	
3	34.69552	3052.63859	5032.14469	18.27847	1534.46427	0.11815	
Mean	34.99848	3079.29383	**5076.08472**	17.77340	1548.90286	0.12022	
Std. Dev.	1.37205	120.71828	198.99895	3.43785	52.72665	0.00986	

Figure 3.3.1. *Measured data from a testing facility at General Dynamics comparing three 3-inch diameter 9-inch-long samples of blue tube. (Blue Tube 2.0).*

3.3.2. Carbon Fiber

Carbon fiber is a popular material in the aerospace industry due to its light weight and strength. It consists of thin, strong crystalline carbon filaments that reinforce the material. When woven into a cloth, it provides additional strength. The cloth can be laid over a mold and coated with resin, allowing it to take on a permanent shape. Carbon fiber is ideal for rocket airframes because of its high stiffness, tensile strength, low weight-to-strength ratio, chemical resistance, and minimal thermal expansion. Table 3.3.1 compares the mechanical properties of carbon fiber, 6061 aluminum, and 4130 steel. With the least volumetric density, carbon fiber has the greatest stiffness-to-weight ratio.

Table 3.3.1. *A comparison of mechanical properties of carbon fiber, 6061 aluminum, and 4130 steel (DragonPlate).*

Material	Elastic Modulus	Volumetric Density	Stiffness-to-Weight	Tensile Strength
Plain-Weave Carbon Fiber Composite	$8\ msi$	$0.05\ lbs./in^3$	160×10^6	$90\ ksi$
6061-T6 Aluminum	$10\ msi$	$0.10\ lbs./in^3$	100×10^6	$42\ ksi$
4130 Steel	$30\ msi$	$0.30\ lbs./in^3$	100×10^6	$97.2\ ksi$

However, carbon fiber has significant drawbacks, primarily its high cost, which CSL cannot afford for this project. Another issue is its tendency to block radio frequency signals, which would interfere with the rocket's payload, avionics, airbrakes, and prevent Global Positioning System (GPS) signals during recovery. To use carbon fiber, CSL would need to relocate the GPS to the nosecone, affecting the design and the rocket's center of gravity. Although carbon fiber offers excellent material properties, due to its cost and signal-blocking issues, it will not be used for the airframe.

3.3.3. Fiberglass

Fiberglass is a composite material made from glass and plastic. The glass is woven into a cloth that comes in tolls and becomes flexible when spread thin. The strength of fiberglass comes from its glass fibers, which have high tensile strength. A weaving process reinforces the fibers which makes the material very strong. To make fiberglass rigid, a polymer plastic like epoxy, is added and cures from a liquid to a solid.

Fiberglass tubes are both durable and strong. These tubes can withstand significant wear without showing damage. Their smooth surface makes it easy to finish without showing damage. Using fiberglass tubes for an airframe offers a lightweight, environmentally friendly, and easily manufacturable option. Though composite materials like fiberglass are resistant to cracking and bending, they have lower tensile strength compared to other materials, which can cause the material to be susceptible to buckling in harsh environments. Table 3.3.2 provides tensile material properties for different types of fiberglass composites.

Table 3.3.2. *Tensile properties of glass composites (Singh).*

Composites	Tensile Strength [MPa]	Tensile Modulus [GPa]	Maximum Tensile Strain [%]
G3	45.00 ± 4.33	1.16 ± 0.08	4.78 ± 0.31
G6	57.92 ± 4.96	1.22 ± 0.09	10.85 ± 0.85
G9	93.68 ± 6.08	1.17 ± 0.10	11.39 ± 0.85
G12	119.46 ± 8.93	1.98 ± 0.11	6.67 ± 0.43

In light of this trade study, combined with the fact that G12 fiberglass tubing is ubiquitous in high-powered model rocketry, CSL has chosen to use a fiberglass airframe for the student launch. Fiberglass is affordable and offers substantial strength and durability, making it a good choice for rocket design. It is also lightweight and can withstand heavy use without showing signs of damage. Additionally, fiberglass is easy to paint with minimal sanding, allowing a singular team member to handle the painting process. By opting for fiberglass, CSL hopes to save both construction time and money. The designs for each of the three main airframe components are shown below in Figures 3.3.2 – 3.3.4, and the mass of each of the G12 fiberglass airframe components is shown in Table 3.3.3. Detailed mass estimates are available in the mass estimate summary in Appendix A.6.

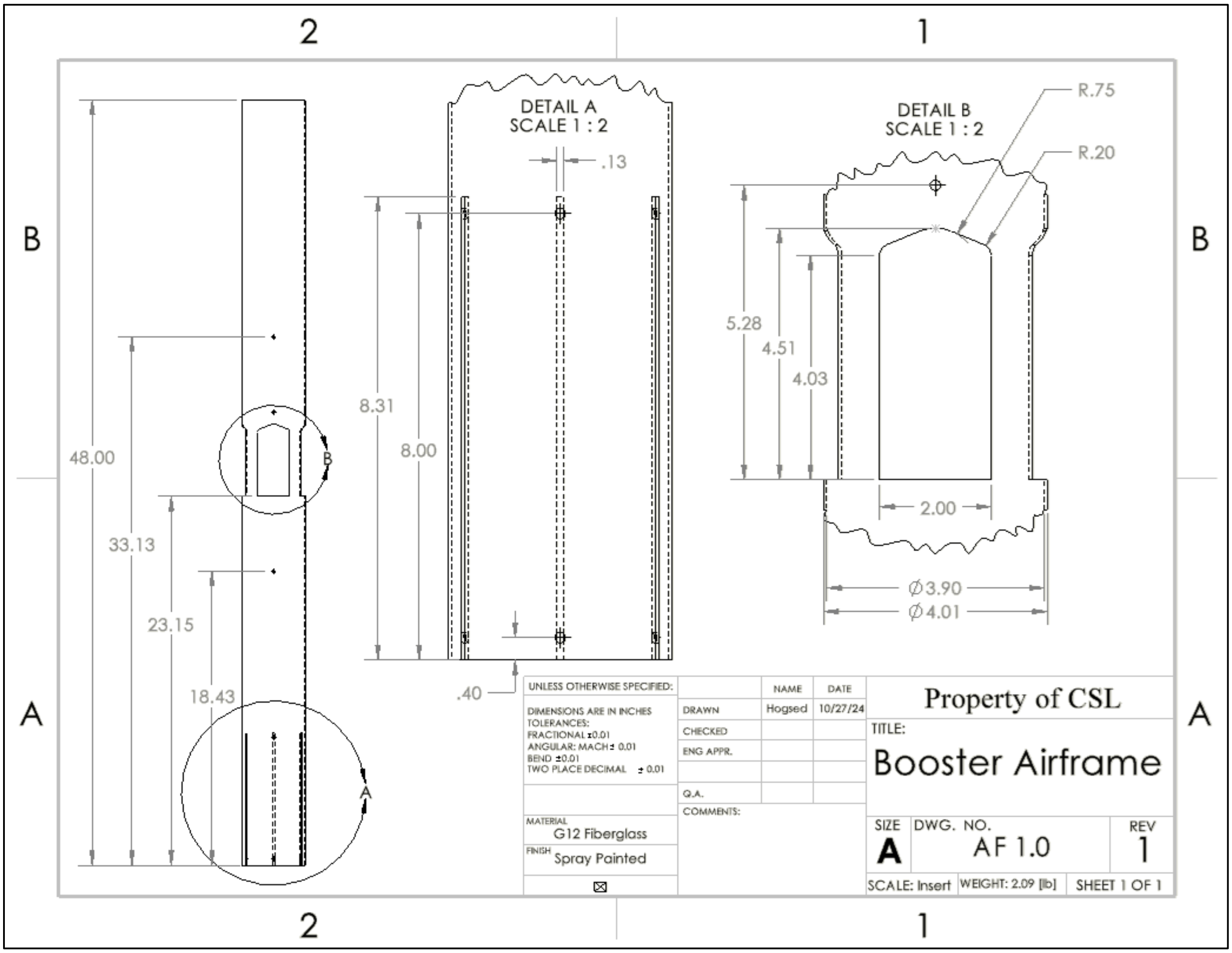

Figure 3.3.2. *SOLIDWORKS drawing of the booster airframe section.*

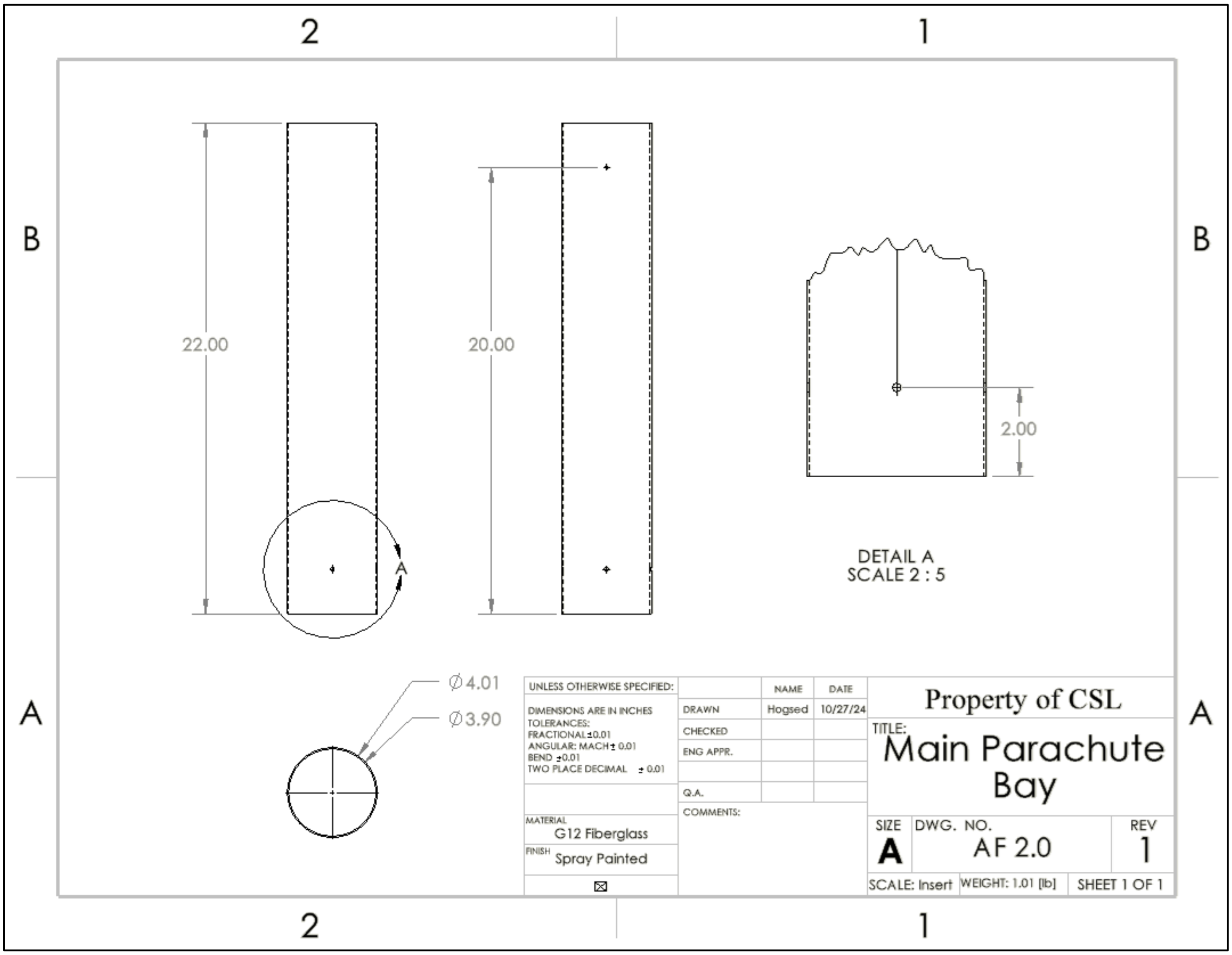

Figure 3.3.3. *SOLIDWORKS drawing of the main parachute bay.*

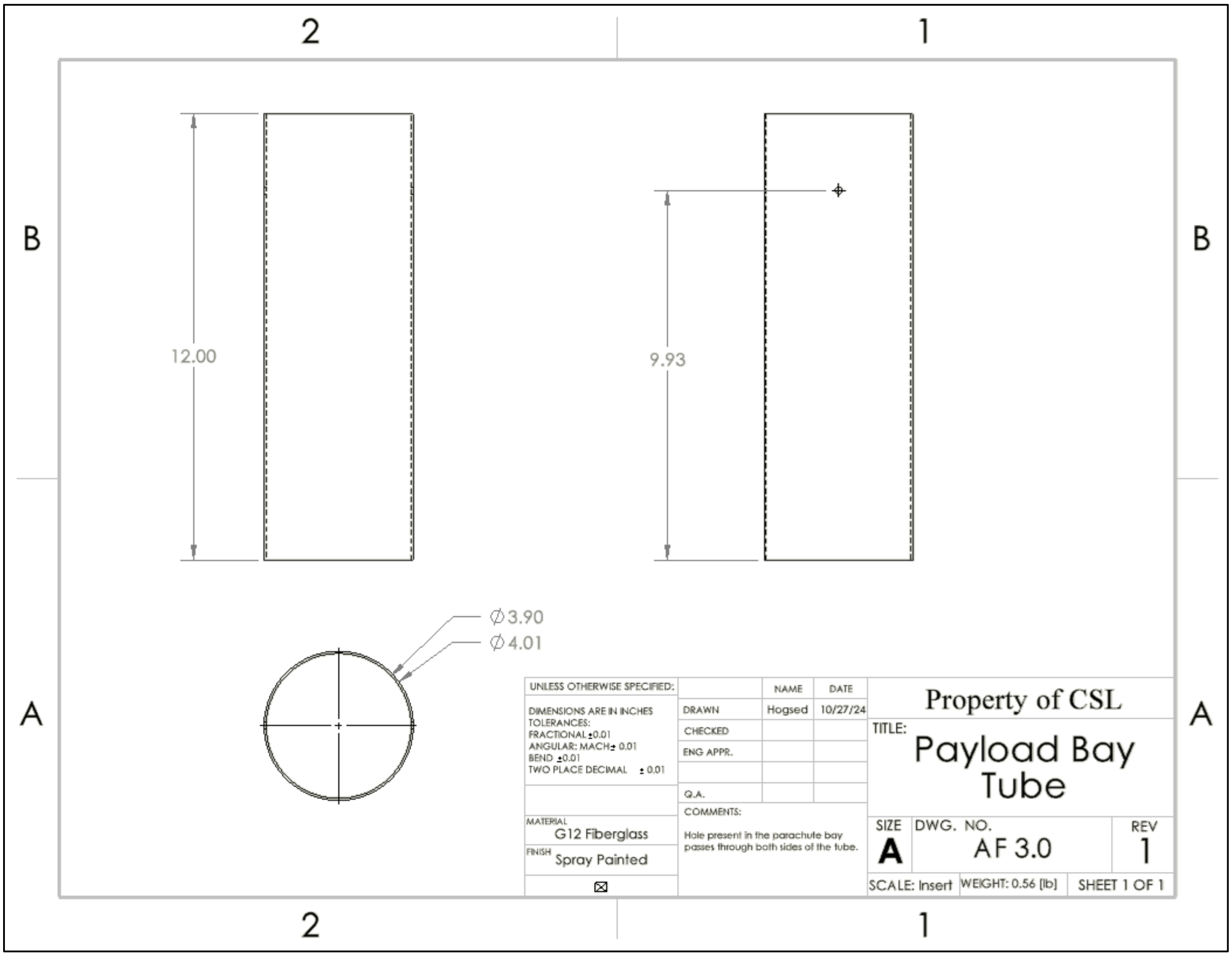

Figure 3.3.4. *SOLIDWORKS drawing of the main parachute body tube.*

3.4. Nosecone

Nosecone design plays a crucial role in the rocket's flight characteristics. As such, a considerable amount of effort was put into researching nose cone designs that would help the vehicle achieve the team's objectives. The desired nosecone is needed to offer the best aerodynamic flight characteristics (minimizing drag) while also being structurally sound to house the payload and relatively easy to manufacture. Based off these parameters, four nosecone designs were selected and compared for the rocket: Conic, Elliptical, Parabolic, and Haak Series. Each alternative presented unique strengths and weaknesses which were carefully weighed against each other to determine the best design for the rocket's given constraints.

3.4.1. Conic Cone

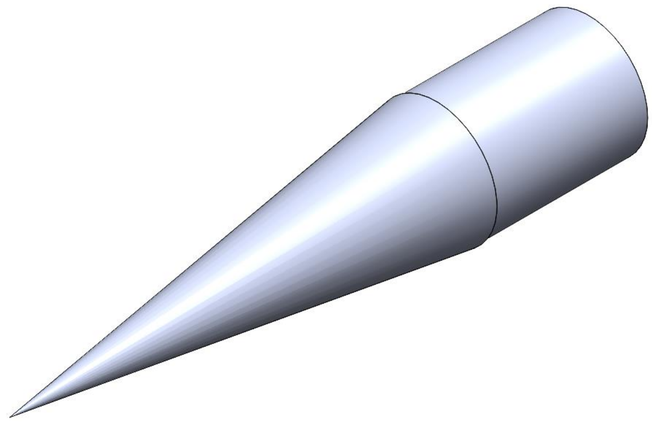

Figure 3.4.1. *SolidWorks Conic Nosecone Alternative.*

The first reviewed design was that of a conic cone shape which can be observed in Figure 3.4.1. A conic geometry was considered as this would allow for easy manufacturing. Furthermore, the mathematical formulas used to derive the geometry were simple and were easy to simulate in modeling programs such as SolidWorks. These equations and their respective diagrams can be seen in Figure 3.4.2 and Equations (3.4.1) through (3.4.3) (Crowell, 1996).

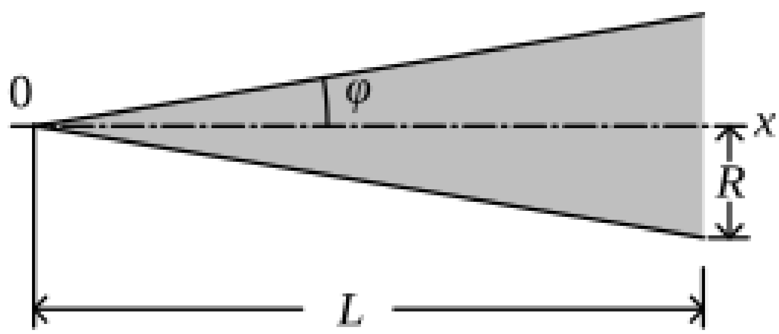

Figure 3.4.2. *Basic Conic Cone Geometry.*

$$y = \frac{xR}{L} \tag{3.4.1}$$

$$y = xtan(\phi) \tag{3.4.2}$$

$$\phi = arctan\left(\frac{R}{L}\right) \tag{3.4.3}$$

However, research indicates that while conic nose cones are indeed simple to manufacture, they do not provide significant aerodynamic advantages over other designs. A study conducted by Jain University of Bangalore examined various nose cone shapes at subsonic flow and observed that conic nose cones do not reduce drag as effectively as other designs. They concluded that for objects in subsonic flow; elliptic, parabolic, and ogive cones have better aerodynamic characteristics (Iyer & Pant, 2020).

A feasibility test was conducted on the shape to determine its suitability for the rocket design. The team concluded that while the conic shape's simplicity allowed for easy assembly, it presented several major drawbacks. Notably, the shape does not offer optimal aerodynamic efficiency for the subsonic speeds that the rocket will operate. More critically, there are concerns that the thin sections of the tip of the conic shape may be prone to breaking upon landing, comprising the cone's structure and its ability to adequately protect the payload. As such, the conic design was rejected.

3.4.2. Parabolic Cone

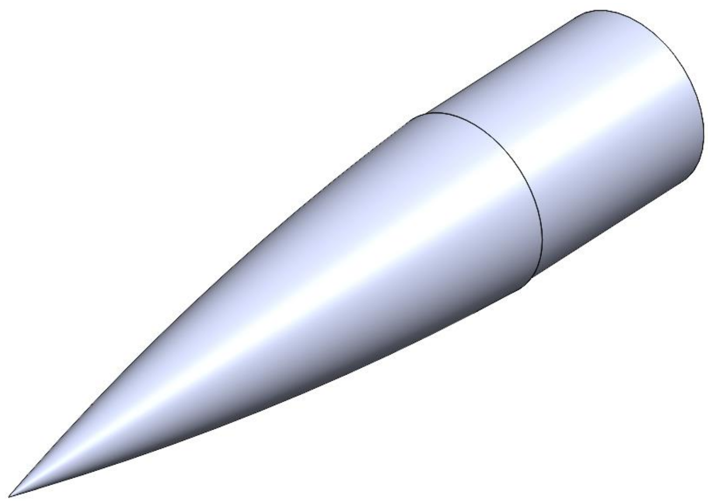

Figure 3.4.3. *SolidWorks ¾ Parabolic Cone Alternative.*

The second alternative cone design researched was a parabolic cone shape. This design was considered mainly due to its enhanced aerodynamic properties compared to the conic design as well as its improved structural rigidity. The SolidWorks design depicted in Figure 3.4.3. was developed using the equations and diagram shown in Figure 3.4.4. and Equation (3.4.4) (Crowell, 1996). For the design iteration, K*'* was set equal to ¾ as that is one of the most common values used for cone shapes (Crowell, 1996).

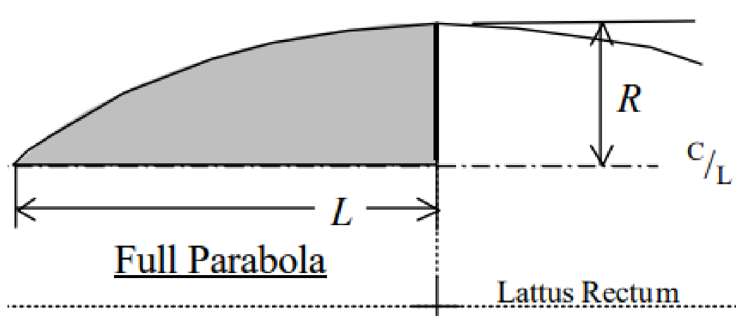

Figure 3.4.4. *Basic Parabolic Geometry.*

For $0 \leq K' \leq 1,$

$$y = R\left(\frac{2\left(\frac{x}{L}\right)-K'\left(\frac{x}{L}\right)^2}{2-K'}\right) \tag{3.4.4}$$

However, the team recognized that parabolic shapes were much more challenging to manufacture, which would be a critical factor in selecting an ideal design. A feasibility study was conducted on this interaction, leading to the rejection of the parabolic design. While manufacturing difficulties could be amended by using 3D printers and it offered significantly better structural integrity compared to the conic design, it was felt that the shape could be further improved upon to achieve greater aerodynamic efficiencies.

3.4.3. Elliptical Cone

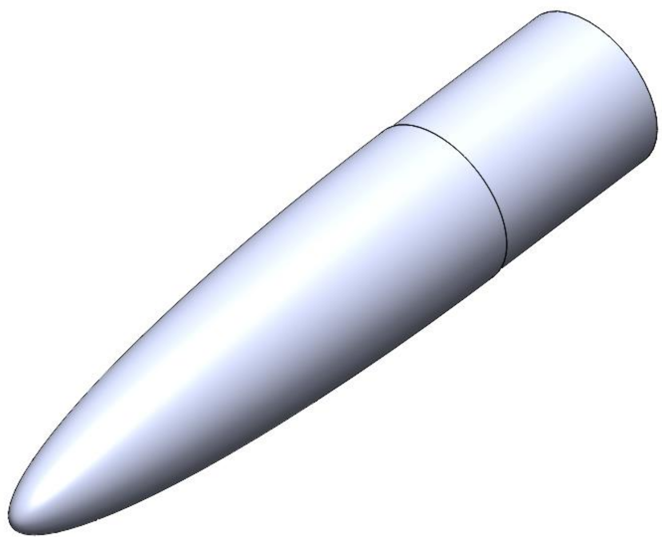

Figure 3.4.5. *SolidWorks Elliptical Cone Alternative.*

The third design alternative considered for the nosecone design was an elliptical cone design as shown in Figure 3.4.5. An elliptical design was considered by the team due to them having ideal aerodynamics as elliptical cones are very efficient for subsonic flight conditions due to their blunt noses and tangent bases (Chalia, 2019). These characteristics were seen as advantageous compared to other design alternatives. The equation used to create the elliptical cone, and its corresponding diagram are shown in Figure 3.4.6 and Equations 3.4.5 (Chalia, 2019).

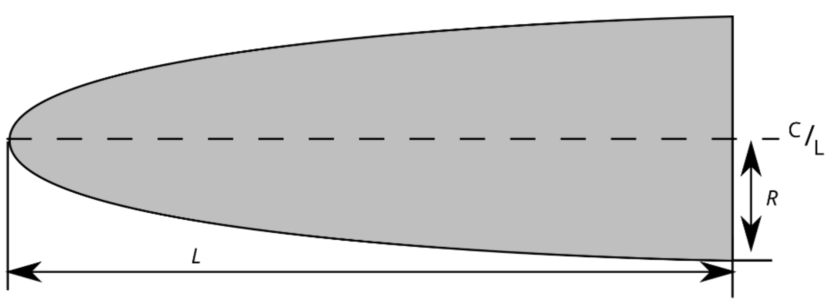

Figure 3.4.6. *Elliptical Cone Geometry.*

$$Y = \left[\left(\frac{D}{2}\right)^{P} * \left[1 - \left(\frac{X}{L}\right)^{P}\right]\right]^{\frac{1}{P}} \qquad (3.4.5.)$$

The team concluded that an elliptical shape would be feasible to construct and manufacture due to its unique aerodynamic properties and its ability to withstand the forces of landing due to its geometry. The shape could be manufactured using 3D printers and would provide an adequate amount of protection for the payload. Although the design iteration was almost selected for its benefits, the design was dropped in favor of the next iteration.

3.4.4. Leading Nose Cone (Haak Series)

The final cone iteration that was reviewed by CSL was a Haak Series design. This shape was considered because of its ability to be mathematically derived from given dimensions to produce the minimum amount of drag (Crowell, 1996). Furthermore, the shape did not sacrifice the structural integrity of previous iterations it would still be able to protect the payload. The team used Figure 3.4.7 and Equations (3.4.6) through (3.4.7) (Crowell, 1996) to derive a design that would give minimum drag for a given length and diameter.

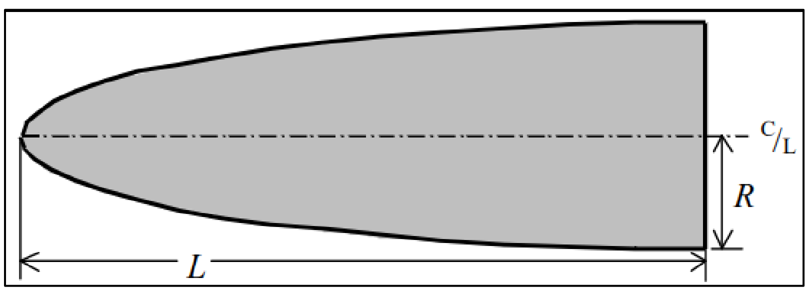

Figure 3.4.7. *Basic Haack Series Nose Cone Profile.*

$$\theta = cos^{-1}\left(1 - \frac{2x}{L}\right) \qquad (3.4.6.)$$

$$y = \frac{R\sqrt{\theta - \frac{sin(2\theta)}{2} + Csin^{3}\theta}}{\sqrt{\pi}} \qquad (3.4.7.)$$

Where: C = 1/3 for Length – Volume Haack series
C = 0 for Length – Diameter Haack series (Von Karman)

The team believed that such a design offered the best overall aerodynamic characteristics while fulfilling the essential roles of the nose cone. The shape was sturdy enough that it could both protect the payload and be reused again for further launches while also minimizing drag. After further analysis, the team concluded that a Haak Series cone would be feasible to use and assemble. The shape could be modeled and derived using the provided mathematical equations, then fabricated using 3D printing technology. Using Equations (3.4.6) through (3.4.7), a Von Karman Haak Series model was created in SolidWorks and is displayed in Figures 3.4.8 and 3.4.9.

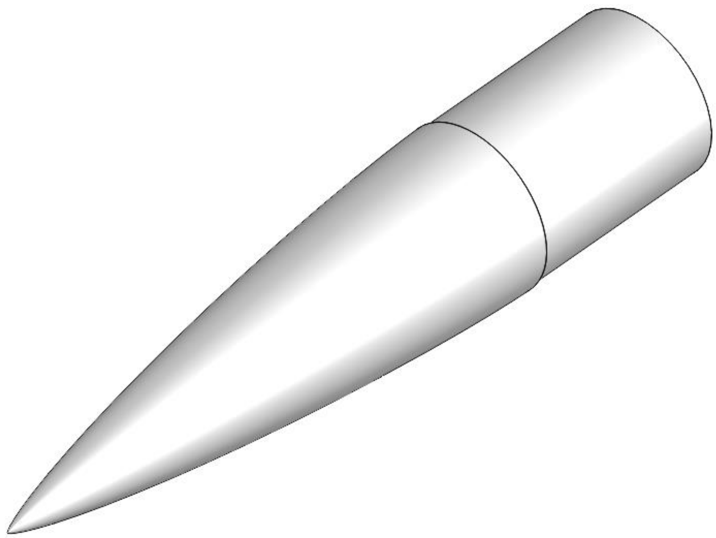

Figure 3.4.8. *SolidWorks Von Karman Haak Series Model.*

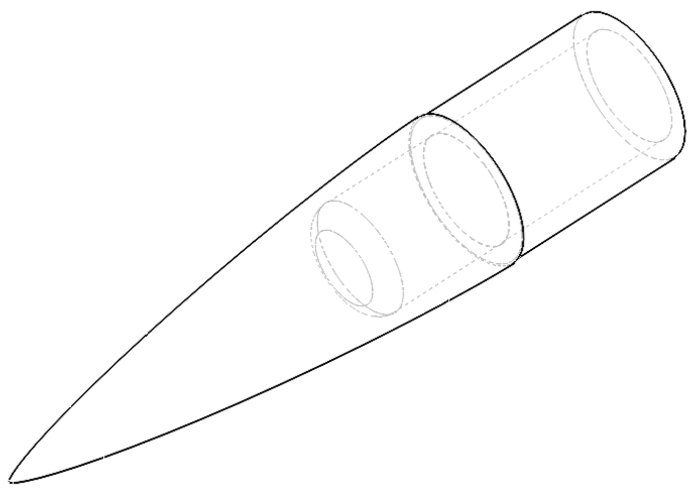

Figure 3.4.9. *SolidWorks Van Karman Haak Series Model (alternate rendering).*

The overall shape of the cone was determined due to the parameters CSL wanted it to achieve. The cone had to be lengthened to allow for a larger area inside of the cone that could be used for payload space as well as for ballasting to counteract the added weight of the air brakes (see section 3.7) to keep the rocket stable. The increased length of the rocket also allowed the rocket to have a larger amount of distance between the tip of the rocket and the valuable payload inside. The thought process was that this increase length would contribute to a higher structural integrity and further protect the rocket.

However, there were some tradeoffs that came with lengthening the cone. Extending the length increased the wetted surface area. This inevitably led to more friction drag which directly affected the overall aerodynamics of the nose cone. Since the rocket is not expected to exceed Mach 0.8, only friction drag is a concern (Iyer & Pant, 2020). A fineness ratio of 3.5 was chosen to counteract the effects of these drags acting on the rocket.

To adhere to design requirements, an opening was included in the rear section of the cone as shown in Figure 3.4.10. This opening allows for part of the payload to be housed within the nosecone. This is to account for the extended portion of the radio in the payload and allows it to broadcast necessary data without obstructing the signal. The opening also offers plenty of room to insert ballast into the cone. The ability to add ballast to the design was an important characteristic to include in the design as it gives the team opportunity to fix or move the center of mass of the rocket and avoid flight instability. Additionally, the opening in the nose cone allows for the ability to integrate a small camera into the design that can record visual data of the rocket in flight.

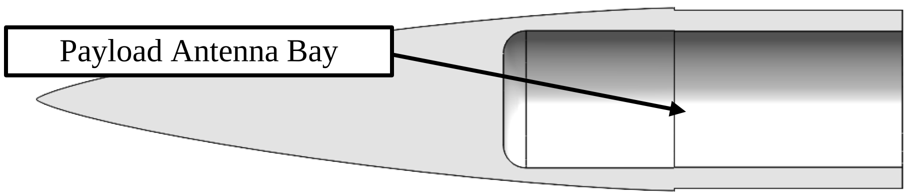

Figure 3.4.10. *Leading Nose Cone Design Payload Bay.*

From the beginning of the project's inception, it was desired that the nose cone would be fabricated in house by the team as this would address manufacturing difficulties often associated with nosecone geometry. To ensure the nose cone's durability and minimize damage upon landing, a significant portion of the structure will be infilled, enhancing its strength and enabling reusability. Before the manufacturing of the nosecone could occur, the team compared various 3D print materials based on their strength, impact resistance, printer compatibility, and cost. These values were

To address the manufacturing challenges of the Haack Series nose cone, the team chose 3D printing as the solution. This method allows for rapid prototyping and the flexibility to integrate design changes over time. To ensure the nose cone's durability and minimize damage upon landing, a significant portion of the structure will be infilled, enhancing its strength and enabling reusability. Additionally, the team compared various 3D printing materials to determine the most suitable option for the nose cone as presented in Table 3.4.1 using values gathered from *Prusa Research's 3D Material Table* (Prusa Research). After comparing the different available 3D printing materials, the team settled on using PETG material due to its relatively high strength characteristics and its relatively cheap pricing. The team decided that the cone would be divided into multiple small parts to make the printing easier as shown in Figure 3.4.11.

Table 3.4.1. *Advantages and disadvantages of 3D printing materials from Prusa Research.*

Material	**Charpy Impact Resistance** $\left[\frac{kJ}{m^2}\right]$	**Strength** $[MPa]$	**Compatibility with printers**	**Approximates Price [$] per** $[kg]$
ABS	25	40	No	25
ASA	40	37	Yes	35
CF Blends	100	85	No	80
PC Blends	75	59	No	70
PLA	16	57	Yes	20
PEGT	50	53	Yes	25

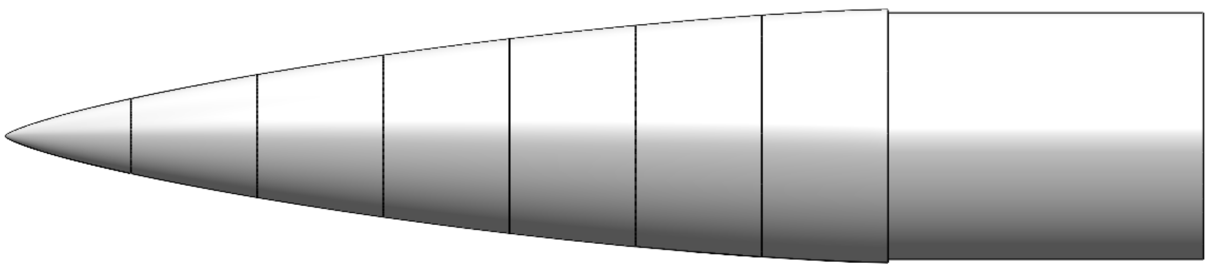

Figure 3.4.11. *SolidWorks Model of Leading Cone Design Divided into Sections for 3D Printing.*

A SolidWorks drawing was created based off the model, as shown in Figure 3.4.12. The drawing highlights the key dimensions of the cone as well as other details such as the materials used in its construction. Using the data from the drawing, and mass properties from the SolidWorks model shown in Figures 3.4.8-3.4.11, the cones defining characteristics were identified and recorded in Table 3.4.2. These characteristics include the material of the cone, its weight, length, diameter, radius, and fineness ratio.

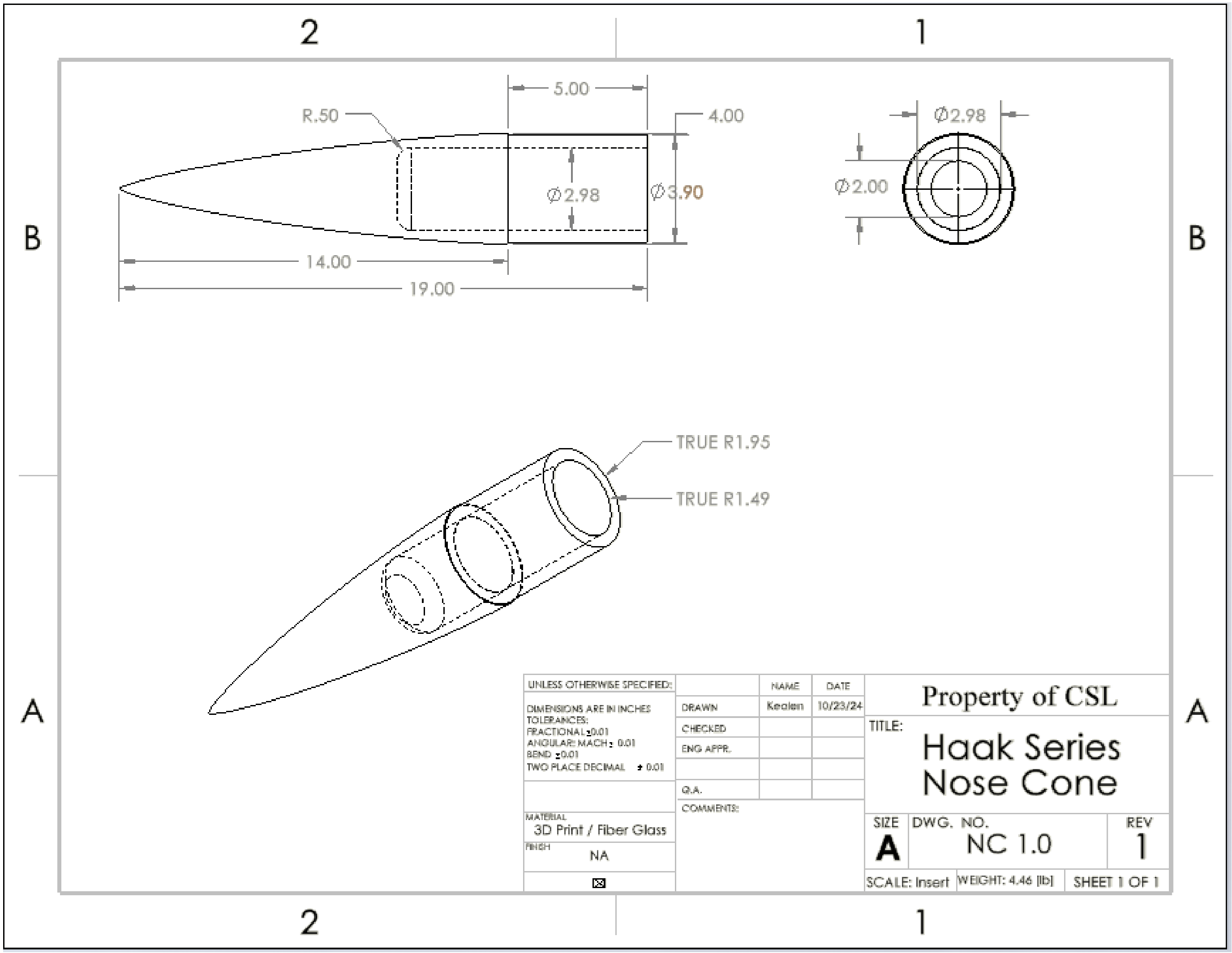

Figure 3.4.12. *Leading Nose Cone SolidWorks Drawing.*

Table 3.4.2. *Leading Nose Cone Characteristics.*

Characteristic	**Value**
Shape	Haak Series
Material	Fiberglass and PETG
Length (L)	14 [in]
Diameter (D)	4 [in]
Fineness Ratio (f_r)	3.5
Weight (W)	4.46 [lb]

3.5. Fin Structure

The design of the fins is a crucial part of the rocket's stability through its flight. The reason for this is because the fins impact the location of the rocket's Center of Pressure (CP) the most. The distance between the CP and Center of Gravity (CG) impacts the stability of the rocket by impacting the magnitude of the restoring force that is generated by the fins.

The team has narrowed down the design of the fins for project *Elijah* into two different options. Those two different options are trapezoidal and clipped delta fins. Figure 3.5.1 shows the different fin geometries. Each fin type has the same parameters: root chord, span, tip chord, and thickness. When these parameters are altered, it affects the stability and predicted apogee of the rocket in a significant way. The purpose of the fins is to stabilize the rocket, so the characteristics that improve stability will be considered with greater importance than how it impacts apogee.

The team has narrowed down the design of the fins for project *Elijah* into two different options. Those two different options are trapezoidal and clipped delta fins. Figure 3.5.1 shows the different fin geometries. Each fin type has the same parameters: root chord, span, tip chord, and thickness. When these parameters are altered, it affects the stability and predicted apogee of the rocket in a significant way. The purpose of the fins is to stabilize the rocket, so the characteristics that improve stability will be considered with greater importance than other effects like how it impacts apogee.

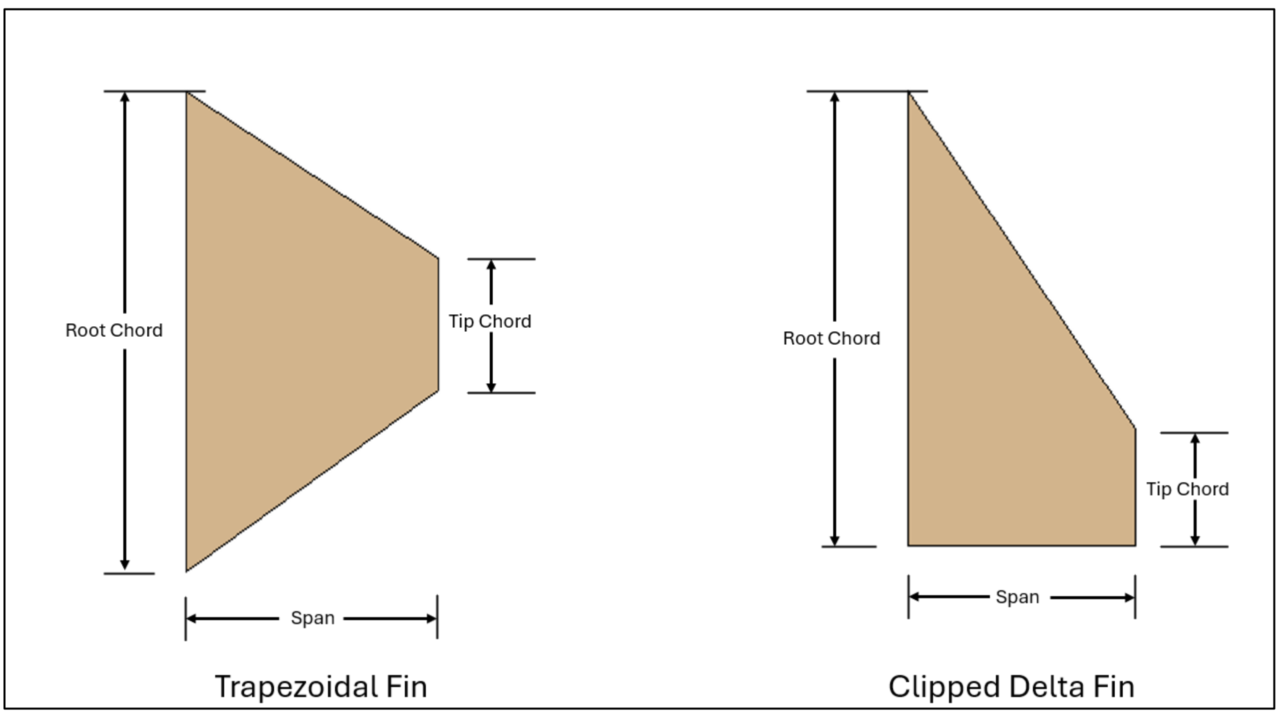

Figure 3.5.1. *Considered Fin Geometries.*

According to Pektas et. Al, increasing the thickness of the rocket can affect the apogee because it increases the weight of the rocket and increases aerodynamic drag. The span is the dominant factor when it comes to impacting the stability of the rocket. With these considerations in mind, the team used an open-source software OpenRocket to enhance the fin geometry. The CG, CP, stability, and apogee are calculated for each iteration by OpenRocket and is shown in Table 3.5.1.

Table 3.5.1. *OpenRocket Calculations.*

	Trapezoidal	Clipped Delta
Center of Gravity [in]	54.68	54.94
Center of Pressure [in]	63.79	63.42
Stability [cal]	2.27	2.11
Apogee [ft]	4428	4623

The main points of concern in Table 3.5.1 are stability and apogee. The stability that is needed should be between 2-4 cal. The higher stability the better. According to Table 3.5.1, the trapezoidal fins would be the best to go with due to their increased stability.

One of the most devastating issues that can occur during flight is fin flutter. Fin flutter can be described as "a dynamic instability associated with the interaction of aerodynamic elastic and internal forces" (Howard, 1). The cause of fin flutter could be insufficiently strong fin material, or unorthodox fin geometry. A way to analyze fins for fin flutter is to solve for the flutter velocity of the fins. The flutter velocity is essentially the maximum velocity the rocket reaches before fin flutter occurs. When calculating the flutter velocity, the necessary outcome is that the flutter velocity is much greater than the rocket's maximum velocity.

Using equations from an Apogee Rockets newsletter, the flutter velocity for trapezoidal fins can be calculated (Sahr, 3). In Equation 3.5.1 all the variables are as follows: C_s is the speed of sound, h is the current altitude of the rocket, H is the atmospheric scale height at sea level, G is the shear modulus of the fiberglass, P_o is the constant sea level pressure, B is the aspect ratio, λ is the fin taper ratio, and T is the normalized thickness.

$$V_f = 1.223 C_{so} e^{\left(0.4\frac{h}{H}\right)} \sqrt{\frac{G}{P_o}} \sqrt{\frac{2+B}{1+\lambda}} \left(\frac{T}{B}\right)^{\frac{3}{2}} \tag{3.5.1}$$

In Equation 3.5.1, there are certain parameters that need to be calculated. These parameters are all normalized ratios. In Equations 3.5.2 through 3.5.5, the variables are as follows: b is the fin height, S is the fin area, c_r is the root chord, c_t is the tip chord, and t is the fin thickness.

$$B = \frac{b^2}{S} \tag{3.5.2}$$

$$S = \frac{(c_r + c_t)b}{2} \tag{3.5.3}$$

$$\lambda = \frac{c_t}{c_r} \tag{3.5.4}$$

$$T = \frac{t}{c_r} \tag{3.5.5}$$

In Table 3.5.2, the constants used to calculate flutter velocity are shown. The shear modulus of G10 fiberglass used in this calculation was found strain imaging in an article by Iliopoulos et. Al.

Table 3.5.2. *Values for Flutter Analysis.*

Constant	Value (Trapezoidal)	Value (Clipped Delta)
C_s [ft/s]	1100	1100
G [ksi]	1767	1767
H [ft]	26500	26500
P_o [psi]	14.7	14.7
t [in]	0.125	0.125
c_r [in]	8	8
c_t [in]	4	3
b [in]	3.2	3.2

Using the previous equations, the rockets flutter velocity can be calculated for both iterations of fins. In Figure 3.5.2, the trapezoidal flutter velocity analysis is shown. This linear relationship matches the results from the Apogee Components Newsletter where Equation 3.5.1 was retrieved from. The results show that the most dangerous part of the flight for the fins is right at the beginning of the flight, but there should be no issues because the max velocity is much lower than the lowest flutter velocity.

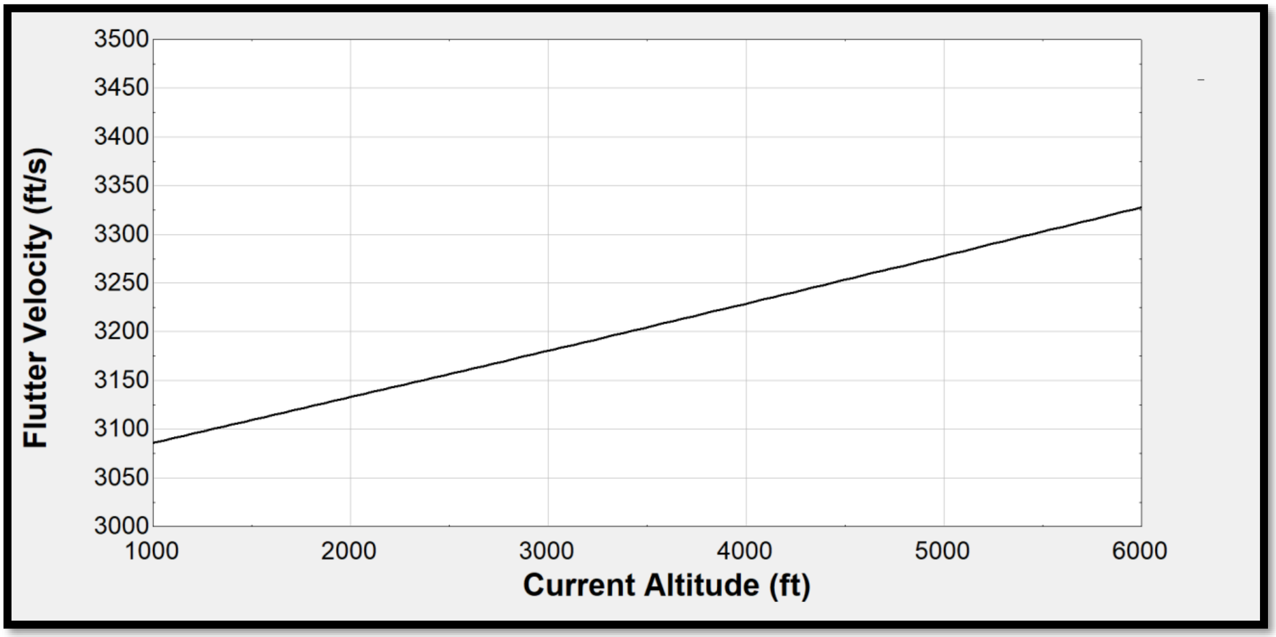

Figure 3.5.2. *Flutter Velocity as a function of Current Rocket Altitude for Trapezoidal Fins.*

The same analysis was done for the clipped delta fins, and the results are shown in Figure 3.5.3.

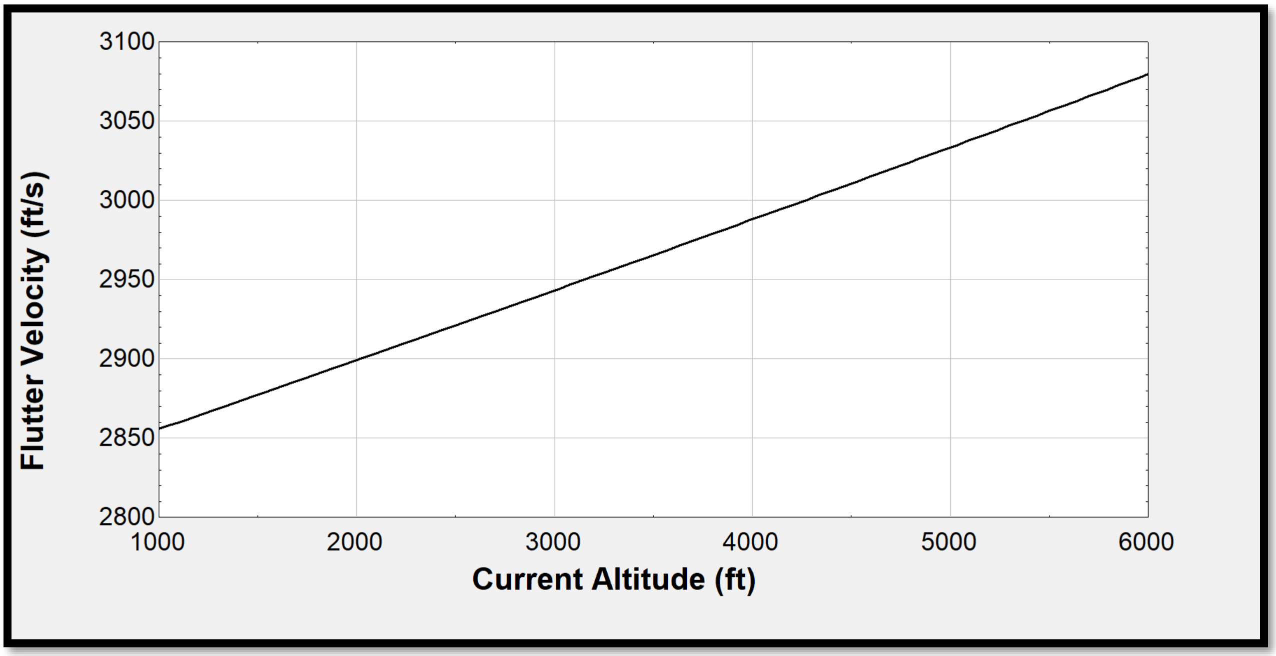

Figure 3.5.3. *Flutter Velocity as a function of Current Altitude for Clipped Delta Fins.*

From the analysis shown, trapezoidal fins are clearly the superior choice. The greater the flutter velocity, the faster the rocket can travel without experiencing fin flutter. Even though the rocket does not even approach the minimum flutter velocity, it is still better to go with the safer option.

In summary, the CSL team will be going with the trapezoidal fin, made of G10 fiberglass with a thickness of 0.125 inches due to the reasons stated in this section. The approximate mass of the fin set will be 247 grams according to the analysis done by OpenRocket. Figure 3.5.4 shows the SolidWorks drawing for the fins.

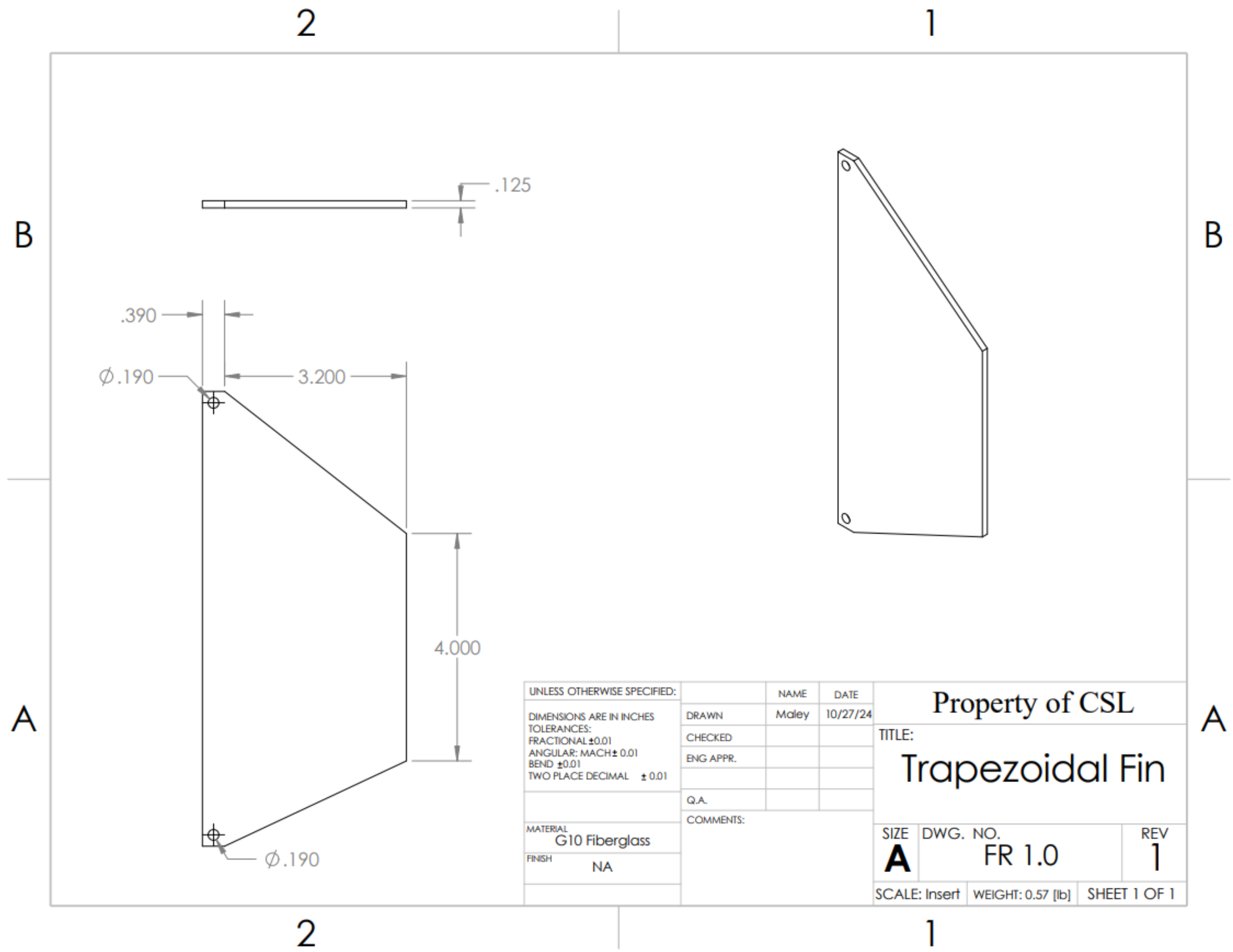

Figure 3.5.4. *SolidWorks drawing for Trapezoidal Fin.*

3.6. Fin Retention System

3.6.1. Centering Rings

The centering rings are essential for high-power rocketry to secure the motor tube and fins within the rocket's airframe. The centering rings provide proper alignment which is crucial for stable flight. Figure 3.6.1 provides the leading design choice for the centering ring. The centering ring will be manufactured using Cedarville University's Computer Numerical Control (CNC) machine and all the holes will be tapped by either the drill press or mill. This design choice provides the holes that attach the centering ring to the airframe offset from the fin connections. Reducing weight and reducing complexity are two of the reasons CSL is choosing this design iteration. The SolidWorks drawing model for the centering rings is shown in Figure 3.6.2. CSL will be using 18-8 Stainless Steel Button Head Hex Drive Screws to connect the fins to the centering rings.

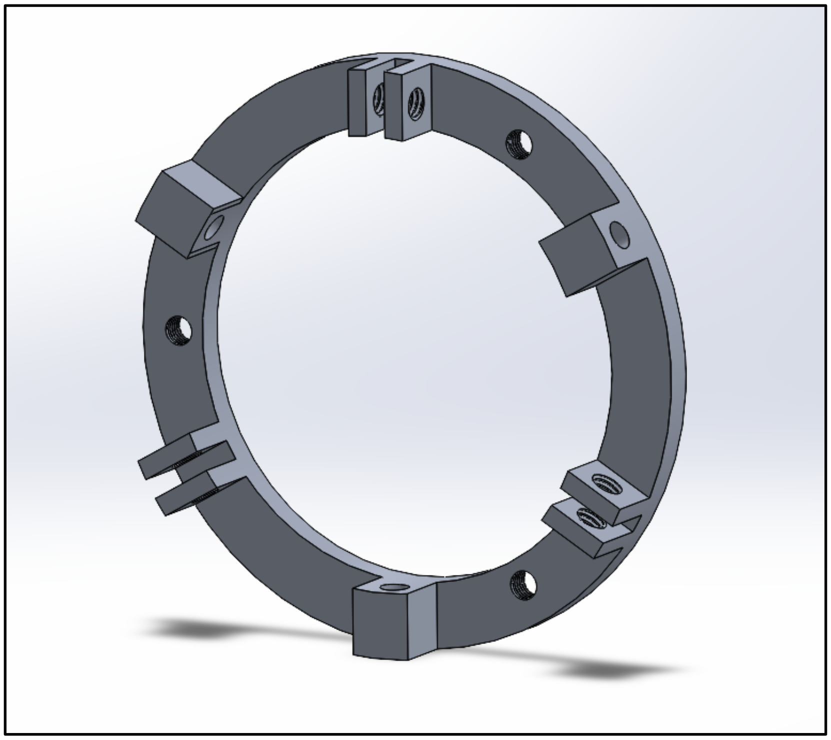

Figure 3.6.1. *Leading Design of the Centering Ring.*

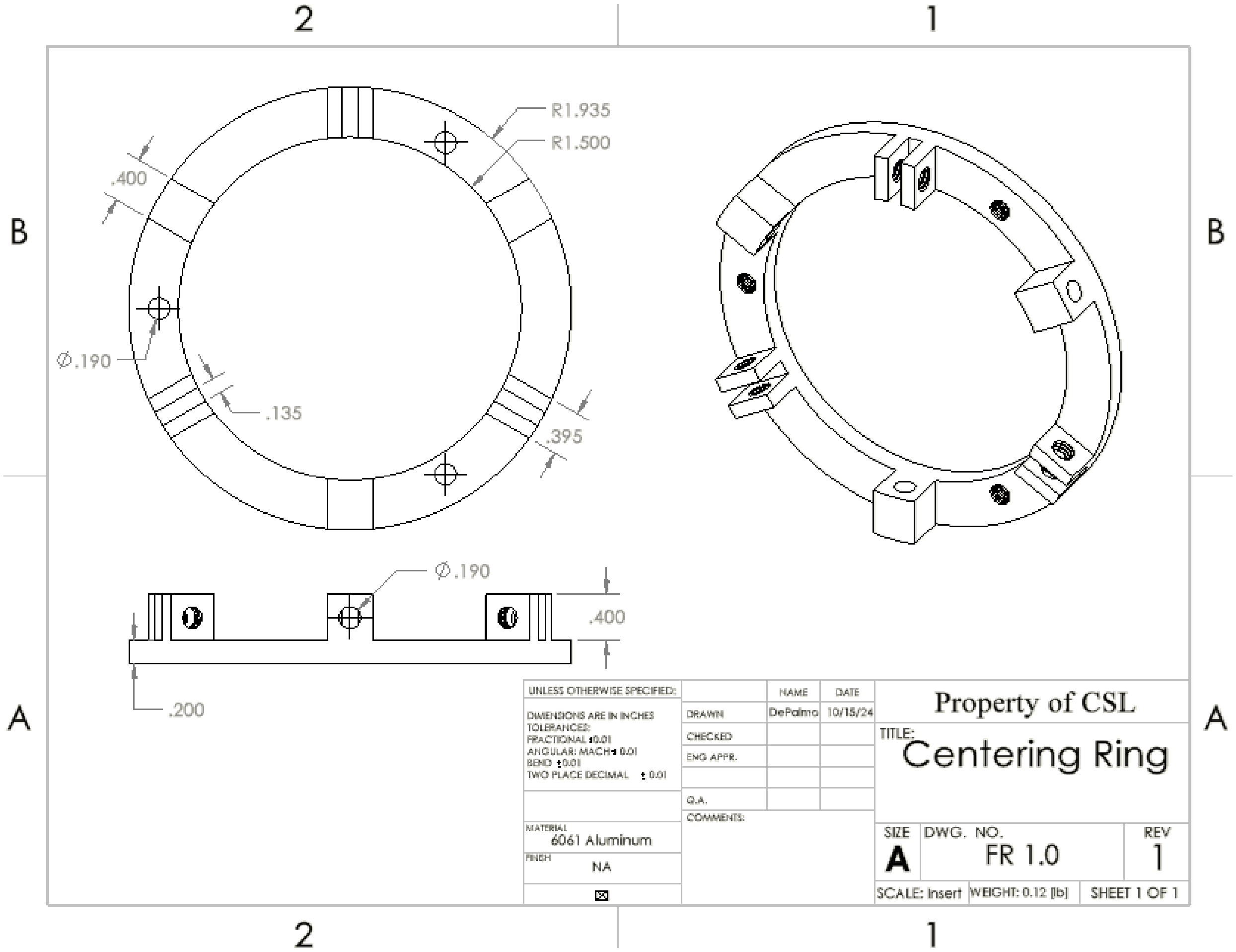

Figure 3.6.2. *SolidWorks Drawing of Centering Ring.*

3.6.2. Motor Retainment Flange

The motor retainment flange is a 3D printed piece designed to keep the motor centered in the motor retention system. The goal of this design is to reduce the weight of the assembly by using 3D printed components. The flange will be glued to the motor retainer so that the motor tube will be installed correctly. Figure 3.6.3 provides an image of the flange while Figure 3.6.4 shows the SolidWorks model with dimensions of the flange.

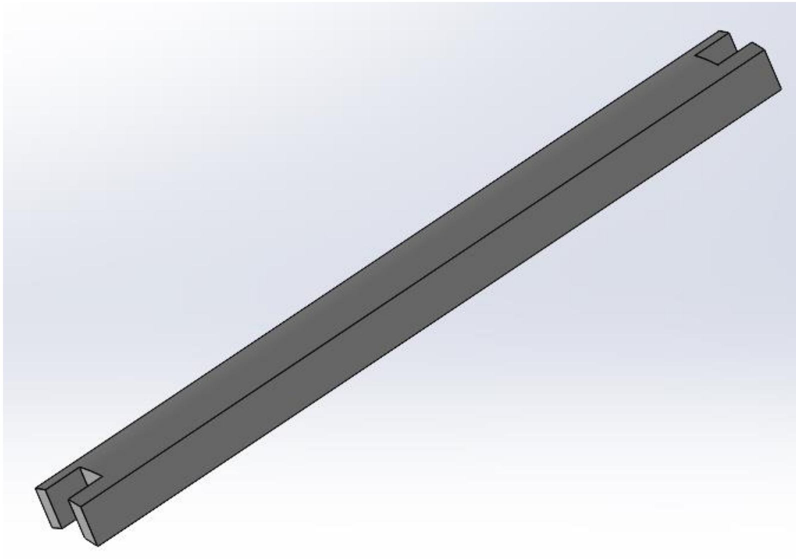

Figure 3.6.3. *Motor Retainment Flange.*

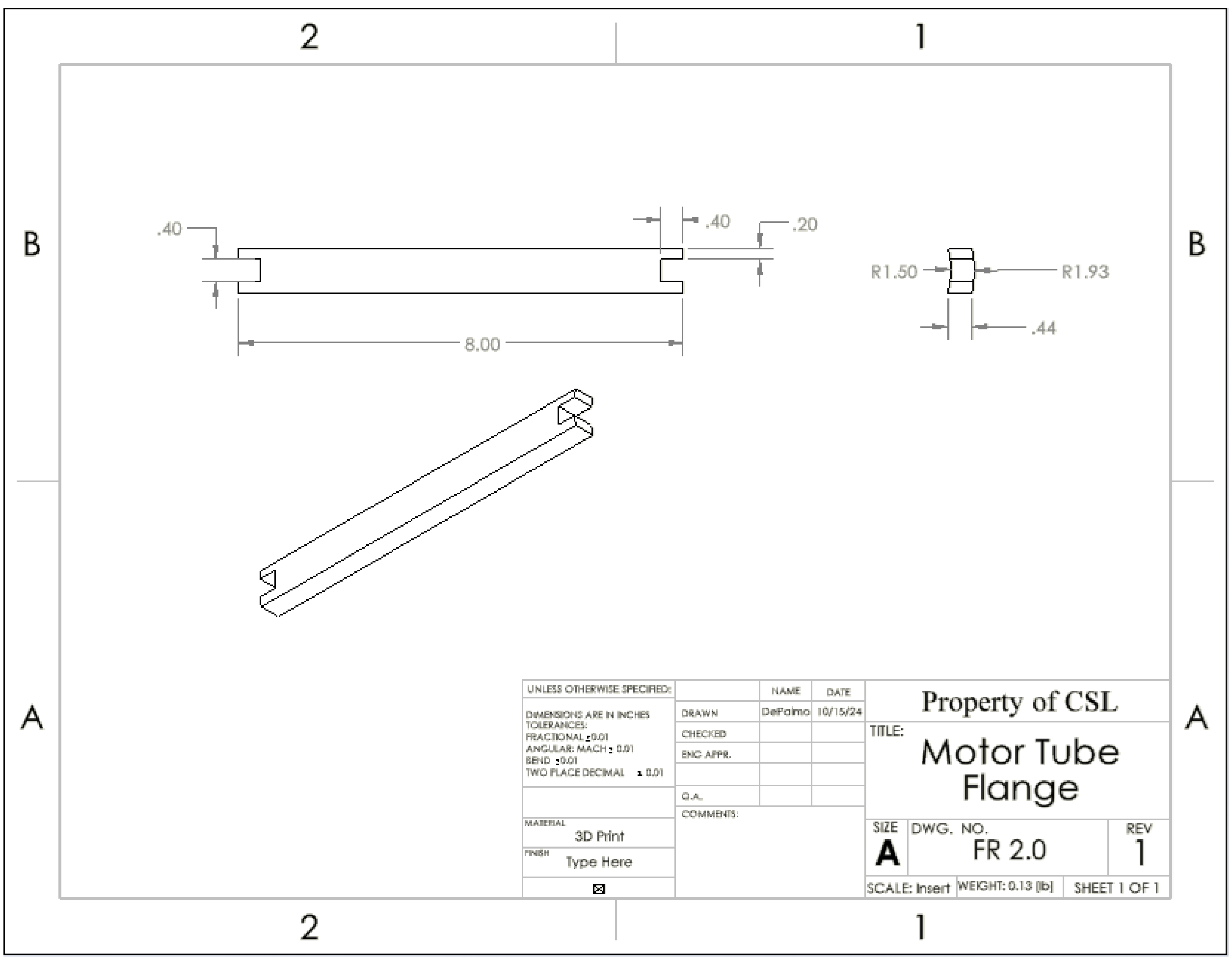

Figure 3.6.4. *SolidWorks Drawing of Motor Retainment Flange.*

The motor retainment flange will be positioned between each centering ring as shown in Figure 3.6.5. The design is simple and reduces complexity compared to previous CSL's design iterations. The main goal is to reduce the amount of complex manufacturing components and still provide the same amount of strength as compared to a metal motor retention plate. Figure 3.6.6 presents a motor retention plate drawing from the 2023 CSL team.

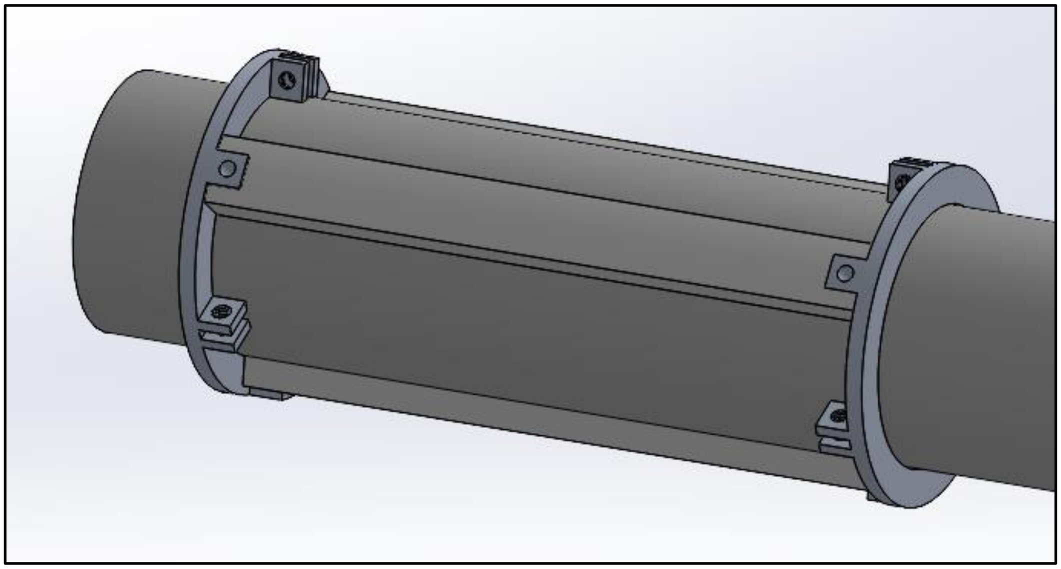

Figure 3.6.5. *Motor Retainment Flange Assembly with Centering Rings and Motor Tube.*

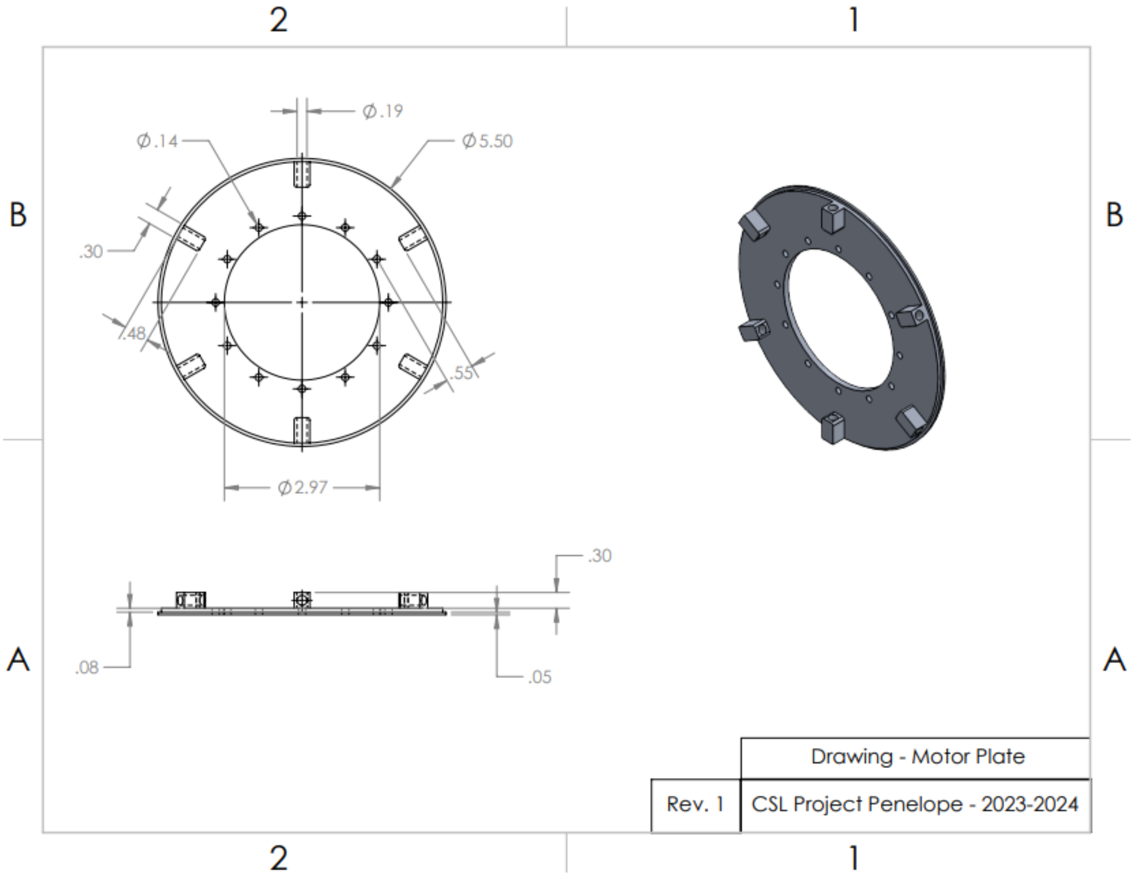

Figure 3.6.6. *Motor Retention Plate from CSL Project Penelope 2023 – 2024.*

3.7. Airbrakes

The rocket apogee without airbrakes is projected to be about 4428 [ft], which exceeds the CSL team prediction. Therefore, the secondary experimental payload will be an airbrake subsystem (AB) to reduce the altitude. The airbrakes system works on ascent after motor burnout, increasing the drag of the rocket which lowers the apogee of the rocket to an ideal predicted altitude of 4100 [ft].

During flight, the AB will activate after motor burnout. The microcontroller, using a state space model, will calculate the predicted apogee using current altitude and speed. If the microcontroller predicts an apogee exceeding the target, it will then deploy the AB proportional to the error between the microcontroller's prediction apogee and the CSL team's desired apogee. After reaching apogee, the airbrakes will retract into the fuselage.

AB success will be evaluated using the following criteria:

1. Confirmation of AB deployment during launch.
2. AB were stowed within ± 2 seconds of apogee.
3. Rocket apogee achieved within ± 25 feet of target altitude.

3.7.1. Airbrakes Surface Selection

The AB requires a surface which will be thrust into the airstream, which the CSL decided through CFD analysis (Computational Fluid Dynamics). Blade brakes were initially considered, a preliminary CFD model was created using an arbitrary rocket with an approximate blade system It is important to note that this rocket does not represent the final CSL rocket, but it was a baseline rocket to compare the drag force induced by the blade and flap brakes. Figure 3.7.1 shows the CFD model of the rocket with blades. It creates a modest drag force along the sides with blades in the flow path. For baseline comparison, a CFD model without brakes was used to calculate drag.

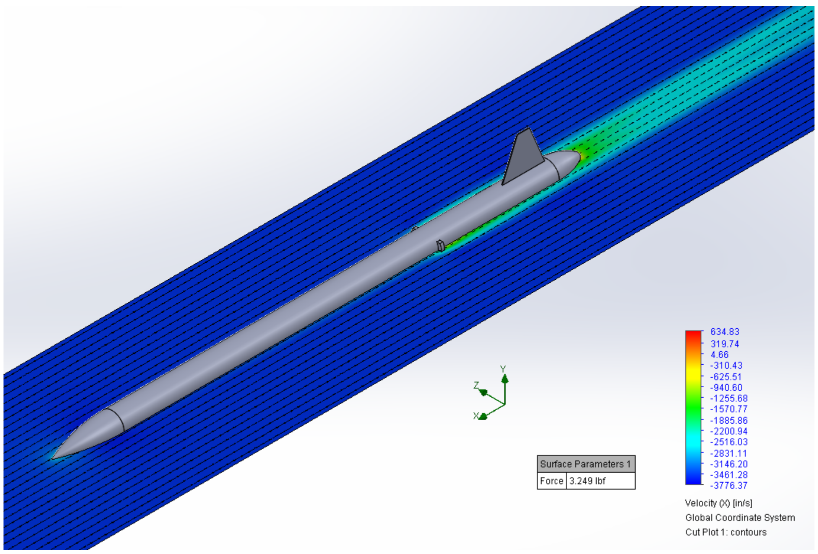

Figure 3.7.1. *CFD simulation of the arbitrary model rocket showing drag forces generated by blade brakes.*

In contrast, Figure 3.7.2 illustrates the flap brake system in the CFD model. The model shows, with color intensity, the flap breaks create a larger drag force than do the blade brakes.

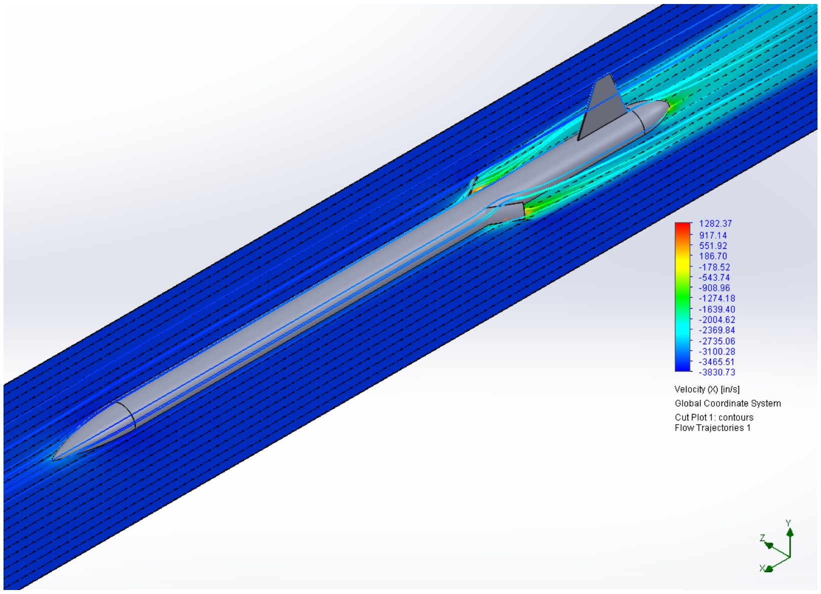

Figure 3.7.2 *CFD of the arbitrary model rocket showing drag force generated by flap brakes.*

Table 3.7.1 shows the approximate drag forces of the rocket with no brakes and the two different types of airbrake systems. Since flap brakes possess the highest drag force it was selected to as the drag surface type.

Table 3.7.1. *The flow characteristics of each CFD model.*

Model Name	Drag Force [lb]
No Brakes	3.0
Blade Brakes	3.2
Flap Brakes	6.0

3.7.2. Airbrakes Kinematics

Kinematics starts with type synthesis, which is a basic crank slider mechanism (Figure 3.7.3). This model serves as the building block through which all ideas came from since it was simple in nature and translated linear motion to angular motion. The design idea was to pivot the flap on a hinge attached to the rocket body (noted as the “pivot position”). A motor, like a 3D printer, would actuate the lead screw, which connects to the output link, forming part of the flap when extended.

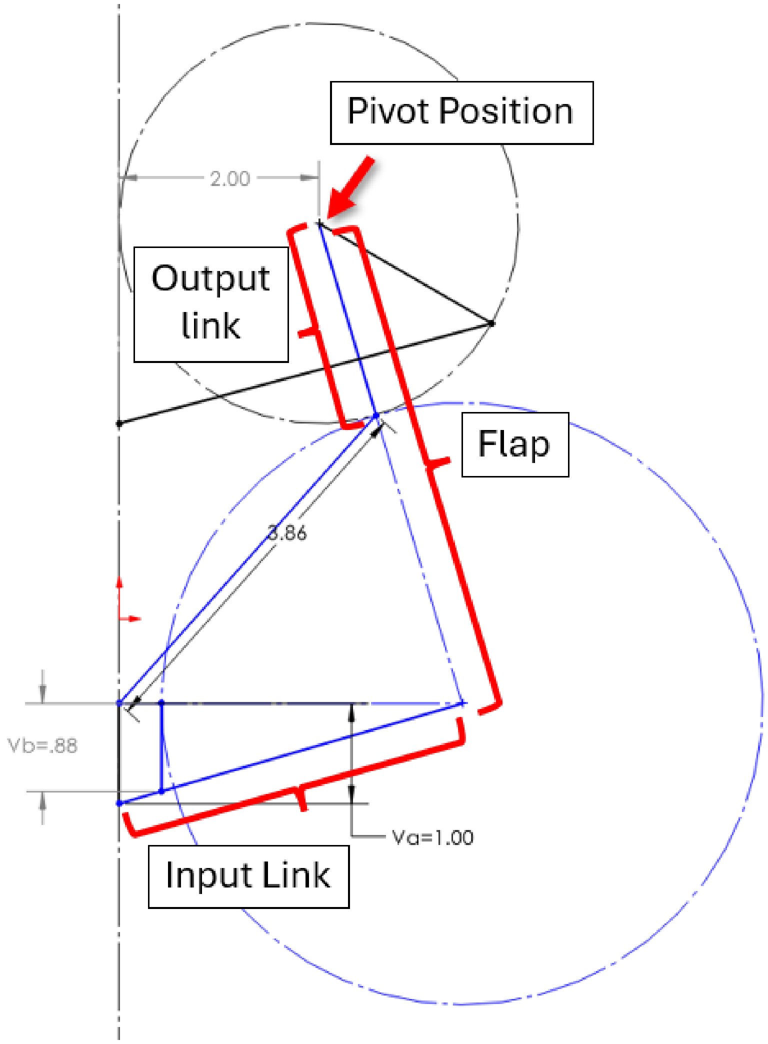

Figure 3.7.3. *AB simple crank slider kinematic synthesis and velocity ratio analysis.*

The second mechanism type synthesized was a four-bar linkage connected to a crank slider (Figure 3.7.4). Adding this four-bar was to flatten out the angular velocity ratio of the flap to make it constant over its the range of motion and to avoid overloading the motor (Norton, 2009). Without this constancy, the mechanism accelerates and decelerates, which causes a nonlinear control in the software due to the change in velocity over its motion. High accelerations in motion cause high forces on the inputs and outputs of the links, which will then increase the battery drain. Thus, achieving a close-to-constant angular velocity ratio was essential.

There were multiple problems with the four-bar/crank-slider. The execution of this idea seemed highly impractical, since the rocket body was four inches in diameter and there was not enough space in the fuselage for the number of members needed. Additionally, the amount of weight added in material was more than a crank slider. Overall, this was a step in the right direction by attempting to level out the velocity ratio, but it seemed quite impractical.

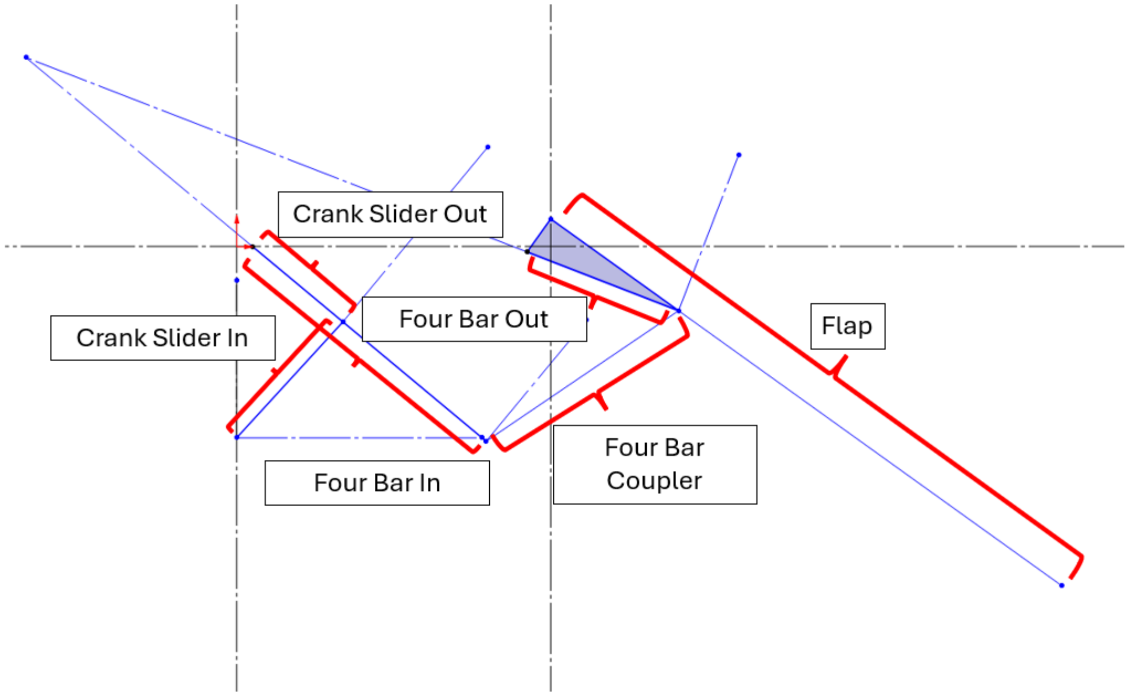

Figure 3.7.4. *AB four bar kinematic synthesis and velocity ratio analysis.*

To address the impracticality of the four-bar mechanics the crank slider was altered by reducing the distance between the hinge pin and the rocket centerline (Figure 3.7.5). This adjustment yielded a more favorable theoretical velocity ratio with a gradual slope near zero slope over the $0 - 30°$ flap angles (Figure 3.7.7) which is the maximum angle the airbrakes will likely actuate, but they are designed to handle angles of up to 60° for contingency. The minimum transmission angle was calculated to be 48.39°, indicating efficient force transmission from the motor to the flap. Unfortunately, this design increased the practical complexity of the system, which necessitated modifications to the flap and airframe cut shapes.

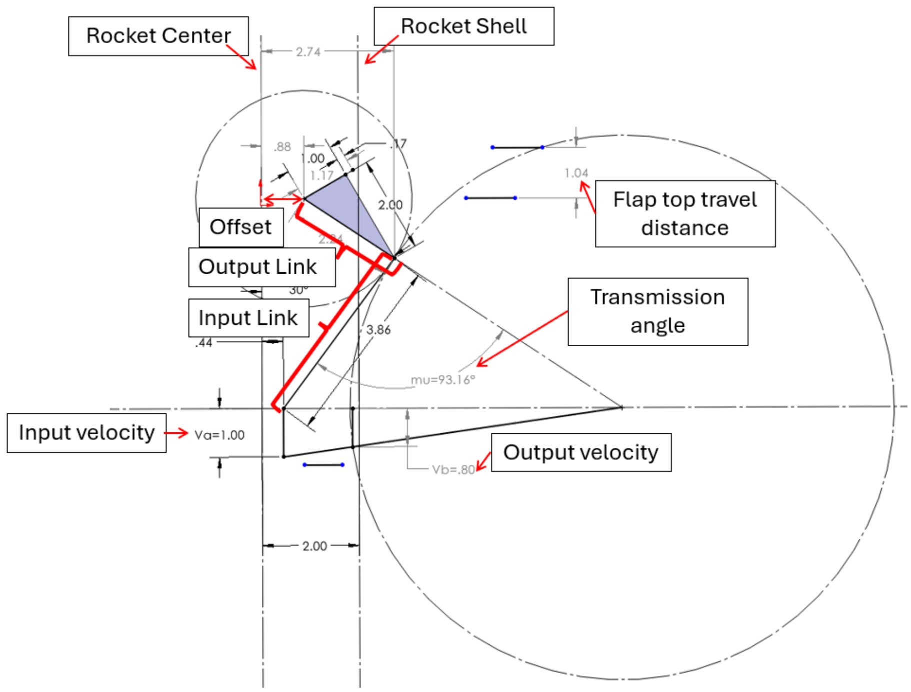

Figure 3.7.5. *AB crank slider V6 kinematic synthesis and velocity ratio analysis.*

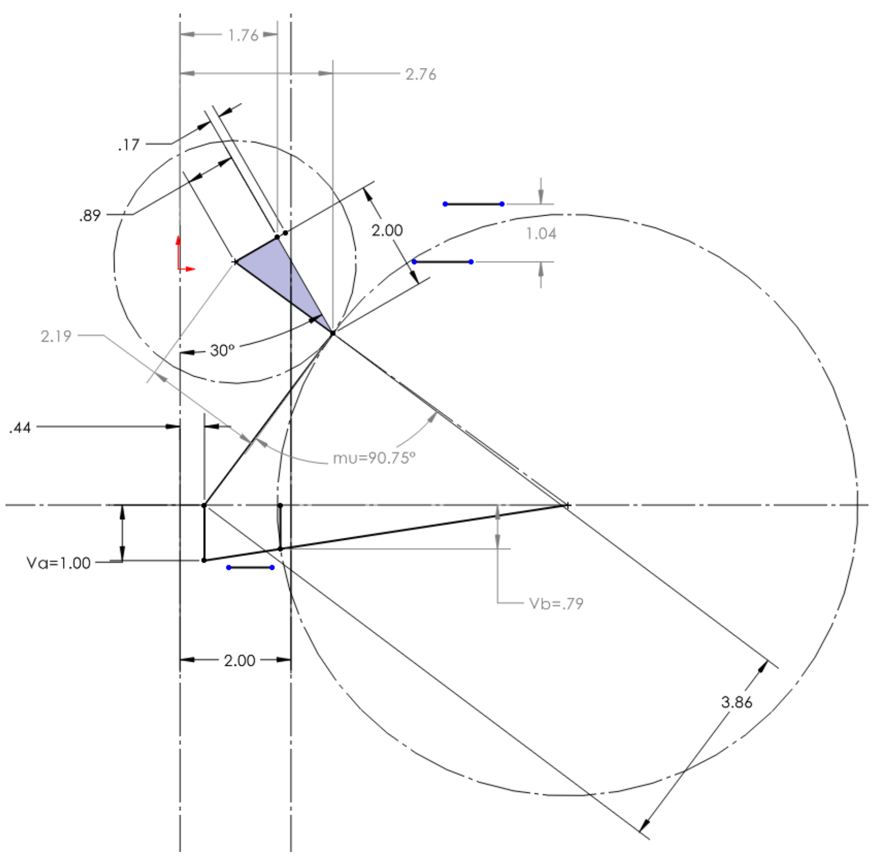

Figure 3.7.6. *AB final crank slider kinematic synthesis and velocity ratio analysis.*

Once the kinematic model was selected to be theoretically superior there were certain concerns with practicality, so to minimize those a final version of the crank slider was synthesized and analysis. (Note: although it is labeled as "final" this version is still under consideration for rework at the discretion of the CSL due to underseen compatibility issues during the manufacturing process.) Only small changes were made with the offset distance, so if the velocity ratios for crank slider V6 and crank slider final are compared they are slightly different which can be seen in Figure 3.7.7.

A final crank slider configuration (Figure 3.7.6) was synthesized to address the practical issues posed by the ideal theoretical crank slider solution (Figure 3.7.4). Minor adjustments were made to the offset distance to ensure no interference between the flap and the airframe. It increased the slope of the velocity ratio but was still a very respectable solution. (Note: This "final" design is still subject to modification as manufacturing issues arise.)

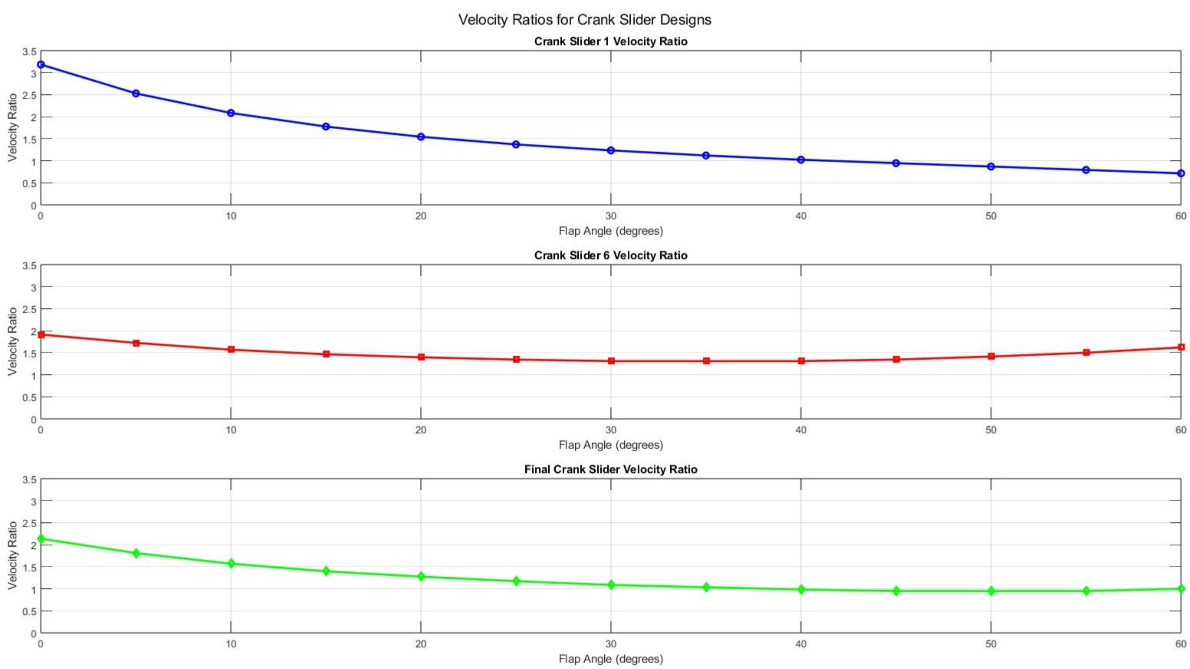

Figure 3.7.7. *Angular velocity ratios for crank slider design on the AB subsystem. Refer to Appendix A.4 for MATLAB analysis code.*

3.7.3. Airbrakes Mechanics

With the kinematics of the AB established, the mechanics were developed using the philosophy of an MVP (minimum viable product) (Ries, 2011) for fast iterations and quick cycle times. In Figure 3.7.8 the mechanics of the air brakes were modeled in SolidWorks giving rigid body shape to the kinematics without focus on compatibility. The L-bracket allows flap removability without compromising rigidity. The ternary link features a moving and fixed pivot and is made from aluminum. While the coupler is carbon fiber, and clevises 1 and 2 are aluminum (full and final material selection is discussed in a later selection of the AB).

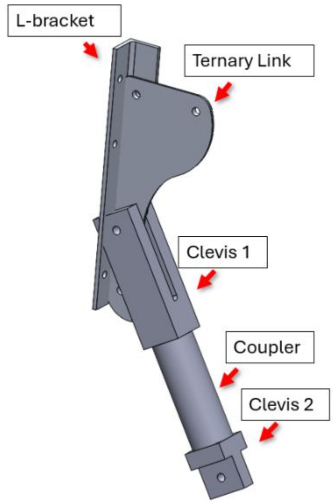

Figure 3.7.8. *Iteration one of AB mechanics.*

Due to challenges with Figure 3.7.8, Figure 3.7.9 is a refinement of the previous iteration. Featuring a clevis which fits with the other components, a reasonably sized coupler, and a 3D printed flap

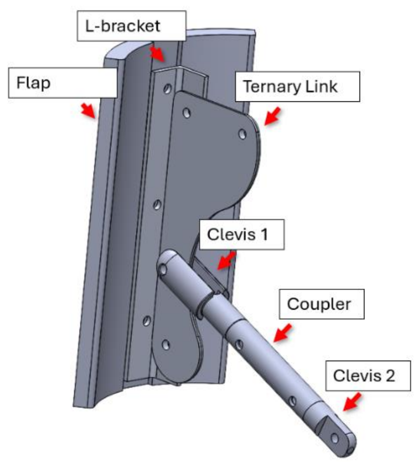

Figure 3.7.9. *Iteration two of AB mechanics.*

The third iteration of the AB (Figure 3.7.10) approached design from a new perspective, prioritizing the lead screw alignment as the base. The coupler is made from carbon fiber pultruded rods with a 3D printed ternary link, gussets, and slider anchor. The ternary link was changed because 3D printed material (Davies, 2021) is much lighter than aluminum (Engineering Toolbox, 2004), and to reduce part count the L-bracket was removed which reported the ternary link in direct contact with the flap.

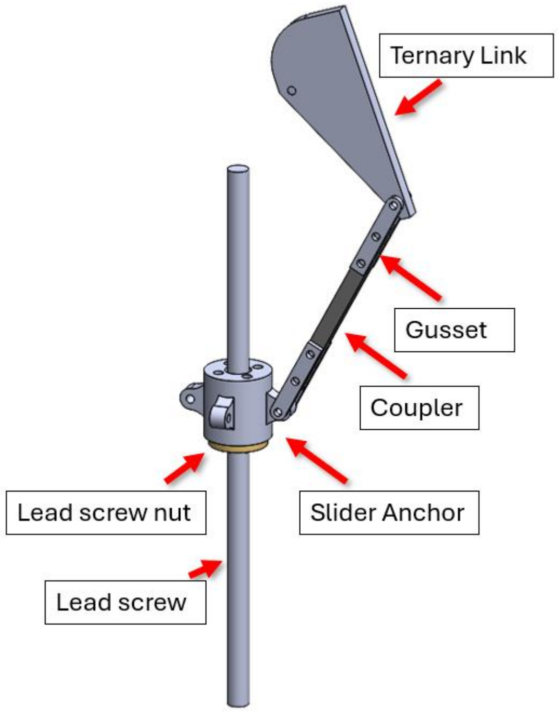

Figure 3.7.10. *Iteration three of AB mechanics.*

In Figure 3.7.11 the fourth iteration features a refined form of the ternary link with a snug fit against the flap. To resist the against flex in the structure the slider was optimized to support a carbon fiber rod. This carbon fiber rod serves two purposes: AB rigidity reinforcement as it runs from the top to the bottom of the AB subsystem keeping it rigid, and second it guides the slider anchor when the motor turns the lead screw, so it will therefore counter any moments induced on the couplers, and drastically reduce bending stresses inside the couplers from out of plane bending.

Figure 3.7.11. *Iteration four of AB mechanics.*

The fifth and final iteration (Figure 3.7.12) incorporates a high-speed, high-precision acme lead screw. Due to the pivot location the shape of the flap could not be rectangular therefore imposing airframe interference. Instead, the top of the flap, using heuristic methods, was modeled until proper fitment was attained later during AB integration. 3D printed spacers were placed between the coupler and gusset to account for tolerance issues.

3.7.4. Rationale for Airbrake Flap Number

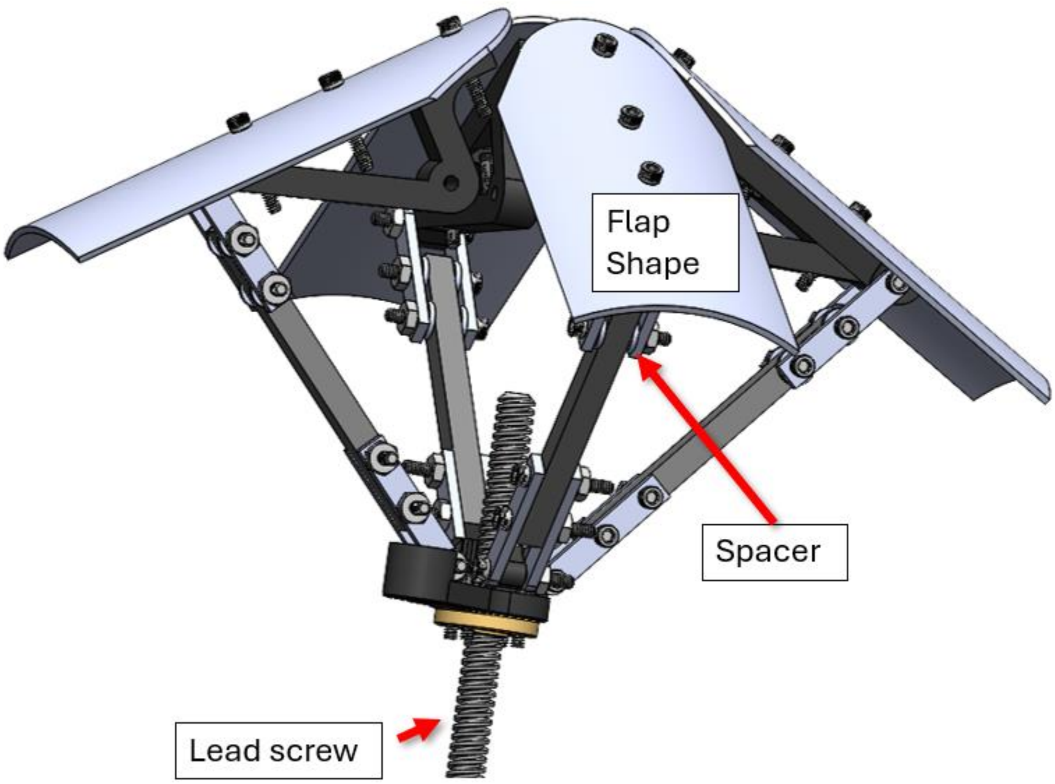

Figure 3.7.12. *Iteration five of AB mechanics.*

Figure 3.7.12 includes four flaps, which were selected based on two primary considerations. First, four flaps distribute force more effectively than a three-flap configuration. With four flaps, each coupler bears the force of the drag induced on its own flap, and using newtons third law, Figure 3.7.13 demonstrates it bears the load for the flap from the coupler across from it. In contrast, a three flap system results in each coupler bearing drag forces from not only its own flap drag force, but also from the drag forces of the adjacent flaps as shown in Figure 3.7.13. In summary, three flap system couplers bear the load of three flaps, and four flap systems bear the load of two flaps.

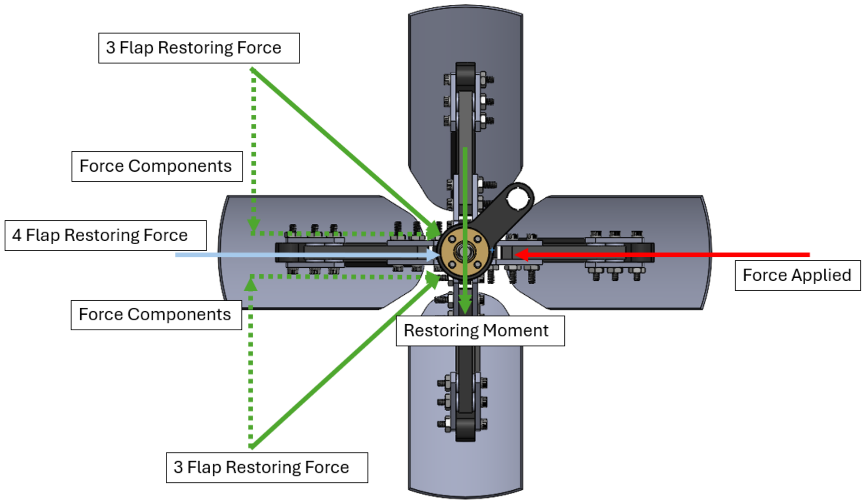

Figure 3.7.13. *Force distribution on the AB for three or four flaps.*

Second, since vertical space and therefore weight are constrained, the most compact design is most desirable. Refer to Table 3.7.2 and notice that the four-flap solution bears the most drag, so the four-flap solution induces maximum drag per inch height. (Note: This analysis was performed similarly to the CFD analysis at the beginning of the AB section.)

Table 3.7.2. *Drag induced per each flap number.*

Flap Number	**Drag Induced [lb]**
2	6
3	7.3
4	8.5

3.7.5. Airbrakes Electrical & Controls

The (AB) system relies on an integrated electrical control system. Figure 3.7.14 shows the flow of this system as it is broken down into three major components.

1. **Sensor Inputs:** The control system gathers data from noisy sensors.
2. **State Estimation:** Due to noisy data, a state estimator processes through this data using an algorithm to parse through outliers and estimate the current position and velocity.
3. **PID Control:** Using the current state of the rocket, the PID control compares target apogee with predicated apogee, and takes action according to the feedback system.

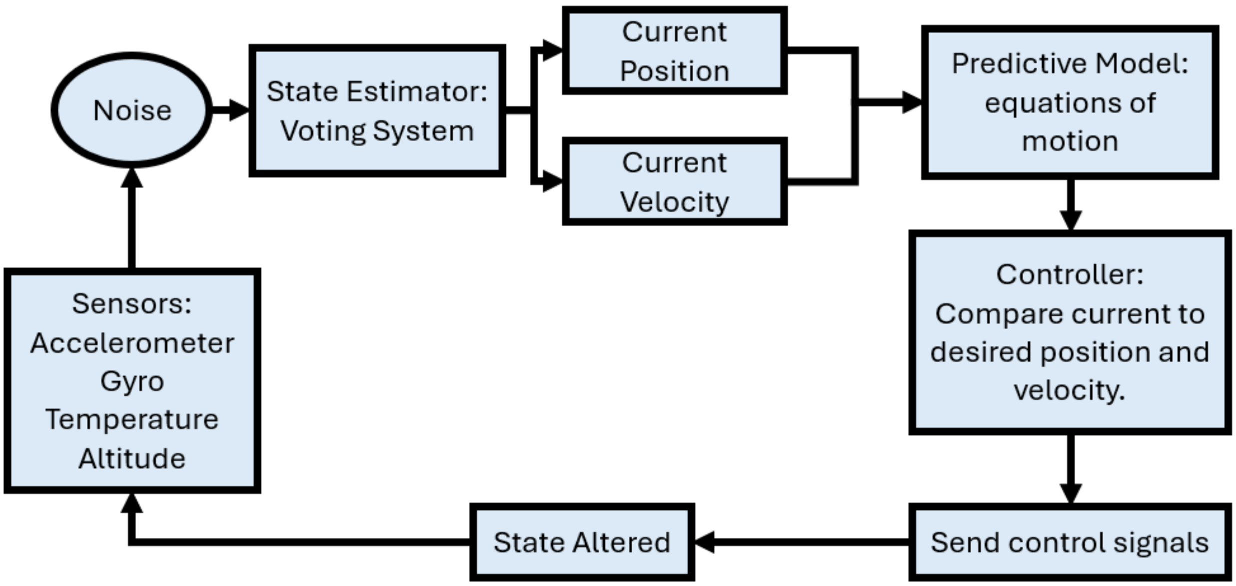

Figure 3.7.14. *Flow diagram of the control system from raw input to control output to mechanical system.*

Figure 3.7.15 and 3.7.16 shows sensors: the GY-521 accelerometer/gyroscope and BMP 280 altimeter/thermometer, respectively. The GY-521 was chosen over the GY-61 due to its digital ignal output, which reduces interference (Turito, 2024; Cepiio, 2024). The BMP 280 was selected over the BMP 180 due to its high-resolution pressure (±0.16 Pa) and temperature (±0.01 °C) measurement capabilities. In addition, it could communicate over SPI, which is a more robust data transfer library over I^{2}C (Main, 2024; John, 2015).

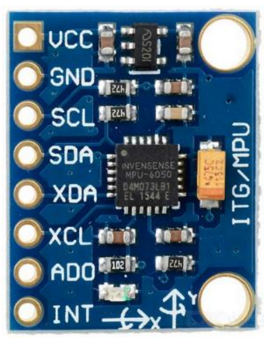

Figure 3.7.15. *The GY-521 accelerometer sensor.*

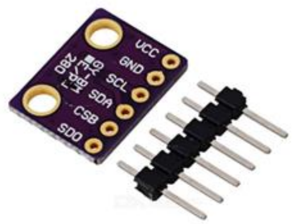

Figure 3.7.16. *The BMP 280 pressure and temperature sensor*.

Microcontroller Trade Study

Table 3.7.3 compares the two potential microcontrollers: the Raspberry Pi Pico and the Arduino Nano. Both have essentially the same communication protocols (I^2C, PSI, UART), the Pico was selected for its dual-core processing, high clock speed, and large memory, making it suitable for simultaneous sensor data handling in a high-speed computing applications. Using the Arduino IDE with the Pico also simplified the programming from the team (Philhower III, 2023). Refer to Figure 3.7.17 for the chosen microcontroller.

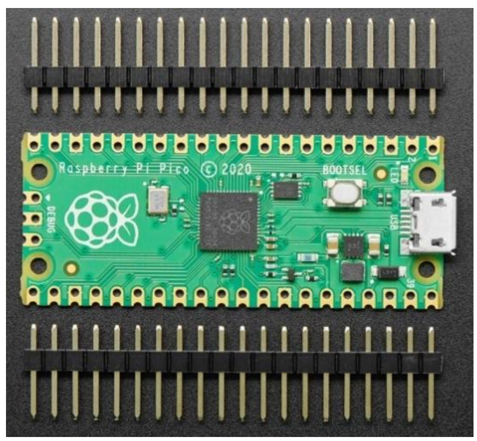

Figure 3.7.17. *Raspberry Pi Pico microcontroller selected.*

Table 3.7.3. Microcontroller trade study.

Microcontroller	Architecture	Clock speed	Memory	I/O	Programing Languages
Raspberry Pi Pico (Pi, 2024)	RP2040: dual-core ARM Cortex-M0+	133 MHz	264KB SRAM, 2MB flash storage	26 GPIO pins, with support for digital, analog (3 ADC pins), PWM, UART, I2C, SPI, and PIO (Programmable I/O)	C++, MicroPython, Arduino IDE
Arduino Nano (Arduino, 2021)	ATmega328: 8-bit AVR architecture	16 MHz	2KB SRAM, 32KB flash	14 digital I/O pins, 6 analog inputs, with PWM, UART, I2C, and SPI	Arduino IDE

State Estimation Trade Study

Table 3.7.4. Trade study of filters for state estimation. 1-3 goes from best/highest to lowest/worst.

Filter Type	Accuracy	Robustness to noise	Computational Complexity	Adaptability	Complexity of Implementation	Experimentation Required?
Kalman (Explained, 2021)	1	1	1	2	1	Yes
Voting & Average	2	2	2	1	2	No
Assuming Correct Sensors	3	3	3	3	3	No

Table 3.7.4 summarizes the trade study of state estimators. A Kalman filter, is quite accurate and robust to noise, was ruled out due to its computational complexity and limiting testing opportunities. The sensors could not be assumed correct because the sensors create intense signal noise and would ruin data reduction performance. Instead, a voting and averaging approach was selected for its adaptability and ease of implementation.

Control System Model

The leading AB control system relies on a PID controller, which adjusts the airbrakes based on current position, velocity and altitude data. After motor burnout, the controller calculates apogee and adjusts airbrake flaps to adjust the projected apogee. Initial drag coefficients will be estimated through CFD modeling and refining with subscale launch data, which will iteratively improve model accuracy. This dynamic control system will allow real-time adjustments using a basic model grounded in newtons laws and NOAA atmospheric models.

Motor and Battery Selection

The motor selection is based on table 3.7.5 which compares a stepper motor to the chosen DC motor, which is displayed in Figure 3.7.18. The DC motor was selected for the following reasons: its lightweight design, high torque, and lower power consumption, which are key appoints of application in the aerospace industry and for the kinematics of this design (Embedded, 2024; Linear, n.d).

Figure 3.7.18. *Motor selected for the airbrakes.*

Table 3.7.5. *AB motor trade study.*

Motor Type	Weight [g]	Speed [RPM]	Amperage [A]	Size [in]	Torque [lb-in]
ZYTD520	203	10	0.16	3.5	15.6
NEMA 17 Stepper Motor	500	200-600	1.4	1.54	1.4

Battery selection was focused on balancing minimizing weight, size and battery discharge, and maximizing motor speed Table 3.7.6 compares the Zeee 3S LiPo Battery and the Liperior 3S battery. The Zeee 3S battery outperformed due to its faster speed and lower discharge rate, making it the optimal choice for sustaining motor performance (Figure 3.7.19).

Figure 3.7.19. *Primary battery selected for the AB.*

Table 3.7.6. *AB main battery trade study.*

Battery Type	**Weight [g]**	**Motor Speed [in/s]**	**Size [in]**	**Battery Discharge [%]**
Zeee 3S Lipo Battery 1500mAh 11.1V 120C Graphene Battery	130	1.480	2.5	2%
Liperior 2200mAh 3S 35C 11.1V Lipo Battery	121	0.882	4.25	3%

Motor Controller and Rotary Encoder

Since the motor is controlled by the Raspberry Pi Pico it must have a motor controller which will deliver the logic to a motor. The motor controller selected to do the job was an RDI0002 which is shown in Figure 3.7.20. This features a logic driven motor control, and a segregation of low voltage and high voltage using a dual high-power H-bridge driver. The second option was to use a small 12-volt relay, but a relay does not have logic to control speed, so it can only turn on or off. Although the motor controller was bigger it was the final decision (Figure 3.7.20).

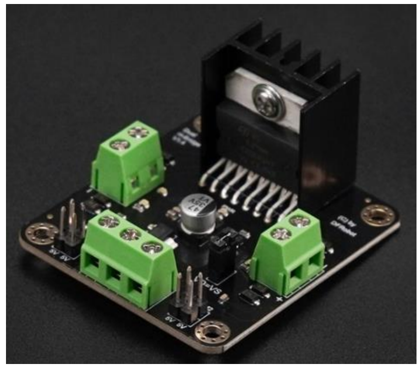

Figure 3.7.20. *Motor controller selected for the AB.*

The lead screw was rotated by a DC motor, so three methods were ideated to solve this problem. Table 3.7.7 compares the different solution types. The first solution was to start the system at a consistent position and use time and motor speed to determine how far it had gone. The main problem with this is the inconsistencies in battery voltages, so the speed would not be constant. Additionally, if the load of the battery changed (as it is expected to do) then the speed would change. The lpd3806-600bm-g5-24c is an optical rotary encoder used for very precise applications, so it gives a very high pulse per revelation count, which is far too great for the application of the AB. If this were used, it would overwhelm the system with data because of the vast amount of data being recorded at once. Therefore, the selected mode of rotary displacement sensor is the HW-040 rotary encoder which is shown in Figure 3.7.21.

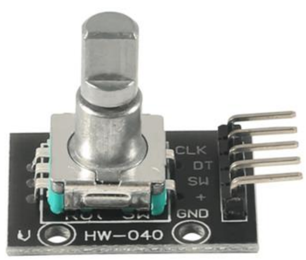

Figure 3.7.21. *Rotary displacement sensor selected for the AB.*

Table 3.7.7. *AB rotary displacement sensor trade study.*

Encoder Type	Performance	Measurement	Size [in]
HW-040 (Cirkit Design, 2024) (Maker Tutor, 2017)	20 pulses per revolution	Position, velocity, and acceleration	0.75
lpd3806-600bm-g5-24c (Fotek, 2024) (Devices, 2022)	400 pulses per revolution	Position, velocity, and acceleration	1.5
No Encoder	N/A	Time	0

The last electrical component in the control system is a stop button for the linear motion, which is a simple three Pin 3D printer micro sensor switch which is shown in Figure 3.7.22 (La Tiendita Online Store, 2024).

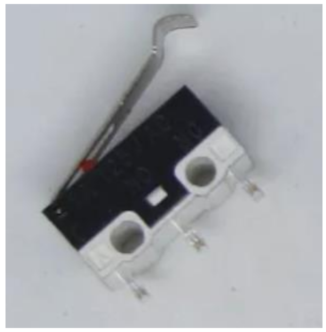

Figure 3.7.22. *The switch used in the AB electrical design.*

With all the components discussed that will be in the main electrical system, they have been arranged in a wiring diagram shown below in Figure 3.7.23. There is discussion of a backup system being implemented into the AB using hardware, but this has not been researched enough to know whether a backup system is necessary or if certain failures can be prevented in programing with no additional hardware required.

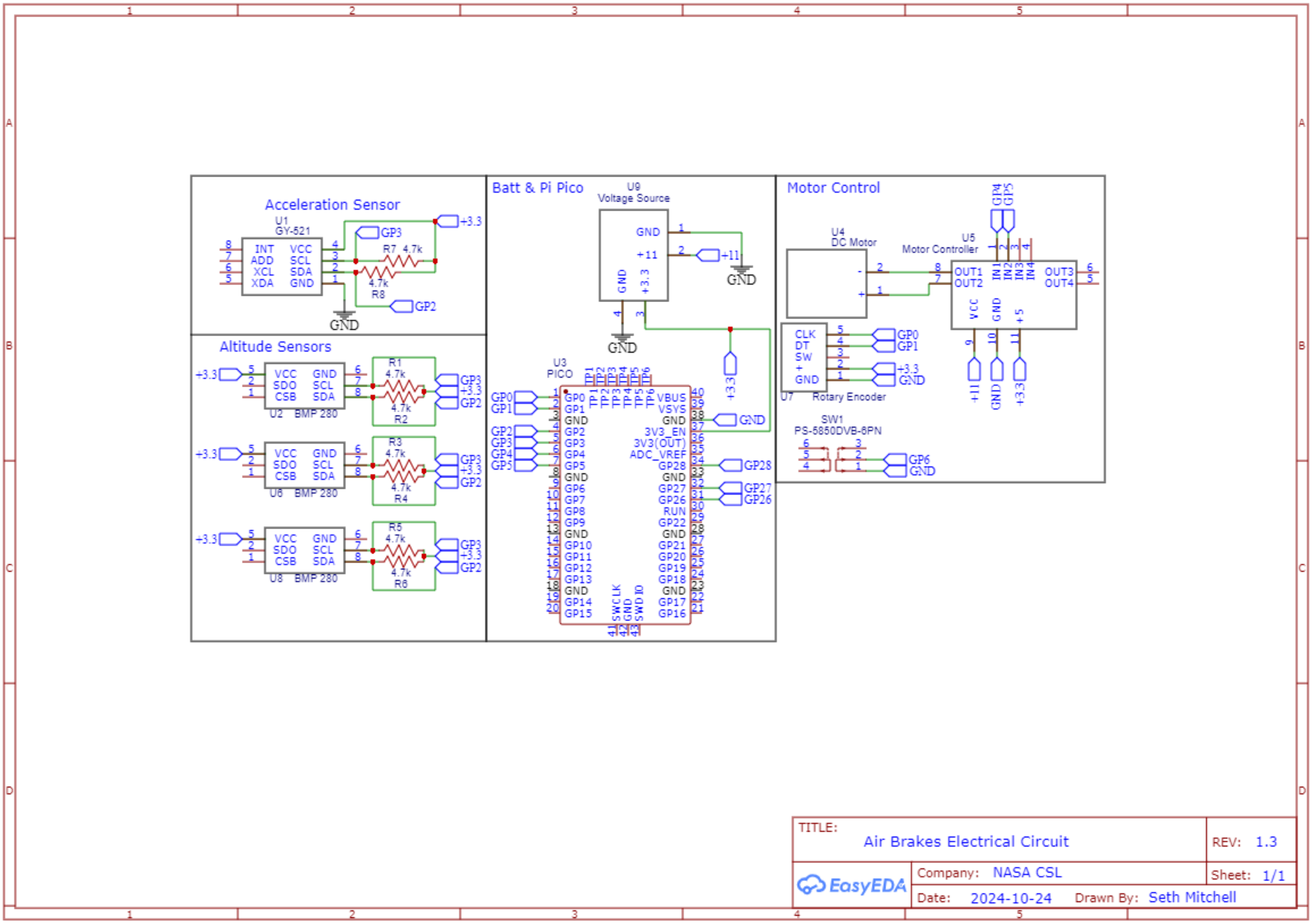

Figure 3.7.23. *Wiring diagram for the main electrical system in the AB.*

3.7.6. Airbrakes Integration

Figure 3.7.24 shows the airbrakes in the rocket airframe. As denoted on the figure, the flap shape changed, but this was predicted at this stage of design. Since the pivot point was not at the edge of the airframe, but pulled in toward the center of the rocket, the top of the airbrake flap pivoted both upward and inward. Therefore, the fin shape changed to fit the airframe once the model was in the assembly.

Holding the motor and motor controller is the motor mount, which will be 3D printed due to its low stress, complex shape, and relatively large size. The shaft is connected to the motor using a helical shaft coupler, this was chosen so any deflection in the threaded rod, which may happen due to air braking during flight, will not translate into the motor and have a change of inducing a stress on the internal components, i.e. bearings, of the DC motor. Last is the electronics canister, which is currently no taller than the battery, but there is currently no Computer Aided Design (CAD) model of each electronic component integrated with the mechanical system.

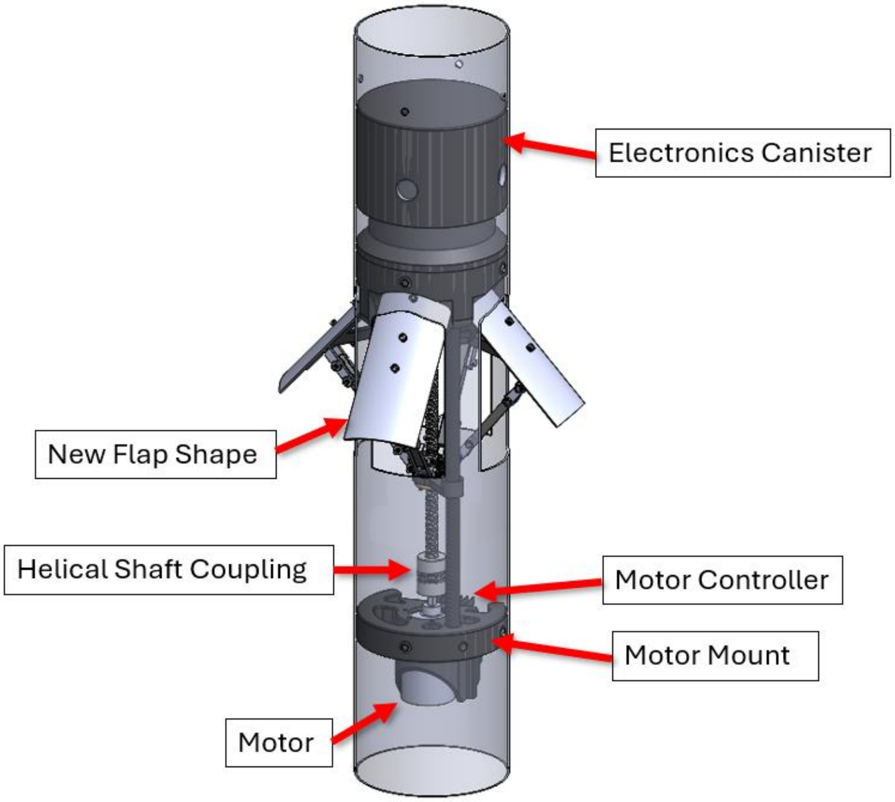

Figure 3.7.24. *AB in the airframe.*

Figure 3.7.25 emphasizes the positioning of the electrical components inside the mechanical design. The canister houses the battery, and the breadboard contains the BMP280 and GY-521. This is a perf board cut into a circular shape to fit the diameter of the rocket body. Not shown in the diagram, the backup electronics are housed below the breadboard and above the battery if it is used. Below this, in the canister, sits the battery.

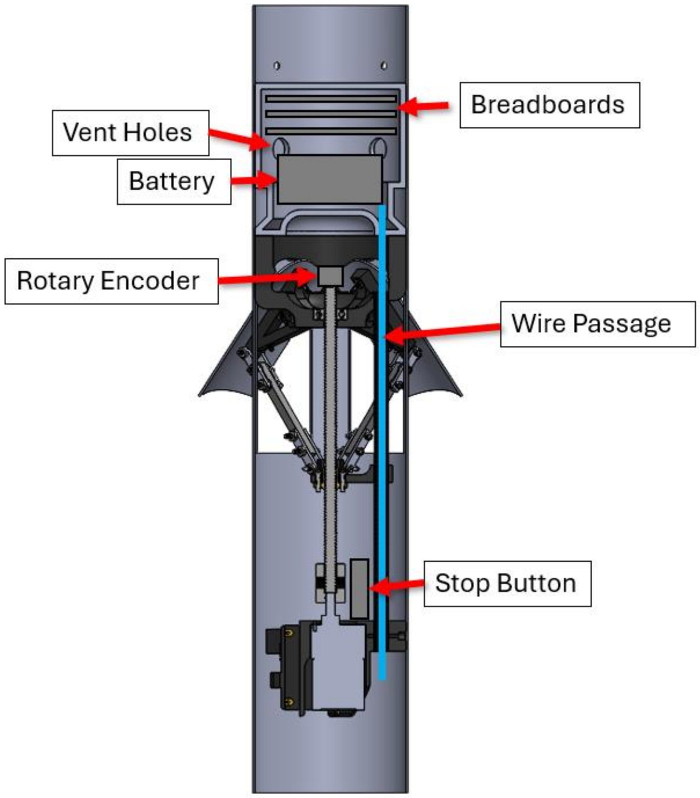

Figure 3.7.25. *AB section view emphasizing the positioning of electrical components inside the mechanical system.*

To go from the canister to the bottom of the airbrakes is a wire passage which can take up to eight wires using a high-quality cat8 cable (Amphenol Cables on Demand Administrator, 2024). At the top, below the canister, is the rotary encoder which will be fastened to the shaft. At the bottom the stop button will be fastened to detect when the mechanics have fully retracted. To see a drawing of the current revision of the AB, please refer to Figure 3.7.26, and refer to Table 3.7.8 to determine the current material selection and rational for each mechanical component.

3.7.7. Airbrakes Materials Selection

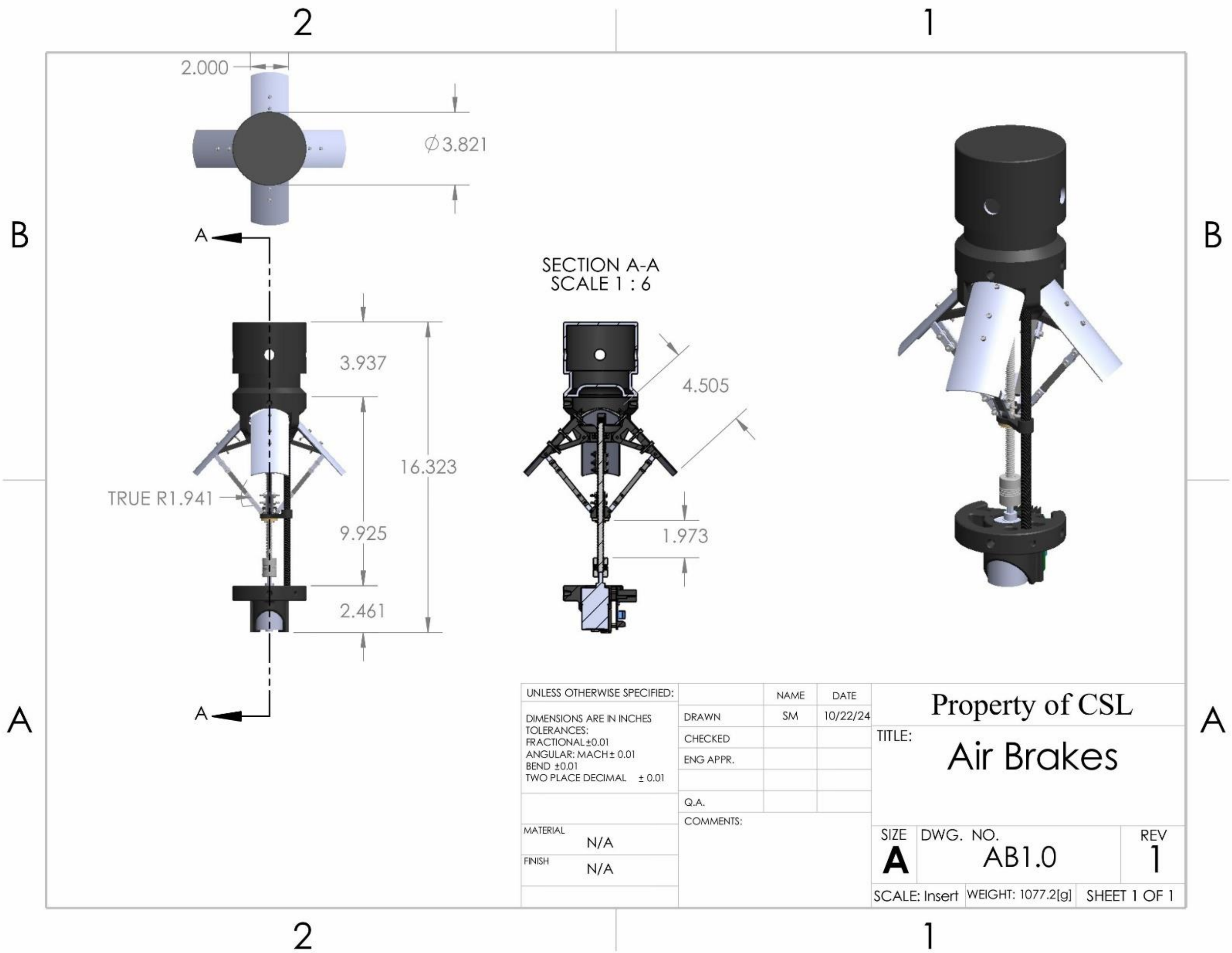

Figure 3.7.26. *Current revision of the AB.*

Table 3.7.8. Current material selection and rationality for each mechanical component.

Component	Material	Rational
Flap	TBD	Fiberglass cutout, PETG, or carbon fiber overlay.
Coupler	Pultruded Carbon Fiber with Epoxy	High stresses with lightest weight and a ridged structure desired.
Gusset plate	Aluminum	High stresses on a small component with tight tolerances.
Slider Anchor	PETG	Complex small geometry.
Spacer	PETG/PLA	very small tight tolerance and light weight.
Ternary Link	PETG	complex geometry and light weight desired.
Shaft Coupling	Steel	Small and structurally integral.
Lead screw	Steel	It will undergo large bending stresses.
Electronics Canister	PETG/PLA	Large and complex geometry.
Motor Mount	PETG/PLA	Large and complex geometry.
Encoder Mount	PETG/PLA	Large and complex geometry.
Wire Passage	Carbon fiber tube	Need space for wires and it acts as a structure rigidity.

As alluded to in Section 7.3.3 and Table 3.7.8, the flap material has not been chosen yet because research into material manufacturing difficulty and surface roughness has not been well documented experimentally, but options have been researched, and a preliminary decision is made. The first option was to overlay multiple layers of carbon fiber on a mold and vacuum seal it. This would be labor intensive, but the epoxy would lead to a very smooth surface roughness. If it was sanded the carbon fiber would be showing which would increase the roughness and therefore increase its drag (Zhang & Huang, 2021).

Second, the flaps could be 3D printed, which would lead to a thicker form factor than the carbon fiber, and it would be hard to print since it is a curved surface. Additionally, the surface roughness cannot be altered as much as carbon fiber because no matter how much sanding the surface would be quite rough (Hartcher-O'Brien et al., 2019). Lastly and the selected solution, the flap could be cut out of fiberglass, and it would be quite smooth, and by far the thinnest of all solutions, but the surface finish can only change via paint.

The coupler links are made from pultruded carbon fiber rods, which have a comparable tensile strength to steel, but are much lighter (Plastics, n.d.) (Performance Composites, 2009) (The Engineering ToolBox, 2003). The gusset plate was going to be made from 3D printed material such as PETG, but since the parts are so small they can be printed out of aluminum cut on the water jet without increasing the overall weight of the build by a significant amount. The slider anchor has very complex geometries for how small it is, so there is no good reason to machine it, therefore it will be 3D printed from PETG. The spacers could be made of small pieces of metal cut with the water jet, but to decrease the weight the material is 3D printed PETG or PLA.

The ternary link is a complex shape, and couple is not machined by hand on a mill with the current tooling available to the CSL, and to conserve weight it will be 3D printed, but if after a structural analysis and practical test they fail under load the material might need to be changed. The coupling and lead screw are steel simply because there are not many of these component's whare are available in other material selections, and steel offers high strength for integral components of the design.

The electronic canister, motor mount, and encoder mount are all large and complex with low stress, therefore it makes sense to print them from PETG. The wire passage is used to transport wires and as a structural brace through the whole of the design. The choices were aluminum, steel or carbon fiber. Since carbon fiber weave is slightly weaker than steel given its geometric and material stiffness (Plastics, n.d.) (Performance Composites, 2009) (The Engineering ToolBox, 2003), but it is much lighter, therefore it was the choice for the wire passage.

3.7.8. Airbrakes Mass

The airbrakes have an estimated mass from conceptual design to PDR reduction from a total of 1155 grams to 1077.2 grams, which is shown in Table 3.7.9. This is broken down into four sections, the first being the main body, which in the AB subsystem will be the components holding the system together, such as the motor mount and encoder mount. The second section is the flap mass, and the number given is the minimum possible design mass, which is the fiberglass material selection. In addition to the first two sections, the third and fourth section includes the electronics and bulk mass, which would be the microcontrollers, sensors, and wires.

Table 3.7.9. *Airbrakes Mass Estimates from conceptual design.*

	Conceptual	PDR
Main Body Mass (g)	454	239
Flap Mass (g)	364	187.2
Electronics Mass (g)	312	531
Bulk Mass (g)	25	120
Total Mass (g)	1155	1077.2

3.7.9. Airbrakes Conclusion

The AB subsystem is the experimental secondary payload, therefore certain elements are not and cannot be known at this point in the design process. Every component mentioned has the potential for slight alternations and revisions due to unforeseen issues during manufacturing, testing, and application.

3.8. Tail Cone

A rocket tail cone, or boattail, is the aft section of the launch vehicle that would bring the diameter of a rocket from the body tube to the engine tube. This would reduce drag on a system and provide an alternative to commercial motor retaining systems (Gregorek, 1970). Many factors should be considered when choosing a tail cone for a vehicle's size, such as tail cone geometry, material selection, and overall manufacturability.

3.8.1. Geometry

Like a rocket nosecone, different tail cone geometry affects attached flow patterns about the rocket base to varying degrees. CSL compared spherical, conical, and ogive tail cone geometries with a flat base design on the rocket modeling simulator, OpenRocket, to evaluate their effect on overall coefficient of drag. While the tail cone reduced drag coefficient and increased altitude as given in OpenRocket, there was not large variations between the effects of the various tail cones. For example, the conical tail cone increased theoretical apogee by 10 feet compared to the ogive tail cone. This showed that tail cones are overall helpful to improving the rocket's flight performance, and that different tail cone geometries improved flight similarly.

Theoretically, the tail cones should have varying levels of performance, as their geometries vary in aerodynamic ability. However, the diameter reduction the tail cone should accomplish is 0.52 inches on either side over 4 inches. This short distance would reduce the curvature of an ogive geometry so that it is nearly conical.

3.8.2. Material Selection

For reusability, the tail cone must be heat resistant and durable to withstand impacts of up to 75 ft-lbf of kinetic energy. To increase the rocket's stability, a lighter tail cone is also preferred. Based on project criteria, eligible materials for tail cone construction were plastic composites or light metals such as aluminum.

One possible material selection is PETG. As discussed in section 3.4.4., PETG is a commercially available 3D printing material with great relative strength and low cost. However, as a plastic, it would be susceptible to melting under the intense heat of the rocket motor. CSL is not certain as to the exact heat that the motor would generate, as that information is not distributed by the motor manufacturer. Without further testing it is difficult to know PETG's performance under such high temperatures. While an aluminum alloy would be resistant to warping due to heat and impact damage, it would be much heavier than a plastic solution.

A way to improve printed plastics resistance to heat would be using a heat-resistant barrier such as an epoxy or ceramic coating. Such coatings have been extensively used throughout the aerospace industry and are a durable, reliable way to protect sensitive equipment from extreme heat (Shojaie-bahaabad, 2023). Commercially ceramic coatings, such as Cerakote, are used by companies such as Lockheed Martin, and offer high heat resistance (up to 1800 [°F]) as well as high corrosion and scratch resistance (Cerakote, 2024).

Another viable alternative would be thin sections of aluminum sheet metal, roll bent into a tail cone. This would reduce the weight of the tail cone while still offering the heat resistance of metal.

3.8.3. Manufacturing Feasibility

An additive manufacturing solution would be the most efficient way to produce a tail cone. With SolidWorks modeling, the tail cone could reliably have complex geometries and smooth curves through 3D printing with PETG. This manufacturing method is by far the most versatile and could produce the most aerodynamic geometries proposed for the tail cone.

If billets of aluminum or another light metal were chosen for the tail cone, subtractive manufacturing would be needed to form the tail cone shape. Based on the complexity of the chosen tail cone geometry, manufacturability would increase in difficulty without the aid of CNC machining. As previously mentioned, the small diameter transition that the tail cone should facilitate would also increase difficulty in manufacturing, as the thin portions of the tail cone would require sophisticated machining to produce a smooth and aerodynamic surface.

Other forms of manufacturing, such as extrusion or casting, could produce a thin but geometrically consistent metal tail cone, but would require custom tooling and equipment. However, a thin metal tail cone could be produced by roll bending sheet metal aluminum. This manufacturing method could produce consistent conical geometry but would have difficulty making ogive or tangential geometries.

3.8.4. Tail Cone Preliminary Designs

Three design alternatives were considered based on geometric, material, and manufacturing considerations as well as the limitations and feasibilities of the mentioned possible design decisions.

First is a 3D printed, PETG, conical tail cone with an inner ceramic coating for heat resistance. The benefit of this design is that it is the easiest to manufacture. CSL would use a 3D printer to create the tail cone itself, applying Cerakote or some other equivalent thermal barrier on the inner portion of the tail cone where it would absorb heat during launch. A cross section of this first alternative is shown in Figure 3.8.1.

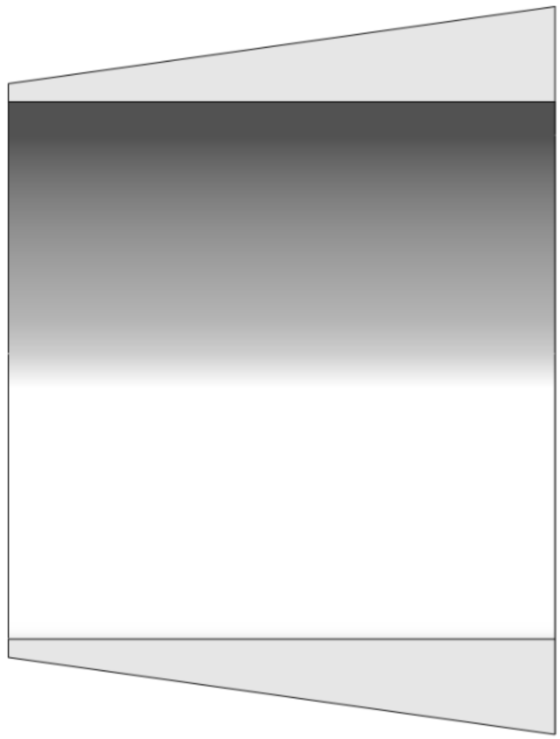

Figure 3.8.1. *Cross Section of SolidWorks Model of PETG Conical Tail Cone.*

As previously mentioned, the heat released by CSL's chosen motor is unknown. Even if a thermal barrier was applied between the plastic tail cone and the motor tube, there is no experimental data that can confirm if a PETG tail cone would not melt or deform during launch. This uncertainty of performance raises questions on the tail cone's survivability. The first alternative is feasible to manufacture but a fully PETG tail cone cannot verifiably perform under launch heat.

The second alternative is a machined aluminum and 3D printed, PETG, ogive tail cone with a Cerakote or equivalent thermal barrier. In this design iteration, a thin aluminum "sock" would surround the motor casing, absorbing much of the heat produced during launch. This aluminum sock would be encased by a PETG "boot" that would make up a majority of the tail cone to minimize weight and provide a curved surface to reduce drag. Both sections of this assembly would have interlocking geometries meant to facilitate easier manufacturing. A thermal barrier would be applied between these two layers to further reduce any melting or warping that the PETG portion would experience during vehicle launch. An ogive geometry was selected for this alternative to allow for additional space that would allow the aluminum sock to be thicker around the rocket exhaust. A cross section of this second alternative is shown in Figure 3.8.2.

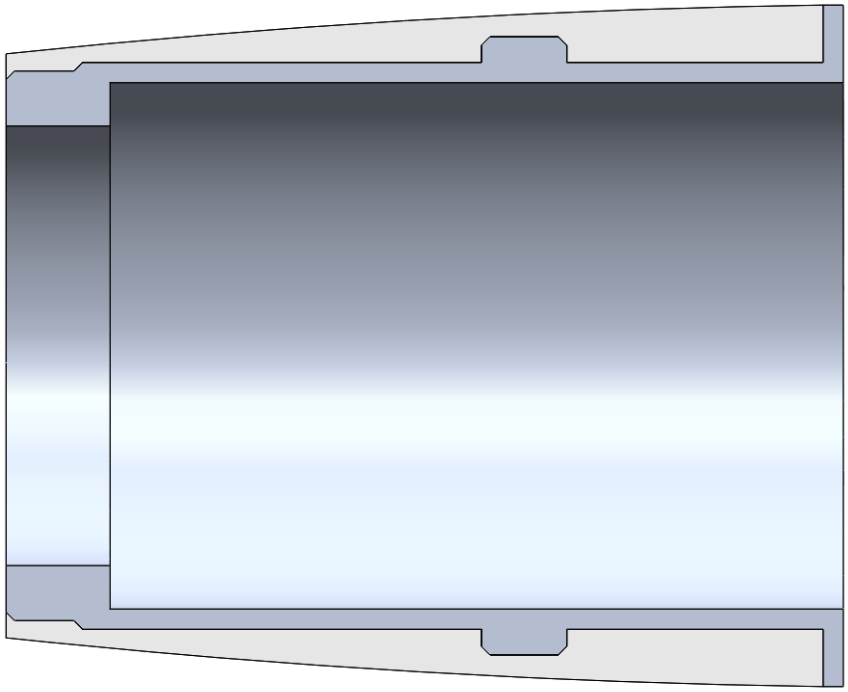

Figure 3.8.2. *Cross Section of SolidWorks Model of Aluminum Sock and PETG Boot Tail Cone.*

This alternative addresses the heat from launch, but the small diameter transition of the tail cone limits the thickness of the aluminum and PETG in certain sections. Overall, manufacturing of such an aluminum "sock" would require extensive planning and multiple machine operation setups, decreasing the manufacturing feasibility of this alternative.

The third alternative, and the alternative that CSL will be moving forward with at this point in the SL challenge, is a rolled and bent sheet metal aluminum, conical tail cone. This alternative, being a thin but sturdy sheet metal, is heat resistant, durable, feasible to manufacture and will perform comparably to the other alternatives. The weights of the three tail cone alternatives are given in Table 3.8.1. A transparent and cut view of this alternative is given in Figure 3.8.3 and 3.8.4.

Table 3.8.1. *Weights and Masses of Tail Cone Alternatives.*

Alternative Iteration	Alternative Weight (lb)	Alternative Mass (g)
PETG Cone	0.50	226.80
Ogive Aluminum "Sock" and PETG "Boot"	1.41	639.57
Sheet Metal Cone	0.36	163.29

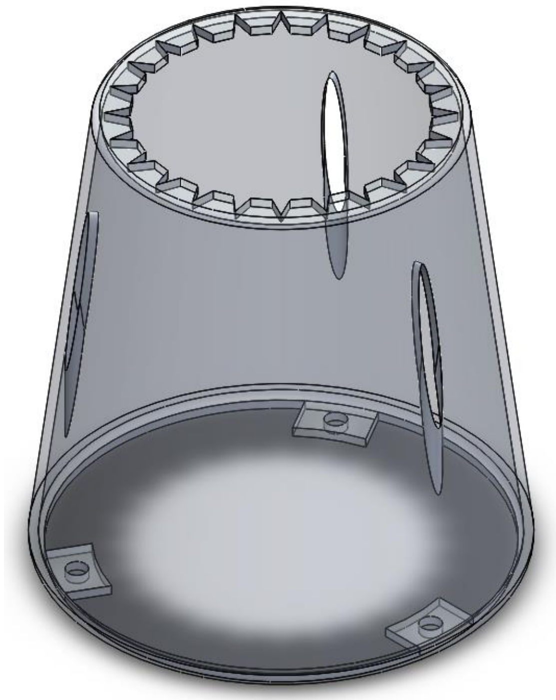

Figure 3.8.3. Transparent Isometric View of Sheet Metal Tail Cone Alternative.

Figure 3.8.4. Cut Isometric View of Sheet Metal Tail Cone Alternative.

To manufacture this alternative, CSL would first model the desired tail cone geometry with desired tabs and flanges for motor casing retention and fastening as a sheet metal part. By flattening this part, a two-dimensional drawing of the sheet metal cone could then be waterjet or laser cut. With controlled bends and rolling operations, the tail cone would be shaped into its proper form, and then TIG welded or blind riveted at its seams. After proper finishing procedures have been completed, such as polishing and painting, a smooth surfaced tail cone would be produced that is also durable and heat resistant. For the tail cone to be mounted to the trust structure such that it can be removed, and the motor casing can be reloaded, holes have been added to the surface to allow fasteners to pass through the tail cone.

A drawing of this chosen alternative is given in Figure 3.8.5.

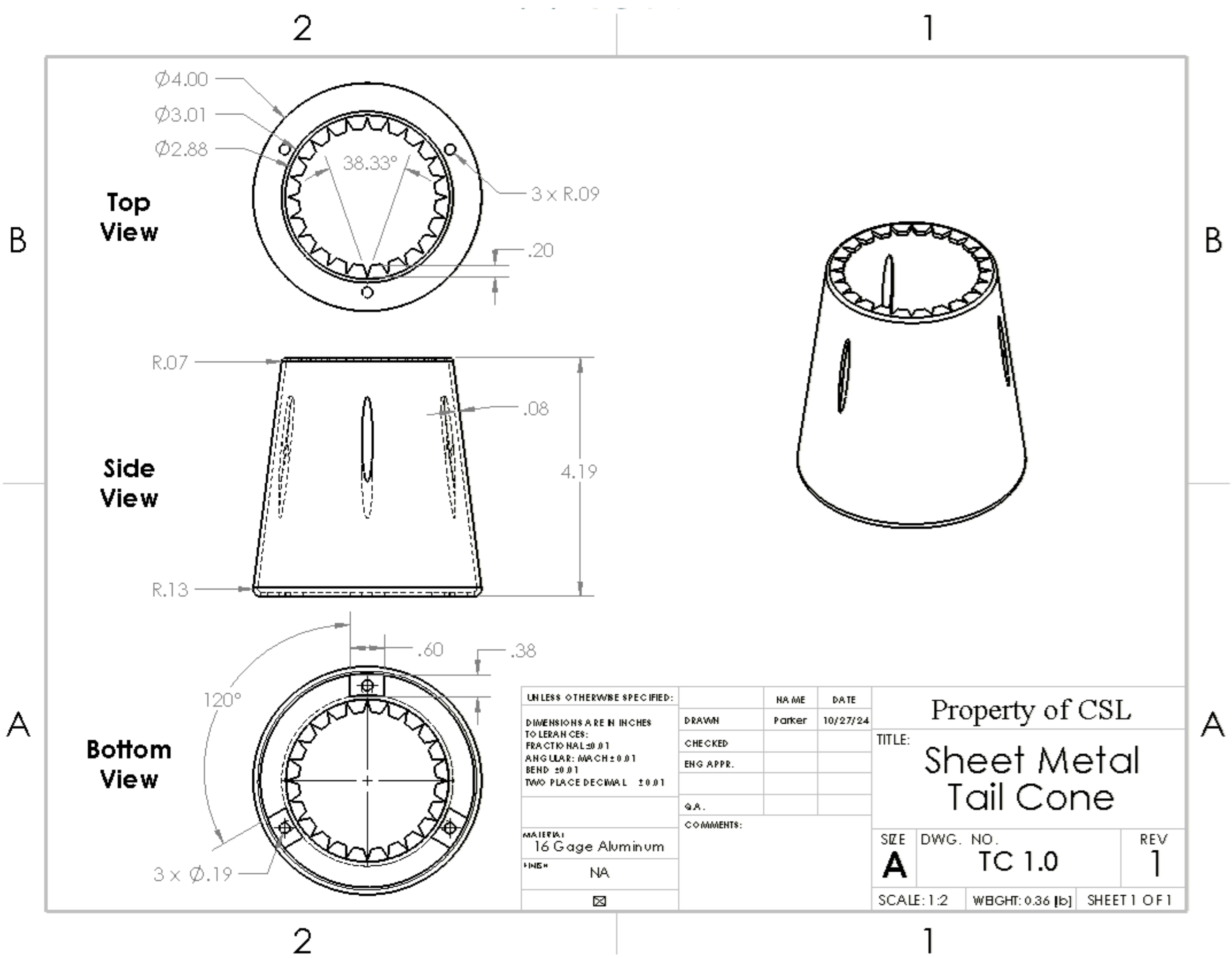

Figure 3.8.5. *Leading Tail Cone Alternative Drawing.*

3.9. Mass Properties Control Plan

In every aerospace project, the mass of the system in question is a critical concern during the design process. Implementing specific protocols for analyzing, simulating, and verifying mass properties can help support project management and risk assessment (American Institute of Aeronautics and Astronautics, 2015). To ensure that the various design changes along the course of the project do not interfere with the completion of the mission, CSL has developed a mass properties control plan (MPCP).

3.9.1. Objectives and Scope

As a design leaves the conceptual phase and becomes more mature over time, various design changes and discoveries can augment the trajectory of the project and flow mass and geometry changes down through the rest of the subsystems. Since launch vehicle mass is critical to the performance of the rocket, one key objective of CSL's MPCP is to characterize and track the mass growth allowance (MGA) of the system. The MGA, expressed as a percentage, is a property estimated for and reassessed at each of the major project milestones and represents the maximum mass increase that the system in question is expected to have grown by before the final design is reached. The Mass Growth Allowance (MGA) of a system is a protective measure, a means of quantifying the worst-case amount of mass growth that may need to be accounted for in future.

The MPCP is to be conducted at a general component level. While the CE will ensure that each engineer is routinely tabulating the mass of every single element in their respective subsystem, the MGA needs only to be assessed in a more high-level manner for each subsystem. Table 3.9.1 shows the MGA estimates established for eight major subsystems at each project milestone and indicates the scope of the MPCP analysis.

Table 3.9.1. *MGA estimates for the chosen subsystems. Note some subsystems are subdivided into two/more categories. These subsystems have major components whose mass is more likely to grow than other components in that subsystem, so it is subdivided to aid MGA estimation.*

Design Maturity	MGA [%]															
	Nose Cone		Airframe	Payload		Recovery Devices	Avionics		Shock Cord Mount	Airbrakes			Thrust Structure			
	Cone	Camera System		Body	Electronics		Body	Electronics		Frame	Brakes	Electronics	Fin Retention	Fins	Tail Cone	Motor
Conceptual	50%	20%	30%	30%	20%	50%	20%	10%	30%	25%	20%	15%	20%	30%	20%	20%
PDR	20%	10%	15%	15%	8%	20%	15%	7%	15%	18%	18%	13%	8%	15%	10%	20%
CDR	10%	8%	10%	10%	3%	10%	2%	2%	5%	7%	10%	5%	5%	5%	5%	2%
Final	3%	3%	2%	2%	2%	1%	1%	1%	1%	4%	3%	1%	1%	1%	1%	2%

3.9.2. Mass Properties Requirements

There are four main mass properties that the MPCP must monitor. The first is *Basic Mass*. Basic mass is the current mass of the design, whether that be mass that is calculated, estimated, or measured. Basic mass is a simple quantity that contains no MGA, it includes only what is known or can be found out about the design at the time it is evaluated (American Institute of Aeronautics and Astronautics, 2015).

Predicted Mass is the maximum mass of the system after the MGA for that system is included. The predicted mass is the mass that, to the best of CSL’s knowledge, is equal to the mass of the final iteration of the system. This prediction is reassessed for each subsystem at each project milestone

The *Allowable Mass* is a mass requirement laid out early in the design process that functions as either an informal or NTE (“not-to-exceed”) mass limit for the designers (American Institute of Aeronautics and Astronautics, 2015). The margin between the predicated mass and allowable mass must be monitored, as when the predicted mass nears allowable mass there is the potential for the design’s mass to eventually exceed that of the mission requirement. For CSL, the allowable mass of the entire launch vehicle is chosen to be the maximum mass that the rocket can accommodate while still flying high enough to use airbrakes to control its altitude. Section 3.9.3 details the specific analysis processes and rationale for all such mass properties.

The *Mass Limit* is the mass figure beyond which the mission performance requirements physically cannot be met (American Institute of Aeronautics and Astronautics, 2015). In the context of Project Elijah, this is the mass at which the rocket cannot reach the minimum competition altitude of 3500 feet or make the thrust-to-weight ratio of 5.0:1.0 as stipulated by NASA. The difference between the allowable mass and the mass limit is that the allowable mass can fluctuate as needed based on changing project requirements (e.g., airbrakes can no longer be used, but a lower altitude can be met by other means) whereas a mass limit will always exist for any aerospace project and cannot be negotiated. Figure 3.9.1 shows the typical mass property lifecycle of an aerospace system.

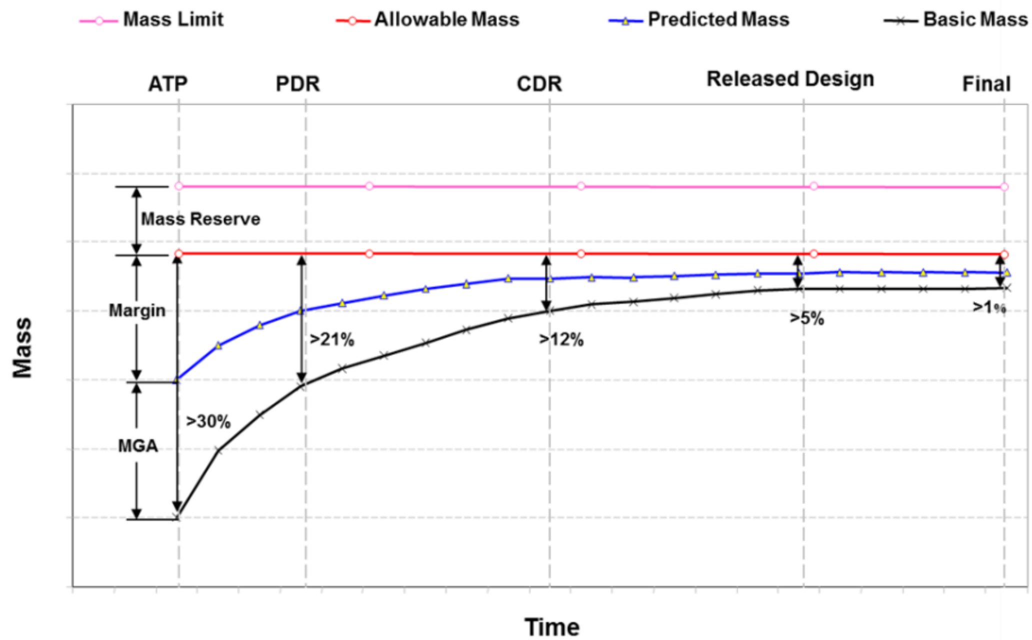

Figure 3.9.1. *Mass properties over design time for a typical aerospace system. CSL hopes to produce a similar plot of the Project Elijah mass properties by the end of the academic year. (Image source: ANSI/AIAA S-120A-2015, draft for public review).*

Table 3.9.2 shows the mass properties of the full-scale launch vehicle as determined using the methods described in section 3.9.3.

Table 3.9.2. *Mass properties for the launch vehicle.*

Basic Mass [kg]	13.1
Allowable Mass [kg]	14.0
Mass Limit [kg]	15.0

3.9.3. Data Collection Procedures and Analysis

All CSL members were required to develop basic mass estimates and MGA estimates for each category of their subsystem as shown in the horizontal axis of Table 3.9.1. In the conceptual design stage, this was accomplished by using material mass data applied to SOLIDWORKS drawings or by weighing any components on hand. The mass of any 3D printed components could be reliably estimated by importing the designs into a 3D printing slicer software and noting the predicted amount of material expended. For elements that could not be modelled and were not on hand, manufacturer data sheets were used for mass estimates.

The basic mass, by definition, can only be tracked in step with CSL's progress in the project lifecycle. However, the MGA for each subsystem is a projected quantity and must therefore be determined for each of the project milestones early in the program lifecycle. Each CSL member created the MGA estimates shown in Table 3.9.3 for each project stage based on the potential design changes that they foresaw in their subsystem. For example, the nose cone MGA for the conceptual stage was placed unusually high at 50% since, at the time, a significant amount of nose cone ballast was predicted to be needed to improve rocket stability. Note from Table 3.9.3 that, as the design reaches the end of its lifecycle, dramatically more accurate mass estimates are available and so the MGA need not be so large.

The allowable mass of the system was arrived at by creating a duplicate OpenRocket simulation of the leading rocket design and setting the mass of each component to the predicted mass figure (that is, the basic mass with the MGA applied). This simulation yielded the rocket performance at the maximum predicted GLOW (gross lift-off weight) and weighted the rocket's potential mass growth to the specific subsystems that could be expected to grow in future. The mass of the entire rocket and its subsystems was then linearly increased until the rocket was no longer simulated to reach a target altitude that would permit the use of airbrakes. The mass limit was found similarly by continuing to increase the mass until the rocket could not reach 3500 feet, although for the final design to become that heavy it is likely that significant changes in the CG/CP location would have to occur. Since the changing CG/CP locations could not be accounted for at this stage in the design lifecycle, a conservative value for the mass limit was chosen as shown in Table 3.9.2.

3.9.4. Tracking and Reporting

Every CSL member reported their basic mass estimates for their subsystem at each project milestone using an Excel reporting form developed by the CE. Though imperial units were preferred for the majority of CSL's design and analysis activities, mass estimates in units of grams were chosen as a less unwieldy unit. The reporting form allowed the team members to input their mass estimates, sign and verify the accuracy of the values, and log major design changes that majorly reflected on the total mass of the launch vehicle. An example page of this reporting form can be seen in Appendix A.5. The values placed in this form automatically populate into a master MPCP table from which the MGA predictions are calculated and plotted into a figure like that shown in Figure 3.9.1. Basic mass and mass predictions from this master form can be seen in Appendix A.6.

3.10. Recovery Subsystem

The recovery system that will be used is a dual bay system. The dual bay was chosen over the single bay recovery system for various reasons. While the single bay system takes up less room in the rocket, a dual bay system is a simpler design than a single bay recovery system and it allows for more redundancy in the deployment sequence (*"Intro to Dual Deployment in Rocketry"*, n.d.). The first recovery event will occur once the rocket reaches apogee; the primary altimeter will send a signal to the e-matches in the drogue bay which will ignite the black powder charge that will separate the aft end of the rocket and deploy the drogue shoot. One second after apogee, the secondary altimeter will command a second ejection event with a slightly larger black powder charge to separate the aft end of the rocket. This second ejection charge will ensure the deployment of the drogue in case of either primary altimeter failure or if the primary ejection charge fails to separate the rocket. This will also fulfil requirement 3.1.2 from the SL Handbook (2025) which states that the apogee event shall have a delay of no more than 2 seconds. The next event will occur at 600 [ft] Above Ground Level (AGL). The primary altimeter will send a signal to the e-matches in the main bay which will again ignite the black powder charges and separate the forward section of the rocket, releasing the main parachute. Similarly, this deployment event will be followed by the secondary altimeter sending a signal to ignite a second primary ejection charge at 550 [ft] AGL This lower deployment will allow for a faster descent time, while also reducing the kinetic energy at landing which will help fulfill requirements 3.1, 3, and 3.12 from the SL Handbook. Figure 3.10.1 shows how this recovery system works from apogee until landing.

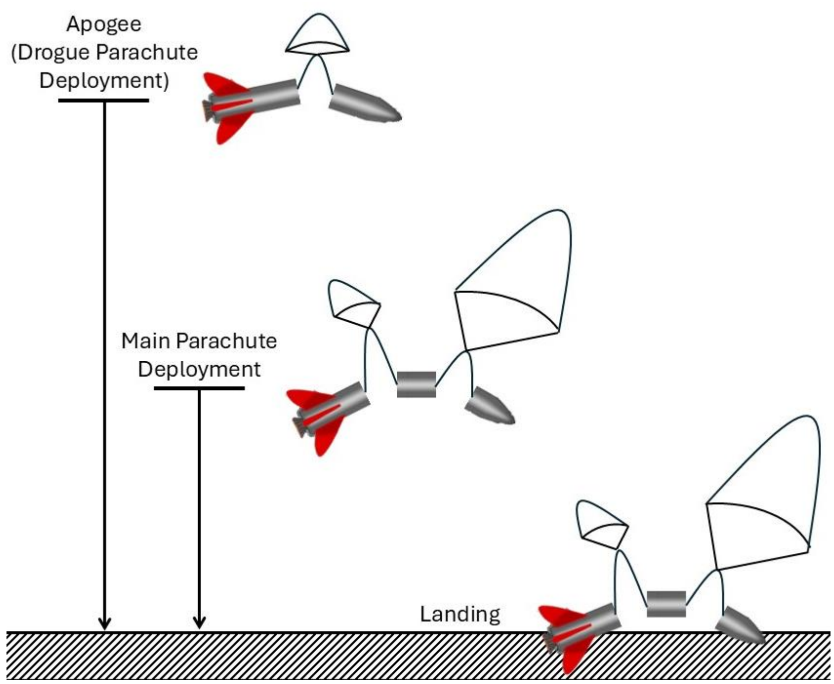

Figure 3.10.1. *Diagram of the three events in the recovery system. Includes the deployment of the drogue and main parachutes and when the rocket touches back down.*

To ensure these requirements are met, the maximum velocity for touchdown of the rocket as well as the minimum parachute size that can be allowed must be found from Equations 3.10.1 and 3.10.2 respectfully. In Equation 3.10.1, T is the max kinetic energy each independent section of the rocket can have upon touchdown (75 [ft·lbf]), m is the mass of the heaviest section of the rocket when completely split to find the max kinetic energy at landing, and V is the velocity at touchdown. For Equation 3.10.2, A is the minimum parachute area, W is the dry weight of the rocket, ρ is the density of the air, C_D is the coefficient of drag of the parachute (an average will be used), and V is the maximum velocity found through Equation 3.10.1. From these equations, the max velocity was found to be approximately 20 [ft/s], and the minimum parachute diameter was found to be 5 [ft] (or an area of approximately 20 [ft^2]).

$$T = \frac{1}{2} m V^2 \tag{3.10.1.}$$

$$A = \frac{2W}{\rho C_D V^2} \tag{3.10.2.}$$

FFFFG black powder will be used for the ejection charges in both bays, this is due to it having a smaller grain size then FFFG powder which means it will have a faster burn rate allowing for a more rapid pressure increase which will be more likely to ensure rocket separation. The amount of black powder needed for each bay is based on the volume of the compartment and the type and amount of shear pins used to hold the rocket together during ascent. When deciding the amount needed for each bay, great care is needed. If there is too much, the rocket itself could be damaged and if there is too little, the rocket may not separate at all. To best calculate the amount needed to better ensure proper deployment Equations (3.10.3) through (3.10.5) will be used. Equation (3.10.3) finds the force needed to break apart the shear pins based on the number and size of the shear pins. For this equation the strength of the shear pins being used is needed. Since 4-40 shear pins will be used due to them being stronger than alternatives and allowing for less of them being needed the tensile strength (U) can be found to be 10500 [psi], with a pin of diameter (D_{pin}) of 0.0813 [in]. From this, the force required to break the shear pins can be found. This value can then be placed into Equation (3.10.4) which finds the pressure needed to break the shear pins based on the force and the cross-sectional area of the rocket. Equation (3.10.5) finds the amount of black powder needed in grams for each bay based on its volume, the pressure found in Equation (3.10.4), as well as the combustion gas constant (R_c) and the combustion gas temperature (T_c). R_c and T_c are constants based on the black powder being used. The values for FFFFG powder are R_c = 22.16 [ft·lbf/(lbm·°R)] and T_c = 3307 [°R] (Mobley, 1997). Through Equations (3.10.3) through (3.10.5) it can be found that the amount of black powder needed for the main bay is 1.31 [g] and the drogue bay is 1.44 [g]. To ensure these charges can separate the rocket, a ground ejection test will be performed before the initial flights of both the subscale and the full-scale rockets. This will also ensure requirement 3.2 from the SL Handbook is fulfilled. If the ground ejection test fails to separate the main bay the amount of black powder used will be increased to 1.5 [g] and if the drogue bay doesn't separate its black powder will increase to 1.6 [g].

$$F = \frac{\pi}{4} D_{pin}^2 U \tag{3.10.3.}$$

$$P = \frac{4F}{\pi D^2} \tag{3.10.4.}$$

$$BP = \frac{P(Vol)}{R_c T_c} \tag{3.10.5.}$$

With using black powder charges for the deployment events, the effect on the parachutes must be considered since the resulting hot gases and burning powder can cause damage. This damage can lead to the parachutes being unable to properly slow the rocket down and cause a touchdown kinetic energy much higher than the maximum allowed. This can be prevented by using a flame blanket or a deployment bag. The flame blanket has an easier set up, being connected to the parachute by a shock cord and simply wrapping around the folded parachute in a way to protect it from the black powder ejection charge. While the deployment bag holds the folded parachute and allows for the shock cords to be safely contained to prevent the lines from wrapping together. The flame blanket is the cheaper option while still affording almost all the same benefits compared to the deployment bag, so the flame blanket will be used to protect the parachutes during deployment.

Once the parachutes are deployed, they will be connected to the rocket body through shock cords. Shock cords are commonly made of either nylon or Kevlar, which both have their own cons and pros. Nylon shock cords allow for greater deformation which is good for deployment at lines taut which is when the shock cords have the greatest force against them. The deformation allowed by the nylon shock cords allows for some of this force to be dissipated and lessen the risk of the shock cords snapping under the load. Kevlar, on the other hand, has very little ability to deform but makes up for it with its high strength (*"Kevlar Shock Cords"*, 2024). Kevlar is also much heavier than nylon, with nylon having a greater strength-to-weight ratio, and would most likely need frangible ties to help dissipate the force at lines taut to decrease the risk of damage to the shock cords and the rocket. When comparing the prices for nylon and Kevlar shock cords with equal strength rating there was not a huge difference that could push one above the other. Due to this and the other differences for the shock cords it was decided to use the nylon shock cords due to their better strength to weight ratio and the decreased risk for failure due to the shock cords snapping. When deciding the length of the shock cords the rule of thumb that they must be between 3-5 times the length of the rocket was used. Based on this, the size of the full-scale rocket, and the characteristics of the nylon shock cords being used, the length of the shock cords to be used is 35 [ft] (approximately 4 times the length of the full-scale rocket).

Some of the shock cords will be attached to forward section via a shock cord mount. The shock cord mount will be absorbing all the force generated from the black powder charges to make sure the recovery system works properly. There were two iterations done for the shock chord mount. The first iteration is shown in Figure 3.10.2, and the SolidWorks model is shown in Figure 3.10.3. This iteration includes an eyebolt to hold the shock cords, and the bolts to attach it to the rocket are located inside the structure itself. The problem with this iteration is that all the force from the black powder charges is concentrated in one spot, the location of the eyebolt, which will make it more liable to fail in that spot.

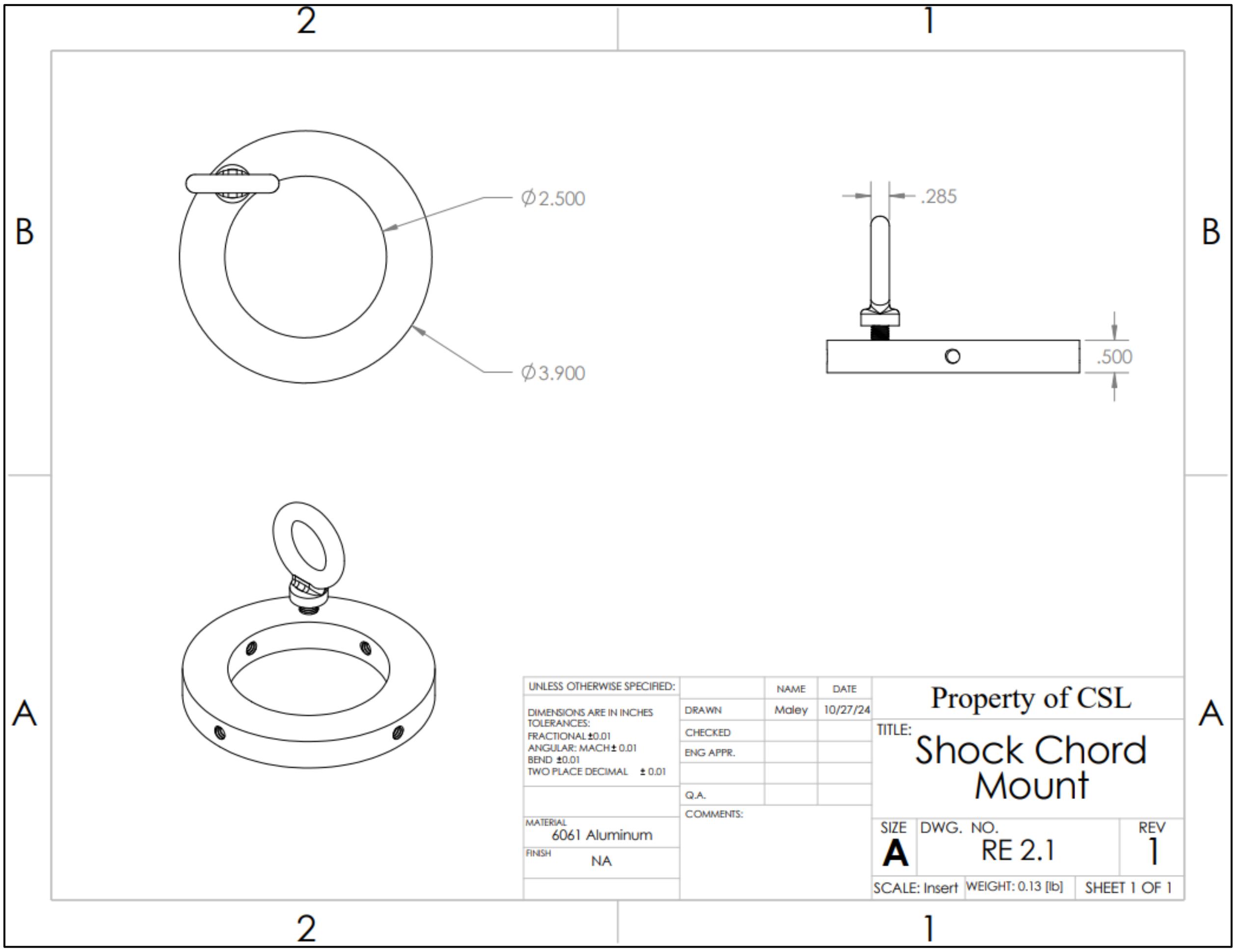

Figure 3.10.2. *SolidWorks Drawing of Shock Chord Mount V1.*

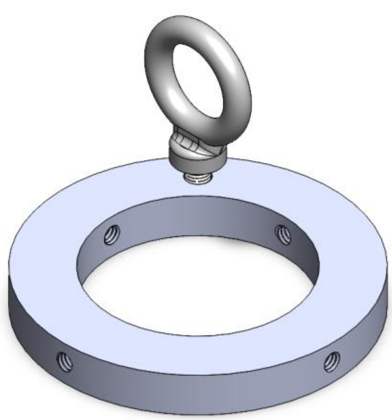

Figure 3.10.3. *SolidWorks Model for Shock Chord Mount V1.*

The SolidWorks drawing of the second iteration is shown in Figure 3.10.4, and the SolidWorks model is shown in Figure 3.10.5. This iteration fixes those issues. Instead of using an eyebolt to hold the shock chords, now a U-bolt is used. This U-bolt is much stronger than the eyebolt which makes it much less likely to fail in tension. Since the U-bolt is connected to the baseplate in two separate locations, the force is now distributed throughout the baseplate instead of concentrated in a single location. This iteration also includes parts on the baseplate where the screws can be located. This design makes the baseplate less likely to break upon absorbing the force due to the geometry used.

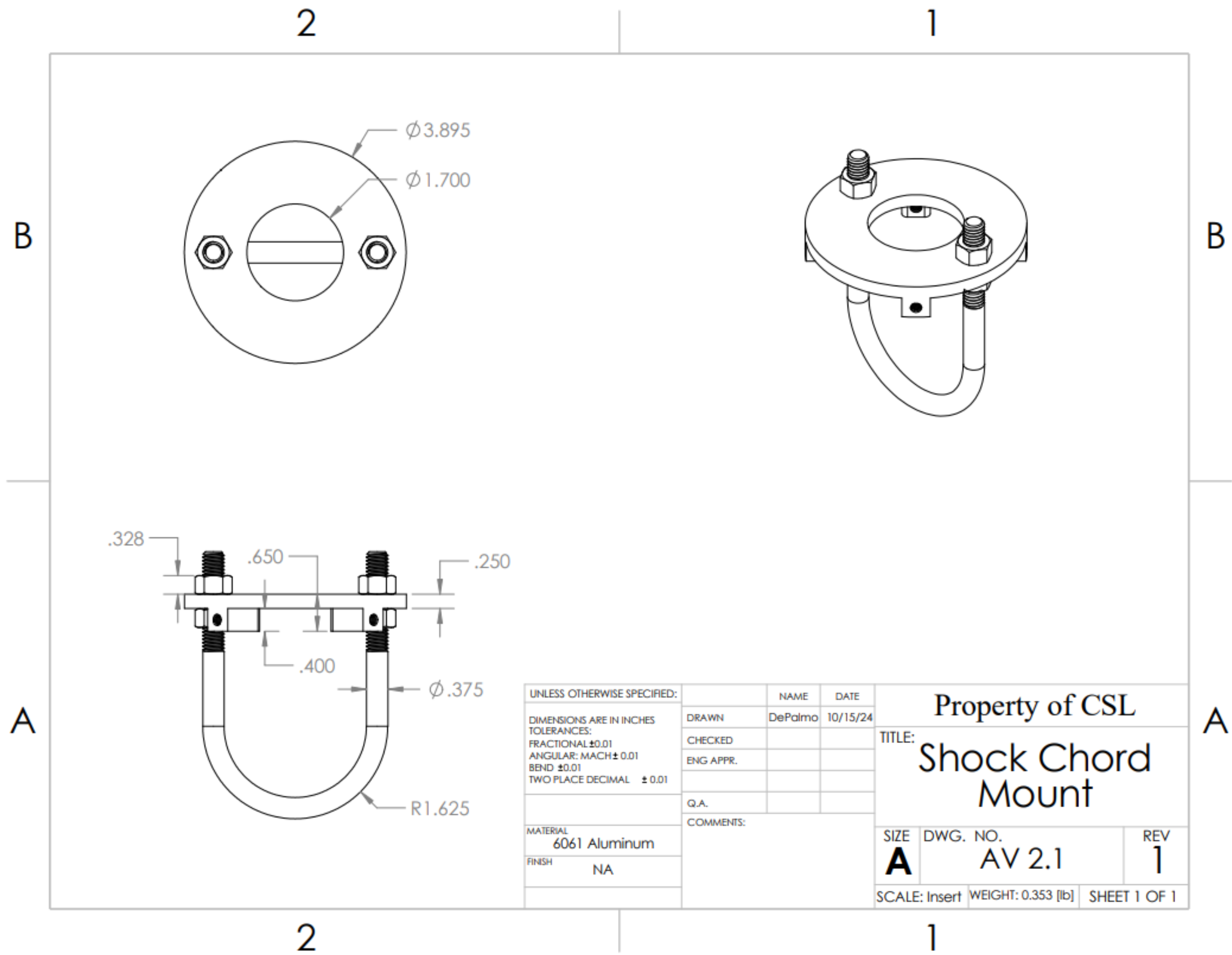

Figure 3.10.4. *SolidWorks Drawing for Shock Chord Mount V2.*

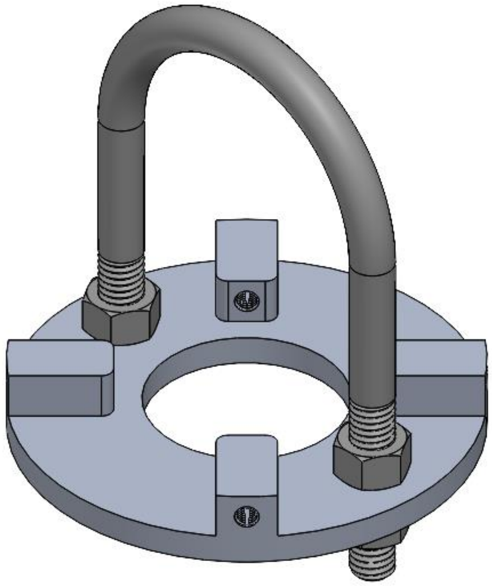

Figure 3.10.5. *Shock Chord Mount SolidWorks Model.*

One final decision that needed to be made was which parachute would be used. Two possible main and drogue parachutes were found and evaluated. For the main parachute two parachutes with a diameter of 10 [ft] and a coefficient of drag of 2.2 were found from *Rocketman* and *FruityChutes*, Table 3.10.1 contains a more in-depth comparison for the size, weight, and price difference between these two parachutes. Through this comparison the parachute from *Rocketman* is both cheaper and lighter when compared to *FruityChutes*. Combining this with the equal size and C_D it is a simple decision to say that the parachute from *Rocketman* is the better deal for what is needed and will be the one used in the full-scale rocket.

Table 3.10.1. *Comparison between two possible main parachutes. Compares the diameter, coefficient of drag, the price, and weight of each parachute.*

	Main			
	Size	C_D	Price	Weight
Rocketman	7 [ft]	2.2	$225.00	15.3 [oz]
FruityChutes	7 [ft]	2.2	$326.66	19 [oz]

The two parachutes found for the drogue parachute both come from *Rocketman* and are shown in Table 3.10.2. Like Table 3.10.1 both the size and coefficient of drag are the same between the two (with a diameter of 1 [ft] and a C_D of 0.97). However, one of them is cheaper but heavier compared to the other. The weight difference between the two parachutes is not very large in comparison to the price and will not make too much of a difference in the rocket so the cheaper parachute from *Rocketman* is the best choice.

Table 3.10.2. *Comparison between two possible drogue parachutes. Compares the diameter, coefficient of drag, the price, and weight of each parachute.*

	Drogue			
	Size	C_D	Price	Weight
Rocketman	1 [ft]	0.97	$28.50	1 [oz]
Rocketman	1 [ft]	0.97	$46.00	0.32 [oz]

As stated above, the avionics bay will be located between the drogue and main parachutes in the middle of the rocket. The leading design for the avionics bay is shown in Figures 3.10.6 through 3.10.8. The main challenge in designing the avionics bay was the space constraints. The typical solution for the avionics sled is a flat plate with two threaded rods running through each side of the sled sandwiching the sled between bulkheads which protect the electronics from the ejection charges. CSL determined that this was not possible due to the limited space and the size of the electronics required. The triangular sled with a single threaded rod as seen below was designed instead. This allows for even mass distribution around the center of the rocket and easy accessibility to the electronics. Using only one threaded rod introduces the possibility of the sled rotating inside of the avionics bay which could possibly pull-out wires or cause other issues. The possibility of this was determined to be minimal because there would be no forces that cause a torque inside the avionics bay. Nonetheless a couple of design decisions were made to eliminate the possibility of the sled rotating. The sled was designed to be the length of the coupler tube causing friction between the sled and bulkhead and the nut from the eyebolts which will be attached to the shock cords will stop the sled from rotating relative to the bulkhead. The final concern with this design is that a singular threaded rode will not be enough to withstand the force from the parachutes opening this was determined not to be an issue based on the tensile strength of the steel and the order of magnitude of the forces that will be experienced.

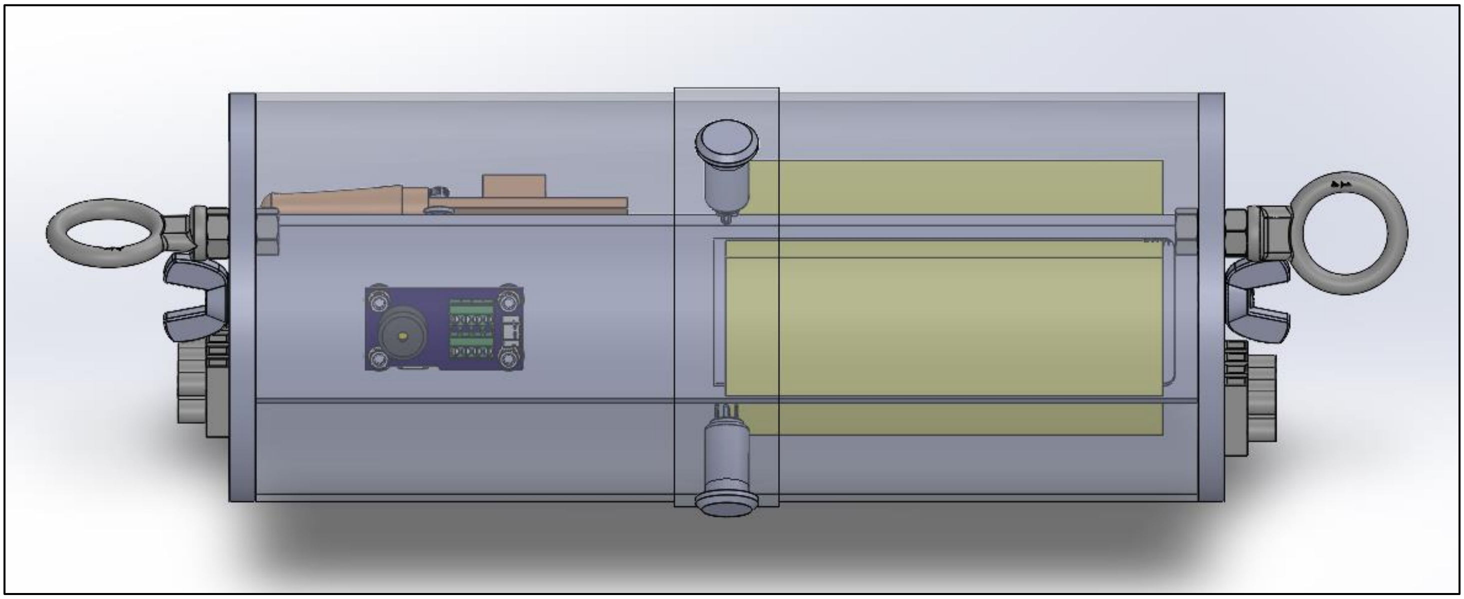

Figure 3.10.6. *Avionics bay leading design.*

ITEM NO.	PART NAME	QTY.
1	Avionics Sled	1
2	Bulkhead	2
3	Coupler Tube	1
4	EasyMini Altimeter	1
5	Eggfinder Mini C4 GPS	1
6	Eyebolt	2
7	Key Switch	2
8	LIPO 2200mAh 7.4V battery	3
9	RRC3 altimeter	1
10	Terminal Block	2
11	Threaded rod 1/4-20	1

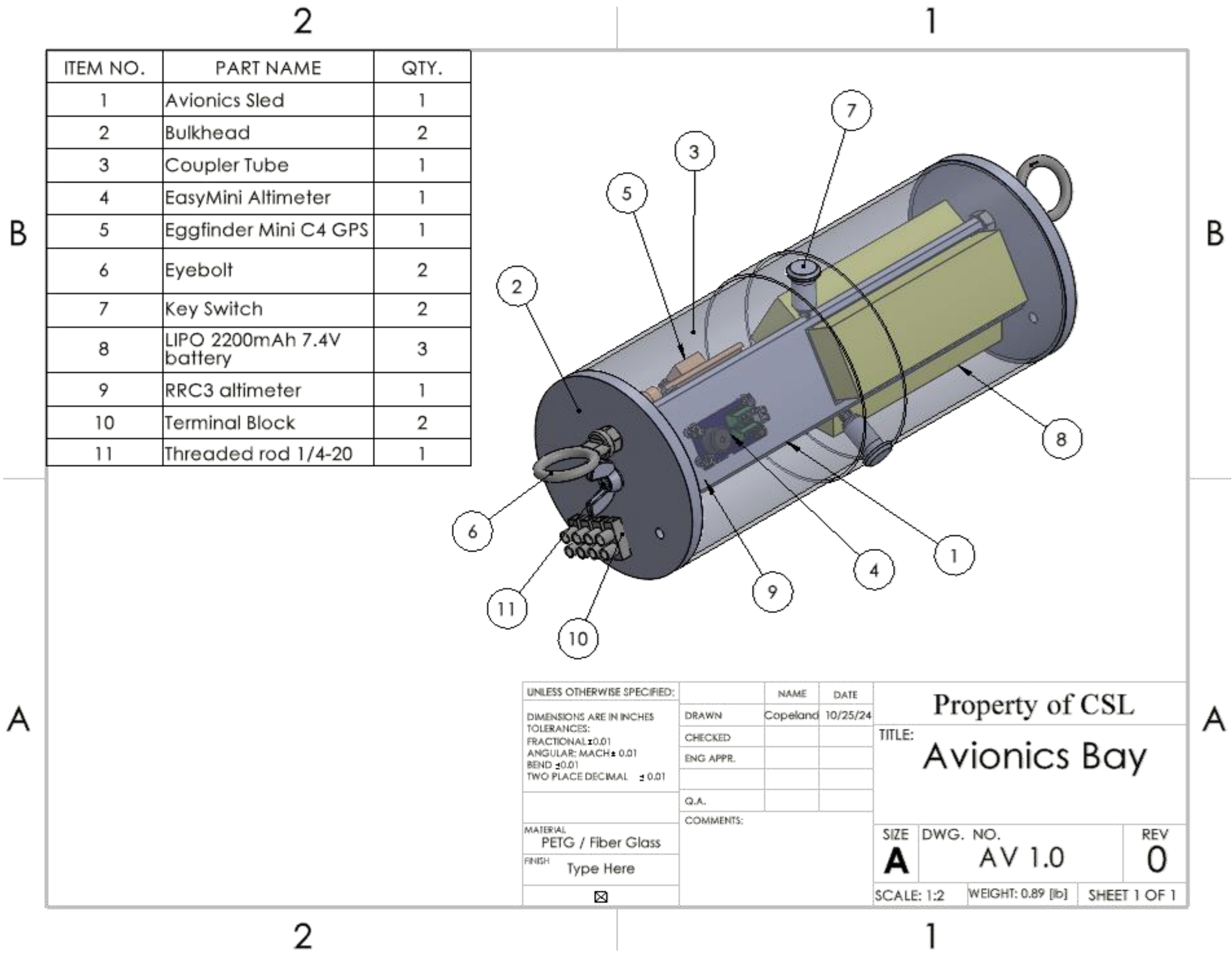

Figure 3.10.7. *Avionics bay leading design with components labeled.*

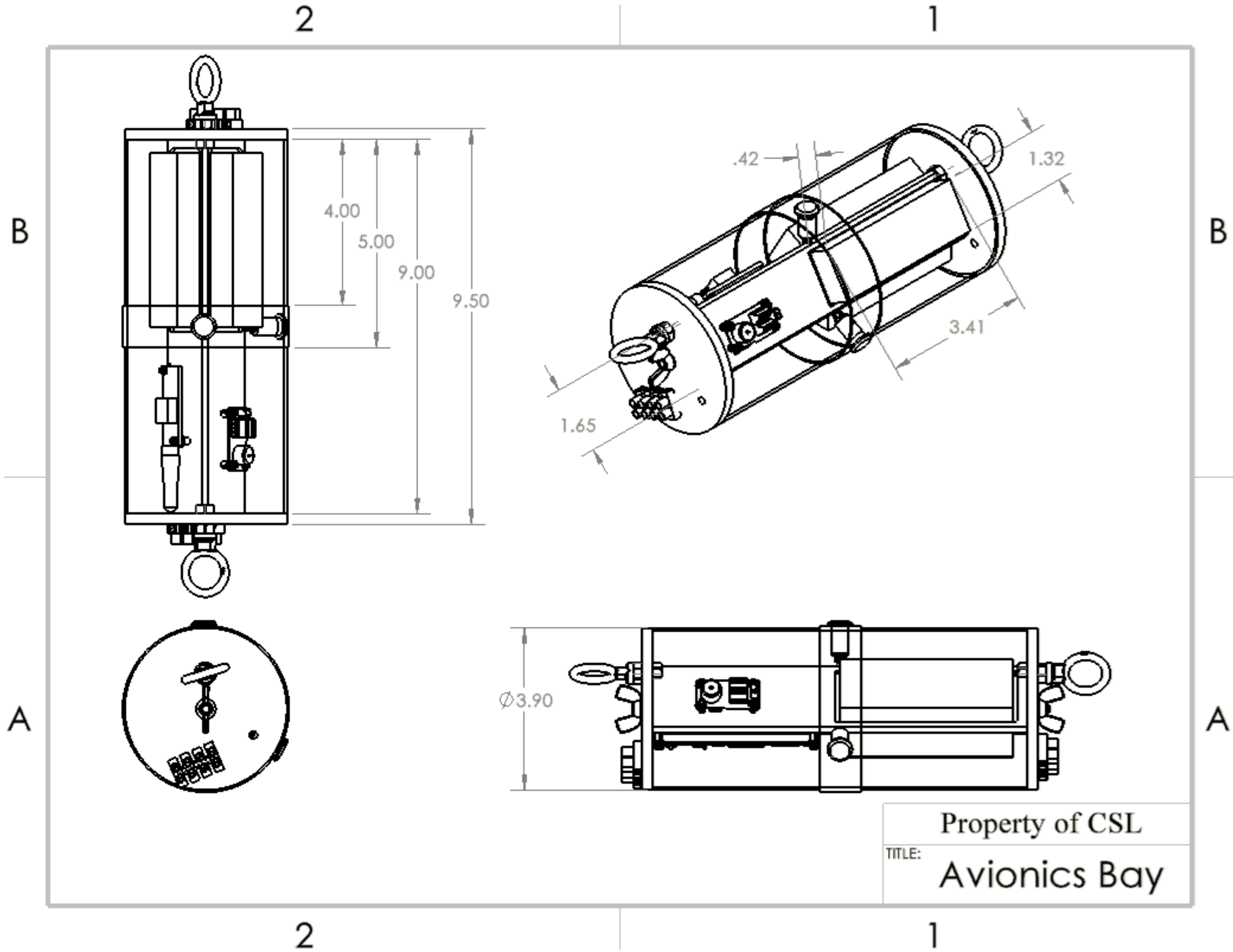

Figure 3.10.8. *Avionics bay leading design dimensioned.*

There were several considerations when deciding which GPS and altimeters to use in the avionics bay including size, features, ease of use, and cost. The four altimeters that were considered were the Missile Works RRC3, the Missile Works RTX, the EasyMini from Altus Metrum, and the StratoLoggerCF from PerfectFlite. Each of these has its own advantages and disadvantages. For example, CSL already has possession of two of the EasyMini and RRC3 altimeters which gives them an advantage over the other options because they do not need to be bought and have a proven track record of reliability with CSL. Table 3.10.3 contains the ratings given to each of the possible altimeters. The RRC3 was chosen to be used as the primary altimeter due to its ease of use and the fact that it has a built-in capacitor that provides continuous power to the altimeter, protecting against brownouts from loose connections. The Eggtimer Quasar was ruled out because of how complex the required assembly is. The StratoLoggerCf and the EasyMini are very comparable to each other, but the EasyMini was chosen as the secondary altimeter because CSL already owns two of them and they have a proven track record with the team.

Table 3.10.3. Comparison table of the potential altimeters.

Brand	Missile Works	Eggtimer	Altus Metrum	PerfectFlite
Model	RRC3	Quasar	EasyMini	StratoLoggerCF
Size	3.9"	5.5"	1.5"	2"
Features	Excellent	Good	Good	Good
Ease of use	Good	Poor	Fair	Fair
Cost	N/A	$100	N/A	$70

The Mini C4 GPS from Eggfinder was chosen to be used in the avionics bay on the rocket since CSL owns one that was assembled by a previous CSL team. This GPS is reliable, compact, and can be powered by the same type of battery as the altimeters. The battery of choice for the avionics bay was a Liperior 2200 mAh 7.4V battery. This battery has enough power to last on the pad for several hours and has the benefit of being already owned by CSL.

The wiring for the avionics bay is relatively simple and the electrical schematics are shown in Figures 3.10.9 and 3.10.10. Each altimeter will be powered by a separate battery and command independent ejection charges for both the main and drogue parachutes. This ensures redundancy in the recovery section and for a parachute to not deploy there will have to be two simultaneous failures in the independent systems. The GPS is also powered by its own battery ensuring if eyesight is lost with the rocket during recovery, CSL will be able to recover it in a timely manner.

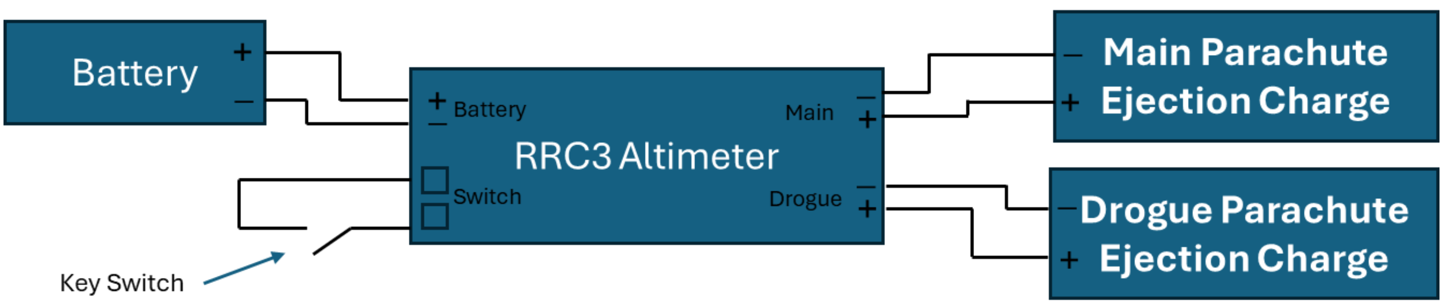

Figure 3.10.9. *Wiring diagram for the primary altimeter.*

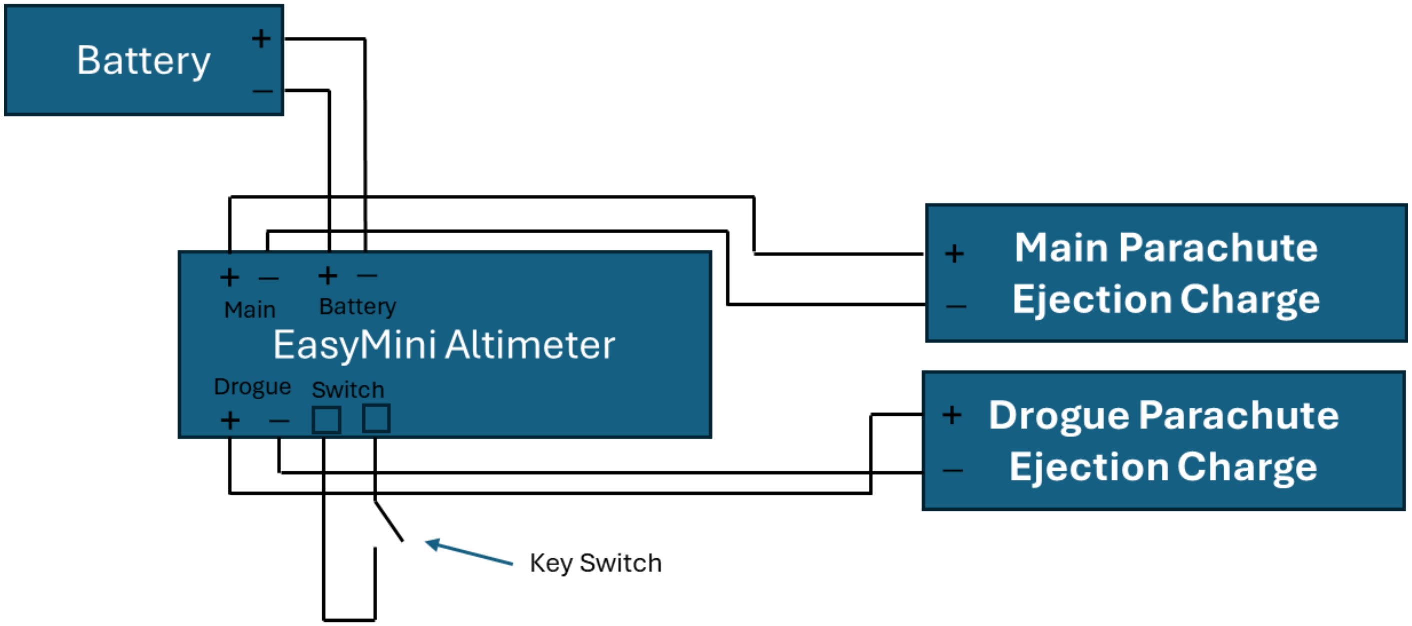

Figure 3.10.10. *Wiring diagram for the secondary altimeter.*

3.11. Mission Performance Predictions

3.11.1. Target Apogee

For simulation purposes, the CE selected a preliminary target altitude of 4,100 feet for the three primary reasons. Firstly, the minimum target altitude allowed by NASA was 4,000 feet, and a buffer of 100 feet required the airbrakes to do less work to lower the rocket's altitude while still demonstrating that they could meaningfully augment the rocket's altitude. Secondly, with airbrakes stowed for the entire flight, the rocket would exceed the target altitude of 4,100 feet by over 300 feet. The airbrakes are expected to affect the rocket altitude by this amount. Thirdly, if the mass of the rocket grows substantially such that it would prevent the airbrakes from being useful to control the flight, the target altitude can be dropped further as necessary. Designing around a target altitude above the competition minimum is a risk-mitigating measure that the CE chose to employ early in the design lifecycle.

3.11.2. Motor Selection

Since the satisfactory performance of Project Elijah is dependent on the successful use of airbrakes, the motor powering the launch vehicle needed to have the proper impulse to carry the rocket high enough and fast enough so that the airbrakes can be effective for flight control, and the motor selection must be relatively affordable to allow for enough flights to properly test the airbrake control system. The primary motor that the team settled on was the 75mm Aerotech K1000T-P, the thrust curve of which is shown below in Figure 3.11.1.

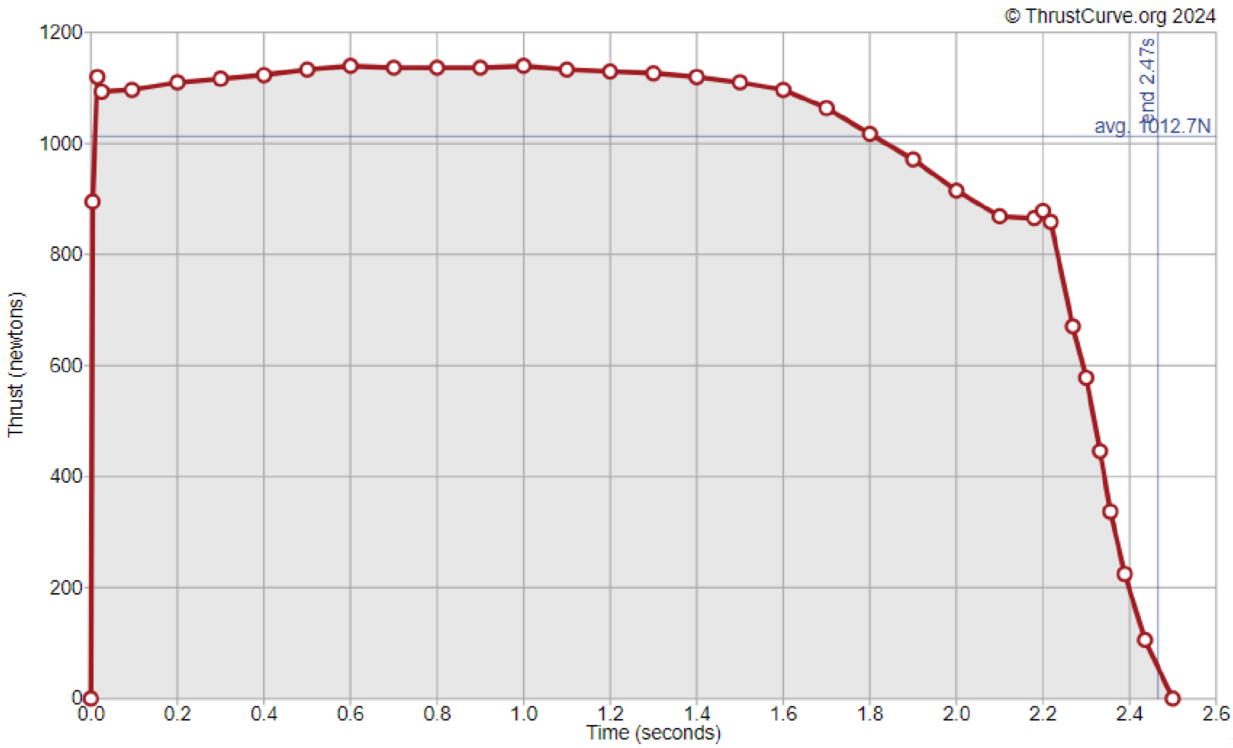

Figure 3.11.1. *Thrust vs Time curve for the K1000T-P rocket motor (data supplied from ThrustCurve.org).*

Class II high-power rocket motors from Aerotech sport a substantial lead time, so if CSL cannot obtain the preferred K1000T-P motors, it is unlikely that a substitute motor could be sourced in its place due to the same lead time issues. However, if the need for a backup motor presents itself and an adequate quantity can be sourced, the Aerotech K1800ST-P would be a suitable substitute. The K1800ST-P thrust curve is shown below in Figure 3.11.2, and the rocket performance for the two motors is compared in Table 3.11.1.

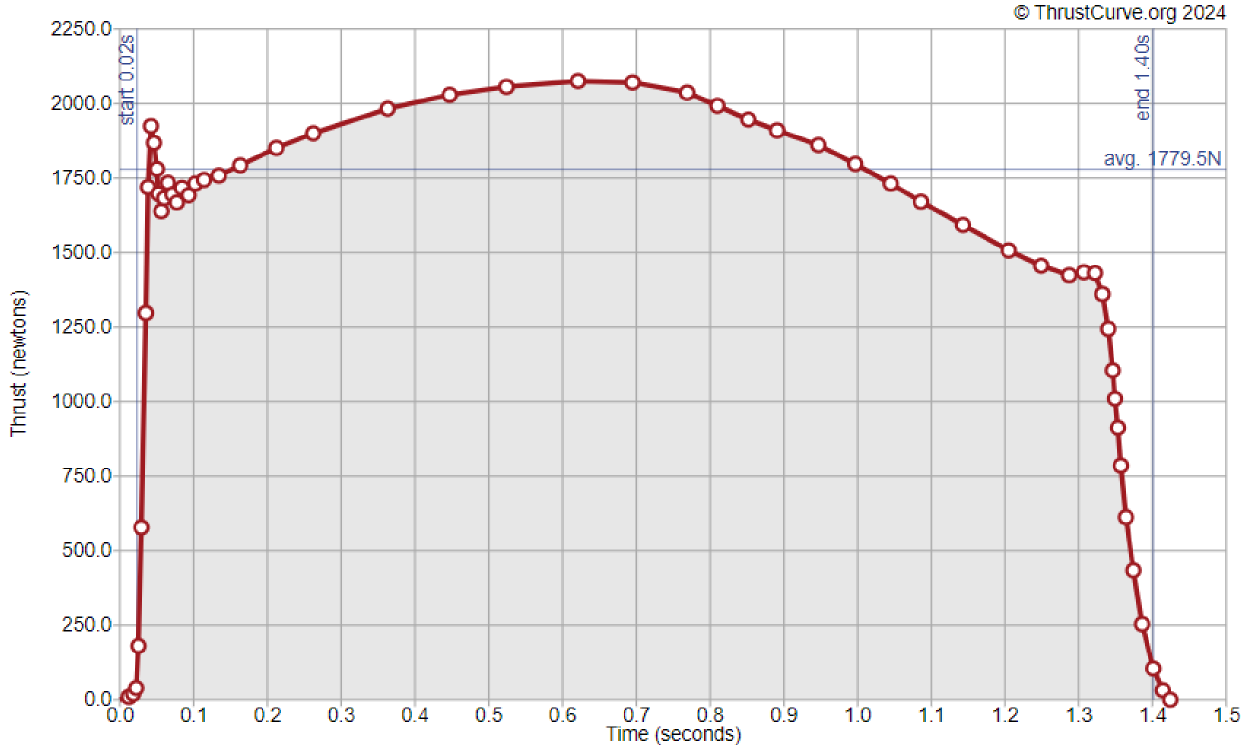

Figure 3.11.2. *Thrust vs Time curve for the K1800T-P rocket motor (data supplied from ThrustCurve.org).*

Table 3.11.1. *Motor performance comparison from OpenRocket simulations.*

Configuration	Velocity off rod	Apogee	Max. velocity	Max. acceleration	Time to apogee	Flight time	Ground hit velocity
[K1000T-P]	78 ft/s	4553 ft	559 ft/s	262 ft/s^2	17.3 s	66 s	16.8 ft/s
[K1800ST-P-P]	103 ft/s	4447 ft	577 ft/s	498 ft/s^2	16.6 s	61.7 s	16.9 ft/s

3.11.3. Flight Path Simulations

In addition to blocking out the major components of the launch vehicle and monitoring their placement's effect on stability, OpenRocket provided a suite of simulation and plotting tools that CSL employed to visualize key flight parameters like the altitude, vertical velocity, vertical acceleration, and stability margin as they relate to flight events. The flight path data shown in Figure 3.11.3 helped CSL to verify that the launch vehicle would meet competition requirements.

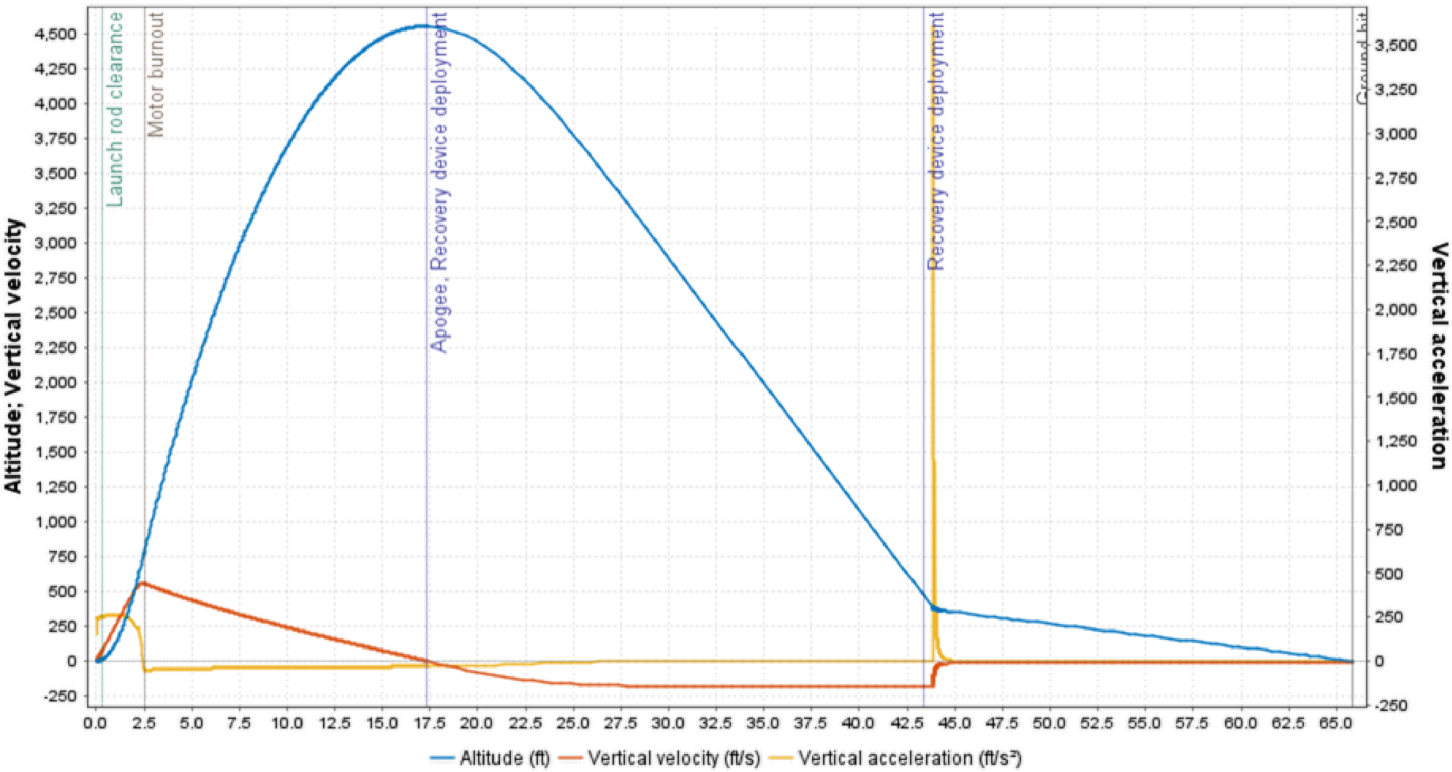

Figure 3.11.3. *Launch vehicle flight path for the rocket loaded with a K1000T-P.*

Figure 3.11.4 is a magnified portion of the plot in Figure 3.11.3 that shows the various flight performance parameters at the time of launch rod clearance. At that moment in the rocket's flight, the rocket is no longer constrained to a vertical path by the rigid launch rail and must be travelling fast enough for the rocket's fins to take over in dynamically stabilizing the rocket. The official NASA USLI requirement for the minimum rail exit velocity is 52 ft/s. According to Figure 3.11.4, the launch vehicle far exceeds this requirement, with the simulation predicting a rail exit velocity of just under 80 ft/s.

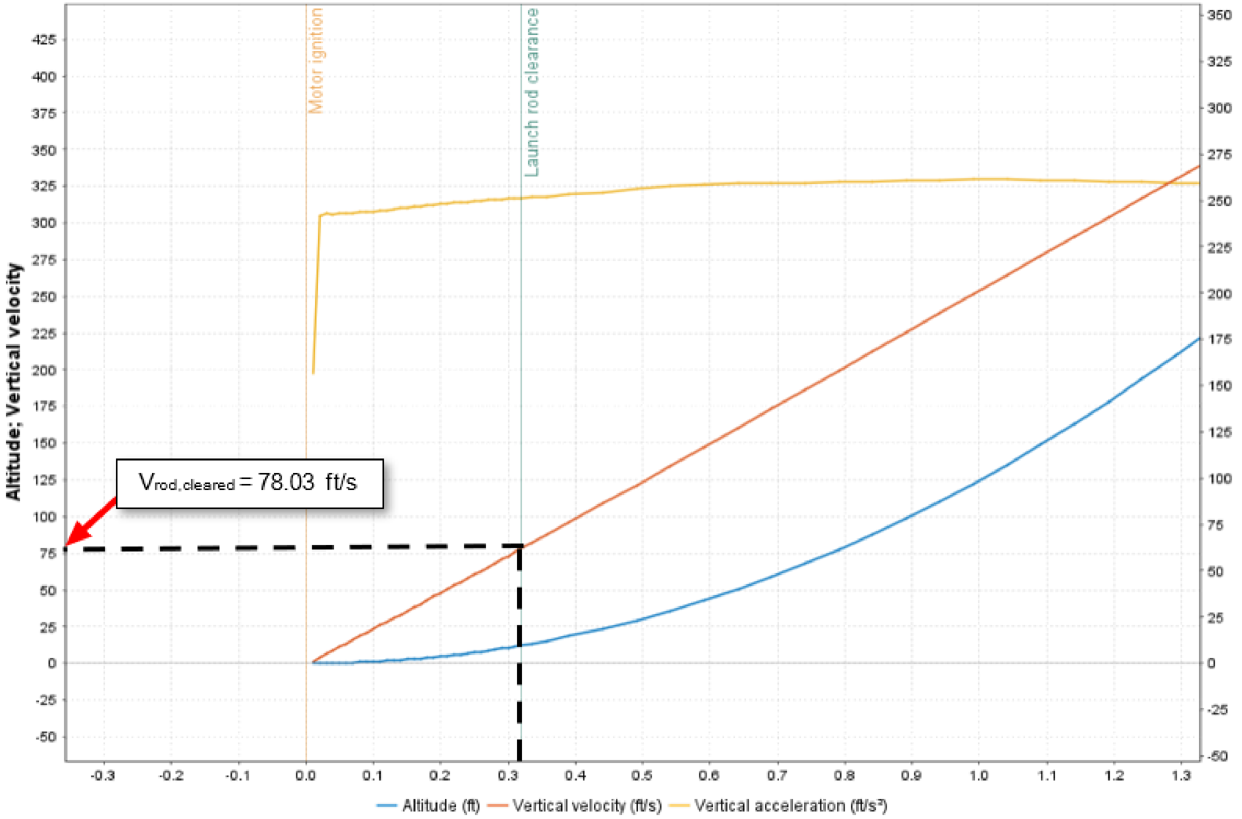

Figure 3.11.4. *Flight performance graph created from OpenRocket showing the rocket velocity at launch rod clearance.*

Airbrakes suddenly protruding from the surface of the rocket airframe, as will be the case in Project Elijah, will dramatically increase the surface area of the rocket. This will sharply change the location of the CP and potentially make the flight unstable. A formal CFD analysis of the rocket with its airbrakes deployed will verify that the design remains stable in flight; however, as a preliminary check to see if the leading design can support a significant stability change, the plot shown in Figure 3.11.5 was created. Beginning the plot from motor burnout (the moment at which the airbrakes will become active) the stability margin was plotted until apogee, when the drogue event was fired. Since the stability margin during the coast phase is significantly higher than the average stability margin found by simulation, CSL is comfortable with proceeding with the current preliminary design until thorough CFD analysis can be performed. As can be seen in the project testing plan in Section 6, an actual flight will be allotted to simply opening the airbrakes fully in flight to verify that the stability of the launch vehicle is not adversely impacted.

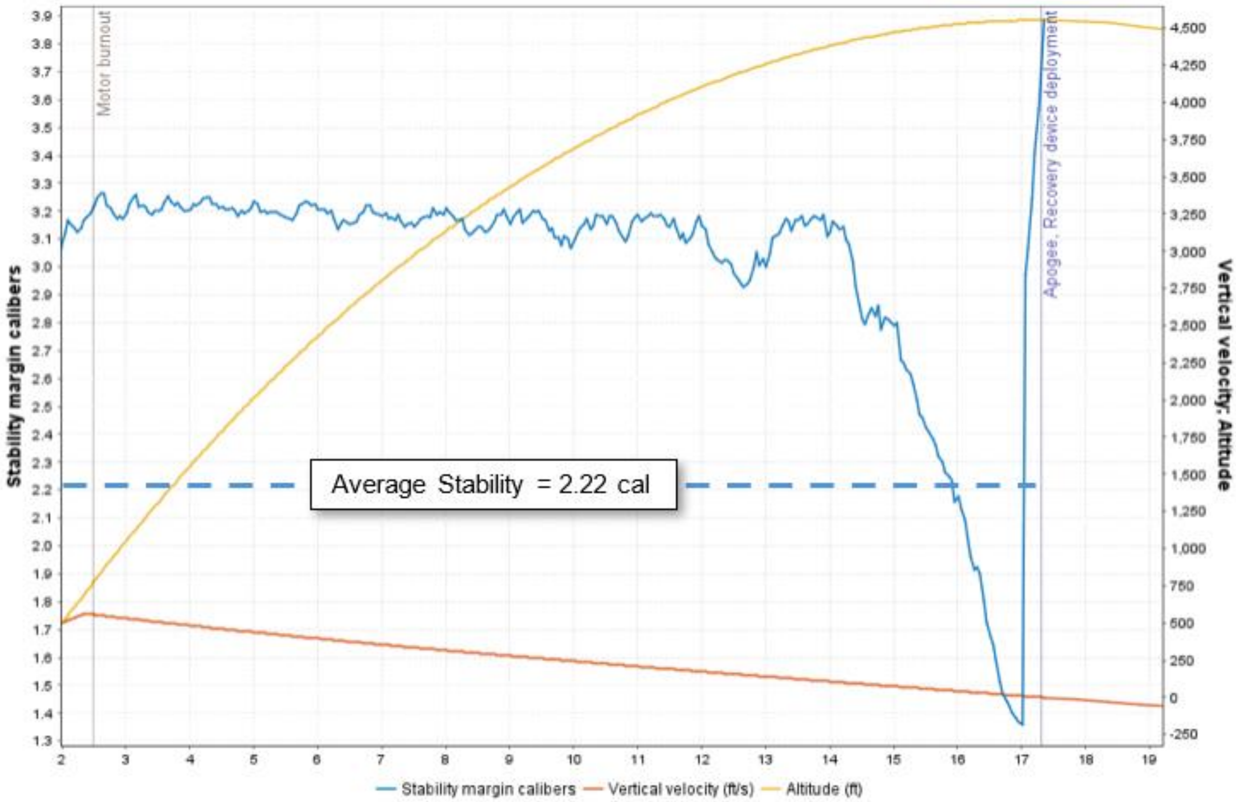

Figure 3.11.5. *Stability margin plotted over flight time as developed from OpenRocket.*

The final NASA USLI flight performance requirement of note is that the rocket must not have thrust to weight ratio of less than 5.0:1.0. To verify that Project Elijah is compliant with this rule, the liftoff thrust from the K1000T-P was retrieved from ThrustCurve.org and divided by the weight of the launch vehicle:

$$\frac{248lbf}{29lbf} = 8.55:1 \qquad (3.11.1.)$$

The thrust-to-weight ratio was thus found to be well within the bounds of the competition requirement.

3.11.4. Drift Predictions

To find the descent time of the rocket based on the predicted mass estimates of each rocket section and the parachutes being used for the drogue and main, the descent path and the three events that occur in the recovery must be considered. This was done in OpenRocket simulation and verified by MATLAB software. To find the equations for the MATLAB code (found in A.4), Newton's laws of motion had to be considered for the three recovery events shown in Figure 3.11.6. These laws outline the position, velocity, and acceleration at each spot, where $x = 0\ [ft]$. This occurs at apogee as the rocket moves back down to earth it moves in a positive direction (*i.e.* when the rocket lands it has traveled the same distance as the apogee).

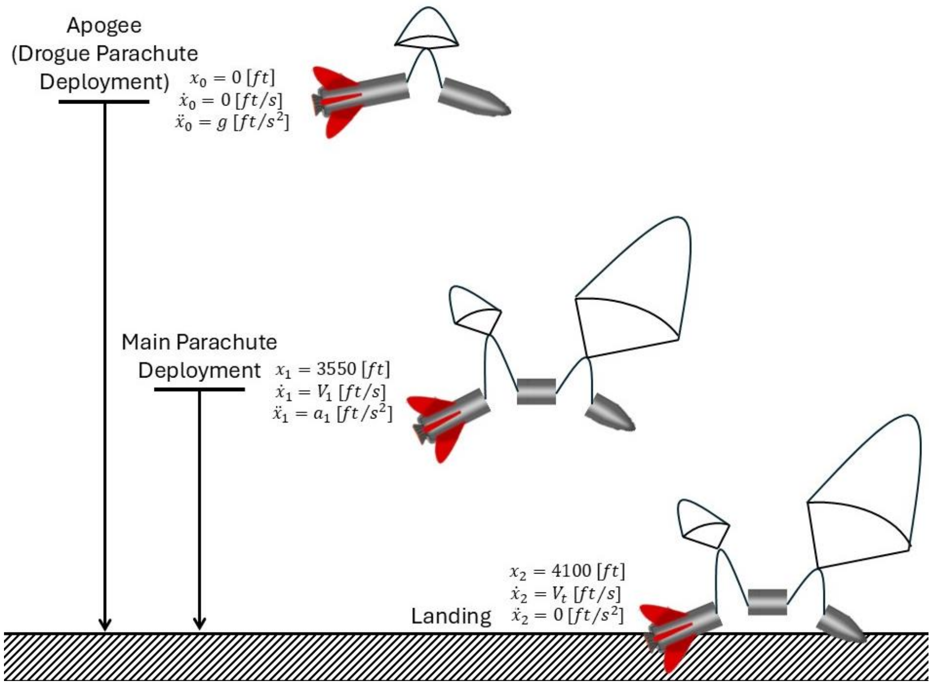

Figure 3.11.6. *Diagram of the three events in the recovery system with the corresponding position, velocity, and acceleration for the full-scale rocket.*

Through Figure 3.11.6 and Newtons laws the sum of forces for the rocket when the drogue and main parachute deploy as well as when the rocket lands can be found in Equation 3.11.2-3.11.4 respectfully.

$$ma_0 = W - \tfrac{1}{2}\rho C_{D,d} A_d V_0^2$$

$$mg = W \qquad (3.11.2.)$$

$$ma_1 = W - \tfrac{1}{2}\rho C_{D,d} A_d V_1^2 \qquad (3.11.3.)$$

$$ma_2 = W - \tfrac{1}{2}\rho V_2^2 \left(C_{D,d} A_d + C_{D,m} A_m\right)$$

$$W = \tfrac{1}{2}\rho V_2^2 (C_{D,d} A_d + C_{D,m} A_m) \qquad (3.11.4.)$$

To find the total descent time the time from apogee to the main parachute needs to be found first. This will be used through Equation (3.11.3) by replacing $a_1 = \frac{d\dot{x}_1}{dt}$ and then adjusting the equation the $\dot{x}_1$ are all on one side. From this Equation (3.11.5) can be found which the integral from $\dot{x}_0 \rightarrow \dot{x}_1$ and $t_0 \rightarrow t_1$ can be used to find Equation (3.11.6) which gives the time from apogee to the main parachute deployment. Equation 3.11.7 can also be found to find V_1 where a_1 is found through iteration. MATLAB performed this iteration through an error analysis which adjusted a_1 until an appropriate error was reached.

$$m\frac{d\dot{x}_1}{W - B_1\dot{x}_1^2} = dt_1 \tag{3.11.5.}$$

Where $B_1 = \frac{1}{2}\rho C_{D,d} A_d$.

$$t_1 = \frac{m}{\sqrt{B_1 W}} \operatorname{arctanh}\left(\dot{x}_1\sqrt{\frac{B_1}{W}}\right) \tag{3.11.6.}$$

$$V_1 = \dot{x}_1 = \sqrt{\frac{W - ma_1}{B_1}} \tag{3.11.7.}$$

To find the final descent time Equation (3.11.4) can be used in MATLAB with the 'ode45' command along with the initial position and velocity (x_1 and $\dot{x}_1$ respectfully) over a time span from t_1 to t_2, where t_2 will be iterated until x_2 equals the apogee. t_2 is the predicted total descent time of the rocket.

To find the drift predictions of the rocket, Equation (3.11.8) should be used to evaluate how increased wind velocity affects the drift. Doing this from 5 [MPH] to 20 [MPH] Table 3.11.2 can be created which shows that the rocket will be able to fulfill requirement 3.11 for a CPR from the SL Handbook (2025) up to a wind velocity of 20 [MPH].

$$drift = t_2 V_{wind} \tag{3.11.8.}$$

Table 3.11.2. *Drift from the launch pad of the full-scale rocket based on the descent time with increasing wind speeds.*

Wind Speed [MPH]	5	10	15	20
Drift [ft]	489.1 485.5	978.3 970.9	1467.4	1956.5 1941.9

3.11.5. Kinetic Energy at Landing

Through Equation (3.11.4) the terminal velocity can be found since it is assumed that the acceleration at touchdown is approximately zero. The equation for the terminal velocity is shown in Equation 3.11.9 and by placing in the values of the full-scale rocket using the mass of the heaviest section when the rocket is separated the terminal velocity can be found to be approximately 12.5 [ft/s]. From this value the kinetic energy at landing for each section of the rocket using Equation (3.10.1) can be found by varying the mass depending on which section of the rocket is of interest.

$$W = \frac{1}{2}\rho V_2^2 (C_{D,d} A_d + C_{D,m} A_m) \tag{3.11.4.}$$

Where $B_2 = \frac{1}{2}\rho(C_{D,d}A_d + C_{D,m}A_m)$

$$V_2 = V_t = \sqrt{\frac{W}{B_2}} \quad (3.11.9.)$$

$$T = \frac{1}{2}mV^2 \quad (3.10.1.)$$

Equation 3.11.9 can also be used to find the kinetic energy of the heaviest section of the rocket which can confirm whether the recovery system successfully fulfills requirement 3.3 from the SL Handbook (2025), or that the heaviest section of the rocket lands with a kinetic energy less than 75 [ft·lbf]. From Equation 3.10.1 Table 3.11.3 is found for the three rocket sections at landing. The largest kinetic energy that can be seen from the full-scale rocket is 36.34 [ft·lbf].

Table 3.11.3. *The kinetic energy of the three rocket sections upon landing for the full-scale.*

	Aft Section	Middle Section	Forward Section
Weight [lbf]	8.641	2.848	9.257
Kinetic Energy [ft·lbf]	33.92 34.87	11.18	36.34 37.35

4. Payload Criteria

4.1. Payload Objective

The objective of the payload, as per requirement 4.1 of the Student Launch Handbook, is to safely hold the STEMnauts and to transmit, “via radio frequency, relevant rocket and STEMnaut landing site data to a NASA-owned receiver located at the launch site.” The relevant data is comprised of up to 8 pieces of information, including the temperature of the landing site, the apogee reached, the orientation of the on-board STEMnauts, the time of landing, the calculated STEMnaut crew survivability, the landing velocity and G-forces sustained, the maximum velocity, and a battery check/power status report. Each of these pieces of information must be gathered by the on-board sensors. Table 4.1.1 shows what sensors the team will use to acquire each piece of data and whether each piece is currently expected to be implemented.

Table 4.1.1. *Payload data priorities and data acquisition hardware.*

Priority	Objective	Expected?	Hardware
1	Temperature of Landing Site	Yes	Temperature Sensor
2	Apogee Reached	Yes	Altimeter
3	Orientation of On-Board STEMnauts	Yes	Accelerometer
4	Time of Landing	Yes	Real Time Clock
5	Calculated STEMnaut Crew Survivability	Tentative	Accelerometer
6	Landing Velocity, G-Forces Sustained	Tentative	Accelerometer/Altimeter
7	Maximum Velocity	Tentative	Accelerometer/Altimeter
8	Battery Check / Power Status	No	Voltage Sensor

The details of each of these sensors will be discussed in section 4.4. A successful payload experiment will consist of gathering the data for the chosen objectives from the sensors, processing the data with the microcontroller, and successfully transmitting the data to the NASA receiver using the Automatic Packet Reporting System (APRS) protocol via the radio transmitter at the required frequency. At the simplest level, the ultimate objective is to successfully transmit the correct data at the correct time using the correct frequency.

4.2. Microcontroller

The payload team decided to use a Raspberry Pi Pico microcontroller for the core of the system. This microcontroller has enough general-purpose pins for all the sensors, and it is powerful enough to perform the tasks. It also has four state machines for *platform-io*, which allows the team to run programs off-chip for very high-speed pin functionality. The Pico is very cheap, at $4.00 per board (Ltd, R. P., n.d.). Additionally, the university already had several in storage. The payload team is considering upgrading the Pico to a Pico 2, which was recently released. This upgrade would provide (on top of the existing features) a floating-point unit, greater speed, and more state-machines for high-speed external functionality.

During the microcontroller selection process, the payload team also considered using an Arduino Nano. The university owns several, and it was also a good choice. Unfortunately, it has a slower clock speed than the Pico. Another microcontroller the payload team considered was the STM32H7. This chip has an onboard digital-to-analog converter (DAC) which was originally thought to be useful for radio transmission. However, the payload team designed different methods which would perform the frequency-shift keying (FSK) logic off-chip. The STM32H7 is also fast with a 600MHz clock and a double-precision floating point unit (STM32H7 - Arm Cortex-M7 and Cortex-M4 MCUs (480 MHz) - STMicroelectronics). Additionally, the STM32H7 has expansive development boards, which can be used for rapid testing. This chip was not chosen because the university did not have any available and because the compilation process is very complicated. This chip varies in price based on the board purchased, and it was decided that the purchase was not worth it.

4.3. Radio Transmitter

The payload team considered several different transmitters for sending the collected data after the rocket's flight. The transmitter is required to operate on the two-meter band at five watts or fewer and obey all NASA and Federal Communications Commission (FCC) guidelines. Additionally, the transmitter would ideally be able to transmit data natively using the APRS protocol rather than simply being intended for voice signals and should have a minimal cost due to the possibility of destruction during durability testing and rocket test flights.

The first transmitter that the payload team considered is the *Friendcom* FC-303. This product has a low cost of $30 and is specifically meant for data transmission (FC-303 Data Radio, 2024). Unfortunately, the FC-303 only transmits in the seventy-centimeter band rather than the two-meter band, which makes it infeasible for this application.

The payload team then considered a similar transmitter from the same company that does operate in the two-meter band. This product, the *Friendcom* FC-302, is specifically designed for sending data transmissions over the two-meter band. The transmitter appears to be durable and is rated to transmit at five watts. The two major disadvantages of using the FC-302 are its high price and lack of thorough documentation. The cost of the FC-302 is $200, which is a significant portion of the payload team budget and would cause the team to go significantly over budget if the transmitter was ever damaged or destroyed in the testing process (FC-302 UHF/VHF Data Radio, 2024).

The final transmitter that the payload team considered is the *Baofeng* UV-5R. This transmitter is a popular and thoroughly documented consumer product. It operates on the two-meter band and only costs $32 for a set of two devices (Baofeng UV-5R Ham Radio, 2024). Additionally, the UV-5R seems to be robust and has a battery pack which simplifies the overall payload power management system (Baofeng Radio, 2019). This device is meant primarily for voice transmission, meaning that data will need to be encoded into the APRS protocol with an external circuit and input to the transmitter using its microphone port.

Additional research was conducted to consider various types of antennas. The rocket could land in any orientation, so a directional antenna is impractical for this application; an omnidirectional antenna is needed. Given the space constraints of the rocket's diameter, the team considered two monopole antennas. The first antenna considered was the RH707 Diamond Antenna. The cost of this antenna is $30, its maximum power is 10 Watts, and its length is 8.25 inches (Diamond Antenna Dual-Band HT Antennas, 2024). The second antenna considered was the *Baofeng* UV-5R Antenna, which comes with the *Baofeng* UV-5R transmitters, so it does not have any extra cost associated with it. Its maximum power is 5 watts, and its length is 6.5 inches (Baofeng Radio, 2019). Both antennas have sufficient power ratings, and either antenna length could be designed around; by far the biggest factor is the price. The team decided to use the *Baofeng* UV-5R antenna because it meets the specifications needed and is far cheaper, since its cost is already included in the cost of the transmitters.

4.4. Sensor Array

The payload team determined that the payload needs to be able to collect the following types of data: altitude, temperature, time, and orientation. For altitude, the team initially considered the BMP390, BMP280, and BMP180. The BMP390 reports altitude at an accuracy of a quarter meter (BMP380, n.d.), while the BMP280 reports altitude at an accuracy of one meter (BMP280, n.d.). However, the BMP390 costs about 10 times as much as the BMP280, so the team favored the BMP280. Initially, the BMP180 was not considered; however, the university had this chip in storage. It is a similar price and reports altitude at an accuracy of one meter as well, which was sufficient (Sensortec, 2013). However, initial tests with it proved the chip is faulty, so the team purchased the BMP280. All the chips considered use the I^2C interface for easy communication with the Pico.

For temperature, the Pico's onboard temperature sensors were initially considered. However, after reading data from these chips, the payload team found the accuracy to be far too low. During testing, the team discovered that the BMP280 provides accurate temperature information, so the team decided to use the data from it instead.

A method of keeping track of time is needed even if the payload is powered off. To do so, the team considered both GPS and a real-time clock (RTC). GPS is more complicated, and since the payload would also need to contain GPS antennas, it would draw significantly more current and retrieve a lot of information that is unnecessary. A GPS module is also far more expensive than an RTC. The upside of GPS, however, is that the clock would not need to be programmed across boot cycles. The payload team decided to use an RTC since it was much cheaper and far less complex to implement. Its isolated battery allows it to keep time even when the payload is disconnected. The team initially looked into the DS3231 chip; however, the university had several DS1307 chips in storage, so these chips were used instead. The DS1307 also has the added advantage of keeping the sea level pressure for BMP280 calibration across power cycles with its general-purpose flash.

Because the orientation being transmitted over radio is the resting orientation of the payload, the team decided to use an accelerometer instead of a gyroscope. The team found that the MPU6050 is widely used, supports I^2C communication, and is inexpensive. The university also had several of these chips on hand. Unfortunately, the chip was discovered to have an address collision with the DS1307, so a separate I^2C bus will be used for this chip.

4.5. External Memory

For debugging purposes, the payload team decided it would be best to be able to retrieve flight and test data from the payload without a computer attached. For this reason, a MicroSD card was chosen to be used since it is compatible with any computer. However, to prevent data loss and corruption in case the MicroSD card temporarily loses connection, the Pico will not write the data to the MicroSD during flight. The Pico is also unable to store all the data in memory, since it only has 264 kilobytes of flash memory on board. Due to the speed requirements of storage, the payload team decided to use serial-peripheral interface (SPI). The team found that the W25Q64 memory chip fits the requirements. It had 8 megabytes of storage space, which allows frequent data collection.

4.6. Power Management

The primary requirement for power management for the payload is that the payload should be able to operate correctly after waiting on the launchpad for two hours. Because the payload module will need to be powered on and ready before the rocket is fully assembled, the estimated battery life for the payload cannot be fewer than three hours. The battery pack attached to the UV-5R transmitter estimates a battery life of twenty-four hours when in standby mode, which is the mode that the transmitter will remain in until landing after the launch (Baofeng UV-5R Ham Radio, 2024). Because the rest of the payload's electrical components have a comparatively low current draw, this allows the payload to have a much smaller battery powering the remaining electronics. While the payload team is unsure of what the average current draw will be from the rest of the circuit during operation, an upper bound of this parameter can be found by adding together the maximum current consumption ratings of all planned electrical components. This is shown in Table 4.5.1 below.

Table 4.5.1. *Electronics Max Current Draw.*

Component Name	Max Current Draw [mA]
DS1307 Real Time Clock	0.3
BMP280 Barometer & Thermometer	1.12
MPU6050 Gyroscope & Accelerometer	3.9
W25Q64 Flash Memory Module	4
Micro SD-Card Reader	30
Raspberry Pi Pico	90
Total	**129.32**

Previous CSL teams have used Lithium Polymer (LiPo) batteries to power their payload, so 2200mAh 3S LiPo and 5200mAh 2S LiPo were the first batteries considered. Both batteries would give the payload well over a day of battery life after being stepped down to five volts with a buck converter (CNHL 2200mAh 3S LiPo Battery, 2024; OVONIC LiPo Battery, 2024). LiPo batteries are especially useful when high current is needed, but this factor is not important for this year's payload design. In many ways, these LiPo batteries are excessive for this year's payload system.

The payload team then considered smaller, cheaper batteries. Batteries such as a 700mAh 6V Nickel-Cadmium (Ni-Cd) are smaller, cheaper, and not explosive when charged incorrectly. This battery provides six volts and has sufficient capacity for the payload to run for more than five hours on a full charge (Elxjar (2-Pack) 6.0V 700mAh Ni-CD AA Rechargeable Battery Pack, 2024). Therefore, the team plans to use a 700mAh 6V Ni-Cd battery to power the main circuit.

4.7. Electrical Schematic

The main circuit for the payload is shown below in Figure 4.7.1. While all initial testing will be done with a lab breadboard to validate each part of the circuit individually, a printed circuit board (PCB) will be manufactured to implement the circuit in the rocket. All electrical schematics are designed in EasyEDA, and the PCBs will be manufactured by JLCPCB using the PCB layout generated in EasyEDA. The first iteration of this PCB will be a daughter board for the Raspberry Pi Pico which makes all the connections to each sensor and external memory component. No component on the board will be surface mounted, which will allow the payload team to somewhat easily make changes if necessary. This electrical schematic for this first PCB is shown in Figure 4.7.1 while the layout for the PCB is shown in Figure 4.7.2. The high-level system design for the main payload is shown in Figure 4.7.3.

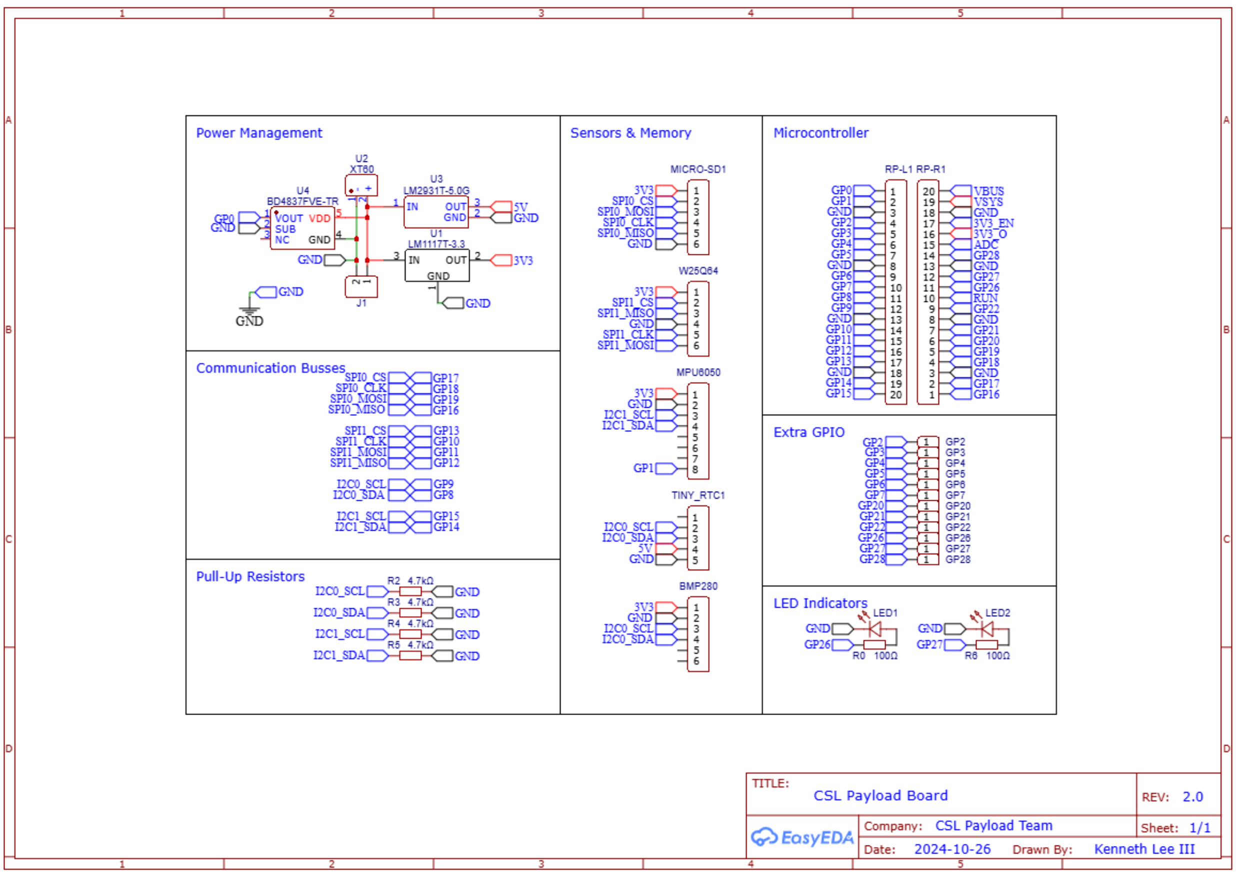

***Figure 4.7.1.** Electrical Schematic for Primary PCB.*

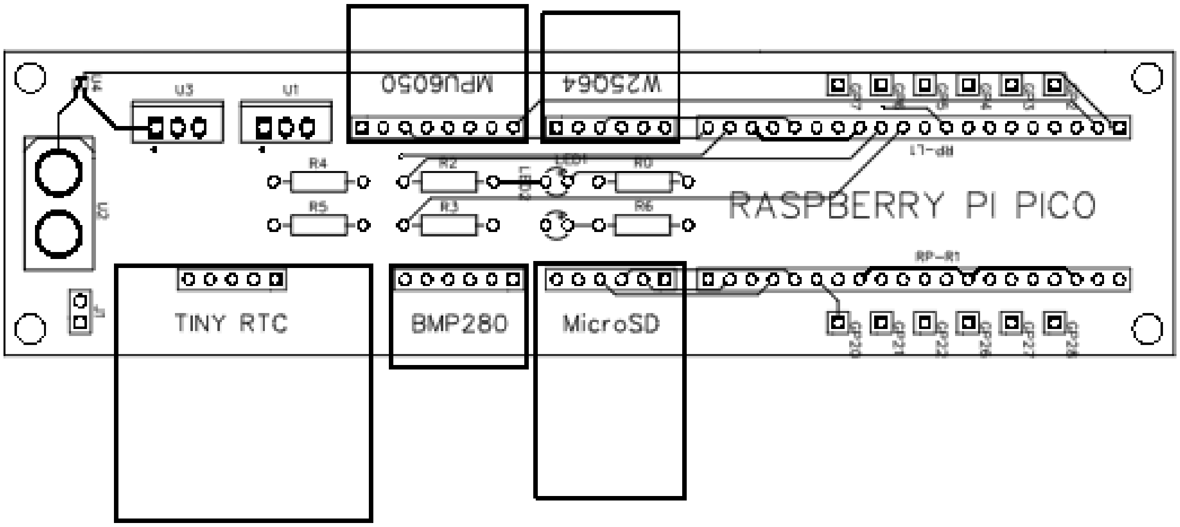

__Figure 4.7.2.__ Primary PCB Layout.

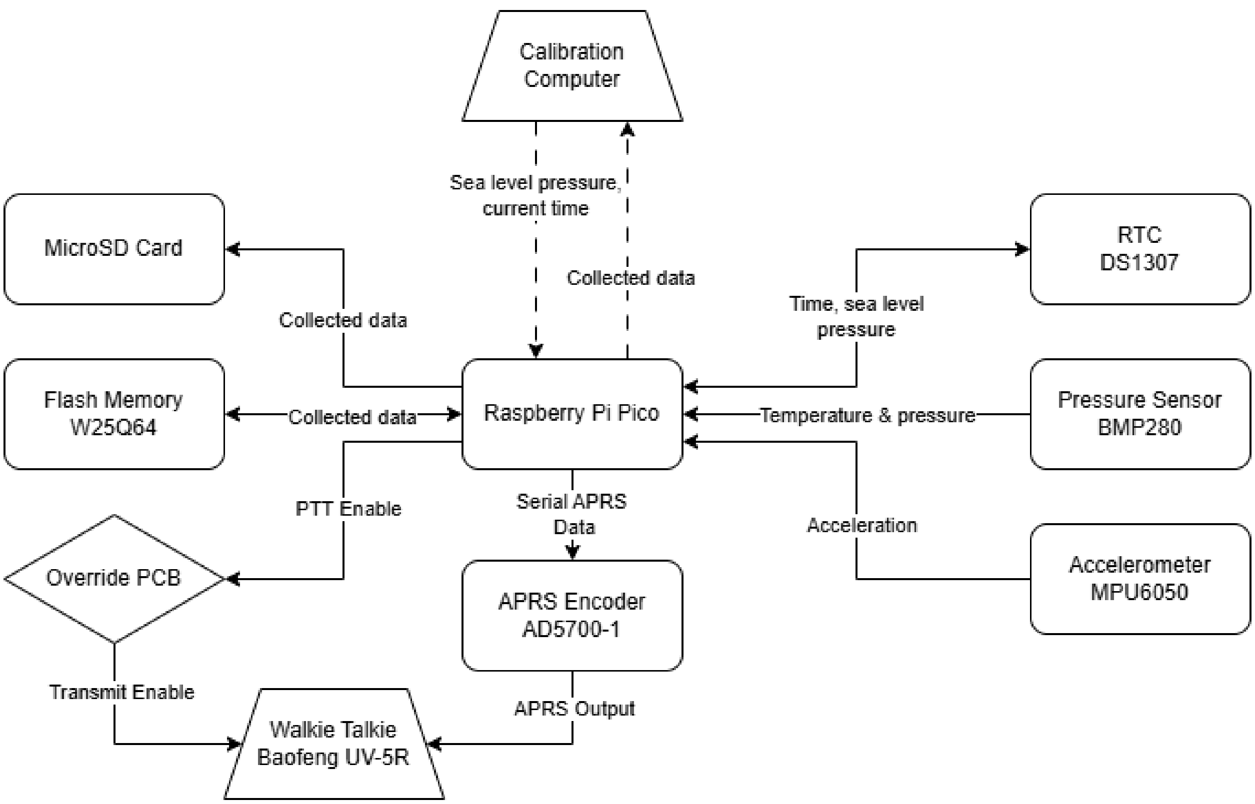

__Figure 4.7.3.__ High Level System Design.

If time permits, the payload team will design a new version of this electrical schematic with surface-mounted sensor, processor, and memory chips instead of a daughter board for the breakout boards. This second version would provide modest durability, performance, and size upgrades, but will not be considered for manufacturing until the first version is completed and thoroughly tested.

If the team's payload is sending transmissions at any time other than immediately after the rocket's flight, this could cause problems for other teams' transmissions. This could be catastrophic because the CSL team is not able to retrieve its rocket to disable the transmitter during the launch window. To avoid the possibility of accidental transmissions, the payload team has instituted a safety measure to override the microcontroller's ability to tell the transmitter to operate. Under normal circumstances, the primary circuit can electronically activate the transmitter's push-to-talk (PTT) switch, sending a transmission. With this new override system, the backup system acts as a middleman between the microcontroller's use of the PTT control and the transmitter's reading of that signal. This means that transmissions can only be sent by the transmitter if both the main and override systems allow the signal to be sent. The electrical schematic for the override system is shown below in Figure 4.7.3. The control signal comes into the backup system from the primary circuit and then exits the backup system to go to the transmitter. A preliminary version of the PCB for the backup system is shown below in Figure 4.7.4.

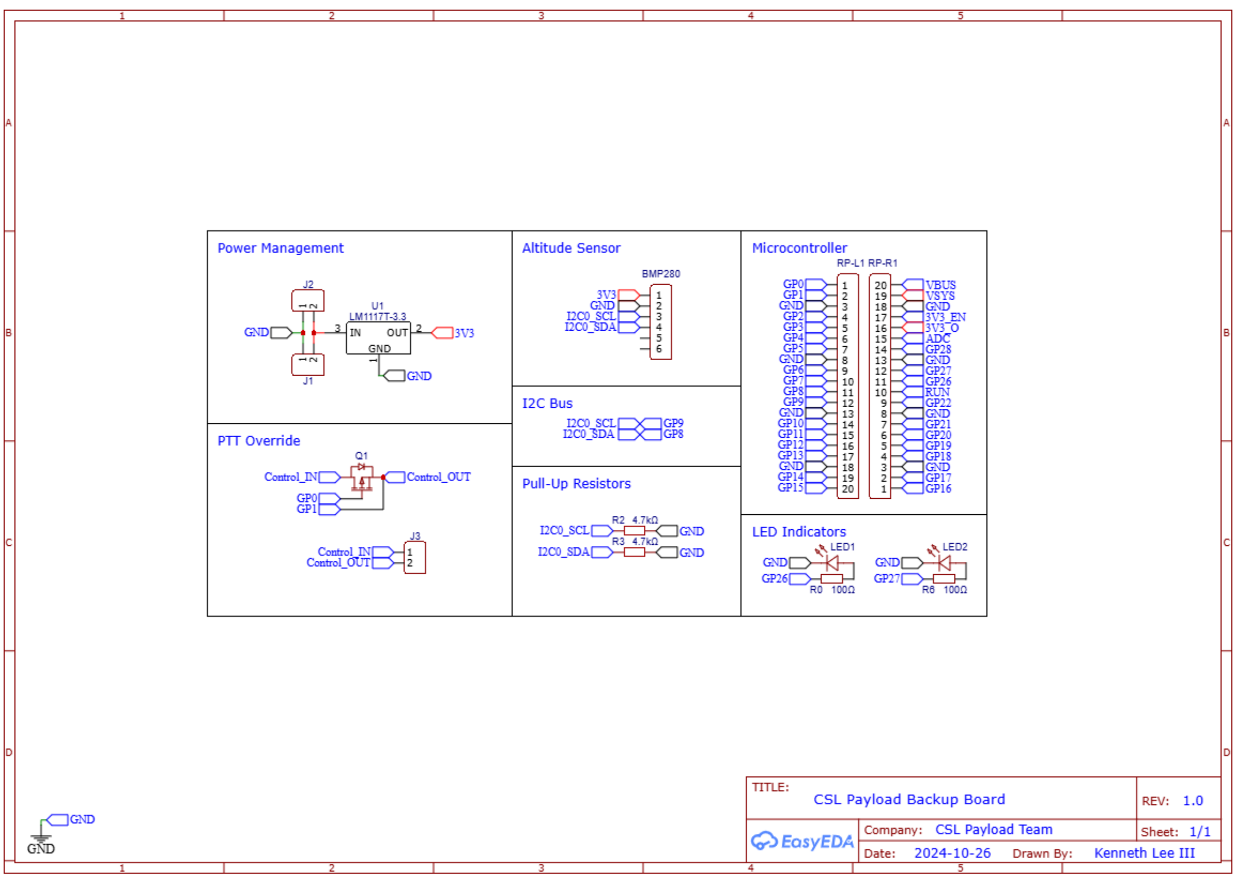

Figure 4.7.3. *Electrical Schematic for Backup PCB.*

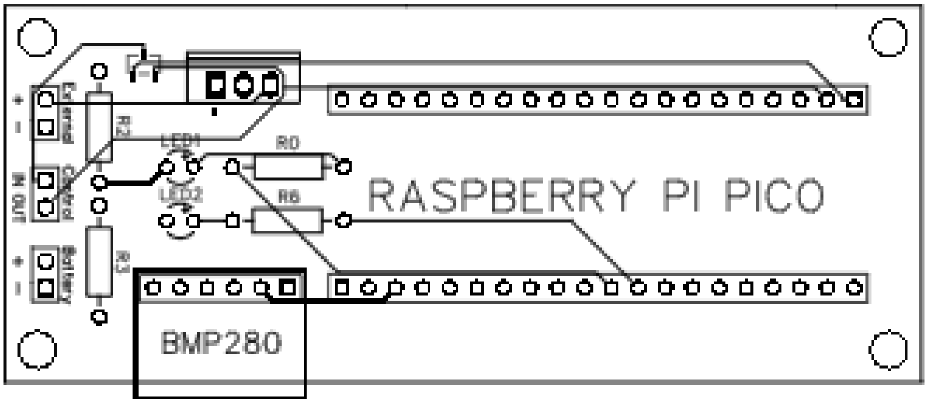

Figure 4.7.4. *Backup PCB Layout.*

As previously mentioned, the *Baofeng* UV-5R is meant primarily for voice transmission, so the data must be encoded into the APRS protocol with an external circuit before being input to the transmitter. The payload team considered several different options for converting the digital data to the analog tones required for APRS. APRS transmits at 1200 bits per second and encodes a digital 1 as a 1.2 kHz sine wave and a digital 0 as a 2.2 kHz sine wave, so the circuit must be capable of executing this conversion (Digital Packet Radio – APRS, 2021). The first option the payload team considered was the PCM5102 DAC chip. This digital-to-analog converter uses the I^2S protocol to communicate with the microcontroller and costs around $5. The next option the team considered was building a voltage divider and analog multiplexer network using parts mainly already contained in the lab, essentially building a digital-to-analog converter in the lab instead of using a premade chip. Figure 4.7.5 shows the electrical schematic for this option. This would be a cheaper alternative to the DAC chip, but ultimately it would likely not be worth spending the time involved in designing and building it by hand.

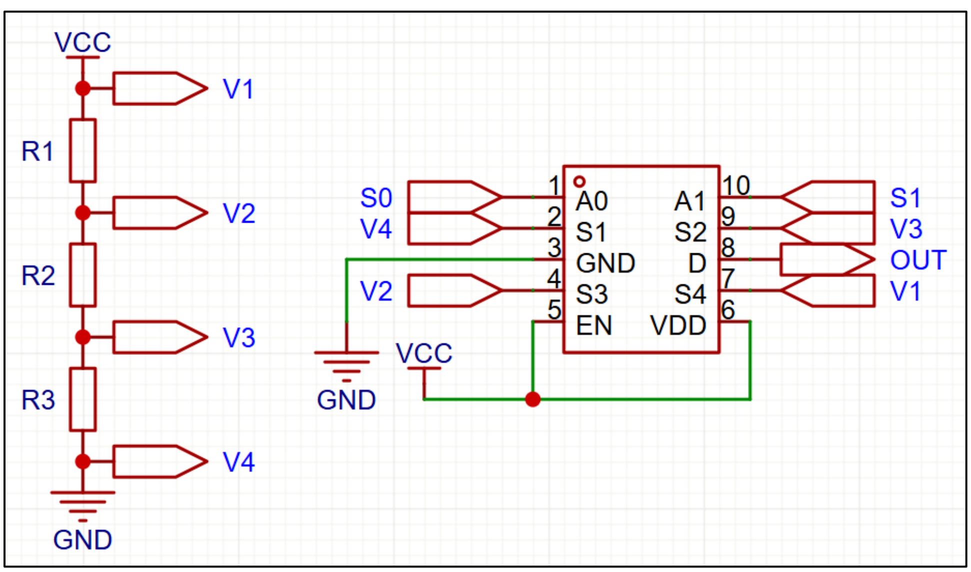

Figure 4.7.5. *Electrical Schematic for Voltage Divider and Analog Multiplexer Option.*

The third option considered was the AD5700-1 chip. We chose the AD5700-1 variant of the AD5700 due to its inclusion of an internal oscillator. This chip was designed for the Highway Addressable Remote Transducer (HART) communication protocol, which, like APRS, operates at 1200 bits per second and uses a 1.2 kHz sine wave for a digital 1 and a 2.2 kHz sine wave for a digital 0. This chip allows the microcontroller to send it digital zeros and ones via the TXD transmit input and automatically converts each bit to a sine wave at the corresponding frequency via its internal FSK modulator (Low Power HART Modem, n.d.). The HART_OUT pin outputs the sine waves, which are phase continuous. While it was not designed specifically for APRS, the protocols are very similar, and the team's research on the AD5700-1 has so far indicated that it can be used for this purpose. This is by far the simplest option; no additional code would be necessary to create the sine waves, unlike the two previous options. The microcontroller would only need to output digital ones and zeros and the AD5700-1 would handle the conversion to APRS entirely. The cost of this chip is between $6 and $8, making it comparable to the PCM5102 DAC chip, but with much less work for the team to implement (JLCPCB SMT Parts Library & Component Sourcing, 2024). This is currently the option the team intends to use for implementing APRS.

4.8. Software

The Raspberry Pi Pico has several options for programming. The payload team opted not to use a real-time operating system since the system is not complicated enough to warrant it. The software is written in C++ using the official Pico software development kit. The team decided against Micropython due to its slower speed and opted to not use Arduino's language due to difficulties with Arduino integrated development environment setup and overall payload team unfamiliarity with Arduino's libraries. The payload also has a custom console running on the computer for simple bi-directional communication with the Pico, written in Python. This console allows calibration, viewing information, and running debugging software on the Pico using serial device communication.

The software uses both cores on the Pico. The primary core is used for data collection and radio transmission, and the secondary core is used to write data to flash memory and to the MicroSD card. The first core collects data as fast as possible and sends it over to the second core. When the payload detects that it has landed, it will stop collecting data and transmit it over radio. The second core writes any data it receives, and when it is notified that the rocket has landed, it will read all the data from flash memory and write it to the MicroSD card.

4.9. Physical Apparatus

For the payload team, rapid prototyping is very important for being able to make changes quickly. For this reason, the main body of the payload will be 3D printed. Because the engineering department's additive manufacturing lab primarily stocks PLA+ and it is easy to print with, the payload will be 3D printed with PLA+. Due to the high number of components that interact with the main body, this will allow the payload team to make hardware alterations quickly.

The 3D printed payload will be a cylinder with two opposing inset faces. The PCB for the primary circuit will be mounted to one side while the PCB for the override circuit and its backup battery will be mounted to the other side; these will both be mounted with standoffs which bolt into nuts embedded in the PLA+. Below the smaller override PCB is a capsule containing four LEGO minifigures representing STEMnauts. Between the two inset faces of the cylinder is a cavity into which the battery will be placed. Beneath the battery cavity will be another cavity accessible from the bottom, which can be used to add more mass to the payload if the CSL team determines that more mass is needed near the front of the rocket.

At the top of the payload is the transmitter, with the antenna extending into the nosecone of the rocket. The payload team considered two ways of affixing the transmitter to the 3D printed body. First, the team could manufacture a bracket to bolt into the belt clip mount of the UV-5R transmitter and then bolt into the body. Second, the transmitter could be secured by having two rubber vibration-absorption feet screwed from opposing sides to tighten down against the grooved edges of the UV-5R. While the first option has the potential to be more robust in the long term, the second option allows the team to be able to insert and remove the transmitter more quickly to make the necessary adjustments. For this reason, the payload team will test the second option for durability and switch to the first option if necessary.

The overall payload assembly is shown below in Figure 4.9.1.

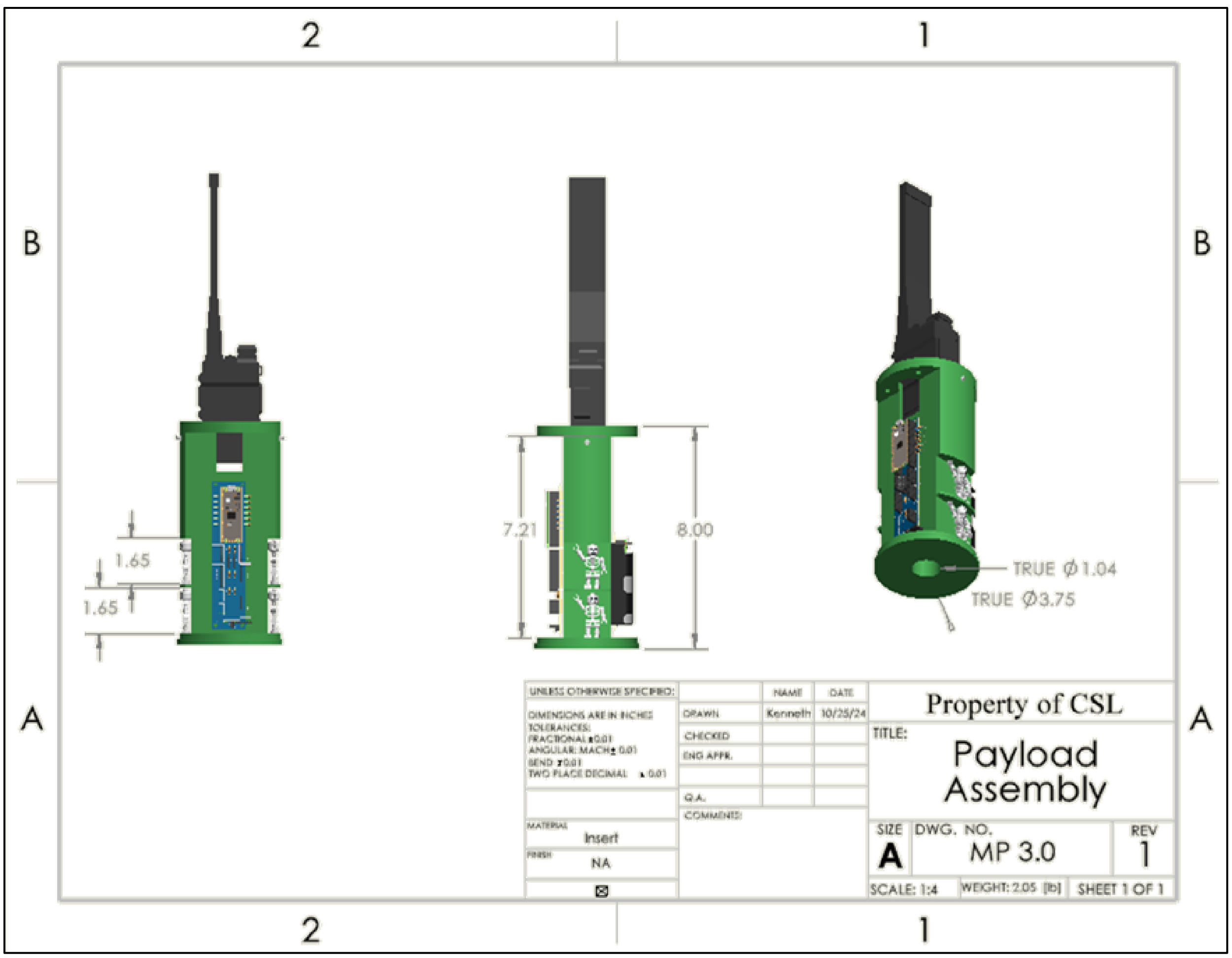

Figure 4.9.1. *Payload CAD Assembly.*

For the sake of simplicity, the interface between the payload and the rocket will be as minimal as possible. There will be no electrical connection between the payload and the rocket. The transmitter and antenna will extend up into the nosecone, but the payload will not be actively connected to the nosecone. The payload will be lowered into the front section of the rocket having already been powered on. Because the nosecone will be bolted to the body tube above it, the payload will be trapped between the payload bulkhead and the nosecone, securing it in place.

Table 4.9.1. *Payload Mass Table.*

Component Name	Flight Quantity	Estimated Mass [g]	Measured Mass [g]	Total Mass [g]
UV-5R Ham Radio Transceiver	1	400	196	196
DS1307 Real Time Clock	1	5	7	75
BMP280 Barometer & Thermometer	2	1.3		2.6
MPU6050 Gyroscope & Accelerometer	1	2.1		2.1
W25Q64 Flash Memory Module	1	1.5	0.5	0.5
Micro SD-Card Reader	1	3	2	2 3
Micro SD-Card 32GB	1	0.5	0.5	0.5
700mAh 6V Ni-CD Battery	1	100		100
9900mAh 18650 Li-ion Battery	1	45		45
RPI Pico	2	3		6
Primary PCB	1	10		10
Secondary PCB	1	5		5
Vibration Absorption Mount	2	1.4		2.8
M4 Threaded T-Slot Nut	2	1		2
M4 Set Screw	2	1		2
LEGO STEMnauts	4	3	3	12
Main Body Mass	-	188		188
Bulk Mass	-	20		20
Total				**603.5**

5. Safety

5.1. Chief Safety Officer

Cedarville Student Launch has elected Jesse DePalmo as Chief Safety Officer (CSO). The CSO is responsible for the safety of all team members, students, and the public participating in the team's activities. This role has the responsibility for the evaluation and mitigation of failure modes that can occur throughout the design, construction, and launch processes. The CSO is required to promote a strong culture of safety across all areas of the team. Once a procedure or plan is set by the team, the CSO has the right to amend team activities to maintain a high level of safety. The general responsibilities and duties of the CSO are, but not limited to, the following:

- Creation of a Safety Handbook to equip team members to perform roles effectively while maintaining safety standards.
- Designing and coordinating launch procedures with the Launch Officer.
- Ensuring compliance with local and federal safety regulations.
- Ensuring all team members comply with NAR and university safety regulations.
- Promoting a safety-first culture that prioritizes proper design.
- Attending sub-scale and full-scale launches to ensure correct adherence to procedures.
- Enforcing general safety practices throughout the design process.
- Assessing failure modes and proposing mitigations using Failure Modes and Effects Analysis (FMEA) tables.
- Understanding of the facilities, equipment, and regulations that exist beyond the team's direct responsibilities.
- Acting as a point of reference for safety-related inquiries from team members.

5.2. CSL Safety Handbook

The CSL team safety handbook, currently being developed by the CSO, is intended to outline the essential rules and guidelines that the team members must follow. It serves as a comprehensive resource aimed at improving expertise and ensuring safety for all team members participating in rocketry. The purpose of this handbook is to provide a shared foundation of knowledge among team members, enhancing both their expertise and safety. By compiling key information on the team's functions, tools, operations, and policies, the safety handbook will equip members to perform their roles effectively while maintaining safety standards.

The handbook will cover various topics such as the proper use of personal protective equipment (PPE), material safety, handling of energetics, construction and testing safety protocols, launch safety measures, and compliance with relevant safety regulations. Additionally, it will include a formal agreement where team members acknowledge their commitment to following the team's safety guidelines.

5.2.1. Personal Protective Equipment

All team members are required to wear the proper personal protection equipment (PPE) while working in any of the university laboratories. Safety glasses, closed-toed shoes, and full-length pants are always required when working in the Engineering Project Laboratory, Advanced Manufacturing Laboratory, and “the Barn.” Using gloves, respiratory protection, and ear protection are required using certain equipment including welding, painting, and woodworking. Clothing worn in laboratories must be fire-retardant and abrasion resistant. Hazards of not wearing the proper PPE include burns, cuts, abrasions, eye irritation, skin irritation, dust inhalation, and eye injury.

5.2.2. Material Safety

The safety handbook will include Material Safety Data Sheets (SDS) for materials used in the construction of the rocket. The SDS is a 16-section document from the Occupational Safety and Health Administration (OSHA) that provides details on handling materials, the proper PPE for using the material, and how to treat potential health hazards using first aid. Hazardous materials such as black powder and Ammonium Perchlorate Composite Propellant (APCP) are stored by the appropriate supervisors at Wright Stuff Rocketeers (WSR). These materials are not to be handled by team members and are not stored on university campuses. The SDS documents are currently provided in a binder in “the Barn,” and on the team’s project OneDrive.

5.2.3. Explosives

Explosives such as black powder, motors, igniters, and batteries can cause safety risks to team members, the public, and the environment if handled incorrectly. The energetics the team uses are managed by CSL’s team mentor, Dave Combs. Motors will be stored in climate-controlled environments and out of reach from team personnel. Igniters will be installed in the motor after the rocket is fully assembled with safety checks confirmed. The igniter installation is managed only by Dave Combs due to potential safety hazards. Black powder is primarily used to separate a rocket during parachute deployment. Mismanaging black powder can lead to premature ignition which can lead to injury to team personnel. Batteries are stored in a cool, dry environment to prevent heating, over-charging, and puncturing. This can cause the chemicals inside the batteries to ignite, leading to injury.

5.2.4. Construction Safety

The construction phase of rocket design generates safety risks to the team. Using unfamiliar tools, adhesives, or construction techniques can cause safety hazards to occur to team members. Team members are required to know and understand the rules and regulations for using the engineering facilities, tools, and equipment. This includes undergoing specific training for operating the CNC mill, lathe, and plasma cutter. Team members are not allowed to use equipment they don’t know how to use. Having an outline and description of the facilities, tools, and equipment Cedarville University provides will help to mitigate safety hazards during the construction of the rocket.

5.2.5. Launch and Testing Safety

Testing a rocket involves significant safety considerations due to the potential risks such as structural weaknesses, unintended ignitions, fuel leaks, and component failures. The point of testing is to make sure the rocket will not fail and is ready for launch day. Testing requires wearing the proper PPE in the facility where testing occurs. If testing occurs on university property, Cedarville University campus security must be notified ahead of time in case of emergencies. Any required testing using motors and black powder needs to be approved and handled by Dave Combs. Establishing testing procedures can help to mitigate risks involved with testing rocket components. Launching rockets can cause serious safety hazards for the team, the public, and the environment if not handled correctly. CSL will have pre-launch checklists to make sure the rocket is safe before any potential flight. The CSO and Launch Officer will create these checklists to ensure every component of the rocket is working correctly. Team members should read launch checklists with the intent to understand the importance of proper caution. Failure to comply with launch safety procedures is a safety hazard and will result in being promptly removed from the launch site.

5.2.6. STEM Engagement Safety

CSL will educate younger students and teach them about the fundamentals of aerodynamics and rocketry. These events still contain potential safety hazards and risks even if they are not with energetics. When students are working on their projects, team members must be supervisors to ensure they listen to directions, especially when using sharp objects. If STEM events are using glue or small materials, team members need to be extra careful around younger students who may accidentally ingest these items. If an event includes a small rocket launch, team members must comply with standard launch procedures and make sure the students are distanced from the launch site. Students who don't listen to safety instructions will be removed from participating in the STEM activity.

5.2.7. Environmental Safety

The CSO and team members are responsible for minimizing the rocket's impact on the environment while checking for potential environmental factors that could affect the rocket's performance during launch. Team members will follow federal regulations and SDS guidelines when handling and disposing of hazardous materials. Weather-related events such as high wind or rain could affect the rocket's performance on launch day. The team mentor, Dave Combs, has the final say on whether to launch or scrub the mission due to weather conditions. The CSL team strives to go above and beyond for safety during this project and at the competition. The team will clean up the launch site after the competition is complete to prevent environmental hazards. If any piece of rocket debris is scattered across a crash site, team members are encouraged to search and clean this up when it is safe to do so.

5.2.8. Safety Compliance

All team members of CSL will follow the National Association of Rocketry (NAR) High Power Rocket Safety Code (HPRSC). This code provides regulations for using high-power rockets including certification, materials used, motors, and ignition systems while also providing insight into launch safety, flight safety, and recovery safety. CSL will adhere to all United States federal regulations concerning the use of the National Airspace System (FAR 14 CFR, Subchapter F, Part 101, Subpart C) and fire prevention guidelines (NFPA 1127) to ensure the safe and legal operation of high-powered rockets. Team members will adhere to the rules and regulations provided by the National Fire Protection Agency (NFPA) 1127 Code for High Power Rocketry to reduce fire dangers and related hazards associated with high-power rocketry. CSL's corresponding compliance to each section of the HPRSC is provided in Table 5.2.1.

***Table* 5.2.1.** NAR High Power Safety Code and the team corresponding compliance action.

NAR High Power Rocket Safety Code	Team Compliance Action
1. Certification. I will only fly high power rockets or possess high power rocket motors that are within the scope of my user verification and required licensing.	Team mentors are certified at NAR Level 2 and will be the only people to handle the rocket motors.
2. Materials. I will use only lightweight materials such as paper, wood, rubber, plastic, fiberglass, or when necessary ductile metal, for the construction of my rocket.	The rocket design avoids the use of materials that do not meet the standard lightweight materials. If there is any uncertainty with the use of other materials, the team will communicate with NASA competition officials.
3. Motors. I will use only certified, commercially made rocket motors, and will not tamper with these motors or use them for any purpose except those recommended by the manufacturer. I will not allow smoking, open flames, nor heat sources within 25 feet of these motors.	The team will exclusively use motors that are certified from trusted motor manufacturers. The usage of motors will be supervised by team mentors, solely for the purpose of launching the rocket under controlled and safe conditions.
4. Ignition System. I will launch my rockets with an electrical launch system, and with electrical motor igniters that are installed in the motor only after my rocket is at the launch pad or in a designated prepping area. My launch system will have a safety interlock that is in series with the launch switch that is not installed until my rocket is ready for launch and will use a launch switch that returns to the "off" position when released. The function of onboard energetics and firing circuits will be inhibited except when my rocket is in the launching position.	The team will only launch NAR/ Tripoli Rocket Association (TRA) operated launch sites to ensure that the appropriate ignition systems are properly installed and function as expected.

5. Misfires. If my rocket does not launch when I press the button of my electrical launch system, I will remove the launcher's safety interlock or disconnect its battery and will wait 60 seconds after the last launch attempt before allowing anyone to approach the rocket.	The team will follow the instructions of the NAR/TRA Range Safety Officer at the launch site after a misfire. Only necessary personnel are allowed to approach the rocket once the ignitor is set in place.
6. Launch Safety. I will use a 5-second countdown before launch. I will ensure that a means is available to warn participants and spectators in the event of a problem. I will ensure that no person is closer to the launch pad than allowed by the accompanying Minimum Distance Table. When arming onboard energetics and firing circuits I will ensure that no person is at the pad except safety personnel and those required for arming and disarming operations. I will check the stability of my rocket before flight and will not fly it if it cannot be determined to be stable. When conducting a simultaneous launch of more than one high power rocket I will observe the additional requirements of NFPA 1127.	The team will rely on the NAR/TRA RSO at the launch site to conduct a 5-second countdown before launch. Team members are instructed to be wary of surroundings and pay attention to spectators that could be too close to the launch pad. They are also instructed to look for and communicate with those around them during the rocket descent. Once the rocket is assembled and the motor is installed, the center of gravity (CG) location will be calculated and marked to ensure the stability of the rocket before launch. The team does not plan to conduct simultaneous launches.
7. Launcher. I will launch my rocket from a stable device that provides rigid guidance until the rocket has attained a speed that ensures a stable flight, and that is pointed to within 20 degrees of vertical. If the wind speed exceeds 5 miles per hour, I will use a launcher length that permits the rocket to attain a safe velocity before separation from the launcher. I will use a blast deflector to prevent the motor's exhaust from hitting the ground. I will ensure that dry grass is cleared around each launch pad in accordance with the accompanying Minimum Distance table and will increase this distance by a factor of 1.5 and clear that area of all combustible material if the rocket motor being launched uses titanium sponge in the propellant.	The team will only use launch rails provided at the NAR/TRA launch sites. The team will fully comply with the launcher specifications.

8. Size. My rocket will not contain any combination of motors that total more than 40,960 N-sec (9208 pound-seconds) of total impulse. My rocket will not weigh more at liftoff than one-third of the certified average thrust of the high-power rocket motor(s) intended to be ignited at launch.	The rocket design will comply with the total motor impulse intended and will comply with the weight limit requirement.
9. Flight Safety. I will not launch my rocket at targets, into clouds, near airplanes, nor on trajectories that take it directly over the heads of spectators or beyond the boundaries of the launch site and will not put any flammable or explosive payload in my rocket. I will not launch my rockets if wind speeds exceed 20 miles per hour. I will comply with Federal Aviation Administration airspace regulations when flying and will ensure that my rocket will not exceed any applicable altitude limit in effect at that launch site.	The team will launch at NRA/TRA approved sites with the RSO present. The team will comply with the Federal Aviation Administration (FAA) regulations of not launching the rocket at any targets, into clouds, or near airplanes. If the wind speed surpasses 20 mph or cloud cover is too low, the launch will immediately be canceled. The team will only use the motor specified in the design so that any part of the rocket will not exceed the expected apogee.
10. Launch Site. I will launch my rocket outdoors, in an open area where trees, power lines, occupied buildings, and persons not involved in the launch do not present a hazard, and that is at least as large on its smallest dimension as one-half of the maximum altitude to which rockets are allowed to be flown at that site or 1500 feet, whichever is greater, or 1000 feet for rockets with a combined total impulse of less than 160 N-sec, a total liftoff weight of less than 1500 grams, and a maximum expected altitude of less than 610 meters (2000 feet).	Team launches will take place at NAR/TRA approved locations. The RSO has the authority to change locations of the launch site to meet safety regulations.
11. Launcher Location. My launcher will be 1500 feet from any occupied building or from any public highway on which traffic flow exceeds 10 vehicles per hour, not including traffic flow related to the launch. It will also be no closer than the appropriate Minimum Personnel Distance from the accompanying table from any boundary of the launch site.	The team will stand back away from the launch site no closer than the Minimum Distance table during launches. If possible, team members are advised to stand further away from potential safety hazards. The RSO and team members will control the traffic flow around the launch site.

12. Recovery System. I will use a recovery system such as a parachute in my rocket so that all parts of my rocket return safely and undamaged and can be flown again, and I will use only flame-resistant or fireproof recovery system wadding in my rocket.	The rocket design will use a parachute as a safe recovery system to ensure the rocket will land safely. Flame-resistant wadding will be used to prevent the spread of fire. A pre-launch checklist will be used provided by the CSO and Launch Officer.
13. Recovery Safety. I will not attempt to recover my rocket from power lines, tall trees, or other dangerous places, fly it under conditions where it is likely to recover in spectator areas or outside the launch site, nor attempt to catch it as it approaches the ground.	The RSO and team members will work together to keep spectators away from the launch site. Team members are not allowed to retrieve the rocket in dangerous situations or contact the rocket as it descends.

CSL will be performing launches with a local rocketry club that has been identified as the WSR. WSR is Section 703 of the NAR in the southwestern Ohio region that uses complete low-power and high-power ground support equipment like launch systems, pads, rods, and rails. They launch rockets in compliance with the NAR Model and HPRSC. Team members who participate in WSR will comply with the rules and regulations that they have set in place. This includes notifying WSR leadership at least one week in advance of a high-power rocket launch.

5.2.9. Team Safety Agreement

The goal of the safety statement is to ensure each team member commits themselves to following all rules and regulations set in place by the NAR, the FAA, the TRA, the CSO, and team mentors. Those who do not comply with the safety statement will be removed from the team as decided by the team leader, CSO, and the team mentor. Signed safety agreements from all team members are provided in Appendix A.1.

5.3. Risk Assessment Method

Implementing safety risk management is an effective approach to identifying potential hazards affecting the team, the public, and the environment. Hazards will be assessed using consistent scales for severity and probability. Each identified safety risk will be documented by the CSO, including its cause, effect, and mitigation strategy. Hazards will receive a score based on severity and probability. A high score indicates a significant safety risk that demands immediate mitigation. Table 5.3.1 outlines the criteria for determining probability levels, while Table 5.3.2 describes the severity of hazards. Table 5.3.3 presents the risk assessment table and associated codes, with color-coding cells representing varying risk levels. Table 5.3.4 explains how different risk values align with specific risk categories.

Table 5.3.1. *Probability Value Criteria.*

Description	Value	Description of Occurrence	Probability of Occurrence
Rare	1	Very Unlikely	Less than 5%
Occasional	2	Event Occurs Occasionally	Between 5% and 25%
Often	3	Event Occurs Often	Between 25% and 50%
Likely	4	Highly Likely Event Will Occur	Between 50% and 75%
Frequent	5	Event Expected	Above 75%

Table 5.3.2. *Danger Level Definitions.*

Description	Value	Team Personnel	Physical Environment	Launch Vehicle	Mission Success
Negligible	1	Minor or No Injuries	No Damage	Insignificant	Complete Mission Success
Minimal	2	Minor Injuries	Minor and Reversible Damage	Mild Damage	Near Complete Mission Success
Major	3	Moderate Injuries	Moderate Reversible Damage or Minor Irreversible Damage	Major Damage	Partial Mission Failure
Catastrophic	4	Life-threatening Injuries	Major Irreversible damage	Irrevocable Damage	Complete Failure

Table 5.3.3. *Risk Assessment Table and Codes.*

Probability	**Severity**			
	Negligible (1)	**Minimal (2)**	**Major (3)**	**Catastrophic (4)**
Rare (1)	1	2	3	4
Occasional (2)	2	4	6	8
Often (3)	3	6	9	12
Likely (4)	4	8	12	16
Frequent (5)	5	10	15	20

Table 5.3.4. *Risk and Acceptance Level Definitions.*

Severity	**Range**	**Acceptance Level**	**Approval Authority**
Low Risk	Less than 5	Desired	CSO approval recommended, but not required.
Medium Risk	5 to 9	Undesirable	Mitigation must occur. Document approval from CSO.
High Risk	Greater than 10	Unacceptable	Mitigation must occur before proceeding.

5.4. Overall Risk Reduction

The CSO and team members researched and identified safety risks for all areas of this project. Table 5.4.1 provides a percentage for each risk distributed between probability and severity. Table 5.4.2 provides the overall percentage and quantity for low, medium, and high risks before mitigation. The total number of safety hazards identified is 97.

Table 5.4.1. *Risk Assessment Before Mitigation.*

Probability	**Severity**			
	Negligible (1)	**Minimal (2)**	**Major (3)**	**Catastrophic (4)**
Rare (1)	0%	0%	3.09%	2.06%
Occasional (2)	0%	5.15%	17.52%	0%
Often (3)	0%	2.06%	28.86%	16.49%
Likely (4)	0%	10.31%	4.12%	10.31%
Frequent (5)	0%	0%	0%	0%

Table 5.4.2. *Risk Classification Before Mitigation.*

Severity	Acceptance Level	Quantity	Percentage
Low Risk	Desired	10	10.3%
Medium Risk	Undesirable	57	58.7%
High Risk	Unacceptable	30	30.9%

CSL has provided a safety plan to reduce the probability and severity of each hazard in all areas of the project. A low risk is acceptable with light documentation and approval from the CSO. A medium risk is not desirable but needs documentation and approval from the CSO. A high risk is extremely dangerous and unacceptable. If any high-risk hazard occurs, extensive documentation and mitigation must occur.

The CSO and team personnel explored mitigation strategies to minimize the risks related to the student launch. After establishing a mitigation plan, the CSO verified it is effective in reducing the risk. The hazard was then reassessed to give a new risk value. Table 5.4.3 reflects the risk assessment after mitigation, and Table 5.4.4 classifies the risk post-mitigation.

Table 5.4.3. *Risk Assessment After Mitigation.*

Probability	Severity			
	Negligible (1)	Minimal (2)	Major (3)	Catastrophic (4)
Rare (1)	0%	24.74%	31.95%	20.61%
Occasional (2)	2.06%	6.18%	8.24%	0%
Often (3)	2.06%	4.12%	0%	0%
Likely (4)	0%	0%	0%	0%
Frequent (5)	0%	0%	0%	0%

Table 5.4.4. *Risk Classification After Mitigation.*

Severity	Acceptance Level	Quantity	Percentage
Low Risk	Desired	85	87.6%
Medium Risk	Undesirable	12	12.3%
High Risk	Unacceptable	0	0%

Failure Modes and Effect Analysis (FMEA) sheets are utilized to identify all safety risks related to the project. The CSO and team personnel categorized these sheets based on the hazards associated with the rocket's various subsystems and team members' roles. Table 5.4.5 outlines each category of FMEA sheets that may contain significant specific hazards.

Table 5.4.5. *Identification for FMEA Tables.*

ID	Category	Description of FMEA
C	Construction	The hazards of construction to personnel.
RS	Rocket Structure	The hazards of the structure of the rocket.
R	Recovery	The hazards of the rocket during the recovery stage.
AB	Airbrakes	The hazards involving the airbrakes.
PS	Payload	The hazards of the payload electronics and control systems.
L	Launch	The hazards of launch operations.
FD	Flight Dynamics	The hazards of the rocket during flight.
RE	Rocket Risks to Environment	The hazards the rocket can have on the environment.
ER	Environment Risks to Rocket	The hazards the environment can have on the rocket.
P	Project Risks	The hazards of completion of the project.
SE	STEM Engagement	The hazards that could occur during STEM Engagement activities.

5.5. Personnel Hazards

Table 5.5.1. *Hazards to Personnel Evaluated by the Defined Risk Assessment Code.*

ID	Hazard	Cause	Effect	Probability	Severity	Risk	Mitigation	Verification	Probability	Severity	Risk
C.1	Contact with hazardous chemicals	Chemical spills, mishandling of chemicals	Burns, skin irritation	3	3	9	Wear appropriate PPE, especially gloves and eye protection, in conjunction with clothing that covers the whole body, and workspace will have a protective layer of material.	Team members are required to sign the team safety agreement to follow all safety rules and regulations set in place. The Safety Violation Form will be filled out and verified by the CSO.	2	2	4
C.2	Inhaling toxic fumes	Inhalation of toxic fumes while handling chemicals, especially in confined areas	Pain, sickness, lung damage	3	3	9	Respirators will be used when handling chemicals that have toxic fumes. These chemicals will only be used in well-ventilated areas.	Team members are required to sign the team safety agreement to follow all safety rules and regulations set in place. Labels will indicate that respirators are needed. The Safety Violation Form will be filled out and verified by the CSO.	1	2	2

C.3	Contact and inhaling dust or debris	Contact with dust and debris	Pain, lung damage, skin irritation	2	2	4	Team members will wear appropriate PPE, including gloves, eye protection, respirator, and clothing that covers the whole body.	Team members are required to sign the team safety agreement to follow all safety rules and regulations set in place. The Safety Violation Form will be filled out and verified by the CSO.	1	2	2
C.4	Electrocution	Contacting electrical terminals, inadequate caution	Pain, burns, physical harm, death	4	3	12	Clearly label high voltage equipment and provide a briefing on the proper handling of electronics.	Regular inspection of electronics will be performed. Students will confirm with CSO that they have had appropriate training prior to using labeled equipment. The Safety Violation Form will be filled out and verified by the CSO.	1	4	4
C.5	Powered equipment injury	Mishandling of machinery	Pain, burns, abrasion, cuts, physical injury, death	3	4	12	Safety training on the proper use of equipment will be required for those using construction. A 10 ft radius will be observed when machinery is in use. Proper PPE will be used.	When power tools are in use the CSO or another team member will be present to supervise and ensure that proper procedure is being observed. The Safety Violation Form will be filled out and verified by the CSO.	2	2	4

C.6	Ear damage	Loud machinery, explosions, chemical reactions	Long term hearing damage	3	3	9	Ear plugs or earmuffs will be worn while using machinery and at launches and testing of black powder, as well as for all other activities above 90 db.	Ear protection will be part of pre-flight and pre-test check lists. The CSO will ensure that proper ear protection is used, and the CSO will ensure use with machinery. The Safety Violation Form will be filled out and verified by the CSO.	3	1	3
C.7	Electronics combust	Overloading of electrical circuits	Burns, destruction of electronics	2	4	8	A chemical-based water extinguisher will be kept near electronics. Team members are required to know how to escape a laboratory for fire emergencies.	Team members are required to sign the team safety agreement to follow all safety rules and regulations set in place. The Safety Violation Form will be filled out and verified by the CSO.	1	3	3
C.8	Incidental black powder explosion	Exposure to high temperatures, accidental connection to a voltage source	Burns, destruction of rocket components, flying debris	4	4	16	Black powder will be kept in a safe explosive chest and will only be handled by the team mentor after reviewing the correct handling procedures.	Team members are required to sign the team safety agreement to follow all safety rules and regulations set in place. The Safety Violation Form will be filled out and verified by the CSO.	1	4	4

C.9	Battery explosion	Battery deterioration, puncture	Burns, physical harm from fire	4	4	16	The batteries will be stored in a cool, dry environment to prevent heating, over-charging, and puncturing. Any damaged or potentially damaged batteries will be disposed of.	Team members are required to sign the team safety agreement to follow all safety rules and regulations set in place. Battery inspections will be performed to ensure battery health. The Safety Violation Form will be filled out and verified by the CSO.	1	4	4
C.10	Tripping	Untidy work area	Scrapes, cuts, concussion	3	3	9	Workspace will be kept clean. Cables will be routed through proper cable covers and marked accordingly.	The CSO will ensure that the work area is clean and make all members aware of any potential tripping hazard. The Safety Violation Form will be filled out and verified by the CSO.	3	1	3
C.11	Eye injury during construction	Lack of eye protection.	Damage to eyes, could cause blindness.	3	4	12	Understanding workshop procedures, wearing appropriate eyewear during construction	All team members are required to follow safety regulations set in place. Team members will wear safety glasses and the appropriate PPE for any construction procedures. The Safety Violation Form will be filled out and verified by the CSO.	1	3	3

C.12	Explosion in the EPL	Failure of a machine or tool, not following proper laboratory procedures	Fire, major injury, damage to rocket and machinery	2	4	8	Understanding and following safe construction procedures, understanding fire code and the emergency exit system in laboratories and workshops	Team members are required to sign the team safety agreement to follow all safety rules and regulations set in place. The Safety Violation Form will be filled out and verified by the CSO.	1	4	4
C.13	Roughhousing in the EPL, the Barn, or Advanced Manufacturing Laboratory	Not following laboratory procedures, distracted team members	Major injury, damage to rocket and machinery	3	3	9	Understanding construction procedures, knowledge of the universities laboratories	Team members are required to sign the team safety agreement to follow all safety rules and regulations set in place. The Safety Violation Form will be filled out and verified by the CSO.	1	3	3

5.6. Failure Modes and Effects Analysis

Table 5.6.1. *Hazards of the Rocket Structure Evaluated by the Defined Risk Assessment Code.*

ID	Hazard	Cause	Effect	Probability	Severity	Risk	Mitigation	Verification	Probability	Severity	Risk
RS.1	Airframe failure during launch	Rocket is dropped, harsh impact during landing sequence	Damage to rocket airframe and potentially internal electronics inside	1	3	3	The airframe material will be thoroughly researched to make sure it is of high quality to withstand force of impact.	The airframe will be bought from a trusted vendor to ensure good quality.	1	2	2
RS.2	Airframe failure during construction	Team personnel drills too many holes into tube, airframe cracks under an increase in pressure	Damage to rocket airframe which results in an increase in budget	2	2	4	The airframe material will be thoroughly researched to make sure it is of high quality to withstand force of impact. Multiple team members will be present during construction to ensure there are no extra holes drilled into airframe.	The airframe will be bought from a trusted vendor to ensure good quality.	1	2	2

RS.3	Centering ring failure	Misalignment between fins and airframe, improper manufacturing technique	Motor is not aligned inside the motor tube, mass imbalance, loss of stability, flight path is not controlled	3	3	9	The centering rings will be manufactured using a high strength material to ensure cracking and failure will not occur. Stress analysis will ensure the design can withstand the stress of the launch.	The centering rings will be installed correctly to ensure alignment of the motor tube and other components.	1	4	4
RS.4	Motor retention failure	Excessive stress within motor retention attachment points or threads	Motor ejection, mass imbalance, loss of stability	4	4	16	The motor retention assembly will be designed to withstand the stress of the launch with a reasonable factor of safety.	The motor retention will be inspected by the CSO, LO, and RSO prior to each flight.	2	3	6
RS.5	Nose Cone failure assembly	The 3D portions of the nose cone my break due to rough handling or dropping	Affects the structural integrity of the nose cone and may potentially affect the rocket's aerodynamics	2	3	6	The nose cone will be designed with a fiberglass outer shell to take the brunt of the stresses acting on it and add rigidity to the design.	The nose cone will be inspected before and after each launch to check for crack propagation to determine its safety for reuse.	1	2	2

RS.6	Nose Cone failure during launch	The rocket lands so that the nose cone takes a large amount of force on landing causing it to break.	Damage to the forward section of the rocket and possible damage to the payload.	3	3	9	The nose cone assembly will be made to withstand potential hard landing forces.	The nose cone assembly will have mechanical design analysis done on the selected design.	1	3	3
RS.7	Shock Chord mount failure during launch	The blast from the black powder charges causes the shock cord mount to fail	The nosecone detaches from the body of the rocket and the rocket does not land safely	3	3	9	The shock chord mount subsystem will be thoroughly researched to make sure it will not fail during launch.	The shock chord mount subsystem will be tested prior to launches to make sure it does not fail during launch.	1	3	3
RS.8	Tail cone is deformed	The tail cone could be warped or deformed by heat from motor burn.	Poor thrust generation during launch, and non-uniform drag around the rocket body.	2	3	6	Before and after test and competition launches, the tail cone will be inspected for proper geometry and any warping.	The CE and Launch Officer will verify integrity of the tail cone and its attachment before and after all flights, ensuring proper action is taken if necessary.	1	3	3

RS.9	Tail cone retention fails.	Stripped threads, fractured fasteners, or damaged tail cone fastening points.	Uncertain flight or to the tail cone and motor reload falling from the airframe.	3	4	12	Before and after test and competition launches, tail cone fasteners and attachment points will be inspected for cracks or deformation.	The CE and Launch Officer will verify integrity of the tail cone and its attachment before and after all flights, ensuring proper action is taken if necessary.	1	4	4
RS.10	Tail cone damaged during flight or test flights.	Tail cone could be cracked, deformed, or otherwise damaged during landing impact.	A damaged tail cone could effect future launch performance or cause future damage if unmanaged.	3	3	9	Before and after test and competition launches, the tail cone will be inspected for cracks or deformation.	The CE and Launch Officer will verify integrity of the tail cone and its attachment before and after all flights, ensuring proper action is taken if necessary.	2	2	4

Table 5.6.2. *Hazards involving Recovery Systems Evaluated by the Defined Risk Assessment Code.*

ID	Hazard	Cause	Effect	Probability	Severity	Risk	Mitigation	Verification	Probability	Severity	Risk
R.1	The wrong altitude is measured by the altimeter.	Pressure difference between outside and inside of rocket	Late or early drogue and main parachute deployment. Possibility of injury or death to bystanders.	3	4	12	The avionics section will be designed with properly sized vent hole large enough to equalize the pressure inside the rocket with atmospheric pressure.	Calculations and actual measurements for vent hole sizes will be checked by a second person to ensure accuracy.	2	3	6
R.2	Ejection charges fail to ignite.	Altimeter loses power due to loose connections. The deployment signal is not sent to ignitor.	Parachutes fail to deploy and rocket nosedives into the ground. Possible injury or death to bystanders.	4	4	16	Redundant altimeters with redundant batteries will be used. Pull tests will be conducted on all wires before every launch.	Continuity will be verified on both altimeters by audio cue after the rocket is placed on the launch rail.	3	2	6

R.3	Ejection charge fails to separate rocket.	Not enough black powder in ejection charge.	Parachutes fail to deploy and rocket nosedives into the ground. Possible injury or death to bystanders.	4	4	16	Ground testing and having the NAR Affiliated mentor double check the amount of black powder calculated to be needed.	Ground testing will allow the team to safely check that the black powder charges will behave as expected.	3	2	6
R.4	Parachute or shock cords become damaged	Parachute is burnt or torn from deployment or packing. Shock Cords snap in deployment.	Coefficient of drag decreases. Parachutes cannot deploy correctly. Rocket falls faster than anticipated.	3	4	12	Parachute and Shock cords will be checked before packing into the rocket and a flame blanket will be used to protect them from the black powder charges.	Packing job will be verified by the NAR Affiliated mentor.	1	4	4
R.5	Shock Cords tangle in deployment	Parachute is not properly folded and stored in the rocket.	Parachute is unable to open correctly.	4	3	12	The team member in charge of folding the parachute will be properly taught how to do it.	Packing job will be verified by the NAR Affiliated mentor.	1	3	3

R.6	Zippering	Shock cords tear at airframe in deployment due to the force when the lines become taut.	Main rocket body is damaged. Damage can range from superficial to crucial.	3	3	9	Airframe will be properly reinforced, and the shock cords will be designed to help diminish some of the force at lines taut.	Various calculation will be performed to find the risk factor and show how it is decreased due to mitigation effort.	1	3	3

Table 5.6.3. *Hazards involving the Airbrake System Evaluated by the Defined Risk Assessment Code.*

ID	Hazard	Cause	Effect	Probability	Severity	Risk	Mitigation	Verification	Probability	Severity	Risk
AB.1	Top motor retainer system fails.	Design or manufacturing defect.	Rogue launch and/or motor ejection.	3	4	12	Ensure structural integrity of the components before launch in addition to preforming calculations to minimize design overlooks.	Analysis will be documented in engineering project reports, and the physical system will be looked over by the range safety officer.	1	4	4

AB.2	Airbrakes fail to retract.	Mechanical or electrical design or manufacturing defect.	The recovery system becomes entangled, and the rocket becomes ballistic.	4	4	16	A redundant system will be built in the system to ensure the brakes will be retracted after apogee. This system will be powered by an extra battery and on a separate PCB.	Analysis will be documented in engineering project reports. Faculty advisors, team leader, CE, CSO will ensure no missteps are taken during development of this system.	1	4	4
AB.3	Internal damage to components.	Lack of tightening nuts and bolts.	Faulty braking system which can hinder the recovery system if brakes do not retract.	3	3	9	The RSO will ensure all nuts and bolts are tightened down with a certain torque prior to launch.	The tightening of these nuts and bolts will be documented.	1	3	3
AB.4	Airbrake control system cannot properly augment the rocket's altitude	Undiagnosed sensor issues, hardware limitations, or software errors	Rocket cannot actively affect its altitude.	3	3	9	The control system will be demonstrated and improved over the course of two flights before the competition launch. If the airbrakes must be abandoned, a mass equivalent will be used.	CE and PM will evaluate the progress of the airbrake control solution and monitor the system's behavior during launches.	1	3	3

Table 5.6.4. Hazards involving the Payload System Evaluated by the Defined Risk Assessment Code.

ID	Hazard	Cause	Effect	Probability	Severity	Risk	Mitigation	Verification	Probability	Severity	Risk
PS.1	Radio transmitter comes loose during flight.	Improperly installed or excessive vibration.	Large unsecured mass in the nose of the rocket could damage other components or cause rocket instability.	2	3	6	Testing will be performed to ensure that the transmitter will not rattle loose.	During assembly, the transmitter will be double checked that it is fastened securely to the payload.	1	3	3
PS.2	Radio transmitter transmits at the wrong time.	Radio transmitter equipment malfunction.	Violates FCC and NASA guidelines and could interfere with another rocket's transmissions or with important 2m radio traffic.	1	3	3	The transmitters will be tested rigorously in many conditions which will reveal any equipment issues.	Any errors discovered during testing will be recorded and the equipment will be inspected.	1	2	2

PS.3	Radio transmitter transmits at the wrong frequency.	Radio transmitter equipment malfunction.	Violates FCC guidelines and could interfere with important 2m radio traffic.	2	3	6	The transmitters will be tested rigorously in many conditions which will reveal any equipment issues.	Any errors discovered during testing will be recorded and the equipment will be inspected.	1	2	2
PS.4	Battery explosion during lab or field testing.	Battery lifespan, improper charging, short circuiting, overheating, and excessive vibration all contribute to battery failure.	Varying levels of damage to humans and property.	3	3	9	NiCd batteries will be used instead of LiPo for increased safety and only batteries in good condition will be used.	Batteries will be verified to not be old, damaged, or likely to overheat.	1	2	2
PS.5	Battery explosion during rocket flight.	Battery lifespan, improper charging, short circuiting, overheating, and excessive vibration all contribute to battery failure.	Major damage to rocket could include damage to many other components and cause major rocket instability.	3	4	12	NiCd batteries will be used instead of LiPo for increased safety and only batteries in good condition will be used.	Batteries will be verified to not be old, damaged, or likely to overheat prior to assembly and flight.	1	3	3

PS.6	Wires or soldering joints come loose during flight.	Excessive in-flight vibration.	Possible payload failure, resulting in transmission of incorrect data or no transmission at all.	3	3	9	Testing will be performed to find weak points ahead of time.	Connections will be verified to be intact before final payload assembly.	1	3	3
PS.7	Sensor failure or memory storage failure.	Malfunction due to vibration or factory defect.	Possible payload failure, resulting in transmission of incorrect data or no transmission at all.	2	3	6	Testing will be performed to find device defects or durability issues ahead of time.	Only devices that have been tested before will be used for the final flight.	1	3	3
PS.8	Radio transmits for too long.	Software fails to stop transmission.	Violates FCC and NASA guidelines and could interfere with another rocket's transmissions or with other important 2m radio traffic.	2	3	6	Isolated transmitter override system will stop transmissions from occurring after a pre-set time duration. Software will be tested rigorously.	Intentional failure of the main transmission system and ensure that the override system is functional.	1	3	3

__Table 5.6.5.__ Hazards of Launch Operations Evaluated by the Defined Risk Assessment Code.

ID	Hazard	Cause	Effect	Probability	Severity	Risk	Mitigation	Verification	Probability	Severity	Risk
L.1	Incorrect motor installation	Disobedience of the safety launch checklist and TRA procedures	Damage to rocket, motor failure during launch, injury to team personnel	4	4	16	Team members will follow the safety launch checklist. All ignition related hardware will be handled by a licensed professional.	Team mentor Dave Combs will be responsible for the handling and installation of motors and other energetics.	2	3	6
L.2	Team personnel or bystanders coming too close to launch pad	Disobedience of the safety launch checklist and NAR safety parameters	Serious injury, burns, possible death	3	4	12	The CSO, LO, and RSO will make sure everyone at launch site stays at the minimum distance away per NAR regulations.	The RSO will have the final say to determine a safe and successful launch.	1	4	4

L.3	Improper black powder handling	Disobedience of the safety launch checklist and TRA procedures	Can cause recovery system to not deploy	3	4	12	Team members will follow the safety launch checklist. All ignition related hardware will be handled by a licensed professional.	Team mentor Dave Combs will be responsible for the handling and installation of motors and other energetics.	1	4	4
L.4	Ignition failure	Improper ignition placement, dysfunctional igniter.	Failure to launch.	4	4	16	All ignition related hardware will be handled by a licensed professional. The pad will not be approached for five minutes after an ignition failure.	Team mentor Dave Combs will be responsible for the handling and installation of motors and other energetics.	2	3	6
L.5	Rocket is lost after launch	Wind creates parachute to have a high drift, visibility is low	Loss of rocket and hindrance in the completion of the project	3	3	9	The team will follow NAR guidelines to not launch rocket if wind speeds are greater than 20 [MPH]. If rocket crashes, team members will clean up the area and not leave any debris behind.	Team mentor Dave Combs and the CSO will be held responsible for making sure the weather is clear for launch.	1	3	3

L.6	Rocket does not exit launch rail	Launch rail is not clean enough to allow the rocket to escape the pad. Rocket may be too heavy.	Motor burns in place, possibly damaging launch equipment and aft rocket assembly.	3	3	9	Clean rail with Scotch Brite pad before loading the rocket. Remove unnecessary ballast.	The launch officer will verify that the rail is clean before launch. The thrust-to-weight ratio will be verified by simulation.	1	3	3

Table 5.6.6. *Hazards of the Rocket during Flight Evaluated by the Defined Risk Assessment Code.*

ID	Hazard	Cause	Effect	Probability	Severity	Risk	Mitigation	Verification	Probability	Severity	Risk
FD.1	Weathercocking	Static stability margin is too large.	Rocket does not recover vertical flight, causing the recovery device to deploy at high speed or not at all.	3	4	12	Stability simulation will be conducted alongside hand calculations.	CG will be verified by balancing the launch vehicle once assembled, CG location estimated by simulations will be checked, CP estimation reliability will be evaluated based on this perceived simulation integrity.	2	3	6

FD.2	Rocket uncontrollability	Static stability margin may be too small. Airbrake flap may be stuck or broken.	Rocket loops, oscillates wildly, and may not return to a vertical flight path.	4	4	16	Stability simulation will be conducted alongside hand calculations. Ballast will be added as needed. Airbrakes will be inspected before each launch.	CG will be verified by balancing the launch vehicle once assembled, CG location estimated by simulations will be checked, CP estimation reliability will be evaluated based on this perceived simulation integrity.	3	2	6
FD.3	Rocket pulls toward onlookers upon rail exit.	Launch rail may be too far from vertical. Rail buttons may have fallen off or degraded.	Rocket leaves the launch pad in an unsafe direction, endangering personnel, vehicles, and equipment.	4	4	16	Rail buttons will be glued in place. Launch rail will be pointed within 15 degrees of vertical, with consideration given to the direction and strength of the wind.	RSO will inspect both the attachment of the rail buttons and the angle of the launch rail.	2	3	6
FD.4	Fin flutter	High aerodynamic forces coupled with poor fin construction can cause fin flutter.	Rocket oscillates uncontrollably, airbrake control system is ineffective, and the apogee will be negatively impacted.	3	4	12	Hand calculations will be conducted to ensure that the velocity at which the fin flutter occurs will be higher than the maximum simulated launch velocity.	RSO will inspect the fin mounting method before launch, fin designer will verify the fin flutter velocity.	1	4	4

FD.5	Drag separation	High aerodynamic forces focused on the aft end of the rocket that bend the airframe.	Forces cause vibrations and flexure in the airframe, possibly separating the rocket prematurely in its flight.	2	4	8	Launch angle will be set within 15 degrees of vertical to reduce unexpected pressure drag early in the flight, and the mitigations applied to ensuring the stability of the rocket will continue to be informative in this area.	RSO will inspect the launch rail angle, launch officer and CE will inspect the separation points on the rocket before launch.	1	3	3

5.7. Environmental Risks

Table 5.7.1. *Hazards of how the Rocket can Affect the Environment Evaluated by the Defined Risk Assessment Code.*

ID	Hazard	Cause	Effect	Probability	Severity	Risk	Mitigation	Verification	Probability	Severity	Risk
RE.1	Waste pollution	Improper disposal of trash and excessive amounts of unorganized material.	Uncleanliness, damage to environment	2	2	4	Team members will be briefed on proper waste disposal practices, and bins for specific product disposal will be placed in the work area.	Individual team leads will ensure that their teams are properly disposing of materials, and the construction lead will check bins for correct disposal.	1	2	2

RE.2	Propellant pollution	Pollution caused by the combustion of the rocket propellant.	Hazardous emissions and fumes	2	3	6	Motors will be properly ignited and only when necessary for tests and launches.	The CSO will understand ignition procedures and will collaborate with the RSO to ensure safe ignition.	1	2	2
RE.3	Battery acid leakage	Puncture and damage to batteries and casings.	Hazardous chemical exposure, risk of fire, and damage to surrounding vehicle airframe.	3	3	9	Batteries will be properly stored and routinely checked before and after launches.	The CSO, LO, and RSO will complete battery inspections before and after launch.	2	2	4
RE.4	Paint and adhesives	Use of paint and adhesives in the construction of the rocket. Improper use, application, and storage of these elements.	Hazardous chemical exposure from spills, hazardous fumes	4	3	12	Paint and adhesives will be stored properly. Proper PPE will be worn and careful application techniques will be utilized.	The team will understand proper PPE use and adhesive application.	2	3	6

RE.5	Noise pollution	Use of power equipment, motor ignition at launches	Hearing damage or loss	2	3	6	Proper PPE will be worn while using power equipment. Equipment will only be used when needed.	The team will understand proper PPE use when operating equipment or conducting launches. The CSO will verify proper PPE use at launches.	1	2	2
RE.6	Wildlife habitat damage	Rocket launches and testing near areas with significant amounts of wildlife. Impact of airframe with wildlife and habitats.	Damage to rocket airframe and animals. Littering of rocket pieces.	2	3	6	Sites will be surveyed prior to launch and points of concern will be identified. Adjustments to the launch area and launch direction will be made accordingly. All components will be firmly attached to the body.	Team members will report any wildlife or environmental related issues to the CSO, LO, and RSO.	2	1	2
RE.7	Impact landing	Recovery system fails	Damage to soil, vegetation, wildlife habitat	2	3	6	The recovery lead along with the CSO, LO, and RSO will ensure recovery system is working and will deploy during launch sequence.	The CSO, LO, and RSO will ensure recovery system deploys correctly prior to launch.	1	3	3

RE.8	Rocket hits spectators or a general crowd	Recovery system fails, spectators not aware of surroundings	Serious injury, death	3	4	12	The CSO, LO, and RSO will make sure everyone at the launch site stays at the minimum distance away per NAR regulations. All team members will be briefed on situations where recovery system fails.	The CSO, LO, and RSO will ensure team members and spectators are aware of NAR regulations at launch sites.	1	4	4

***Table 5.7.2.** Hazards of how the Environment can Affect the Rocket Evaluated by the Defined Risk Assessment Code.*

ID	Hazard	Cause	Effect	Probability	Severity	Risk	Mitigation	Verification	Probability	Severity	Risk
ER.1	Extreme Temperatures	Heat wave or cold front	Damage to electrical equipment leading to reduced performance or functionality	2	2	4	Weather conditions will be monitored prior to flights and outdoor tests. Electronics will be stored in shaded or cooled areas and will only be installed just before launch.	The recovery lead and payload team will ensure electronics remain functional during high/low temperature conditions and will halt launch activities if any failures occur.	2	1	2

ER.2	Water leaking into electronics	Moisture infusing into water sensitive components	Damage to sensitive electronics, motor propellants, adhesives, and surface treatments	2	2	4	The weather will be monitored before flights and outdoor tests. The team will ensure storage areas have reasonable humidity levels.	The CSO will coordinate with the faculty advisors to ensure that the motor propellant is undamaged. Performance tests will be performed to ensure electronics are working properly.	1	2	2
ER.3	Wind	High winds during descent	Larger drift distances, erratic flight path, instability	3	3	9	Weather conditions will be monitored prior to flights and outdoor tests. The team will follow NAR guidelines for launches.	The CSO, LO, and RSO will monitor weather before launches.	2	3	6
ER.4	Fog	Poor weather conditions	Low visibility, difficult retrieval of vehicle, and potential danger of vehicle impacting observers	2	3	6	Weather conditions will be monitored before launches. In any case where there is a risk for fog, there will be a delay until fog risk has decreased.	The CSO, LO, and RSO will monitor weather before launches.	2	2	4

ER.5	Storms	Water damage to rocket, hail damage, lightning	Damage to vehicle airframe, onboard electronic systems	3	3	9	Team members will use weather apps to monitor and receive alerts for severe weather. All outdoor activities will be postponed accordingly.	The CSO, LO, and RSO will monitor weather before launches. Team members will have severe weather alert systems on their phones to warn if any threat will impede launch operations.	1	2	2
ER.6	Tornadoes	Seasonal weather patterns	Extreme risk to team members, extreme damage to buildings and the rocket itself	3	4	12	Team members will use weather apps to monitor and receive alerts for severe weather. All outdoor activities will be postponed accordingly. The team will follow the university's emergency plan for tornado warnings.	The CSO, LO, and RSO will monitor weather before launches and team activities. Team members will have severe weather alert systems on their phones to warn if any threat will impede launch operations or team activity.	2	2	4
ER.7	Fire	Dry grass, improper motor use	Burns to team personnel, damage to the airframe and electronics, potential for small brush fires to escalate into major wildfires	3	3	9	Prior to launches, the surrounding area will be inspected for dry grass and brush. Heat sources will be kept clear of the launch zone before flights.	The CSO, LO, and RSO will do a final check and observe the conditions on the launch procedures checklist prior to launching.	1	2	2

ER.8	Terrain	Launch site selection, bodies of water, uneven ground	Difficult to retrieve rocket, tripping and falling hazards, potential for airframe or water damage	2	2	4	Prior to launches, the surrounding area will be assessed for challenging terrain and cleared of major obstacles. The launch site and direction will be adjusted as needed.	The RSO will make sure team members are aware of the surrounding terrain prior to launch. The CSO will ensure team members have the appropriate attire for the recovery of the rocket.	1	2	2
ER.9	Tall structures	Trees, buildings, powerlines, and other man-made structures	Damage to the airframe upon impact and potential challenges in recovery	3	3	9	Prior to launch, the surrounding area will be assessed for tall structures and obstacles. Adjustments to the launch site and direction will be made if needed.	The RSO and CSO will make sure team members are aware of the surrounding structures and obstacles prior to launch.	1	3	3
ER.10	UV Light	Exposure to sunlight	Skin damage, sunburns	1	3	3	The UV index will be checked prior to outdoor activities. Sunscreen will be applied to team members.	The team lead will ensure that sunscreen is brought to launch and other team activities	1	2	2

ER.11	Wildlife Interference	Animals interfere with launch operations	Incorrect launch trajectory, flight interference	2	3	6	The launch area and air space will be carefully inspected prior to launch.	The CSO, LO, and RSO will use launch checklists to ensure of the safety of the launch site.	1	2	2

5.8. Project Risks Analysis

Table 5.8.1. *Hazards that could Affect the Completion of the Project Evaluated by the Defined Risk Assessment Code.*

ID	Hazard	Cause	Effect	Probability	Severity	Risk	Mitigation	Verification	Probability	Severity	Risk
P.1	Motor order shipping is delayed	Poor inventory practices on Aerotech's part and late ordering on CSL's behalf	Fewer to no full-scale flights can be conducted, competition would not be possible, and abbreviated testing schedule.	4	3	12	Motors will be ordered well in advance of project milestones to accommodate long lead times.	A motor order invoice will be sufficient to prove that the order has been placed.	3	2	6

P.2	Launch vehicle mass does not agree with MGA figures	Faulty mass figure bookkeeping	Simulation integrity would be low, contributing to unpredictable flight performance.	3	4	12	Subsystem designers will tabulate the real mass of each element in their system. The CE will conduct a mass properties audit of each subsystem and its associated records.	The CE will ensure that all subsystem MGA tables are updated after auditing.	1	4	4
P.3	Machined parts have poor tolerances	Poor machining practices and invalid SOLIDWORKS designs	Time and material will be lost turning parts down to the proper tolerance.	3	3	9	Detailed engineering drawings and material information will be provided to the machinists.	The CE will verify the integrability of each machined part before manufacturing begins.	1	2	2
P.4	Subscale rocket does not perform successfully	Recovery system failure, airframe failure, improper assembly, and faulty mass distribution	New motor for a second subscale launch must be sourced, repairs or complete redesign may be needed to redistribute mass in the vehicle.	2	3	6	Careful simulation and construction methods will be employed to ensure that the mass distribution will result in stable flight and that the rocket is manufactured in a sound manner.	The CE will verify that the subscale rocket is designed competently and manufactured to specifications.	1	3	3

P.5	Rocket takes longer to assemble than the time allotted for launch.	Poor equipment organization, missing crew members, inclement weather, missing equipment, and unclear communication	Testing and evaluation timeline is pushed back, possibly resulting in cutting a vital test launch.	3	2	6	The rocket and its subsystems will be assembled as completely as possible to make sure the time spent on field is minimal. All launch equipment will be organized by the launch officer.	The launch officer, CE, and PM will oversee the assembly of the launch vehicle and the communication surrounding the launch. The launch officer will direct on-field operations.	1	2	2
P.6	Subsystems do not fit in the airframe or with each other.	Dimension miscommunication, SOLIDWORKS design errors, and imprecise manufacturing methods	Testing and evaluation timeline is pushed back. Materials may need to be reordered. 3D printing time will increase.	3	3	9	Component fit and finish will be continuously tested using all parts on hand throughout the design process.	CE will verify the fit of each subsystem in the final assembly.	1	3	3
P.7	Rocket or its subsystems are dropped during transport or storage.	Carelessness and unsafe shop conditions	Rocket airframe and/or subsystems can be damaged, introducing extensive manufacture or repair times.	2	3	6	CSL members will be properly trained in handling the launch vehicle and its components, as well as maintaining a clean, obstruction-free work area.	The CSO will enforce safety regulations.	1	2	2

P.8	An assembled motor or motor reload is dropped or otherwise damaged.	Carelessness and unsafe shop conditions	Motor is unfit for launching if fissures are present in the propellant grain. Launch schedule is affected for motor lead times.	3	4	12	CSL members will be properly trained in handling rocket motors, as well as maintaining a clean, obstruction-free work area.	The CSL mentor will oversee the assembly and storage of the rocket motors. The SO and launch officer will ensure that the motors are handled responsibly in every space.	1	4	4
P.9	Amount of ballast needed in nose cone exceeds space available.	Major design changes or discrepancies in the mass properties figures would necessitate adding more ballast.	Not enough room for the STEMnaut capsule or antenna. The cone would have to be redesigned and re-printed.	3	3	9	Extensive simulation and mass properties planning will indicate the amount of ballast needed and therefore the amount of space needed in the nose cone.	The CE will ensure that the simulations reflect the current nose cone and payload design and will continuously reevaluate the mass growth of the design.	1	3	3
P.10	The CNC machines available to CSL may be out of order.	Machine misuse on the CNC mill, router, or the 3D printers.	Some parts may need to be outsourced or redesigned for a different manufacturing process.	2	3	6	Personal 3D printers will supplement the university 3D print farm as necessary. The CNC machines will only be operated by trained lab technicians to reduce instances of misuse.	The status and availability of all necessary machines will be monitored in advance of any manufacturing undertakings.	1	3	3

P.11	Vital flight computers are damaged.	Improper wiring, catastrophic launch events, or careless storage and handling can damage flight computers.	Parts of the avionics, payload, and recovery systems will not be operable until new computers are sourced.	3	3	9	CSL will store all flight computers safely and will borrow replacement computers as needed from the local WSR club members.	The launch officer will oversee the handling of all flight computer hardware.	1	2	2
P.12	Team fails to submit any project deliverable before due date.	Improper time management, and inability to understand deliverable requirements could affect ability to submit items.	Team could be penalized or disqualified from the NASA USLI Challenge.	2	4	8	CSL will implement artificial deadlines on deliverables and deliverable items to ensure completion and review before submission to NASA.	Discussions will be held with all relevant CSL personnel when setting/changing artificial deadlines, and a schedule will be created. If these deadlines are not met, the PM and CE will meet to discuss issue delaying deliverable.	1	3	3
P.13	Purchasing exceeds proposed budget limit.	Design changes, improper use of materials, or failing to properly quantify proper materials.	CSL will require additional funding/donations to acquire materials needed to finish project.	3	2	6	CSL will keep close track of all purchasing requests and inform the team accountant and team leadership if item prices change.	Team accountant will regularly update team records of all purchased materials, giving reports if CSL is over or under budget.	1	2	2

P.14	Inability to follow launch test plan.	Improper time management or failure to adequately prepare for tests.	Proper testing is not conducted and CSL does not have data-verified confidence in their rocket systems.	3	4	12	Create test specifications clearly outlining test safety and performance requirements and have Launch Officer and Safety Officer involved in the planning process.	CE and PM will ensure tests occur as planned and will verify if the results of each test meet validation requirements.	1	4	4
P.15	Confusion on project requirements/rules occurs between CSL and NASA.	Improper interpretation of NASA USLI rules, improper monitoring of communication channels, or failing to ask questions.	Team could be penalized for failing to meet requirements or disqualified from the NASA USLI Challenge.	2	4	8	Verify rules that could have multiple interpretations with NASA USLI personnel and team mentor and create deliverable requirement lists.	Keep records of all communication between NASA and CSL, verify deliverable requirements are completed as defined by the 2025 NASA USLI Handbook.	1	3	3
P.16	CSL personnel are unable to attend regular team meetings and miss important information.	Individual CSL member failure to manage time or miscommunication on team meeting expectations.	Team members do not have pertinent information and are restricted from doing satisfactory work.	1	4	4	If a CSL member is unable to attend team meetings, share meeting notes and team updates with them. If any changes to schedule, plans, or design occur, also notify relevant personal effected by said changes.	Keep records of weekly team meetings and system updates and ensure they are available to all team members. Have all team members update the Mass Growth Allowance plan per project deliverable.	1	2	2

P.17	CSL personnel are unable to continue working on NASA USLI competition.	Personal injury, sickness, or other life events.	Rocket subsystem(s) could be left without a dedicated team member, and manpower decreases.	2	3	6	Ensure proper documentation of rocket subsystems and cross team interaction such that no subsystem is understood solely by one person.	Have all subsystem information, including documentation and models, available to all CSL team members. Follow safety measures put in place by the CSO. Ensure team members have proper rest and resources.	1	2	2

5.9. STEM Engagement Risks

Table 5.9.1. *Hazards involving STEM Engagement Activities Evaluated by the Defined Risk Assessment Code.*

ID	Hazard	Cause	Effect	Probability	Severity	Risk	Mitigation	Verification	Probability	Severity	Risk
SE.1	Uncontrolled bottle rocket launch.	Improper construction of bottle rocket.	Damage to property or harm to student upon impact.	2	4	8	Guide students along during construction to ensure no unsafe designs are made.	Students will follow the process their instructor has given the on the STEM Engagement handouts.	1	4	4

SE.2	Cutting oneself on during construction of bottle rockets	Student uses improper construction technique	The student incudes bodily injury.	3	3	9	Proper construction techniques will be shown for each item that might cause harm during the process.	No student will be allowed to continue if they break the rules.	1	3	3
SE.3	Debris falling away during bottle rocket launch	Bottle rocket construction allows for loose material to hang away from the fuselage.	The debris falls off and impacts a student during flight.	2	3	6	Team members will not allow bottle rockets to have unsafe debris hanging off prior to launch.	The bottle rocket cannot launch with any possible debris.	1	3	3
SE.4	Bottle rocket landing on individual during descent	An individual is below a bottle rocket during launch.	The impact can lead to minor bodily harm	3	3	9	Students will be informed to move out of the way if a rocket is headed their direction.	All students will be standing in one area, and the rockets will be launched such that they have a low chance of hitting the students.	1	3	3

SE.5	Over pressurizing bottle leading to explosion	The operator does not know the max pressure of a 2 [L] bottle.	The bottle explodes causing plastic shrapnel to explode and possible serious bodily harm.	2	4	8	Overpressure vent holes will be used on the launchers.	No other launcher can be used that is homemade.	1	3	3
SE.6	Proximity during stomp rocket launching	Students draw too close to the rocket launcher during launch.	Bodily injury to an individual, especially if the rocket contacts the eye.	2	4	8	Create a perimeter that the students cannot cross while launching the rockets.	If the students cross this perimeter, then the rockets will not be allowed to fire.	1	4	4
SE.7	Model rocket misfire.	Improper care or handling of the model rocket.	Explosions causing debris to injure a bystander.	2	4	8	Only trained personnel can handle the launching equipment.	If students touch contraband items, they will be disciplined.	1	4	4

SE.8	Unpredictable model rocket launches	Misaligned launch rod or unsecured rocket	Impact upon landing causing bodily injury.	3	3	9	Double check rocket is ready to launch before launching. This will be checked by the safety officer of the current event.	If the rocket needs adjusted, it will be before the launch.	1	3	3
SE.9	Rocket retrieval	Students try to catch rockets in mid-air.	Students do not pay attention to the surroundings and cause bodily injury to themselves or others.	2	4	8	Ensure students run away from rockets instead of running to them via verbal instruction.	If they do not, then no more rockets will be launched.	1	4	4

5.10. Safety Violation Form

The overall purpose of the Safety Violation form is to encourage team personnel to follow safe construction and design practices throughout this project. This form must be completed for each personnel hazard that transpires. The form includes fields describing the hazard and the location where it occurred. Additionally, the form provides a section to propose methods for mitigating the hazard that has been identified. It includes a legal notice to remind team members of the team safety statement that was signed at the start of the project. The CSO must approve the form to ensure it is completed correctly. If it is not approved, the team member completing the form must re-submit it with changes to the mitigation strategy.

To reduce the high risks, the CSO has created the Safety Review Board (SRB) to review mitigation and verification strategies. This committee consists of the CSO, Team Leader, Chief Engineer, and faculty advisors. Once a mitigation plan is proposed, the SRB will meet and confirm the mitigation strategy is effective. If any unacceptable high-risk hazards identified occur within the scope of this project, the CSO and team personnel involved must fill out a Safety Violation Form. The SRB will review the completed form and determine if any additional mitigations and precautions should occur. A copy of the safety violation form is provided in Appendix A.2.

6. Project Plan

6.1. Requirements Verification

6.1.1. NASA Requirements

To ensure that Project Elijah meets NASA given requirements, CSL created a list of every NASA handbook requirement pertaining to the 2025 Student Launch Challenge in Table 6.1.1. Each requirement has been given a verification plan and status that will be updated as the project develops.

Table 6.1.1. 2025 Student Launch Challenge NASA Requirements and Verification Plan.

Req. #	NASA Requirement	Verification Plan	Status
1.1	Students on the team will do 100% of the project. The team will submit new and original work.	The team will ensure they do all project reports, designs, construction, and testing.	In Progress
1.2	The team will create and maintain a project plan for project milestones, budgets, community support, checklists, personnel assignments, STEM engagement, and risks and mitigations.	In addition to the project plans outlined in this proposal, the team will maintain the high and low level project plan using project management tools such as Notion	In Progress
1.4	The team will engage at least 250 participants in hands-on STEM activities. This must be completed between moment of project acceptance and the Flight Readiness Review (FRR) addendum due date.	The team will designate a STEM engagement lead and supporting team members. A multi-stage engagement plan will be created and is outlined in Section 5 of this report.	In Progress
1.5	The team will create a social media presence to inform the public about team activities.	A social media lead outside of the engineering division will be utilized, and an engineering team member will meet regularly with her to ensure an active social media page	In Progress
1.6	Teams will email all deliverables to NASA by the deadline specified in the handbook. Late submissions of milestone documents will not be accepted	A NASA deliverables checklist will be created to ensure all reports are properly formatted and submitted, and designated editors will be appointed specifically for reviewing the deliverables.	In Progress
1.8	All deliverables will be in PDF format.	A NASA deliverables checklist will be created to ensure all reports are properly formatted and submitted, and designated editors will be appointed specifically for reviewing the deliverables.	In Progress

Req. #	NASA Requirement	Verification Plan	Status
1.9	In every report, teams will provide a table of contents, including major sections and their respective sub-sections.	The team has created a pre-formatted document that all new reports will be based on.	In Progress
1.10	In every report, the team will include the page number at the bottom of the page.	The team has created a pre-formatted document that all new reports will be based upon.	In Progress
1.11	The team will provide all computer equipment for video teleconferences with the review panel.	Acquisition of proper rooms, audio equipment, and video equipment will be ensured before every teleconference.	Incomplete
1.13	The team will identify a mentor prior to the PDR. The mentor will be an adult, and they will be certified through the NAR or TRA for the motor impulse of the launch vehicle.	The team has identified a local rocketry club (WSR) and has identified a mentor whose contact info is in Section 1.2 of this document.	Complete
1.14	The team will track the hours it spent working on each milestone.	Per Cedarville University Engineering senior design rules, each team member will keep a logbook that tracks weekly progress and hours worked. Hours will also be logged by spreadsheet.	In Progress
2.1	The vehicle will deliver the payload to an apogee between 4,000 and 6,000 feet AGL.	The team will design the rocket so that simulations and test launches ensure that the rocket reaches an apogee between 4,000 and 6,000 feet.	Incomplete
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.	The team will identify reliable means of simulating the flight path and predicting the altitude so that a target will be determined by CDR.	In Progress
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 vehicle and recovery design will ensure the rocket safely lands. The propulsion system will be designed so that the rocket is reusable.	In Progress

Req.	NASA Requirement	Verification Plan	Status
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 vehicle. Coupler/airframe shoulders which are located at in-flight separation points shall be at least two airframe diameters in length.	The chief engineer will ensure when creating the high-level design that the number of independent sections in the launch vehicle complies with the rules. The chief engineer is responsible for verifying that the engineering contributions of each team member follow the specific construction guidelines provided.	Complete
2.5	The rocket will be able to be prepared for flight at the launch site within 2 hours of the time the FAA flight waiver opens.	The team will conduct launch preparation practices to ensure that they can prepare the rocket comfortably under 2 hours.	Incomplete
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.	Tests will be conducted to verify that the rocket and payload systems will maintain all functionality on the launchpad for at least 3 hours.	Incomplete
2.7	The rocket will be capable of being launched by a 12-volt DC firing system.	The chief engineer will ensure that the launch protocol will only employ commercially available igniters rated for a 12-volt DC firing system.	Incomplete
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).	The chief engineer will ensure that all electronic subsystems will function in an entirely self-contained manner.	Complete
2.9	Each team shall use commercially available e-matches or igniters. Hand-dipped igniters shall not be permitted.	The chief engineer will ensure that the launch protocol will only employ commercially available igniters rated for a 12-volt DC firing system.	Incomplete
2.10	The rocket will use a NAR/TRA approved solid motor using ammonium perchlorate composite propellant (APCP). Final motor choices will be outlined by CDR.	The rocket will use an approved solid motor using APCP, this motor will be purchased from a licensed vendor and will follow all competition guidelines.	In Progress

Req. #	NASA Requirement	Verification Plan	Status
2.11	The rocket will be limited to a single stage.	The chief engineer will ensure that the vehicle is a single-stage rocket.	Complete
2.12	The impulse for the launch vehicle will be no more than 5,120 Newton-seconds (L-class).	We will be using a L-class motor that does not exceed 5,120 Newton-sconds as informed by the Motor Data Sheet.	Complete
2.13	Pressure vessels on the rocket will be approved by the RSO, have a safety factor of at least 4:1, and will have detailed documentation included in all milestone reviews.	Pressure vessels on the rocket will be approved by the RSO have a safety factor of at least 4:1, and have detailed documentation that will be stored with all other safety documents.	Complete
2.14	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.	Using OpenRocket and possibly other calculation methods, the team will ensure that the static stability margin will be at least 2.0 at rail exit.	Complete
2.15	The rocket's thrust to weight ratio will be at least 5.0:1.0	We will determine the weight of the rocket, and then, using OpenRocket and the motor thrust curve data, we will ensure that the thrust to weight ratio exceeds 5:1.	Complete
2.16	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.	Burnout CG will be calculated using a testing rig and multiple other methods. Camera housings will be simulated to determine compliance.	Complete
2.17	The rocket will have a minimum velocity of 52 fps at rail exit.	Theoretical analysis will be performed on the rocket using OpenRocket, and practical experimentation will be performed to ensure that the rocket has a minimum velocity of 52 fps at rail exit.	Complete
2.18			Incomplete

	The team will successfully launch and recover a subscale rocket before CDR. The subscale must be a separate, newly constructed rocket and must have an altimeter. Proof of flight is required in the CDR.	The team will construct, launch, and recover a subscale rocket for testing and qualification purposes. This will be done with the help of a local rocketry club and will be completed by CDR.	

Req. #	NASA Requirement	Verification Plan	Status
2.19	The team will complete both the Vehicle Demonstration Flight and the Payload Demonstration Flight as outlined by the SL Handbook.	The team lead will ensure that the Vehicle and Payload Demonstration Flights are performed as outlined by the SL Handbook, and prior to any deadlines. They will also submit the results to NASA as necessary.	Incomplete
2.20	The team will create an FRR Addendum for any Payload Demonstration Flight or NASA required Vehicle Demonstration Re-flight after the submission of the FRR.	The team will write an FRR addendum for all necessary changes needed after the submission of the FRR.	Incomplete
2.21	The team will place the team name and Launch Day contact information on the rocket airframe and all untethered sections of the rocket.	The team lead will ensure that their name and launch day contact information are on the airframe and untethered sections.	Incomplete
2.22	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.	The safety officer will ensure that lithium polymer batteries will be stored in a fireproof LiPo bag. Stickers will denote that they are a fire hazard.	Incomplete
2.23.1-5	The rocket will not use forward firing, hybrid, cluster, or friction-fitted motors.	The team will use a single commercial motor that will be anchored using a motor retainer system.	Complete
2.23.6-7	The launch vehicle will not exceed Mach 1 or contain excessive ballast.	Theoretical analysis will be performed on the rocket using OpenRocket, and practical experimentation will be performed to ensure that the rocket does not exceed Mach 1. Ballast use will be reasonable.	Complete
2.23.8-9			Incomplete

	Transmissions from the vehicle will not exceed 250 [mW] of power per transmitter and will use unique frequencies and other methods to reduce interference.	The appropriate transmitters will be purchased such that they do not exceed the 250 mW power limit. Research into appropriate frequencies and techniques will be performed.	
2.23.10	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.	The team will not use dense metals for structural components, only aluminum will be utilized in moderation where metal parts are necessary.	In Progress
3.1	The rocket will deploy a drogue parachute at apogee with a delay of 2 seconds or less. A main parachute will be deployed no lower than 500 feet. Both deployments will not utilize motor ejection.	The launch officer will ensure that altimeters will trigger black powder charges at apogee and at an altitude no lower than 500 feet in order to deploy the parachutes.	Incomplete
3.2	The team will conduct successful ground tests for parachute ejection before the subscale and full-scale flights.	The recovery team will trigger the altimeters so that the black powder charges are fired in a controlled and safe environment for ground testing.	Incomplete
3.3	Each separate section of the rocket will have a landing energy that does not exceed 75 [ft-lbf].lbs.	Theoretical analysis will be performed on the rocket using OpenRocket and hand calculations to ensure that the rocket's landing energy does not exceed 75 [ft-lbf].lbs.	In Progress
3.4	The recovery system shall contain redundant, commercially available barometric altimeters that are specifically designed for initiation of rocketry recovery events.	Two altimeters of different brands will be used for recovery. The team member in charge of avionics will ensure altimeter compliance.	In Progress
3.5	Each altimeter shall have a dedicated power supply, and all recovery electronics shall be powered by commercially available batteries.	Each altimeter will have a dedicated, commercially available battery as a power source.	In Progress
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.	Key-switches or equivalent means will be used to arm the flight avionics.	In Progress
3.7	Every arming switch will be able to be locked in the ON position.	Key-switches or equivalent means will be used to arm the flight avionics.	In Progress
3.8	The recovery system, GPS and altimeters, and electrical circuits shall be completely independent of any payload electrical circuits.	Recovery system and payload circuits will be placed in isolated electronics bays within the rocket.	Complete
3.9	Drogue and main parachute sections will use removable shear pins.	The recovery lead will be responsible for the insertion and inspection of shear-pins prior to every launch.	Incomplete
3.10	Bent eyebolts shall not be permitted in the recovery subsystem.	Forged eyebolts will be used where required.	Complete
3.11	The recovery area will be within a 2,500 [ft]. radius from the launch pads.	Simulations will be performed on the rocket using OpenRocket and Systems Toolkit, and practical experimentation will be performed to ensure that the drift stays within a 2,500 [ft]. radius.	Complete
3.12	The vehicle descent time will be a maximum of 90 seconds.	Simulations will be performed on the rocket using OpenRocket and Systems Toolkit, and practical experimentation will be performed to ensure that the descent time is below 90 seconds.	Complete
3.13	The launch vehicle will contain a GPS device that transmits the position of the vehicle or any independent section to a ground receiver.	A GPS will be purchased by the avionics lead, the appropriate tracking software and ground station set up to receive signals will be taken care of by the recovery lead.	In Progress
3.14	The recovery system electronics will be carefully protected and separate from other transmitters in the launch vehicle.	Electronics will be shielded from interference. Insulation will be applied to electronics. The avionics bay will physically isolate it from all other electronics.	In Progress

4.1	Design, build, and fly a STEMnaut flight capsule capable of safely retaining four STEMnauts and transmitting, via radio frequency, relevant rocket and STEMnaut landing site data to a NASA-owned receiver located at the launch site. The methods and designs must be safe, obey FAA and legal requirements, and adhere to the intent of the challenge.	The designs and prototypes of the payload will be reviewed and tested for safety, reliability, and conformity to FAA, FCC, and legal requirements.	In Progress
4.2	The payload must transmit 3-8 pieces of the provided data to NASA. Transmissions may not exceed 5 [W],5W, and transmissions should start and end with a team member's callsign. The data to be transmitted must be submitted by March 17.	The team will purchase the same radio NASA will use at the competition, and through extensive testing, ensure the data received fulfills these requirements in replications of the final launch.	In Progress
4.3	The payload will abide by FAA and NAR rules and regulations, and will abide by additional rules if the payload is deployed during descent, especially if classified as an unmanned aircraft system (UAS).	The payload will remain attached to the main body of the rocket and will not be jettisoned or deployed from the rocket's body.	In Progress
5.1	The team will use a launch safety checklist that will be included the FRR and used during the LRR.	The SO will create a safety check list.	Incomplete

Req. #	NASA Requirement	Verification Plan	Status
5.2	The team will select a safety officer that is responsible for the items in section 5.3.	Jesse DePalmo will be the 2024-2025 Student Launch SO.	Complete
5.3.1			In Progress

	The safety officer will monitor the safety of the following activities: ▪ Design of vehicle and payload ▪ Construction, methods ▪ Assembly, methods ▪ Ground testing, ▪ Subscale and Full-scale launch test(s),) ▪ Competition Launch ▪ Recovery, activities, ▪ STEM Engagement Activities	The SO will write FMEA, RPN sheets, safety sheets, verification sheets, and procedure sheets. He will also monitor and observe all events to ensure that rules and regulations are being followed.	
5.3.2	The SO will create safety procedures for construction, assembly, launch, and recovery activities.	The SO will write FMEA, RPN sheets, safety sheets, verification sheets, and procedure sheets.	In Progress
5.3.3	The SO will maintain revisions of the team's hazard analyses, failure modes analyses, procedures, and Material Safety Data Sheet (MSDS) information.	The SO will write FMEA, RPN sheets, safety sheets, verification sheets, and procedure sheets.	In Progress
5.3.4	The SO will help develop the team's hazard analyses, failure modes analyses, and procedures.	The SO will write FMEA, RPN sheets, safety sheets, verification sheets, and procedure sheets.	In Progress
5.4	The team will abide by the rules and guidance of the local RSO during test flights.	The SO will ensure that all FAA rules are followed and will collaborate with the RSO to ensure proper test flight safety.	Incomplete
5.5	The team will abide by all FAA rules.	The SO will ensure that all FAA rules are followed.	Incomplete
6.1	The team will pass the LRR during Launch Week. The team's mentor shall be at Launch Week and will oversee rocket preparation and procedures. The team will only launch once at competition.	Team leads will coordinate to ensure that each part of the rocket is prepared for launch. The Engineering lead (Daniel Hogsed) will oversee complete assembly preparations and ensure that all requirements are met.	Incomplete
6.2			Incomplete

	If the team does not attend Launch Week, it will launch at a NAR or TRA sanctioned launch. The team will closely collaborate with the RSO, team mentor, and the Launch Control Officer, ensuring that all NASA procedures are followed.	If the team does not attend Launch Week, the team leader (Grant Parker) will organize and schedule proper launching times and delegate responsibilities to ensure that procedures are followed.	

6.1.2. Mass Control Plan

To design Project Elijah with margin in consideration, CSL has created an extensive mass control plan. Closely detailed in section 3.9 of the Vehicle Criteria portion of this report, the mass control plan is a predictive model for anticipating and designing for changes of mass in launch vehicle design. With this predictive model, CSL has created margins for allowable mass growth and limitations that ensure successful mission completion. Each member of CSL has been informed of this project requirement and will utilize tracking processes to ensure project subsystems fall in allowed margins. The scope and details of the mass control plan are given in section 3.9 as previously mentioned.

6.1.3. Work Breakdown Structure & Test Launch Plan

To better understand the scope of Project Elijah, CSL created a Work Breakdown Structure (WBS) to map the modeling and simulation, testing, payload system, and launch vehicle systems required for complete mission success, as well as finding additional data that would contribute to future CSL team success. This WBS includes a static fire and wind tunnel test that have been removed from internal team requirements but could be pursued if CSL encounters few problems in launch vehicle manufacturing. The WBS is given in Figure 6.1.1.

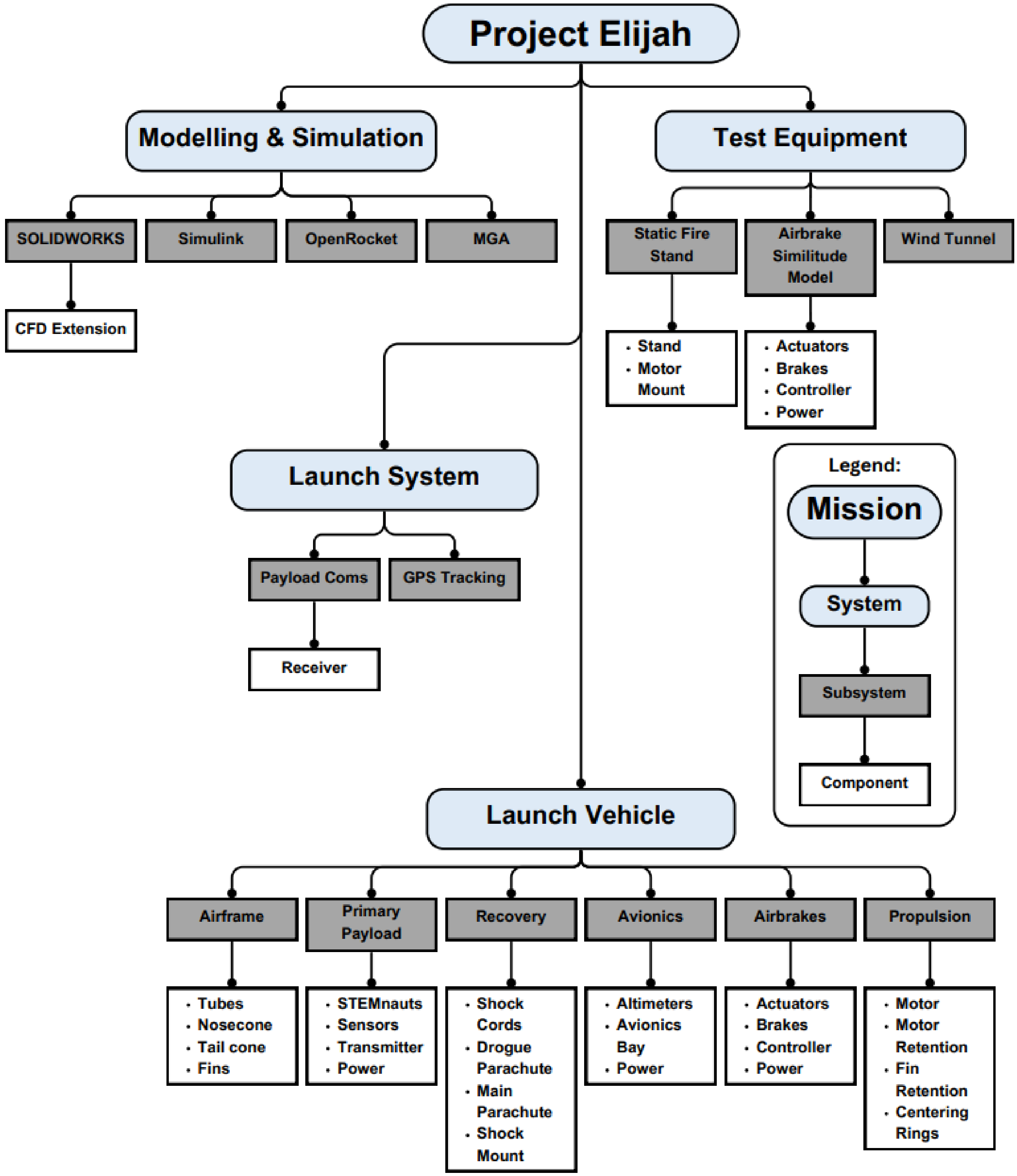

Figure 6.1.1. *Project Elijah Work Breakdown Structure.*

CSL also created a plan for Project Elijah's test launches, where each launch is assigned a system or deliverable that is to be verified or showcased. This launch test plan includes validation of the subscale, as well as the full-scale rocket with the primary payload onboard, with active airbrakes performing simple braking, with the airbrakes control system fully activated, and with the primary payload onboard and fully functional. Included in this test plan are launches for the Vehicle Demonstration Flight (VDF) and Payload Demonstration Flight (PDF). This test plan is given in Figure 6.1.2.

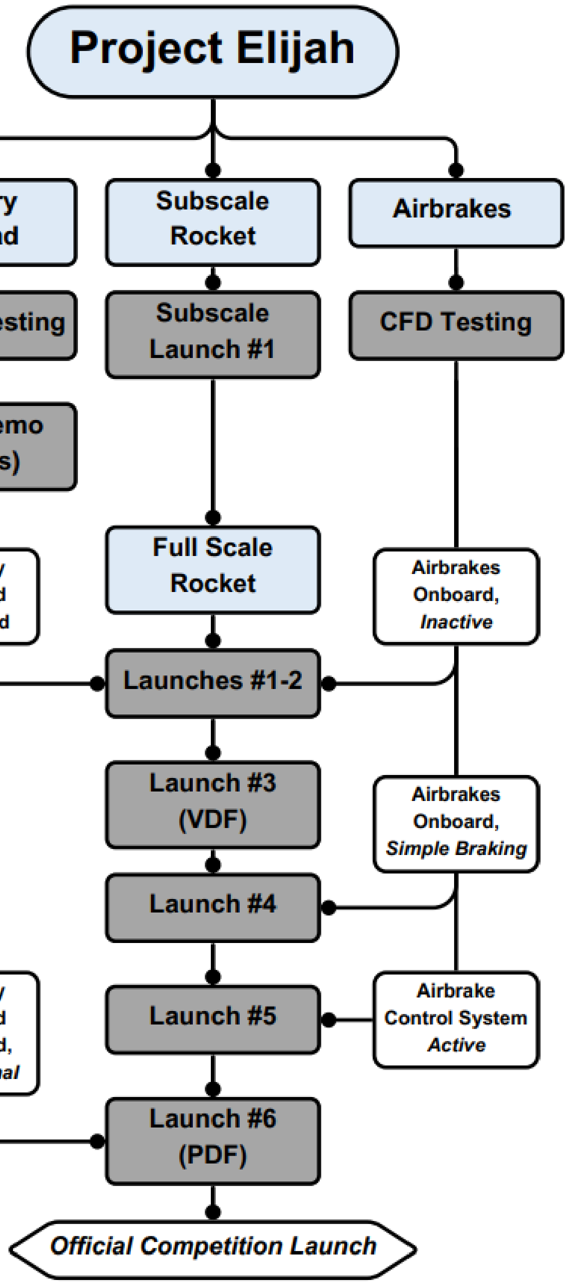

Figure 6.1.2. *Project Elijah Launch Test Plan.*

6.2. Budget and Timeline

6.2.1. Team Budget and Funding

The budget for the NASA project has changed slightly since the proposal. There are now links in the spreadsheet for CSL use that link directly to the source page where the item can be purchased. There is also now an indication whether the item has been purchased. If the item does not have a link, the item will either be manufactured, or a decision has not been made yet on what exactly the CSL team will need. More items have been added and some have been taken off the budget. There is also a new section called “Flight Consumables”, which are items that will need to be repeatedly purchased as they are consumed during vehicle launch. The Electronics portion of the budget is kept by a separate team, and it is CSL’s job to track what they have purchased. The updated budget is shown in Table 6.2.1.

The CSL team receives funding from a few different sources. Cedarville University’s engineering department will supply a grant for any necessary costs associated with the competition including full and subscale rocket construction, necessary tools, and outreach not covered by sponsors or donors.

Table 6.2.1. *CSL Line-Item Budget.*

Overall Budget for Proposal						
System	**Qty**	**Item Name**	**Price**	**Total**	**Source**	**Purchsed?**
Airframe	2	4 ft of fiberglass airframe (4 in) (G12)	$ 80.00	$ 160.00	Link	X
	6	Bulkheads/Centering Rings	$ 5.00	$ 30.00		
	2	4 in body coupler (9 in length)	$ 24.00	$ 48.00	Link	X
	1	22" motor tube 75mm dia	$ 55.00	$ 55.00	Link	X
	2	18" motor tube 54mm dia	$ 41.00	$ 82.00	Link	X
	Total			**$ 375.00**		
Recovery/Avionics	1	Black Powder Charges (10 oz.)	$ 50.00	$ 50.00		
	1	Flame blanket for drogue parachute	$ 10.29	$ 10.29	Link	X
	1	Main Parachute	$ 225.00	$ 225.00		
	100	1yd of Shock Cord	$ 1.50	$ 150.00	Link	X
	1	Drogue Parachute	$ 72.00	$ 72.00		
	Total			**$ 507.29**		
Electronics/Payload	2	FCC Ham Radio License	$ 35.00	$ 70.00		X
	1	BTECH APRS-K1 PRO	$ 34.49	$ 34.49		
	2	UV-5R Ham Radio Transceiver	$ 31.69	$ 63.38		
	3	Diamond Antenna Dual-Band HT Antennas RH707	$ 29.99	$ 89.97		
	1	W25Q64 Flash Memory Module (5-pack)	$ 7.99	$ 7.99		
	2	PCB Manufacturing per Version	$ 40.00	$ 80.00		
	4	LEGO STEMnauts	$ 5.00	$ 20.00		
	Total			**$ 365.83**		
Stem Engagement	4	Model rockets	$ 7.00	$ 28.00	Link	X
	2	Chloroplast corrugated cardboard	$ 125.00	$ 250.00		
	2	Foam Footballs	$ 19.99	$ 39.98	Link	X
	1	Table Cloth	$ 9.99	$ 9.99	Link	X
	1	Dish Set	$ 13.49	$ 13.49	Link	X
	1	Toy Cars	$ 7.60	$ 7.60	Link	X
	1	Wood	$ 4.42	$ 4.42	Link	X
	1	Tennis Balls	$ 3.94	$ 3.94	Link	X
	1	Stuffed Toy	$ 9.99	$ 9.99	Link	X
	1	Balloons	$ 5.99	$ 5.99	Link	X
	1	Compressed Air	$ 12.00	$ 12.00	Link	X
	1	Toothpicks	$ 3.99	$ 3.99	Link	X
	1	Glasses	$ 3.99	$ 3.99	Link	X
	1	Forks	$ 5.99	$ 5.99	Link	X
	1	Baseball Bat	$ 10.99	$ 10.99	Link	X
	1	Fan	$ 30.99	$ 30.99	Link	X
	1	Corugated Card Board	$ 26.74	$ 26.74	Link	X
	1	Ruler	$ 6.99	$ 6.99	Link	X
	3	Pencil	$ 16.99	$ 50.97	Link	X
	60	2 Liter Bottles	$ 1.00	$ 60.00	Link	X
	1	Corrugated cardboard	$ 9.88	$ 9.88	Link	X
	1	Gravel	$ 5.59	$ 5.59	Link	X
	1	Plastic Cups	$ 5.84	$ 5.84	Link	X
	1	Straws	$ 5.98	$ 5.98	Link	X
	1	Rubber Bands	$ 6.80	$ 6.80	Link	X
	1	Tissue Paper	$ 5.99	$ 5.99	Link	X
	1	String	$ 4.99	$ 4.99	Link	X
	1	Popsicle Sticks	$ 4.99	$ 4.99	Link	X
	1	Construction Paper	$ 5.99	$ 5.99	Link	X
	1	Markers	$ 13.75	$ 13.75	Link	X
	1	Tape	$ 23.39	$ 23.39	Link	X
	1	Hot Glue Gun	$ 9.99	$ 9.99	Link	X
	1	Scissors	$ 13.99	$ 13.99	Link	X
	1	Scale	$ 9.98	$ 9.98	Link	X
	1	Micro Balloons	$ 22.00	$ 22.00		
	1	Measuring Cups	$ 7.99	$ 7.99	Link	
	1	Launching Material	$ 100.00	$ 100.00		
	Total			**$ 843.19**		

Subscale	1	5 ft of 3in fiberglass airframe (G12)	$ 98.00	$ 98.00	Link	X
	4	PETG plastic	$ 20.00	$ 80.00	Link	X
	2	Two 9-inch long 3-inch diameter coupler tubes	$ 22.00	$ 44.00	Link	X
	1	fiberglass cloth	$ 30.00	$ 30.00		
	4	G10 Fiberglass for fins	$ 29.82	$ 119.28	Link	X
	Total			**$ 371.28**		
General Construction	2	Epoxy (quart)	$ 80.00	$ 160.00		
	1	4 inch Alumninum Roundstock (1/2 ft)	$ 82.73	$ 82.73	Link	X
	2	Hardener (quart)	$ 80.00	$ 160.00		
	10	Threaded eye bolt 1/4" X 20" 1"	$ 7.00	$ 70.00	Link	X
	10	Fire wire Initiator	$ 7.00	$ 70.00	Link	X
	2	10-10 Rail Buttons	$ 3.00	$ 6.00	Link	X
	2	Shock Cords	$ 50.00	$ 100.00	Link	X
	2	Fasteners (50 ct) 18-8 Stainless Steel Button Head	$ 7.56	$ 15.12	Link	X
	1	Fiberglass cloth (5 yd)	$ 30.00	$ 30.00		
	4	PETG plastic	$ 20.00	$ 80.00	Link	X
	50	Breather and Bleeder Cloth	$ 1.62	$ 81.00		
	10	1/4" x 20" 1" Threaded eye bolts	$ 6.59	$ 65.90	Link	X
	3	36" Smooth T-Slotted Almuminum Extrusion	$ 8.42	$ 25.26	Link	X
	6	9.5" Smooth T-Slotted Almuminum Extrusion	$ 2.48	$ 14.88	Link	X
	2	10/10 Rail buttons	$ 2.99	$ 5.98	Link	X
	2	Cerakote Glacier Black	$ 35.00	$ 70.00	Link	
	2	1/4-20 Threaded Rods	$ 7.47	$ 14.94	Link	X
	1	Fiberglass	$ 50.00	$ 50.00		
		Carbon Fiber Square Rods 6mm x 6mm			Link	
	Total			**$ 1,101.81**		
Flight Consumables	7	Motor reload kit	$ 250.00	$1,750.00		X
	10	Igniters	$ 6.99	$ 69.90	Link	
	1	Shear Pins (100 ct)	$ 5.50	$ 5.50	Link	X
	Total			**$ 1,819.90**		
Grand Total				**$5,384.30**		

6.2.2. Deliverable and Test Timeline

To track NASA and Cedarville University Senior Design course deliverables, test/validation requirements, and launches, CSL made use of a Gantt-style chart, given in Table 6.2.2 on the next page. Due to scheduling conflicts, CSL will not be traveling to competition in Huntsville, AL, but will be launching their competition vehicle at the local NAR chapter WSR. As previously mentioned, this Gantt chart has been updated with scheduled test launches given in section 6.1.3.

Based on a reported lead time of 16 to 20 weeks for the ordered primary motor choice, test launches could begin as early as the weekend of January 25th or as late as the weekend of February 22nd. CSL has also made an internal goal to successfully launch a subscale rocket before Thanksgiving, or November 28th. After adding an additional margin of a week in case of further unexpected delays and making the assumption that each test could take two weeks to launch due to unforeseen factors such as weather or damage, the test launch plan was developed and included in Table 6.2.2. This test plan was developed based on worst case scenario assumptions, and CSL expects to complete test launches well before their time frames.

Table 6.2.2. *CSL Project Timetable.*

Cedarville University NASA Student Launch 2024-25 Plan

CSL: Project *ELIJAH*	8/14/2023	05/03/2024
PROJECT NAME	START DATE	END DATE

Task	Start Date	End Date	Progress	8/12/2024	8/19/2024	8/26/2024	9/2/2024	9/9/2024	9/16/2024	9/23/2024	9/30/2024	10/7/2024	10/14/2024	10/21/2024	10/28/2024	11/4/2024	11/11/2024	11/18/2024	11/25/2024	12/2/2024	12/9/2024	12/16/2024	12/23/2024	12/30/2024	1/6/2025	1/13/2025	1/20/2025	1/27/2025	2/3/2025	2/10/2025	2/17/2025	2/24/2025	3/3/2025	3/10/2025	3/17/2025	3/24/2025	3/31/2025	4/7/2025	4/14/2025	4/21/2025	4/28/2025	5/5/2025	5/12/2025
NASA Deliverables																																											
Student Launch Proposal	8/14/2024	9/11/2024	100%																																								
Preliminary Design Review (PDR)	10/3/2024	10/28/2024	--																																								
PDR Teleconferences	11/4/2024	11/26/2024	--																																								
Gateway Registration	11/26/2024	11/29/2024	--																																								
Huntsville Roster (for in person teams)	11/30/2024	12/16/2024	N/A																																								
Critical Design Review (CDR)	11/30/2024	1/8/2025	--																																								
Subscale Flight	10/7/2024	1/8/2025	--																																								
CDR Teleconferences	1/15/2025	2/6/2025	--																																								
Team Photos	2/6/2025	2/10/2025	--																																								
Flight Readiness Review (FRR)	2/6/2025	3/17/2025	--																																								
Vehicle Demonstration Flight	1/8/2025	3/17/2025	--																																								
Payload Demonstration Flight	3/17/2025	4/14/2025	--																																								
FRR Teleconferences	3/24/2025	4/11/2025	--																																								
Launch Window	4/5/2025	5/4/2025	--																																								
Post-Launch Assessment Review (PLAR)	4/5/2025	5/18/2025	--																																								
Test Launch Plan																																											
Subscale Launch #1	10/28/2024	11/28/2024	--																																								
Launch #1 (Inactive Payload & Airbrakes)	2/26/2025	3/12/2025	--																																								
Launch #2 (Inactive Payload & Airbrakes)	3/5/2025	3/19/2025	--																																								
Launch #3 (VDF)	3/12/2025	3/26/2025	--																																								
Launch #4 (Simple Airbrake Actuation)	3/19/2025	4/2/2025	--																																								
Launch #5 (Active Airbrakes)	3/26/2025	4/9/2025	--																																								
Launch #6 (PDF)	4/2/2025	4/16/2025	--																																								
Launch #7 (Competition Launch)	4/9/2025	4/23/2025	--																																								
Cedarville University Course Deliverables																																											
Background Research	8/17/2024	9/6/2024	100%																																								
Senior Design Proposal Rough Draft	9/6/2024	9/16/2024	100%																																								
Senior Design Final Proposal	9/16/2024	9/30/2024	100%																																								
Oral Committee Design Review	11/18/2024	11/22/2024	--																																								
End of Semester Report (Fall)	11/22/2024	12/6/2024	--																																								
Final Report (Draft)	1/7/2025	4/11/2025	--																																								
Final Presentations (Oral)	4/11/2025	4/15/2025	--																																								

Bibliography

American Institute of Aeronautics and Astronautics. (2015). *S-120A: Section public review and co-ballot draft*. Retrieved October 25, 2024, from https://www.aiaa.org/docs/default-source/uploadedfiles/publications/standards/s-120a-sec-public-review-andco-ballot-draft.pdf?sfvrsn=ac4256aa_0

Amphenol Cables on Demand Administrator. (2024, July 19). *Category-8 (cat-8) ethernet cable guide: Frequently asked questions [CAT8 cable FAQ] by amphenol cables on demand*. The “Ask the Cable Guy” Blog:. https://cablesondemand.com/blog/category-8-cat-8-ethernet-cable-guide-frequently-asked-questions-cat8-cable-faq-amphenol-cables-on-demand/

Arduino. (2021). *Arduino® Nano*. https://docs.arduino.cc/resources/datasheets/A000005-datasheet.pdf

Apogee Components, Inc. (2020). *38mm Blue Tube*. Apogeerockets.com. https://www.apogeerockets.com/Building_Supplies/Body_Tubes/Blue_Tubes/38mm_Blue_Tube?cPath=42_43_56&#comparison.

Apogee Components, Inc. (n.d.). *“Intro to dual deployment in rocketry”*. Apogee Rockets, Model Rocketry Excitement Starts Here. https://www.apogeerockets.com/Intro-to-Dual-Deployment.

Athanasios P. Iliopoulos a, a, b, AbstractThe mechanical properties of the glass-epoxy composite material known as “G-10, Dasgupta, A., Lamberson, L., NEMA Standards Publication No LI 1-1998, 60893-3-1, I. I. S., MIL-I-24768, Zherlitsyn, S., Watt, T., Challita, A., Ravi-Chandar, K., Mechanical, E., & Shindo, Y. (2015, December 17). *Determination of anisotropic mechanical properties of G-10 composite via direct strain imaging*. Polymer Testing. https://www.sciencedirect.com/science/article/pii/S0142941815301094

Baofeng Radio. (2019). *UV-5R*. Baofeng. https://www.baofengradio.com/products/catalog-uv-5r

Baofeng UV-5R Ham Radio. (2024). Amazon.com. https://www.amazon.com/Baofeng-Handheld-Talkies-Earpiece-Black-2Pack/dp/B0CDB5W3Y8/ref=sr_1_6?crid=3RIFZUUAJT30L&dib=eyJ2IjoiMSJ9.l_bnarSvkehP3k9tzuTrCzSduXCaptXvzdmqZoIwZ3p8ql1RkMENxQwmpUwGmkUy70jA6lU84naPjn2mM1CLWQKcKI0weWWTBasT8z3tDcUsZliF33t6W_rSh71p

Blue Tube 2.0 – Always Ready Rocketry. (2023). Alwaysreadyrocketry.com. https://alwaysreadyrocketry.com/blue-tube-2-0/

BMP280. (n.d.). Bosch Sensortec. https://www.bosch-sensortec.com/products/environmental-sensors/pressure-sensors/bmp280/

BMP380. (n.d.). Bosch Sensortec. https://www.bosch-sensortec.com/products/environmental-sensors/pressure-sensors/pressure-sensors-bmp390.html

Cepiio. (2024). *Analog vs digital: Understanding the pros and cons of each signal type – exploring the world of electronic instruments*. Cepi.io. https://www.cepi.io/analog-vs-digital-understanding-the-pros-and-cons-of-each-signal-type/

Cerakote. (n.d.). Cerakote Protection for Aerospace & UAVs | Cerakote in industry. Retrieved October 27, 2024, from https://www.cerakote.com/cerakote-industries/aerospace

Cirkit Design. (2024). *How to Use the HW-040 Rotary Encoder*. Cirkitdesigner.com. https://docs.cirkitdesigner.com/component/fb77c67b-258e-42e8-840b-9cf445a0d2f2/hw-040-rotary-encoder

CNHL 2200mAh 3S Lipo Battery. (2024). Amazon.com. https://www.amazon.com/CNHL-2200mAh-Battery-Airplane-Quadcopter/dp/B08KD1YN9F/ref=sr_1_1_sspa

Chalia, S. (2019). Investigation on aerodynamic performance of elliptical and secant give nose cones. *vol*, *5*, 1291-1300.

Components101. (2019). *NEMA 17 Stepper Motor Datasheet, Wiring, Specs & Alternatives*. Components101.com. https://components101.com/motors/nema17-stepper-motor

Crowell, G. A. (1996). The descriptive geometry of nose cones. http://servidor.demec.ufpr.br/CFD/bibliografia/aerodinamica/Crowell_1996.pdf

Davies, M. (2021, September 16). *What Is the Density of PETG & How Does It Affect 3D Printing? - 3D Print Beast*. 3D Print Beast. https://www.3dprintbeast.com/petg-density/

Devices, Q. (2022, May 31). *Incremental Optical Rotary Encoders made in USA | Quantum Devices*. Quantum Devices, Inc. https://www.quantumdev.com/products/rotary-encoder/

Diamond Antenna Dual-Band HT Antennas. (2024). DX Engineering. https://www.dxengineering.com/parts/dmn-rh707

Digital Packet Radio – APRS. (2021). Stanford.edu. https://web.stanford.edu/class/ee179/labs/Lab8.html

Direcn. (2024). *ZYTD520 6V-12V-24V 10 RPM 37mm Geared DC Motor*. Https://Www.direnc.net/. https://www.direnc.net/zytd520-6v-12v-24v-10rpm-37mm-reduktorlu-dc-motor-en

DragonPlate. (2019). *What Is Carbon Fiber? | DragonPlate*. Dragonplate.com. https://dragonplate.com/what-is-carbon-fiber

Elxjar (2-Pack) 6.0V 700mAh Ni-CD AA Rechargeable Battery Pack. (2024). Amazon.com. https://www.amazon.com/Rechargeable-Battery-Excavator-Amphibious-Vehicles/dp/B08LYL92BL/ref=sr_1_3

Embedded, M. (2024). *Gearbox DC motor 12v ZYTD520*. Microscale Embedded. https://www.microscale.net/products/gearbox-dc-motor-12v-zytd520

Engineering Toolbox. (2004). *Metals and alloys - densities*. Engineeringtoolbox.com. https://www.engineeringtoolbox.com/metal-alloys-densities-d_50.html

Explained, V. (2021, January 28). *Visually Explained: Kalman Filters*. Www.youtube.com. https://www.youtube.com/watch?v=IFeCIbljreY

FC-302 UHF/VHF Data Radio. (2024). Friendcom America Inc. https://www.friendcom.us/products/uhf-vhf-data-radio

FC-303 Data Radio. (2024). Friendcom America Inc. https://www.friendcom.us/products/data-radio-fc-303

Fotek. (2024). *Rotary encoder LPD3806-600BM-G5-24C*. Hi-Ip.com. https://m.hi-ip.com/en/industrial-automation/sensors/encoders/incremental-rotary-encoder-lpd3806-600bm-g5-24c.html

Gregorek, G. (1970). Aerodynamic Drag of Model Rocket. In Estes Industries, Inc. (TR-11). Estes Industries, Inc. Retrieved October 27, 2024, from https://www.oldrocketplans.com/pubs/Estes/estTR-11/TR-11.pdf

Hartcher-O'Brien, J., Evers, J., & Tempelman, E. (2019). Surface roughness of 3D printed materials: Comparing physical measurements and human perception. *Materials Today Communications, 19*, 300–305. https://doi.org/10.1016/j.mtcomm.2019.01.008

Howard, Zachary. "How to Calculate Fin Flutter Speed." *Peak of Flight Newsletter*, 2011, www.apogeerockets.com/education/downloads/Newsletter291.pdf.

Iyer, A. R., & Pant, A. (2020, August 8). *A review on nose cone designs for different ...* A REVIEW ON NOSE CONE DESIGNS FOR DIFFERENT FLIGHT REGIMES. https://www.irjet.net/archives/V7/i8/IRJET-V7I8605.pdf

JLCPCB SMT Parts Library & Component Sourcing. (2024). Jlcpcb.com. https://jlcpcb.com/parts/componentSearch?searchTxt=ad5700

John. (2015). *BMP280 sensor | barometric sensor for arduino projects, datasheet*. PCB Assembly, PCB Manufacturing, PCB Design - OURPCB. https://www.ourpcb.com/bmp280.html

La Tiendita Online Store. (2024). *Left Type 5 Pcs 3 Pins 3D Printer Stop Micro Sensor Switch Button Clicker Click*. EBay. https://www.ebay.com/itm/295700067319?mkevt=1&mkcid=1&mkrid=711-53200-19255-0&campid=5338766894&toolid=20006&customid=69929c1453d9292a637ed0c3e6caf0d8&_trkparms=ispr%3D1&amdata=enc%3A1BVQ7i6kCTXyl4fOkArbCcA20

Linear, P. (n.d.). *Dimensions: mm (in)*. https://pages.pbclinear.com/rs/909-BFY-775/images/Data-Sheet-Stepper-Motor-Support.pdf

Low Power HART Modem. (n.d.). https://www.analog.com/media/en/technical-documentation/data-sheets/AD5700_5700-1.pdf

Ltd, R. P. (n.d.). *Buy a Raspberry Pi Pico*. Raspberry Pi. https://www.raspberrypi.com/products/raspberry-pi-pico/

Main, J. (2024). *How to use the BMP280 Barometric Pressure chip with the Arduino*. Best Microcontroller Projects. https://www.best-microcontroller-projects.com/bmp280.html

Maker Tutor. (2017, December 6). *Rotary Encoder Incremental Rotary Encoder How to use it with Arduino*. YouTube. https://www.youtube.com/watch?v=QE4IQlwOgiA

Mobley, D. (1997). *"Ejection Charge Calculations"*. ARS. https://www.arsabq.org/ejection.htm#:~:text=The%20ejection%20charge%20equation%20is%3A%20W%20%3D%20PV%2FRT,22.16%20%28ft-%20lbf%2Flbm%20R%29%20for%20FFFF%20black%20powder.

NAR. (2024). *Kevlar*. National Association of Rocketry. https://www.nar.org/educational-resources/model-rocket-building-techniques/kevlar/.

Norton, R. L. (2009). *Kinematics and dynamics of machinery*. McGraw Hill.

OVONIC Lipo Battery. (2024). Amazon.com. https://www.amazon.com/Ovonic-Battery-5200mAh-Connector-Vehicle/dp/B09CTSJHQJ/ref=sr_1_17

Performance Composites. (2009, July). *Mechanical Properties of Carbon Fibre Composite Materials*. Www.performance-Composites.com. https://www.performance-composites.com/carbonfibre/mechanicalproperties_2.asp

Pektas, Ayşenur. "(PDF) Effects of Different Fin Shapes on Apogee and Stability of Model Rockets." *Effects of Different Fin Shapes on Apogee and Stability of Model Rockets*, Sept. 2019, www.researchgate.net/publication/334631989_Effects_of_Different_Fin_Shapes_on_Apogee_and_Stability_of_Model_Rockets.

Philhower III, E. F. (2023, March 18). *Arduino-Pico*. GitHub. https://github.com/earlephilhower/arduino-pico

Pi, R. (2024). *Pico-series microcontrollers - raspberry pi documentation*. Raspberrypi.com. https://www.raspberrypi.com/documentation/microcontrollers/pico-series.html

Plastics, T. (n.d.). *Pultruded carbon rods & tubes*. TAP Plastics. Retrieved October 25, 2024, from https://www.tapplastics.com/image/pdf/Pultruded_Carbon_Rods__Tubes.pdf

Prusa Research. (n.d.). Prusa material table. Prusa Knowledge Base. https://help.prusa3d.com/materials

Ries, E. (2011). *The Lean Startup*. Portfolio Penguin.

Sensortec, B. (2013). *BMP180 Digital pressure sensor*. https://cdn-shop.adafruit.com/datasheets/BST-BMP180-DS000-09.pdf

Shojaie-bahaabad, M., Bozorg, M., Najafizadeh, M., & Cavaliere, P. (2024). Ultra high temperature ceramic coatings in thermal protection systems (TPS). Ceramics International, 50(7), Part A. https://www.sciencedirect.com/science/article/pii/S0272884223043080

STM32H7 - Arm Cortex-M7 and Cortex-M4 MCUs (480 MHz) - STMicroelectronics. (n.d.). Www.st.com. https://www.st.com/en/microcontrollers-microprocessors/stm32h7-series.html

The Engineering ToolBox. (2003). *Young's Modulus - Tensile and Yield Strength for common Materials*. Engineeringtoolbox.com; Engineering Toolbox. https://www.engineeringtoolbox.com/young-modulus-d_417.html

Turito. (2024, May 26). *Analog Vs Digital Signals - Advantages and Disadvantages*. Turito Blog. https://www.turito.com/blog/general/analog-vs-digital-signals-advantages-and-disadvantages

Singh, S., & Gupta, P. K. (2022). Investigations on tensile and flexural properties of wheat straw fibre reinforced polymer composite. *Advances in Materials and Processing Technologies*, 1–19. https://doi.org/10.1080/2374068x.2022.2153523

Zhang, D., & Huang, Y. (2021). Influence of surface roughness and bondline thickness on the bonding performance of epoxy adhesive joints on mild steel substrates. *Progress in Organic Coatings*, *153*, 106135. https://doi.org/10.1016/j.porgcoat.2021.106135

Appendix

A.1. Safety Statement

The goal of the safety statement is to ensure each team member commits themselves to following all rules and regulations set in place by the NAR, the FAA, the TRA, the Range Officer, the CSO, and team mentors. Those who do not comply with the safety statement will be removed from the team as decided by the team lead, CSO, and the team mentor. All team members of Cedarville Student Launch will sign and agree to the following safety statement:

As a Cedarville Student Launch team member, I commit to following all safety standards. I will comply with national, state, local, and school regulations in all team-related activities. I will adhere to the safety guidelines and documents concerning the rocket's design, construction, testing, launching, and transportation. This includes those provided by the university, team, and national organizations such as the NAR, FAA, and TRA. Before performing any tasks, I will make sure I understand all relevant safety materials. I will comply with range safety inspections whether subscale or full scale before it is launched. I understand that the RSO has the final say on all rocket safety issues and can deny the rocket launch due to safety reasons. I understand that by following the safety rules and regulations the team will be rewarded for participation in the exhilarating pursuit of high-power rocketry.

I acknowledge that failure to comply with this statement may result in my expulsion from the team. My signature confirms I have read and agree to abide by the statements provided.

Name Grant Parker

Signature Grant Parker Date 10/11/2024

Name Daniel Hogsed

Signature Date 10/11/24

Name Jesse DePalmo

Signature Date 10/11/24

Name Joseph Copeland

Signature Date 10-11-24

Name Jack Kealen
Signature Jack Kealen Date 10/11/2024

Name Jackson Maley
Signature Jackson Maley Date 10/11/24

Name Seth K. Mitchell
Signature Seth K. Mitchell Date Oct 11, 2024

Name Elisa Schmitt
Signature Date 10/11/2024

Name Rebekah Porter
Signature Rebekah Porter Date 10/15/2024

Name Kenneth Lee III
Signature Kenneth Lee III Date 10/11/24

Name Arkin Solomon
Signature Date 11 Oct 2024

A.2. Safety Violation Form

Department of Safety

Cedarville Student Launch Safety Violation Form

***PRINT** CLEARLY IN BLACK OR BLUE INK.*

IDENTIFICATION INFORMATION

FULL LAST NAME

FULL FIRST NAME

DATE OF HAZARD

SEVERITY OF HAZARD

☐ LOW RISK ☐ MEDIUM RISK ☐ HIGH RISK

LOCATION OF HAZARD

DESCRIPTION OF HAZARD

MITIGATION DESCRIPTION

APROVAL FROM CSO

☐ APPROVED

☐ NOT APPROVED

CSO INITIALS

LEGAL NOTICE

BY SIGNING THIS FORM, I VERIFY THAT THE INFORMATION PROVIDED IS ACCURATE, AND THAT ALL SAFETY MEASURES AND MITIGATION ACTIONS HAVE BEEN TAKEN ACCORDING TO CEDARVILLE STUDENT LAUNCH AND LEGAL SAFETY REGULATIONS. I ACKNOWLEDGE MY RESPONSIBILITY TO ENSURE ONGOING SAFETY IN THIS AREA.

I ACKNOWLEDGE THAT FAILURE TO COMPLY WITH CSL'S SAFETY REGULATIONS MAY RESULT IN MY EXPULSION FROM THE TEAM. MY SIGNATURE CONFIRMS I HAVE READ AND AGREE TO ABIDE TO CSL'S SAFETY REGULATIONS FROM THIS POINT FORTH.

SIGNATURE

DATE

A.3. MATLAB Code for Kinematic Analysis

```
clc; clear; close all;

% Velocity ratio analysis
%% Crank Slider 1
   % Where offset is 2, coupler is 3.86, and inputlink is 2
% scale is 1 in = 1 in/s
a=3.86;
b=2;
Va = ones(1,13);
wa = Va ./ a;
Vb = [1.65 1.31 1.08 .92 .80 .71 .64 .58 .53 .49 .45 .41 .37];
wb = Vb./b;
FlapAngle = 0:5:60;

mv = wb./wa; % angular velocity ratio

Range = max(mv)-min(mv)

hold on
figure(1);
subplot(3,1,1);
ylim([0 3.5])
plot(FlapAngle,mv);

%% Crank slider 2
   %Where offset is 1.5, coupler is 3.86, and inputlink is 2.06
a2=3.86;
b2=2.06;
Va2 = Va;
wa2 = wa;
Vb2 = [1.14 .99 .88 .79 .73 .68 .64 .61 .60 .59 .59 .61 .65];
wb2 = Vb2./b2;
mv2 = wb2./wa2; % velocity ratio
% figure(2)
% plot(FlapAngle,mv2);
Range2 = max(mv2)-min(mv2)

%% Crank slider 3
   %Where offset is 1, coupler is 3.86, and inputlink is 2.24
a3=3.86;
b3=2.24;
Va3 = Va;
wa3 = wa;
```

```
Vb3 = [.98 .88 .81 .76 .72 .70 .68 .68 .69 .72 .76 .83 .92];
wb3 = Vb3./b3;
mv3 = wb3./wa3; % velocity ratio
% figure(3)
% plot(FlapAngle,mv3);
Range3 = max(mv3)-min(mv3)


%% Crank slider 4
   %Where offset is .25, coupler is 3.86, and inputlink is 2.5
a4=3.86;
b4=2.5;
Va4 = Va;
wa4 = wa;
Vb4 = [.90 .84 .79 .76 .74 .74 .75 .77 .8 .86 .94 1.04 1.18];
wb4 = Vb4./b4;
mv4 = wb4./wa4; % velocity ratio
% figure(4)
% plot(FlapAngle,mv4);
Range4 = max(mv4)-min(mv4)

% The velocity ratio is most constant at offset=1 inch
% therefore the team will take it from there, and then iterate
% the lengths of the other linkages.

%% Crank slider 5
   %Where offset is 1, coupler is 4, and inputlink is 2.24
a5=4;
b5=2.24;
Va5 = Va;
wa5 = wa;
Vb5 = [1.00 .91 .83 .78 .74 .72 .71 .71 .72 .74 .78 .84 .93];
wb5 = Vb5./b5;
mv5 = wb5./wa5; % velocity ratio
% figure(5)
% plot(FlapAngle,mv5);
Range5 = max(mv5)-min(mv5)

%% Crank slider 6
% For this experiment, I made it more to scale where there is an offset of
% screw distance from the middle of the rocket and on the flap
   %Where offset is .63, coupler is 3.86, and inputlink is 2.24
a6=3.86;
b6=2.24;
Va6 = Va;
```

```
wa6 = wa;
Vb6 = [1.11 1 .91 .85 .81 .78 .76 .76 .76 .78 .82 .87 .94];
wb6 = Vb6./b6;
mv6= wb6./wa6; % velocity ratio
% figure(6)
subplot(3,1,2);
plot(FlapAngle,mv6);
ylim([0 3.5])
Range6 = max(mv6)-min(mv6)
minTransAngle6 = 46

%% Crank slider 7
% For this experiment, I want to determine what the input length does with
% the motion.
   %Where offset is 1, coupler is 3.86, and inputlink is 3.16
a7=3.86;
b7=2.24;
Va7 = Va;
wa7 = wa;
Vb7 = [1.24 1.05 .91 .81 .74 .68 .63 .6 .57 .55 .55 .55 .58];
wb7 = Vb7./b7;
mv7= wb7./wa7; % velocity ratio
% figure(7)
% plot(FlapAngle,mv7);
Range7 = max(mv7)-min(mv7)


% The Chosen Design will be crank slider 6

%% Crank slider Final
% For this experiment, I made it more to scale where there is an offset of
% screw distance from the middle of the rocket and on the flap
   %Where offset is .63, coupler is 3.86, and inputlink is 2.24
aF=3.86;
bF=2.19;
VaF = ones(1,13);
waF = VaF ./ aF;
VbF = [1.23 1.09 .99 .91 .85 .82 .79 .78 .78 .79 .81 .85 .91];
wbF = VbF./bF;
mvF= wbF./waF; % velocity ratio
FlapAngle = 0:5:60;
% figure(101)
subplot(3,1,3);
plot(FlapAngle,mvF);
ylim([0 3.5])
```

```
Range6 = max(mvF)-min(mvF)
% minTransAngleF =


clc; clear; close all;

% Velocity ratio analysis
%% Crank Slider Data
% Predefined parameters
FlapAngle = 0:5:60; % Flap angles

% Crank slider 1
a=3.86;
b=2;
Va = ones(1,13);
wa = Va ./ a; %Is this right?
Vb = [1.65 1.31 1.08 .92 .80 .71 .64 .58 .53 .49 .45 .41 .37];
wb = Vb./b;
FlapAngle = 0:5:60;

mv1 = wb./wa; % velocity ratio

% Crank slider 6
a6=3.86;
b6=2.24;
Va6 = Va;
wa6 = wa;
Vb6 = [1.11 1 .91 .85 .81 .78 .76 .76 .76 .78 .82 .87 .94];
wb6 = Vb6./b6;
mv6= wb6./wa6; % velocity ratio

% Crank slider final
a7=3.86;
b7=2.24;
Va7 = Va;
wa7 = wa;
Vb7 = [1.24 1.05 .91 .81 .74 .68 .63 .6 .57 .55 .55 .55 .58];
wb7 = Vb7./b7;
mv7= wb7./wa7; % velocity ratio

% Create the figure and subplots
figure('Units', 'Inches', 'Position', [1, 1, 6, 8]); % Adjusted size for better fitting
hold on

% Subplot 1
```

```
subplot(3, 1, 1);
plot(FlapAngle, mv1, 'b-o', 'LineWidth', 2, 'MarkerSize', 6);
title('Crank Slider 1 Velocity Ratio', 'FontSize', 12);
xlabel('Flap Angle (degrees)', 'FontSize', 10);
ylabel('Velocity Ratio', 'FontSize', 10);
ylim([0 3.5]);
grid on;
set(gca, 'FontSize', 10);

% Subplot 2
subplot(3, 1, 2);
plot(FlapAngle, mv6, 'r-s', 'LineWidth', 2, 'MarkerSize', 6);
title('Crank Slider 6 Velocity Ratio', 'FontSize', 12);
xlabel('Flap Angle (degrees)', 'FontSize', 10);
ylabel('Velocity Ratio', 'FontSize', 10);
ylim([0 3.5]);
grid on;
set(gca, 'FontSize', 10);

% Subplot 3
subplot(3, 1, 3);
plot(FlapAngle, mv7, 'g-d', 'LineWidth', 2, 'MarkerSize', 6);
title('Final Crank Slider Velocity Ratio', 'FontSize', 12);
xlabel('Flap Angle (degrees)', 'FontSize', 10);
ylabel('Velocity Ratio', 'FontSize', 10);
ylim([0 3.5]);
grid on;
set(gca, 'FontSize', 10);

% Adjust layout
sgtitle('Velocity Ratios for Crank Slider Designs', 'FontSize', 14);
```

A.4. MATLAB Code for Mission Performance Predictions

```
% Corrected Eqs to find the descent time and drift
% Assumption that acceleration continues to occur at state 1
% While function will be used to iterate until a v1 is found
% V1 must give correct (or approximate) s1 (= apogee - main deployment)
% Will give descent time of rocket from state 0 > 1 and initial condition for state 2
% 'ode45' used to find the velocity, time, and position of state 2
% Total descent item adjusted so fall position is equal to apogee
% Total descent time is used to find the drift of the rocket at wind speeds
% Units are ft, s, lbm, lbf unless stated otherwise

% Constants
mainDeploy = 550;
apogee = 4100;
in.g = 32.174;
density = 0.0020809;
t0 = 0;

% Rocket Constants
% Including total weight and individual masses for each section
% Sections from aft > middle > forward
% oz > lbf (/16) oz > lbm (/(16*in.g))
m_drogue = 1/(in.g*16); m_main = 15.3/(in.g*16); m_parachutes = m_drogue + m_main;
in.m = [8.641/in.g 2.848/in.g 9.257/in.g];
in.W = in.g*(sum(in.m, "all") + m_parachutes);

% Drogue Parachute Values
Dd = 1;
Ad = (pi/4)*Dd^2;
C_Dd = 0.97;
in.B1 = (1/2)*density*C_Dd*Ad

% Main Parachute Values
D_om = 7;
D_im = 14.78/12;
Am = (pi/4)*(D_om^2 - D_im^2);
C_Dm = 2.2;
in.B2 = (1/2)*density*(C_Dd*Ad + C_Dm*Am)

A1 = 1E-3;
err1 = 10;

% Inital Position Conditions
in.x0 = 0;
```

```
in.x1 = apogee - mainDeploy;
s1 = 0;
in.x2 = apogee;

% Finding Drogue Interval (0 -> 1)
while abs(err1) > 0.01
    V1 = sqrt((in.W - (in.W/in.g)*A1)/(in.B1));

    in.t1 = (in.W/in.g)/sqrt(in.B1*in.W)*atanh(V1*sqrt(in.B1/in.W));

    s0 = s1;

    s1 = (in.W/in.g)*(-log(in.W - in.B1*V1^2)/(2*in.B1));

    err0 = in.x1 - s0;
    err1 = in.x1 - s1;

    if abs(err1) < abs(err0)
        A1 = A1 + 1E-9;
    elseif abs(err1) > abs(err0)
        A1 = A1 - 1E-7;
    else
        A1 = A1 + 1E-6;
    end

    if A1 <= 0
        A1 = 1E-13;
    end
end

V1t = sqrt(in.W/in.B1)
Vt = sqrt(in.W/in.B2)

% Initial Velocity Conditions
in.x0dot = 0;
in.x1dot = V1;
in.x2dot = Vt;

% Initial Acceleration Conditions
in.x0dot2 = in.g;
in.x1dot2 = A1;
in.x2dot2 = 0;

% Time Values
t0 = t0;
```

```
t1 = in.t1;
t2 = 66.2;
tstep = 0.01;
tspan = t1:tstep:t2;
t_tot = t2

% Solving second differential equation (1 -> 2)
[T2,X2] = ode45(@(t,x) odefcn2(t,x,in), tspan, [in.x1, in.x1dot]);

% Kinetic Energy at Touchdown
KE = (1/2)*in.m*Vt^2
KE_fail = (1/2)*[in.m(1) (in.m(2)+in.m(3))]*V1t^2

% Drift Due to wind (MPH -> ft/s)
V_wind = 5:5:20;
Drift = t2*V_wind*(5280/3600)

% Function to solve second-order differential (1 -> 2)
function dxdt = odefcn2(t,x,in)
   dxdt = [x(2); in.x0dot2 - (in.B2*in.g/in.W)*(x(2).^2)];
end
```

A.5. Example Mass Estimate Reporting Form Entry

AIRBRAKES SUBSYSTEM

Mass Estimates [g]

	Conceptual	PDR	CDR	Final
Main Body Mass	454	239		
Flap Mass	364	187.2		
Electronics Mass	312	531		
Bulk Mass	25	120		

Note: Include battery and motor mass in the elctronics mass section. Also, I am including the mass of the flaps separately since they are a specific part of focused analysis where their material and geometry may change often.

Important Mass Estimate Terminology Reference

Main Body Mass -- The mass of the main component of your subsystem . For most cases, this is probably a large 3D printed or machined assembly. If you have electronics, their mass is accounted for separately. Bolts and heatset inserts can be included in this category.

Electronics Mass -- The mass of any circuitboards or microcontrollers. This is just the mass of the major electronic components. For example, this would include switches, altimeters, LEDs, etc, but not the wires connecting them

Bulk Mass -- The mass of indiscrete quantities in your subsystem that is difficult to account for until the "Final" stage. Examples of bulk mass items would include paint, primer, epoxy, fiberglass fabric, wires, hot glue, and zip ties. These are items that you may be able to get an accurate mass estimate for eventually, but will remain sort of fluid and nebulous until the final iteration.

% Mass Growth Allowance

	Conceptual	PDR	CDR	Final
Main Body MGA	25%	18%	7%	4%
Flap MGA	20%	18%	10%	3%
Electronics MGA	15%	13%	5%	1%

Note: Conisdering the above statement on the flaps, think about other materials you may need to switch to down the road when estimating MGA.

Important Mass Growth Allowance Reference

Do your research on reasonable estimates for these categories will weigh and use your intuition and good judgement to evaluate how much they will expand (%MGA) for each project milestone.

Ask yourself for each project milestone, "Looking forward to some design/material changes *I know I may have to make*, about how much heavier would my subsystem get **considering the materials I may need or the components I may need to add?**" Express that amount as a percent of growth that you would want design buffer on. Remember to be mindful of the trickle-down impact your subsystem has on the rest of the design. How much heavier should the Chief Engineer assume your subsystem could be when he is refining the design at a particular project milestone?

As the design matures and you become more confident of the type and arrangement of components you need, your MGA for the subsequent milestones should dramatically decrease. Eventually the Final project milestone mass growth estimates should be known within 2-3%.

A.6. PDR Basic Mass and Predicted Mass Figures

Design Maturity	Basic Mass Figures [g]															
	Nose Cone			Payload			Avionics			Airbrakes			Thrust Structure			
	Cone	Camera System	Airframe	Body	Electronics	Recovery Devices	Body	Electronics	Shock Cord Mount	Frame	Brakes	Electronics	Fin Retention	Fins	Tail Cone	Motor
Conceptual	2038.0	16.0	2957.0	226.0	531.4	1510.0	557.6	364.1	160.0	454.0	364.0	312.0	638.1	306.9	653.1	2183.6
PDR	2039.0	16.0	3231.6	208.0	395.5	1186.3	331.7	450.0	160.0	359.0	187.2	531.0	291.2	306.9	180.5	2183.6
CDR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Final	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Maximum Predicted Mass Figures [g]															
Conceptual	3057.0	19.2	3844.1	293.8	637.7	2265.0	669.1	400.5	208.0	567.5	436.8	358.8	765.7	399.0	783.7	2620.3
PDR	2446.8	17.6	3716.3	239.2	427.1	1423.6	381.5	481.5	184.0	421.8	220.9	600.0	314.5	352.9	198.6	2620.3
CDR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Final	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0