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NOTRE DAME ROCKETRY TEAM PRELIMINARY DESIGN REVIEW

NASA STUDENT LAUNCH 2021

PLANETARY LANDING SYSTEM AND APOGEE CONTROL SYSTEM

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1 Summary of Report

1.1 Team Summary

Team Name:	Notre Dame Rocketry Team
Location:	365 Fitzpatrick Hall of Engineering Notre Dame, IN 46556
Mentor:	Dave Brunsting (NAR/TAR Level 2) e: dacsmem@gmail.com p: (269)838-4275
NAR/TRA Section:	NAR: 85879 L2/TRA: 12369 L2
Total Hours Logged:	1334 hours

1.2 Launch Vehicle Summary

A brief summary of the launch vehicle design is provided in Table 1.

Table 1: Summary of the Launch Vehicle Design

Feature	Value
Target altitude (ft.)	5,300
Selected Motor	Cesaroni L1395 Blue Streak
Length (in.)	134.0
Outer diameter (in.)	6.17
Mass (oz)	756.12

The recovery system will slow the vehicle to a safe kinetic energy through a modified dual-deployment system. At apogee, a drogue parachute will deploy. At 600 ft AGL, the main parachute will deploy, and at 550 ft AGL the nose will jettison, meaning the vehicle will land in two untethered pieces. Both of these pieces will meet the descent time, drift radius, and kinetic energy requirements set in NASA requirements [3.3](#), [3.10](#), and [3.11](#).

1.3 Payload Summary

The Planetary Landing System (PLS) will jettison from the launch vehicle at 550 ft AGL, land safely within the allowable drift radius, self orient to vertical within a tolerance of 5 degrees, and take a 360 degree photo of the launch site (NASA Req. [4.3](#); NASA Req. [4.4](#)).

2 Changes Made Since Proposal

2.1 Vehicle Criteria

The overall length of the launch vehicle design has been altered from 112 in. to 134 in. due to various component selections following trade studies, and in order to provide ample space for sub-systems. Refined component designs also yielded a different range of predicted apogees from flight simulations in different weather conditions, ranging from 5714 ft. to 5340 ft., which lead to the target apogee selection of 5300 ft. to ensure that the ACS will intervene in all predicted flights. Additionally, the fin design was modified from swept trapezoidal to elliptical following an inspection of the performance of different planform shapes.

2.2 Payload Criteria

The maximum weight allotment for the Planetary Landing System (PLS) has decreased from 90 oz to 80 oz. The mechanical design consisting of a horizontal cylinder with hinged loaded half-cylinder doors was found to be outperformed by a design with four vertical body-tube sections as spring loaded legs that deploy to leave a bare main frame with the electronics to self-level. The PLS deployment was set to 525 ft and the deployment was designed to consist of a free-moving bulkhead attached to the nose-cone which will secure and aid in the deployment of the PLS parachute.

2.3 Project Plan

The team is currently still on schedule. The only major change to the schedule is that the PLS team will not start prototype construction until next semester. This change was made to allow for more refinement of the design and analysis prior to building the system. The subscale vehicle construction has progressed ahead of the schedule listed in the Proposal. This will ensure the team is prepared for the launch scheduled for November 13th. The team has also received additional funds from sponsor Collins Aerospace and fundraising efforts. These additions can be seen in the budget in Table 101.

3 Technical Design: Launch Vehicle

3.1 Launch Vehicle Design Overview

The design of the launch vehicle was determined through a series of trade studies outlined in the following sections. First, several options for the system-level vehicle design were identified by considering the requirements imposed by the mission and sub-systems, and were comparatively evaluated to yield the vehicle design outlined in the OpenRocket model shown in Figure 1 below, accompanied by relevant parameters provided in Table 2 and Table 3.

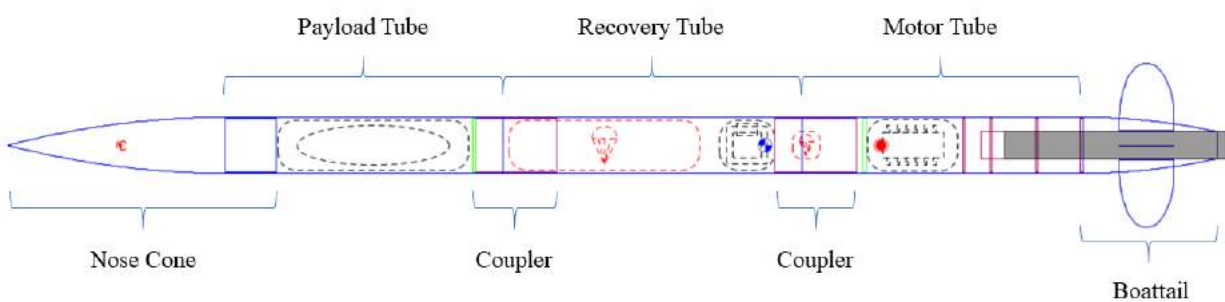


Figure 1: Outline of the Launch Vehicle design

Table 2: Launch Vehicle section outline

Section	Integrated Components	Length (in)	Structural Weight (oz)
Nose Cone	CRAS-S, parachute	29.0 (including shoulder)	28.2
Payload Tube	Payload, bulkhead, coupler	30.5	69.21
Recovery Tube	Main Parachute, CRAS-M, Drogue Parachute, coupler	33.0	65.95
Motor Tube	ACS, Bulkhead (x2), Motor, Motor Retention	31.0	102.94
Boattail	Fins	14.75	39.0

Table 3: Launch Vehicle overall measurements

Parameter	Value
CG Location (in)	83.121
CP Location (in)	96.224
Static Stability Margin (calibers)	2.12
Overall Length (in)	134
Outer diameter (in)	6.17

The design specifications of the individual launch vehicle sections and components, including material, weight, and dimensions, is provided in the following sections where trade studies were used to select the components. An outline of the materials used for each structural component in the launch vehicle is provided in Table 4.

Table 4: Summary of vehicle materials

Component	Material
Nose Cone	Fiberglass
Airframe Tubes	Kevlar and Filament-Fiberglass
Boattail	Fiberglass
Fins	Fiberglass
Motor Mount Tube	Phenolic
Centering Rings	Fiberglass
Payload Bulkhead	Fiberglass

3.1.1 Mission Statement and Success Criteria

The mission of the launch vehicle is to safely and reliably deliver the payload to an altitude of 5300 ft at apogee and return to ground level with all components structurally intact such that the vehicle may fly again on the same day (NASA Req. 2.4). To achieve a safe and reliable flight, the vehicle must be statically stable from launch rail clearance to apogee, and must not be overstable, as both under and over stability may result in an erratic flight path. A suitable static stability margin range was deemed to be 2.0 - 3.0 calibers, to prevent excessive weather cocking from altering the flight angle and significantly lowering the apogee altitude (NASA Req. 2.14) (NDRT Req. VD.8).

Given that the vehicle is required to launch in a range of rail cant angles from 5 - 10 degrees, and in winds from 0-20 mph, the final design will inevitably yield a sizable range of predicted apogee altitudes. For this reason, the launch vehicle will be designed to overshoot

the target apogee altitude in all but the worst-case launch scenarios, so that the ACS is ensured to intervene and control the projected apogee altitude, yielding a much smaller margin of uncertainty.

The other primary criterion for a safe and reliable flight is the assurance that all structural components must be able to withstand the expected loads induced during flight. In order to demonstrate that this requirement is satisfied, the components involved in each critical loading scenario throughout flight are subject to stress analysis, and must demonstrate a safety factor of at least 2.0 (NDRT Req. VF.4).

In addition to these success criteria, two design decisions have been fixed from the outset to prevent an excess of variability from creating uncertainty in the performance of the design. Namely, the primary body tube size was fixed to an inner diameter of 6 in. to provide the sub-systems with a known amount of design space (NDRT Req. VD.6). The specific choice of 6 in. was based on its widespread commercial availability and its historical success in previous years. Similarly, the motor was fixed to the Cesaroni L-1395 Blue Streak motor. The team owns three of these motors due to launch cancelations in the 2019-2020 season, and the motor has historically proven to be reliable. Fixing these two decisions at the beginning of the design process allowed the team to more easily design the launch vehicle without too many unknowns.

3.1.2 Updated Mass Estimate

In order to track the mass and mass growth of the vehicle, and its subsystems and payloads throughout the design process, a mass properties control method patterned after AIAA Standard S-120A, "Mass Properties Control for Space Systems." In accordance with this standard, three types of mass are tracked for all major subsystems of the vehicle: Basic, Predicted, and Allowable. Basic mass is an estimate of the mass of a component or system based on the current design, either with basic layouts and experience, calculations from CAD or measurements from existing hardware. From this basic mass, a Mass Growth Allowance (MGA) is added to find the Predicted Mass. The percentage of MGA added is dependent on the type of component and maturity of the system. The allowable mass of a system is set during preliminary design, and is the maximum mass a system can be allowed to reach. The difference between the Allowable and the Predicted is the Estimated Mass Margin, and the difference between the Allowable and Basic masses is the Total Margin. The overall mass statement for the vehicle can be seen in Table 5. A typical total margin target for the preliminary stage of a design is between 13% and 30%. The vehicle as it currently stands is well within this range, with a total margin of 21.6%. Table 6 shows the component-level mass statement of the launch vehicle airframe, with basic and predicted masses, as well as

the MGA percentage applied to each component.

Table 5: Overall Preliminary Mass Statement with Mass Margins

Component	Basic Mass (oz)	Predicted Mass (oz)	Allowable Mass (oz)	Total Margin (%)
Airframe	464.22	484.76	525	13.09
Main Recovery	127.13	134.39	160	25.85
Nosecone Recovery	15.54	16.61	20	28.72
ACS	62.55	72.77	80	27.90
Payload	57.44	64.20	80	39.28
Total	711.34	756.12	865	21.61

Table 6: Launch Vehicle Preliminary Mass Statement with Mass Margins

Component	Basic Estimate (oz)	MGA %	Predicted Mass (oz)
Nose cone	28.2	12	31.584
Payload Fairing	53	4	55.12
Payload Fairing Coupler	8.65	4	8.996
Payload Fairing Bulkhead	7.56	4	7.8624
Recovery Tube	57.3	4	59.592
Recovery Tube Coupler	8.65	4	8.996
Fin Can Body Tube	53.9	4	56.056
Motor Mount	14.9	4	15.496
Centering Rings (x3)	17	4	17.68
ACS Bulkhead	16.5	10	18.15
Fins (x4)	16.9	4	17.576
Fin Can Bulkhead	7.56	4	7.8624
Boattail	22.1	12	24.752
CTI L1395 Motor	152	2	155.04
Total	464.22	-	484.7628

3.2 System Alternative Designs

The overall layout of the vehicle design was primarily informed by the requirements of its internal systems: namely the recovery, apogee control system (ACS), and planetary landing system (PLS). Because the design of the recovery system involves the deployment of two separate parachutes, and the payload must jettison from the vehicle in flight (NASA req. 4.3.1), a minimum of 2 separation points is required. Next, the placement of the ACS is constrained along the vehicle length, as any protuberance must be located aft of the center of pressure (NASA req 2.15). Next, to ensure that the primary recovery avionics are able to control at least 2 points of separation, it was deemed most sensible to place them in the middle section of the vehicle, leaving the upper section for the PLS.

Given the above constraints, three system designs were evaluated, particularly with regard to number of separation points and single vs. variable diameter body tubes. Each of these options is outlined in Table 7 below, with the selected configuration highlighted in blue.

Table 7: Vehicle system alternative designs and associated report sections

Section	Separation points	Locations of Energetics	Transition? (Y/N)
3.2.1	3	Payload bay (x1) recovery section (x2)	N
3.2.2	3	Payload bay (x1), recovery section (x2)	Y
3.2.3	2	Recovery section (x2)	N

As indicated, the current leading vehicle configuration consists of a single diameter airframe with four sections (3 separation points). In order to evaluate the rationale behind this decision, each of the alternatives is outlined in more detail below.

3.2.1 Single-diameter 4 Sections

The first system design evaluated, and the one that was ultimately chosen, consists of a single diameter from the nose cone shoulder to the boattail shoulder, and includes three points of separation, resulting in four independent sections (NASA req. 2.5). An OpenRocket diagram of this design, including energetics locations (indicated in red) and separation points (indicated with arrows), is shown in Figure 2.

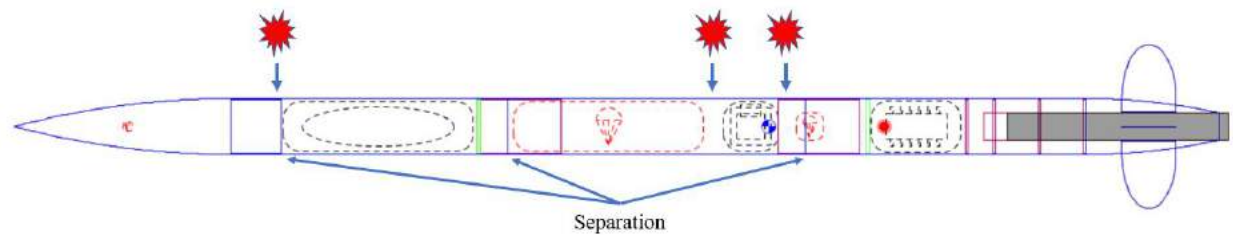


Figure 2: Single-diameter 4 Sections design showing locations of separation points and energetics

The rationale behind using three points of separation is to provide an unobstructed separation point for each of the deploying components: the payload, main parachute, and drogue parachute. Fewer separation points, as seen in Section 3.2.3, would require the payload to jettison from the same point as the main parachute. The main drawback of the chosen design is that it requires a more complex recovery solution, with separate avionics hardware for ejecting the nose cone in addition to those for ejecting the two parachutes. This design also requires the nose cone to be recovered separately using its own parachute, because tethering it to the body tube would obstruct the payload from jettisoning.

3.2.2 Variable-diameter 4 Sections

The second design evaluated was identical to the first design in terms of energetics and separation points, but utilizes a larger payload bay diameter and a transition to the smaller aft diameter for the remaining vehicle length. An OpenRocket diagram of this design, indicating the black powder energetics locations and separation points, is shown in Figure 3.

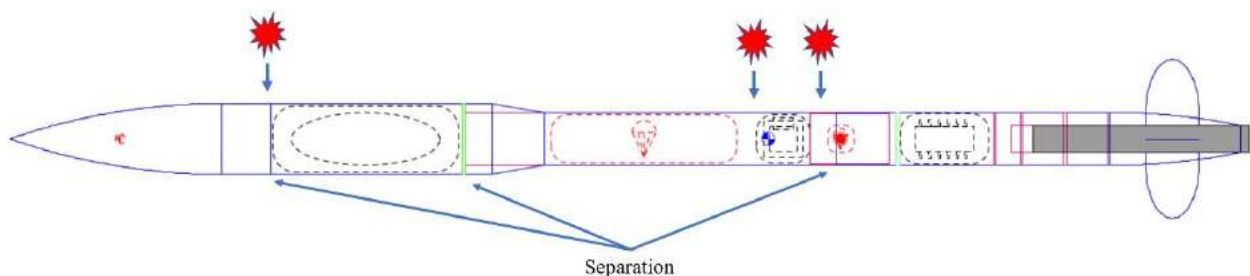


Figure 3: Variable-diameter 4 Sections design showing locations of separation points and energetics

The main advantage of the variable-diameter design is that it provides additional space for the payload. In previous years, this was deemed a necessary accommodation based on the payload requirements. However, this year's mission allows for a more compact payload design, so both configurations were deemed feasible. The downsides of a variable-diameter

design include higher skin-friction drag, added structural weight, and increased construction complexity. With these considerations in mind, the variable-diameter design was not selected in the interest of vehicle performance.

3.2.3 Single-diameter 3 Sections

The third and final alternative system design considered uses only two points of separation, and consequently two black powder energetics locations. An OpenRocket diagram of this design, indicating the black powder energetics locations and separation points, is shown in Figure 4.

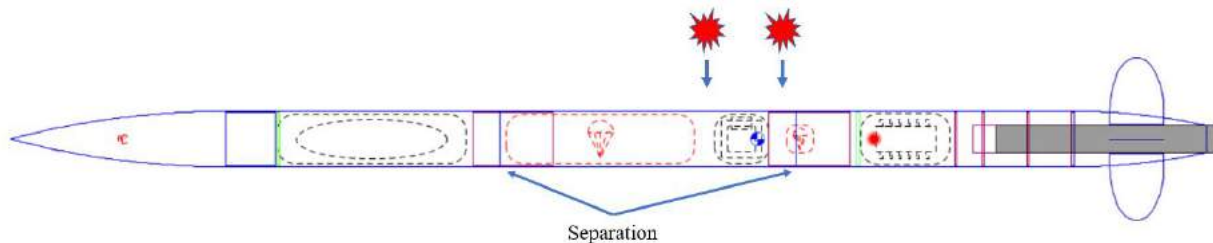


Figure 4: Single-diameter 3 Sections design showing locations of separation points and energetics

Using only two separation points reduces the complexity of the recovery system, as separation can be controlled by avionics at a single location. This design also eliminates the need to recover any components separately, as the three sections can remain tethered throughout descent.

The biggest disadvantage of this design is that it requires the payload to jettison from the same separation point as the main parachute, resulting in several potential hazards, including one or both components failing to deploy due to blocking, or tangling between the payload and the parachute chords or the tether. In the interest of minimizing the probability of mission failure, this design was not selected, and the additional complexity in the 3-separation-point design was justified. Ultimately, the chosen system design was the single-diameter, 4 section vehicle outlined in Section 3.2.1.

3.3 Component Level Design

With the overall launch vehicle design determined, each of the individual airframe components were chosen, starting with the body tubes, followed by the nose cone, boattail, and fins. The method for choosing these components involved first defining a set of

requirements and identifying a set of candidate options. Next, the design drivers and relative importance of each parameter were used to perform a trade study, ultimately yielding the chosen design.

3.3.1 Airframe Tubes and Couplers

In order to identify candidate options for the airframe tubes, the following set of requirements were applied. As discussed in Section 3.1.1, all possible airframe tubes must have a 6 in. inner diameter (NDRT Req VD.6). Additionally, signals must be able to pass through the chosen material to ensure that recovery electronics are able to transmit the vehicle location upon landing. Based on these requirements, several commercially available airframe tube materials were identified for comparison in a trade study, based on the criteria outlined below. The option of custom building composite airframe tubes was not considered feasible with the workshop resources available to the team.

The most important aspect of the airframe tube is the yield strength, as this is critical for the vehicle to be structurally sound. The weight of the airframe tube was taken into account as well, because a heavy airframe results in a lower apogee altitude and lower off-rail velocity. However, upon performance inspection, it was found that light airframe tubes tended to yield higher apogee altitudes than desired, given the chosen motor, so the material weight was given low importance in the trade study. Cost was also considered in the study. Taking these design drivers into consideration, the yield strength, weight, and cost were normalized and given weights of 50%, 20%, and 30%, respectively. In each trade study, *Norm* represents the given values after being normalized by all other criteria values, and *W.N.V.* represents the normalized value multiplied by the criteria weight.

The trade study of airframe tubes is shown in Tables 8 and 9, with the selected material highlighted in yellow.

Table 8: Airframe Tubes material trade study (1/2)

Airframe Tubes		Fiberglass (G11)		Plastic (PVC)		Pre-Glassed Phenolic	
Criteria	Weight	Value	WNV	Value	WNV	Value	WNV
Weight (oz/in)	20%	2.016	0.0641	4.884	0.0136	1.083	0.0805
Yield Strength (psi)	50%	30000	0.1607	8000	0.0429	12000	0.0643
Cost (\$)	30%	195.43	0.0208	40.76	0.0863	203.95	0.0172
Total WNV		0.246		0.143		0.162	

Table 9: Airframe Tubes material trade study (2/2)

Airframe Tubes		(Kraft) Phenolic		Kevlar and Filament Fiberglass		Blue Tube	
Criteria	Weight	Value	WNV	Value	WNV	Value	WNV
Weight (oz/in)	20%	0.769	0.0861	1.729	0.0692	0.867	0.0843
Yield Strength (psi)	50%	8270	0.0443	30000	0.1607	5076	0.0272
Cost (\$)	30%	48.95	0.0828	169.99	0.0316	50.15	0.0823
Total WNV		0.213		0.261		0.194	

From the results of the trade study, the kevlar and filament-fiberglass airframe tubes, supplied by Giant Leap Rocketry, were chosen. These tubes have an inner diameter of 6 in. and length of 48 in. The kevlar tubes will be lightweight yet strong at a reasonable price point, and were therefore chosen for the airframe of the launch vehicle. Giant Leap Rocketry supplies couplers of the same material. With this tube selection in hand, the length of each airframe tube section was determined by considering the space required for the integration of sub-systems within each section, and the purchased tubes shall be cut to those lengths accordingly. A summary of the airframe tube sections and their dimensional parameters is provided in Table 10 and a CAD drawing of the assembly is provided in Figure 5.

Table 10: Dimensional parameters of airframe tube sections

Section	Outer Diameter (in.)	Inner Diameter (in.)	Length (in.)	Weight (oz)
Payload Tube	6.17	6.00	30.5	53.0
Recovery Tube	6.17	6.00	33.0	57.3
Motor Tube	6.17	6.00	31.0	53.9
Couplers	6.00	5.775	9.0	8.65

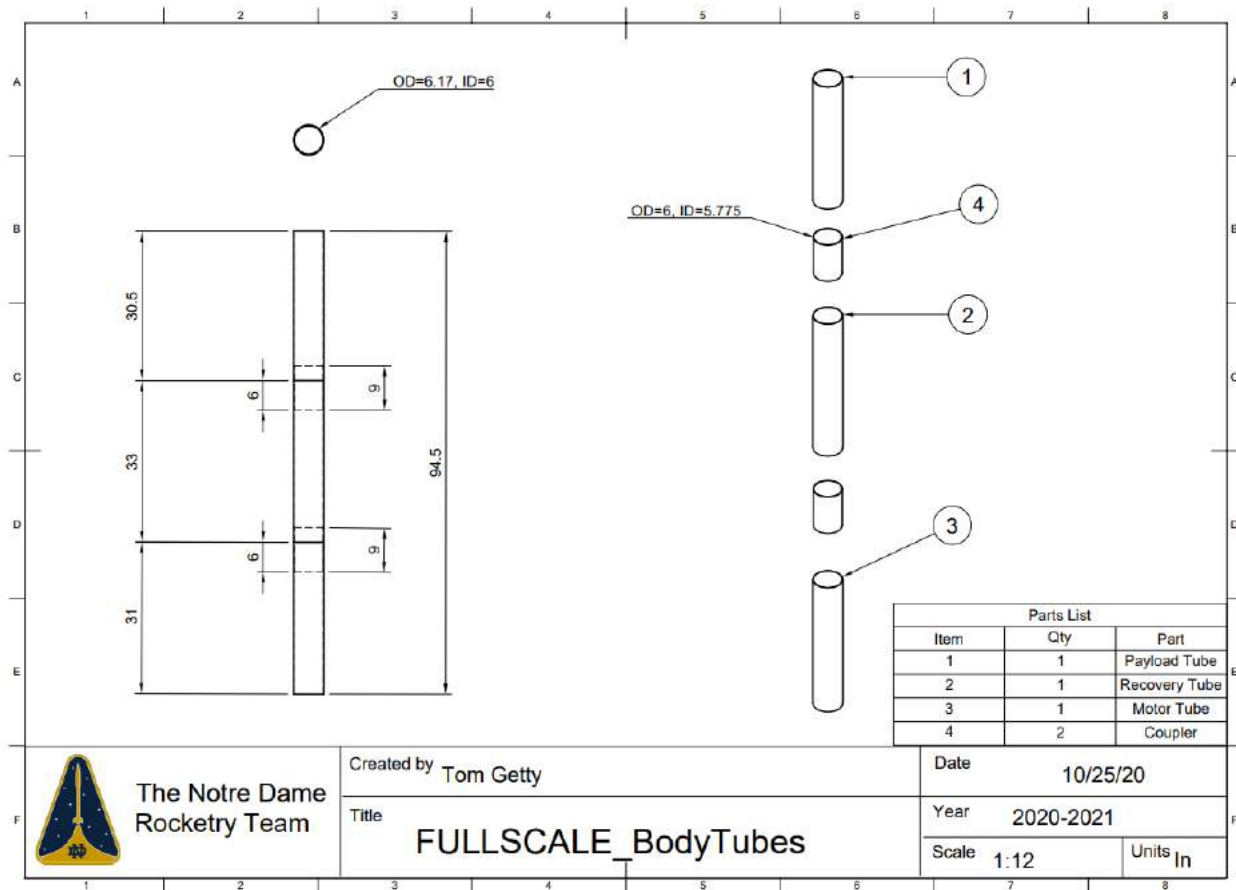


Figure 5: CAD drawing of airframe tube assembly

3.3.2 Nose Cone

The only design requirement for the nose cone was that it must have an outer shoulder diameter of 6 in. The primary design drivers in selecting the nose cone for this year’s launch vehicle were drag and weight minimization. Secondary drivers included cost minimization and internal volume maximization in order to provide additional space for payload recovery.

Three nose cones that fit the design specifications above were identified and compared in a trade study. The first was a custom 3D printed nose cone, the second was the fiberglass FNC-6.0 from Coast Rocketry, and the third was the Fiberglass SKU:FWNC60-VK-BLA-MT Von Karmen from MadCaw Rocketry. The trade study evaluated each of these nose cones on their drag, weight, cost, and internal volume.

The team 3D printed a nose cone for the 2019-2020 Launch Vehicle, and its parameters yielded approximate values which were used in Table ???. To characterize the coefficient of drag, each nose cone was modeled in OpenRocket, and a qualitative score was generated based on the impact on apogee altitude. To calculate the internal volume of each nose cone,

a MATLAB program was written to estimate the internal volume using Equation 1.

$$V = \frac{2\pi d^2 h}{15} \quad (1)$$

Where V is the internal volume of the nose cone (in^3), d is the diameter of the base of the nose cone (in), and h is the height of the nose cone (in). The results of the trade study performed are shown in Table ?? below.

Table 11: Nose Cone Selection Trade Study

Nose Cone		3D Printed		FNC-6.0		FWNC Von Karmen	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V
Drag	0.4	1	0.18	1.5	0.13	2	0.09
Weight (oz.)	0.4	69.7	0.10	28	0.19	88	0.06
Cost (USD)	0.1	800	0.01	127.5	0.07	149.9	0.07
Internal Volume (in^3)	0.1	500	0.04	361.9	0.03	520.2	0.04
Total WNV		0.33		0.42		0.26	

The trade study revealed that the best nose cone option is the FNC-6.0 from Coast Rocketry. It fulfills the 6 in. outer shoulder diameter requirement, and has the most optimal combination of low drag, low weight, low cost, and high internal volume. A summary of the important parameters of the chosen nose cone is provided in Table 12, and a CAD drawing with dimensions is shown in Figure 12.

Table 12: Parameters of the selected nose cone

Feature	FNC-6.0 Nose Cone
Exposed length (in.)	24.0
Shoulder length (in.)	5.0
Shape parameter	Ogive
Weight (oz)	28.0
Material	Fiberglass

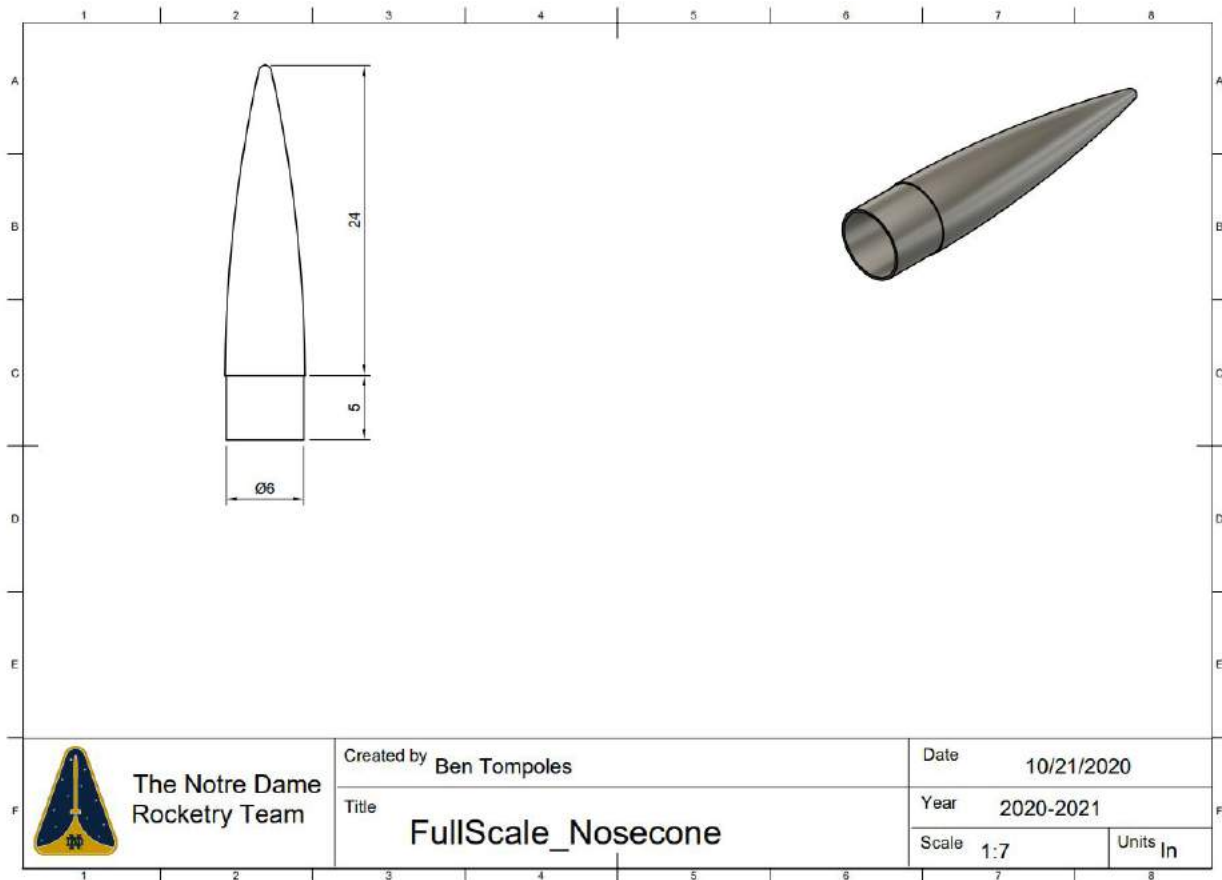


Figure 6: CAD drawing of selected nose cone

3.3.3 Boattail

A boattail will be implemented at the aft end of the launch vehicle airframe in order to provide a smooth transition from the outer diameter of 6.17 in. to the motor diameter of 3.00 in. A boattail is beneficial in that it reduces the pressure drag on the launch vehicle by providing a smaller diameter at the aft end, yielding a smaller low-pressure wake. The only downside of using a boattail is the added cost, as it does not weigh more than the corresponding length of airframe tube that would otherwise take its place. The exact benefit afforded by the addition of the boattail in terms of pressure drag reduction will be further analyzed using CFD, and the results will be demonstrated in CDR. A commercially available boattail that matches the dimensions of the chosen airframe tubes was identified as the BTL-6.0-3.0 manufactured by Public Missiles Ltd., and was selected for this design. The manufacturer also offers the ability to cut slots in the boattail, which will be implemented to interface the fins with the motor mount tube inside of the boattail. An overview of the relevant features for the selected boattail is provided in Table 13 and a CAD drawing with dimensions is shown in Figure 7.

Table 13: Boattail parameters

Feature	BTL-6.0-3.0
Exposed length (in.)	14.75
Forward diameter (in.)	6.00
Aft diameter (in.)	3.00
Shape parameter	Ogive
Weight (oz)	22.0

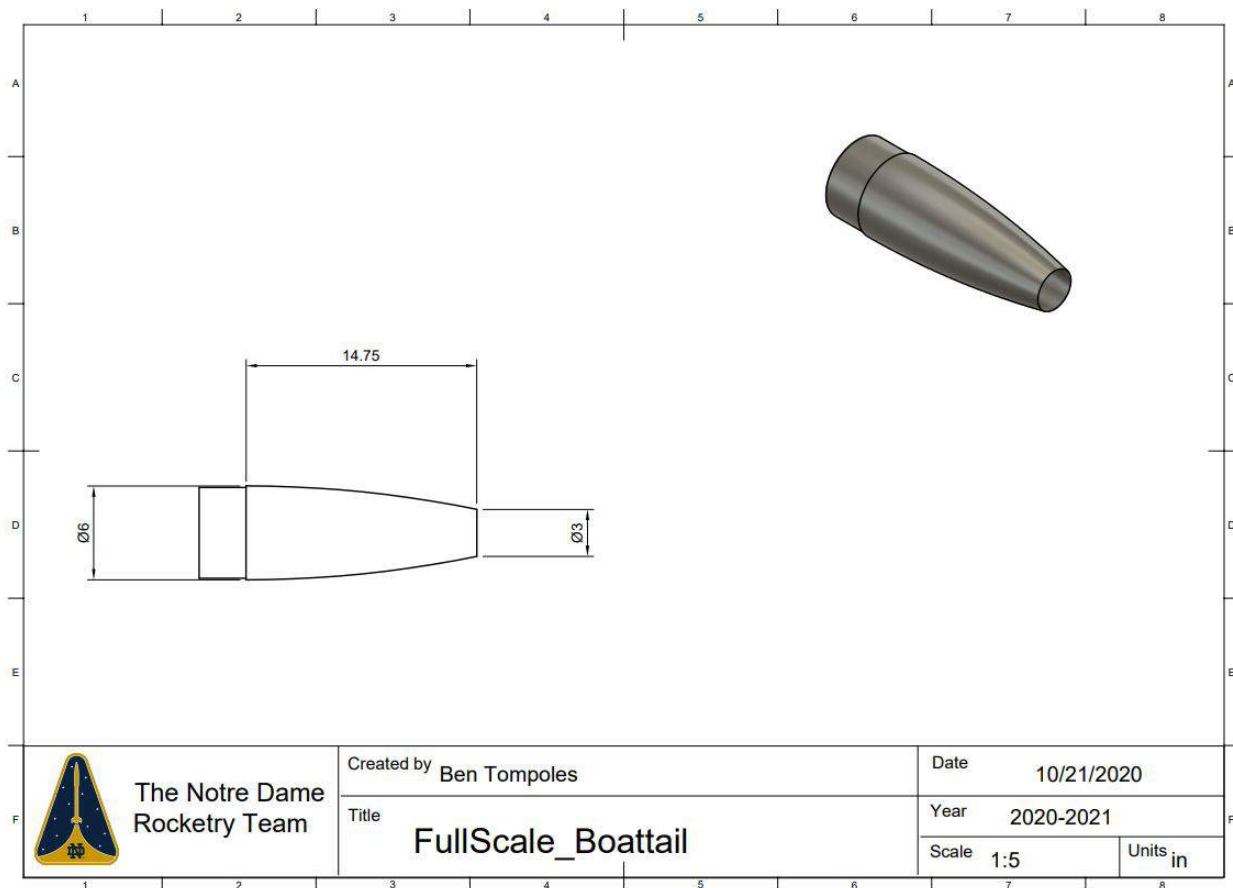


Figure 7: CAD drawing of selected boattail

3.3.4 Fins

Given the accessibility of CNC Techno Routers in the workshop spaces available to NDRT, it was determined that any fin planform shape will be feasible. In particular, the following shapes were considered: elliptical, swept trapezoidal, straight trapezoidal, rectangular, and delta rectangular.

When analyzing these shapes, the primary goal was to minimize drag. Given that the

drag is inversely related to the apogee altitude, simulations were run using OpenRocket to find the fin shape that yielded the highest apogee, while comparing fins of equivalent area, thickness, and airfoil cross-section, and holding all other variables constant. The results of the OpenRocket Simulations can be seen in Table 14.

Table 14: Simulated apogee results for different fin planforms

Fin Planform Shape	Simulated Apogee (ft)
Elliptical	5473
6" Swept Trapezoidal	5465
Straight trapezoidal	5450
Rectangular	5380
Delta Trapezoidal	5456

From the above study, it was found that the elliptical fins yielded the highest apogee altitude, and therefore the lowest drag. This is expected, as elliptical fins produce the lowest induced drag when the launch vehicle is at a non-zero angle of attack. For this reason, elliptical fins will be used on this year's launch vehicle.

With the planform shape finalized, the dimensions of the fins needed to be defined to produce a static stability margin between 2.0 and 3.0 calibers throughout flight. Additionally, the team chose to use four fins so that each fin is equally offset from each ACS drag tab surface, as well as for ease of construction.

When determining the dimensions of the fins, the following requirements were defined. First, the launch vehicle must never have a stability under 2.0 cal (NASA Req. 2.14. Second, the launch vehicle must never have stability that goes over 3.0 cal. to prevent excessive weather cocking (NDRT Req. VD.8.) Third, it was decided to make the root chord 6 inches, to match the airframe diameter and ensure a strong base. Given these requirements, the only variable dimension was height. In order to determine the best fin height for elliptical fins to meet these requirements, the OpenRocket optimization tool was utilized. In the simulation, wind speeds were set to 0.0 mph, and the launch angle was set to 5.0°. The optimization was run to seek the minimum value of 2.0 cal in flight, which yielded a fin height of 5.959 in. After analyzing the simulation, nowhere on the expected trajectory does the stability drop below 2.0 cal, and nowhere on the flight path does it ever surpass 3.0 cal. Therefore, the fin height of 5.959 in. satisfies all requirements.

It should also be noted that a fillet of radius 0.25 inches will be added at the interface between the fin and motor tube using epoxy. The fin cross section will be approximated as an airfoil shape with a rounded leading edge and a sharp trailing edge in order to further

reduce drag. A fin thickness of 0.125 in. was selected because of its commercial availability in raw materials. Finally, a tab length of 1.5 in. will be included at the bottom of each fin to allow them to interface with the interior motor mount tube. A CAD drawing of the fin design with dimensions is provided in Figure 8.

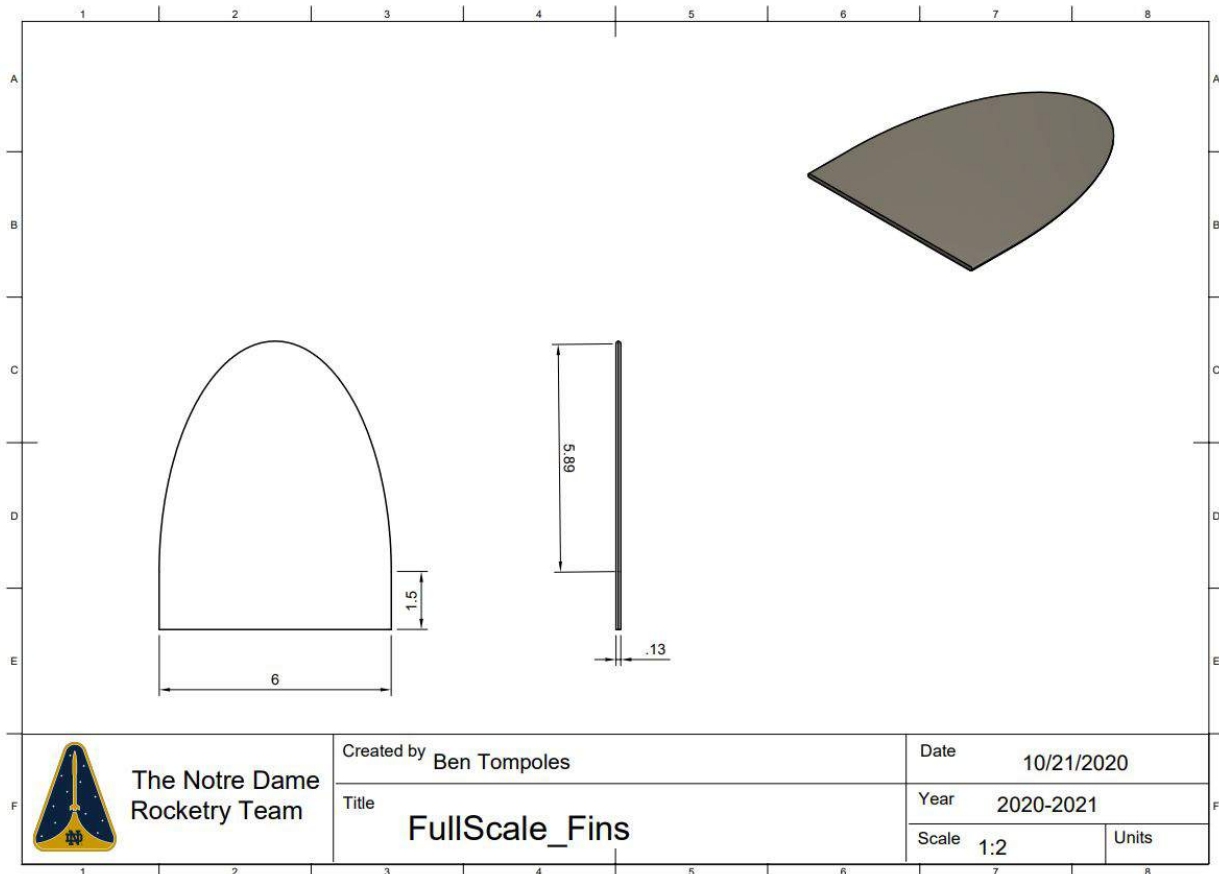


Figure 8: CAD drawing of selected fin design

Next, a trade study was conducted in order to select a material for the fins. The only requirement was that the material must be machinable using a CNC Techno Router. From this, several candidate material options were identified based on historically common model rocket fin materials. The primary design drivers for the material selection were low weight and high strength, in order to ensure a minimal decrease in apogee altitude as well as structural integrity. Each of these criteria were given a weight of 40% in the trade study, while the secondary design driver of cost was given a 20% weight. The fin material selection trade study is provided with the normalized weighted scores for each material in Tables 15 and 16.

Table 15: Fin Material Trade Study (1/2)

Material		Birch Plywood		Fiberglass		Birch Plywood	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V
Weight (oz/in ³)	0.4	0.37	0.12	1.01	0.04	0.61	0.09
Yield Strength (psi)	0.4	5000	0.03	30000	0.18	10000	0.06
Cost (USD/ft ²)	0.2	0.96	0.07	10.69	0.02	9.34	0.03
Total		0.22		0.24		0.18	

Table 16: Fin Material Trade Study (2/2)

Material		PVC		Water Resistant Nylon	
Criteria	Weight	Value	W.N.V	Value	W.N.V
Weight (oz/in ³)	0.4	0.8	0.07	0.66	0.08
Yield Strength (psi)	0.4	8000	0.05	15000	0.09
Cost (USD/ft ²)	0.2	4.66	0.05	14.09	0.01
Total WNV		0.17		0.18	

The result of the trade study yielded fiberglass as the best material choice for the fins. With the fins fully designed, a summary of their parameters is provided in Table 17.

Table 17: Parameters of the selected fin design

Feature	Specification
Planform shape	Elliptical
Number of fins	4
Material	Fiberglass
Weight (oz)	16.9
Root chord (in.)	6.0
Height (in.)	5.959
Tab length (in.)	1.5
Thickness (in.)	0.125
Cross section	Airfoil

3.3.5 Motor Selection

NDRT has three Cesaroni L1395 Blue Streak motors that were purchased last season and went unused due to the COVID-19 outbreak. By using the Cesaroni L1395 motor this year,

the team will save approximately \$300 dollars per motor. Additionally, the motors that have already been purchased are a sunk cost, and to minimize total cost, it is most advantageous to use the Cesaroni L1395 motors from last year. This motor has also proven to be reliable through several demonstration flights in the past two years, which gives it an additional benefit over other possible motors. This financial incentive was the primary driver in the decision to use the Cesaroni L1395 this year. The motor specifications are provided in Table 18, and the motor thrust curve is shown in Figure 9.

Table 18: Cesaroni L1395 Blue Streak Motor Specifications

Feature	Value
Diameter (in.)	2.95
Length (in.)	24.25
Loaded Weight (oz)	151.31
Propellant Weight (oz)	82.77
Burnout Weight (oz)	64.68
Impulse (N-s)	4895.40
Average Thrust (N)	1395.70
Maximum Thrust (N)	1779.90
Burn time (s)	3.51
Cost (USD)	292.99

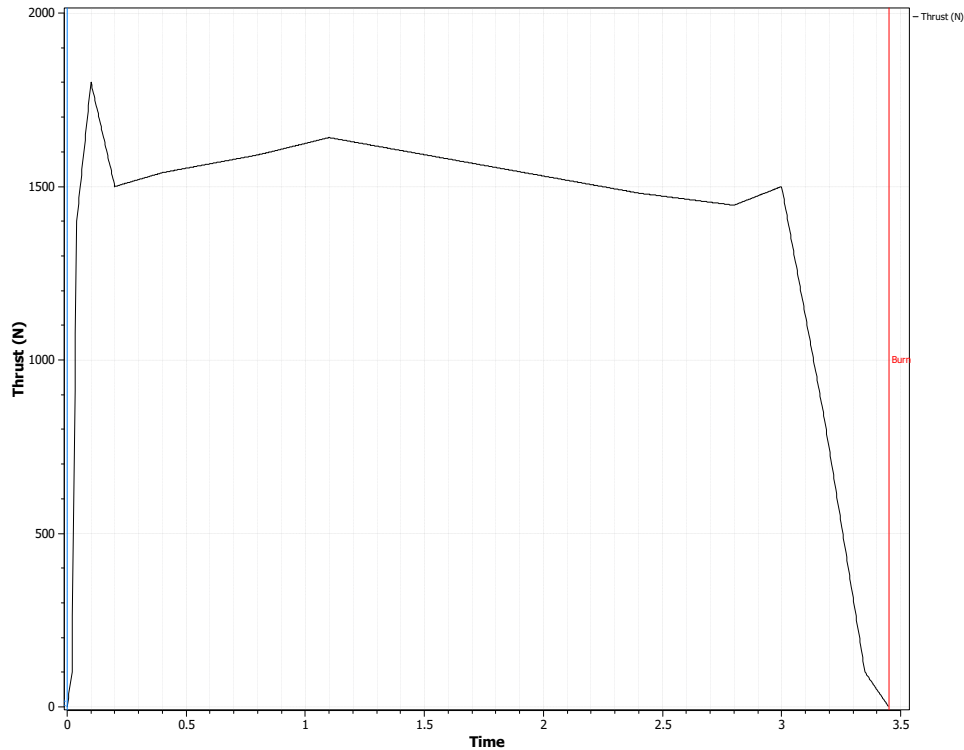


Figure 9: Cesaroni L1395 Blue Streak Motor Thrust Curve simulated using RockSim

3.3.6 Motor Retention

The motor retention system fixes the motor into the vehicle. It consists of the motor tube, the centering rings, and the retainer, centering the thrust force vector to the centerline of the vehicle, to ensure stability during ascent. The motor tube is a 3 in. diameter, 30 in. tube into which the motor will be inserted. The motor tube will be secured into the airframe using fiberglass centering rings that are 0.125 in. thick, as seen in Figure 10 below, that are attached to the airframe, that will center the motor along the axis of the vehicle. The tube will be fixed onto the centering rings using the heat resistant JB weld. Three centering rings will be attached towards the front of the motor mount, as the aft end of the mount is encased by a variable diameter boattail. For ease of manufacturing, it was desirable that the centering rings be equal, and thus must be attached fore of the variable diameter section of the boattail.

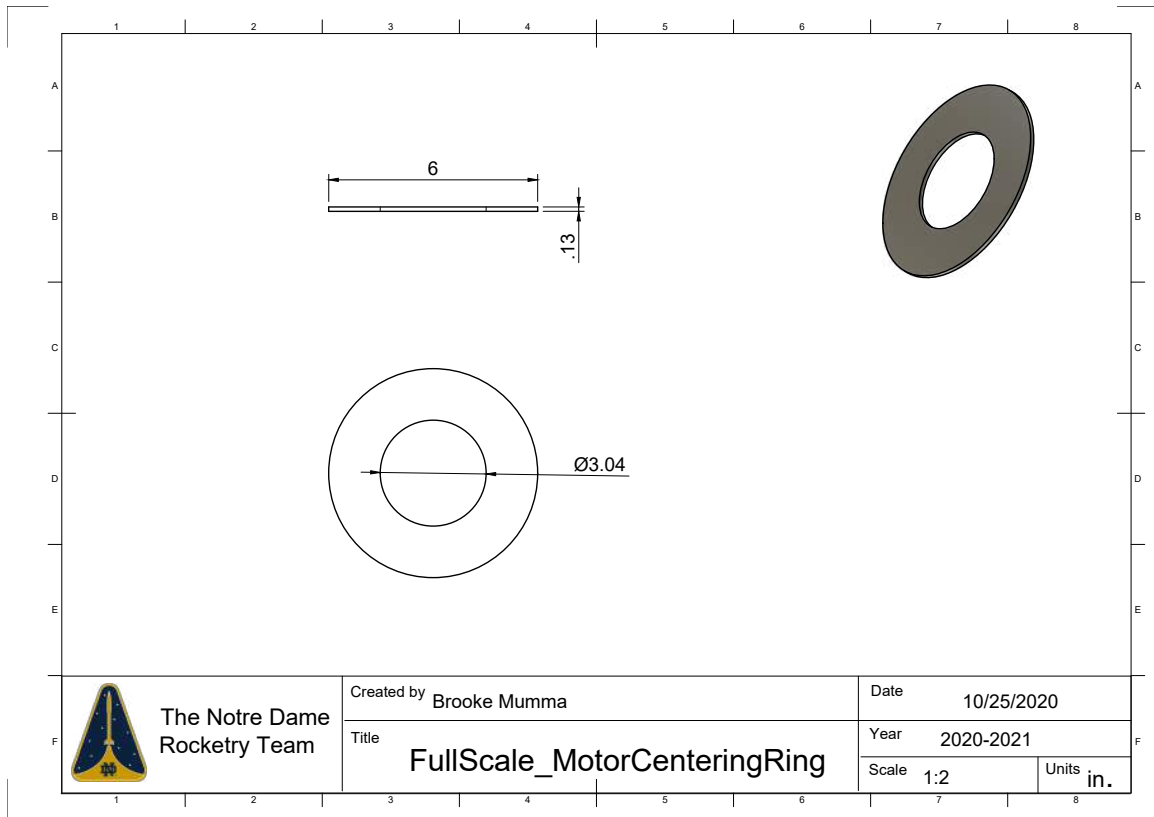


Figure 10: CAD drawing of the centering ring

The three centering rings will be equally spaced 5 in. from each other. The configuration of the motor tube with centering ring can be seen in Figure 11.

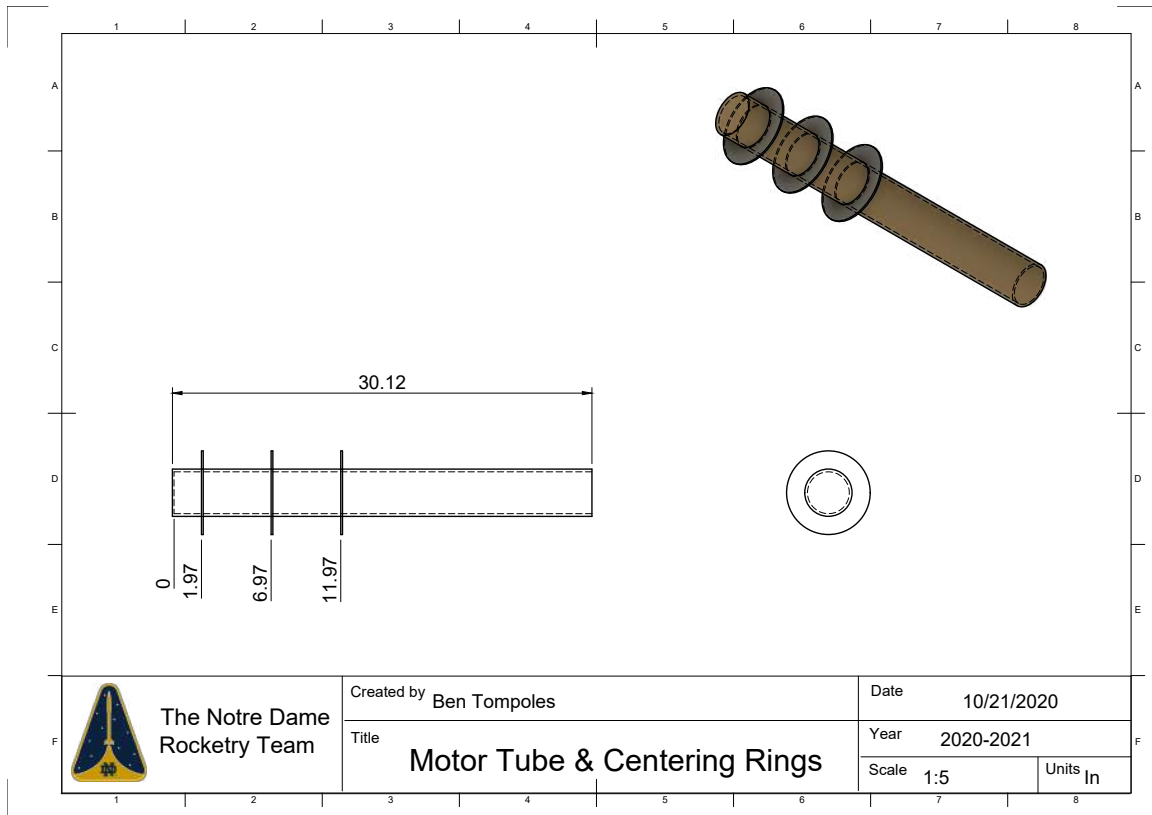


Figure 11: CAD drawing of the centering rings mounted on the motor tube

The motor will be secured into the motor tube using a motor retainer. The retainer base is epoxied to the end of the tube using JB Weld, and a threaded retainer cap is used to secure the motor within the motor mount system. In determining what material to use for the motor mount tube, four options were examined in the following trade study.

Table 19: Motor Mount Tube Material Trade Study

Material		Carbon Fiber		Phenolic		Fiberglass		Blue Tube	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V	Value	W.N.V
Yield Strength (psi)	0.1	467000	0.09	8270	0.002	30000	0.006	5076	0.001
Price (\$/in.)	0.35	0.53	0.03	3.33	0.18	1.78	0.09	3.19	0.17
Weight (g/ft.)	0.25	241.5	0.10	227.7	0.10	99.2	0.04	198.2	0.08
Heat Tolerance	0.3	5	0.1	3	0.06	4	0.08	3	0.06
Total WNV		0.32		0.33		0.22		0.31	

It was determined that phenolic is the best option for the motor mount. A high yield strength was desirable, but it was less valued in a motor tube than in the airframe due to being subject to less aerodynamic forces. A high heat tolerance is also desired as the motor tube will be in direct contact with the motor. While carbon fiber and fiberglass both present higher yield strength and heat tolerance, the lower price of phenolic makes it the most practical option.

3.4 Recovery Subsystem

3.4.1 System Overview

The recovery system will reliably reduce the kinetic energy of the launch vehicle by deploying parachutes at different altitudes (NASA Req 3.1). The launch vehicle will first be slowed by a drogue parachute, deployed by black powder charges at apogee, and then by the main parachute, which will also be deployed by black powder charges at 600 ft AGL (NASA Req 3.1.1). At 550 ft AGL, the nose cone will separate from the payload bay and deploy a small chute, allowing the payload to jettison. All parachutes will be protected from the ejection charges with deployment bags or fire-retardant blankets (RF.2), and they will be connected to the recovery bulkheads via shock cords, quicklinks, and eyebolts. The main and drogue parachutes will be deployed by the same altimeters, located in the Compact Removable Avionics System-Main, or the CRAS-M. As the nose cone will descend untethered, it will have its own independent avionics system, the Compact

Removable Avionics System-Secondary, or the CRAS-S. The black powder charges will be contained in PVC charge wells located on each of the CRAS-M and CRAS-S bulkheads. Both the CRAS-M and the CRAS-S will contain independently redundant Integrated Avionics Packages, or IAPs (NASA Req 3.4). These IAPs will be entirely separate from any payload circuitry (NASA Req 3.8) .

3.4.2 Mission Success Criteria

The success of the recovery system will be judged on the successful completion of the following tasks:

1. All vehicle components land with a kinetic energy of less than 75 ft-lb. (NASA Req 3.3)
2. All vehicle components land within a 2500 ft radius of the launchpad. (NASA Req 3.10)
3. All vehicle components land within 90s of reaching apogee. (NASA Req 3.11)
4. The recovery system will collect the official altitude readings from battery-powered altimeters, which will serve as proof of flight (NASA Req 3.4, NASA Req 2.3)

3.4.3 Deployment

Various ejection and deployment methods were considered for both the CRAS-M and CRAS-S, including the use of compressed CO₂ and the use of black powder. A mechanical system was also considered, but was deemed too unreliable and taken out of consideration. Between the compressed CO₂ and black powder, black powder was chosen because of its light weight, low complexity, and low cost as compared to a compressed CO₂. Both compressed CO₂ and black powder have a high reliability. Black powder ejection will be used to deploy all the parachutes in both the CRAS-M and the CRAS-S.

3.4.4 Parachute Design

In order to ensure that all vehicle components land with a kinetic energy of less than 75 ft-lb, three parachutes will be deployed; two of which will slow the launch vehicle to a safe landing velocity, and one of which will slow the nose cone and payload to a safe landing velocity. The specifications of these parachutes are discussed in more detail in the following sections.

3.4.4.1 Parachute Selection and Sizing

The parachutes were sized using the following equations:

$$V_t = \sqrt{\frac{2m_1g}{\rho C_d A}} \quad (2)$$

$$K.E. = \frac{1}{2}m_2V_t^2 \quad (3)$$

where V_t is terminal velocity, m_1 is the total mass of all tethered sections, g is the acceleration due to gravity, ρ is the density of air, C_d is the drag coefficient, A is the projected area of the parachute, $K.E.$ is the kinetic energy, and m_2 is the mass of the heaviest tethered section. Table 20 shows the different parachutes that were considered that meet the kinetic energy requirement.

Table 20: Main Parachute Parameters

Brand	Diameter (ft)	Shape	C_d	KE at Landing (ft-lb)	Cost
Rocketman	12	parabolic	0.97	70.07	\$155.00
Fruity Chutes	8	toroidal	2.2	69.51	\$348.15

Elliptical and flat chutes were also considered, but none commercially available slowed the vehicle to an appropriate kinetic energy on landing. Between the 12 ft Rocketman and the 8 ft Fruity Chutes, the Rocketman was chosen because of its lower cost as compared to the 8 ft Fruity Chutes.

Various drogue parachutes were considered to reduce the descent time and drift radius, including several parachutes that were already in inventory. Ultimately, a 2 ft Fruity Chutes elliptical parachute was chosen due to its ability to lower the descent time and drift radius to acceptable value (NASA Req 3.10; NASA Req 3.11) in even the most extreme launch day conditions. A 2 ft Fruity Chutes elliptical chute was also chosen for the nose parachute for the same reasons. Table 21 details the parameters for the selected parachutes.

Table 21: Selected Parachute Parameters

Parameter	Drogue	Main	Nose
C_d	1.5	0.97	1.5
Diameter (ft)	2	12	2
Descent Speed (ft/s)	89.45	18.04	20.60
Shape	elliptical	parabolic	elliptical
Brand	Fruity Chutes	Rocketman	Fruity Chutes

Table 22 shows the performance of the recovery system for both the main vehicle and for the jettisoned nose, including the kinetic energy at landing, descent time from apogee, and drift radius for the maximum expected wind speed.

Table 22: Parachute Performance

Parameter	Main Vehicle	Jettisoned Nose
KE at landing (ft-lb)	70.07	24.98
Descent Time (s)	84.83	78.20
Max Drift Radius (ft)	2489	2294

The performance for the recovery system will be discussed further in Section 3.6.

3.4.4.2 Parachute Protection

Various methods of parachute protection were considered, including wadding, baffles, pistons, fire-retardant blankets, and deployment bags. A description of each of these protective systems, as well as their relative strengths and weaknesses, are described in Table 23.

Table 23: Parachute Protection Design Alternatives

Method	Description	Strengths	Weaknesses
Wadding	Fire-retardant shield made of cellulose housing insulation stuffed between ejection charges and parachute system.	Very inexpensive	Not reusable, ineffective for large diameters, very messy
Ejection Charge Baffles	A coupler with wooden bulkheads cut to slow ejection gasses long enough to cool. Sometimes filled with steel wool to speed up cooling.	Reusable, inexpensive to make	Susceptible to clogging, takes up a lot of body tube length, hard to source commercially for large diameters
Pistons	A bulkhead floating between the parachute and the ejection gasses. Pushed by ejection gasses out of the body tube along with the parachute system.	Guides recovery system out of the body tube	Hard to source for large diameters, generally long compared to other methods.
Fire Retardant Blankets	Fire-retardant cloth used to wrap parachute system.	Protects shroud lines, recovery harness, and parachute. Low weight and very simple.	Large potential for user error.
Deployment Bags	Fire-retardant sleeve that contains and protects a parachute.	Guides parachute to open fully	Leaves shroud lines and recovery harness unprotected.

Recovery wadding was deemed ineffective because of its low effectiveness at larger diameters. While ejection charge baffles and pistons were considered effective at protecting the recovery harness and parachutes from ejection gasses and debris, their high weight, high cost, and large length proved them less desirable than fire-retardant blankets and

deployment bags. Piston and baffle systems are also difficult to source commercially for large diameter vehicles, meaning that more time would have to be allocated to create an in-house design. A combination of fire-retardant blankets and deployment bags were then selected for parachute protection because they offer a similar level of protection to baffles and pistons while remaining simple and cost-effective. Every parachute and recovery harness will be wrapped in a fire-retardant blanket. The main parachute will also be stowed in a deployment bag, which has the added benefit of helping the parachutes to open fully without tangling.

3.4.5 Component Design

The parachute deployment will be controlled from the Compact Removable Avionics Systems, which will also transmit the the in-flight loads to the airframe. The following subsections contain a detailed description of both the CRAS-M and the CRAS-S.

3.4.5.1 Compact Removable Avionics System- Main

The Compact Removable Avionics System- Main (CRAS-M) will contain the avionics system responsible for deploying the main and drogue parachutes. It will be located in the recovery tube, aft of the payload tube and fore of the fin can. Figure 12 shows the CRAS-M assembly.

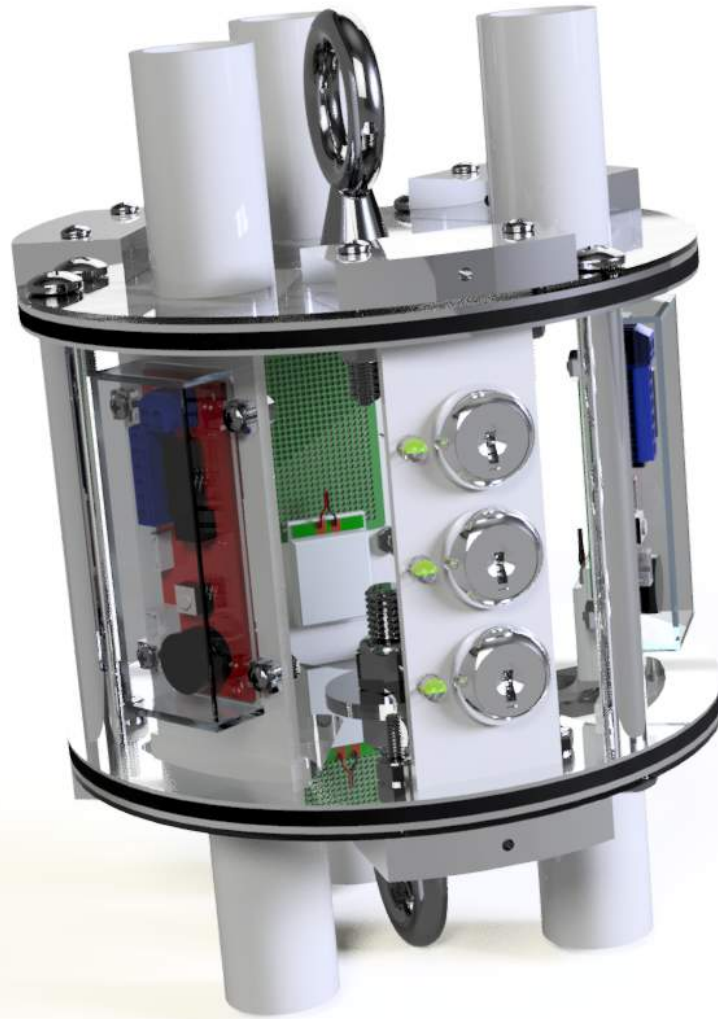


Figure 12: CRAS-M Assembly

The main structural components of the CRAS-M are the bulkheads, which transmit the in-flight loads to the airframe. Each bulkhead will house three PVC charge wells and an eyebolt to connect to the recovery harness. Three integrated avionics packages (IAPs) and a switchboard containing the switches for each IAP will be housed between these two bulkheads, which are connected by aluminum standoffs.

3.4.5.1.1 Bulkhead Material

The material for the CRAS-M bulkheads was selected based on its cost, strength to weight ratio, and ease of machining. Because lateral screws will be placed parallel to the face of each bulkhead to affix it to the airframe, the selected material must be commercially available in a thickness which allows for this weakening without sacrificing structural stability. Each considered material was evaluated based on these criteria in a trade study shown in Table

Table 24: CRAS-M Bulkhead Material Trade Study

CRAS-M Bulkhead Material		Aluminum		Wood		Polycarbonate	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V
Cost per Bulkhead	30%	\$20.00	.127	\$10.00	.173	\$37.00	0.047
Strength-to-Weight	55%	350000	.304	120000	.104	162791	.141
Ease of Machining	15%	3	.050	2	.033	4	.067
Total WNV		.481		0.311		0.255	

As demonstrated, aluminum was chosen for the load bearing portions of the CRAS-M bulkheads, mainly due to its high strength to weight ratio at reasonable cost. Figure 13 shows a drawing of the main load-bearing section of CRAS-M bulkhead. In order to further reduce weight without compromising structural stability, speed cuts will be performed to remove unnecessary material interior to the bulkhead. More detailed analysis on the bulkhead speed cuts will be performed for CDR.

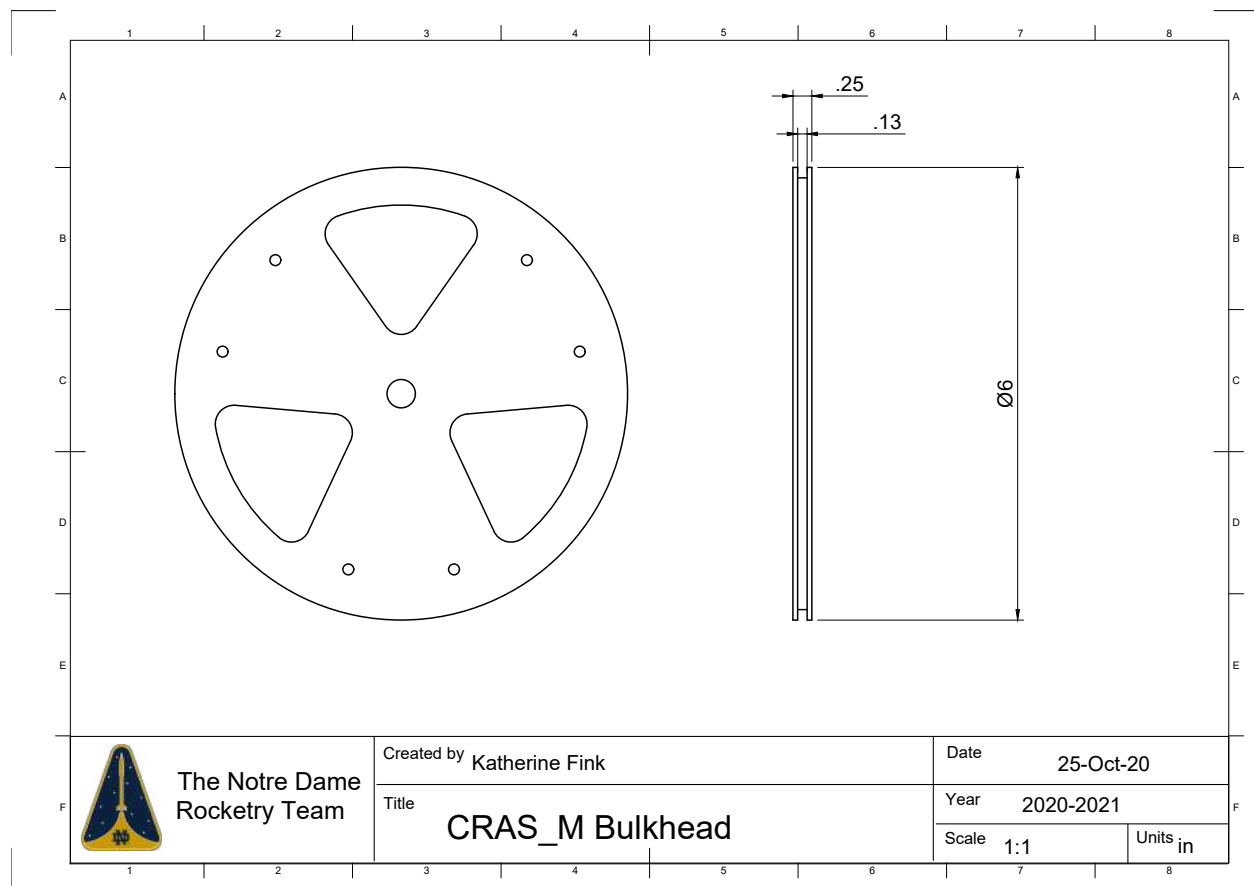


Figure 13: CRAS-M Bulkhead Drawing

3.4.5.1.2 Sealing and Integration

Though the speed cuts will reduce the bulkhead weight, they allow for ejection gasses to reach the avionics stowed within the CRAS-M. Various methods of sealing the bulkhead cuts were considered, including rubber, clay, and a thin polycarbonate sheet. In addition to sealing the bulkhead cuts, the space between the bulkhead outer diameter and the airframe inner diameter must also be sealed to prevent any ejection gasses from harming the avionics. A few methods for doing this were considered including using an o-ring, holding tight tolerances, and sealing with clay. From these options, the polycarbonate sheet and o-ring were chosen because of their reusability and reliability. The CRAS-M bulkhead will then be attached to the airframe through mounting blocks. These blocks will be screwed directly into the airframe and will bolt together the aluminum and polycarbonate discs. The fore and aft CRAS-M bulkheads will then be screwed into aluminum standoffs. Because each bulkhead will directly transmit the load to the airframe, the interior structures of the CRAS-M will not be load-bearing.

3.4.5.2 Compact Removable Avionics System- Secondary

The secondary compact removable avionics system (CRAS-S) contains the altimeters responsible for jettisoning the nose parachute and will be located in the nose of the vehicle. Figure 14 shows the CRAS-S assembly.

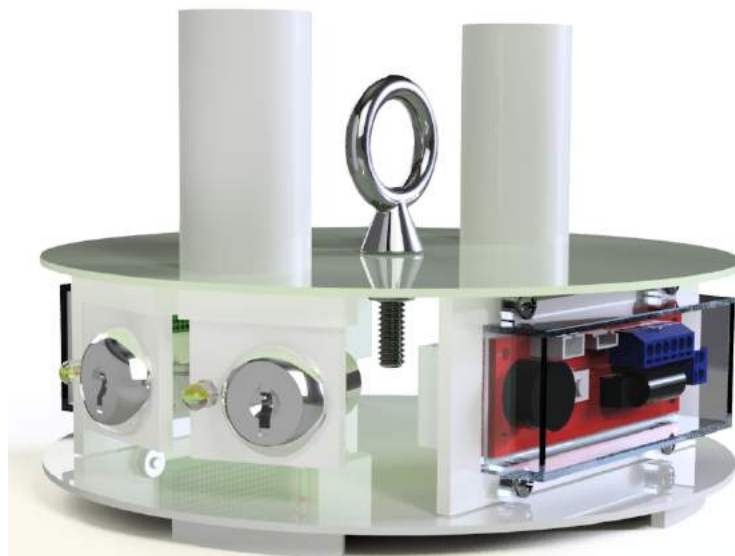


Figure 14: CRAS-S Assembly

3.4.5.2.1 Bulkhead Material

The main structural component of the CRAS-S is the bulkhead, which carries the load from the recovery harness. The trade study to determine the material for the bulkhead is shown in Table 25.

Table 25: CRAS-S Bulkhead Material Trade Study

CRAS-S Bulkhead Material		Aluminum		Fiberglass	
Criteria	Weight	Value	W.N.V	Value	W.N.V
Cost per Bulkhead	35%	13.860	.088	10.750	.104
Strength-to-Weight	45%	350000	.134	545455	.208
Ease of Machining	20%	2	.031	3	.358
Total WNV		.253		.358	
CRAS-S Bulkhead Material		Wood		Polycarbonate	
Criteria	Weight	Value	W.N.V	Value	W.N.V
Cost per Bulkhead	35%	22.92	.0043	8.67	.114
Strength-to-Weight	45%	120000	.046	162791	.062
Ease of Machining	20%	4	.062	4	.062
Total		.151		.238	

The material chosen for the CRAS-S bulkhead was fiberglass because of its high strength to weight and low cost. Fiberglass can also be much thinner than plastics or wood, making it ideal for the tight spacing in the nose cone.

3.4.5.2.2 Sealing and Integration

Unlike the CRAS-M, which will be fixed to the airframe, the CRAS-S will be "floating" above the PLS in the payload bay. A mounting ring bolted to the underside of the CRAS-S will be machined to fit in between the legs of the PLS, ensuring the CRAS-S is properly aligned with any static pressure or access ports. Because the CRAS-S will not be fixed, traditional sealing methods such as using clay or o-rings cannot be employed, as they would hinder the system's jettison upon nose cone ejection. The CRAS-S bulkhead will instead be machined to a tight tolerance in order to prevent the ejection gasses from harming the avionics.

3.4.5.2.3 Avionics

Both the CRAS-M and the CRAS-S will contain redundant Independent Avionics Packages, which contain the altimeter, battery, electronics board, electromagnetic

shielding, and mounting hardware. Each avionics component was selected using a trade study, the results of which are discussed below and shown in tables 26 through 28.

Altimeters: Three altimeters (1 Featherweight Raven3 and 2 Perfectflite Stratologger SL100s) were already in inventory and have been flight tested, which makes them desirable for the avionics systems. However, since the CRAS-M will contain 3 IAPs and the CRAS-S will contain 2 IAPs, a total of 5 altimeters is required for the recovery system, and two additional altimeters must be purchased. The altimeters for the recovery system must be capable of dual deploy flight and have the ability to download flight data. Five altimeters which meet the above requirements were then evaluated based on their cost, mass, and area, with low values for each of these parameters being desirable. The trade study is shown in Table 26.

Table 26: Altimeter Trade Study

		Featherweight Raven 4		EggTimer Classic	
Criteria	Weight	Value	W.N.V	Value	W.N.V
Cost (\$)	40%	160	0.02	35	0.11
Mass (g)	20%	6.6	0.07	20	0.02
Area (in ²)	40%	1.4	0.11	3.9	0.04
Total WNV		0.21	0.17		
Perfectfite StratologgerCF		Missileworks RRC3		Missileworks RRC2L	
Value	W.N.V	Value	W.N.V	Value	W.N.V
70	0.09	74	0.08	50	0.10
10.8	0.05	17	0.03	–	.02
1.68	0.11	3.626	0.05	2.23	0.09
0.25		0.16		0.21	

The StratologgerCF was chosen for the remaining two altimeters because of its compact size, mid-range price, and low mass. In addition to this, the StratologgerCF has a low power draw, allowing for a small battery.

Switches: The switches for the recovery system must be able to remain in the armed position, be easily accessible from the outside of the vehicle, clearly indicate switch state, and be reasonably cost effective. The various switches considered were evaluated on this criteria and compared in the trade study shown in Table 27.

Table 27: Switch Trade Study

		Keyed Rotary		Rocker		Toggle	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V
Cost (\$)	20%	8.9	.011	1.04	.097	1.49	.092
Ease of Access	20%	4	.666	4	.067	4	.022
Clarity of State	20%	5	.833	4	.067	3	.021
Rigidity of State	40%	5	.182	3	.109	3	.050
Total WNV		.343		.339		.285	

The keyed rotary switch was selected for both the CRAS-M and the CRAS-S. In addition to the physical switch, there will be an indicator light that will light up when the recovery system is armed, which will further increase the switch's clarity of state.

Electronics Board: Within the rocket, the electronics board is responsible for connecting the electrical components of the altimeter to the deployment system. There are 3 altimeters in the main body tube and 2 altimeters in the nose cone that will utilize these boards to deliver power, connect to external switches, and deploy the drogue and main parachutes. The two approaches considered in the trade study are a perfboard and a printed circuit board (PCB). In order to which type to use, five criteria were considered: cost, adaptability, reliability, durability, and ease of assembly. Reliability and durability are the two most important criteria because the successful deployment of the recovery system depends upon the functionality of the electronics boards. Next was cost which is ranked high due to attempts to reduce cost of the system this year. Finally adaptability and ease of assembly were ranked lowest because although they are important for prototyping and construction, once complete they have no effect on the actual performance of the boards. As seen in Table 28 below, the trade study resulted in a PCB being the best approach. It's main strengths are its high reliability, durability, and ease of assembly because printed traces are more durable and reliable than a hand soldered one, and boards can be mass produced. Its main weakness is its lack of adaptability because the board cannot be changed once printed and long shipping times in between iterations slows down development.

Table 28: Electronics Board Trade Study

		Perfboard		PCB	
Criteria	Weight	Value	W.N.V	Value	W.N.V
Reliability	25%	5	.0833	10	.167
Durability	25%	5	.0893	9	.1607
Cost (\$)	20%	7	.0833	5	.1167
Adaptability	15%	8	.133	1	.0167
Ease of Assembly	15%	4	.05	8	.10
Total WNV		.439		.561	

The avionics will be connected with a PCB. Insert a circuit diagram

GPS Transmitters: Two GPS transmitters will be utilized. One will be used to track the location of the nose cone after deployment and one will be used to track the main vehicle. The transmitter selected was the Eggfinder TX Transmitter. This transmitter was chosen for its ease of assembly and reliability. The team has used the Eggfinder multiple times in the past proving its reliability. The Eggfinder is also relatively inexpensive compared to other GPS transmitters and is compact which will help with integration into the vehicle.

3.4.5.2.4 Electromagnetic Shielding

In order to protect the Stratologger, a Faraday shield will be constructed to block electromagnetic fields. This Faraday shield will consist of an PLA plastic printed box with external tabs with holes to screw the shield onto the platform. The PLA plastic box will be lined internally with copper foil. The shielding box can be seen in Figure 15.

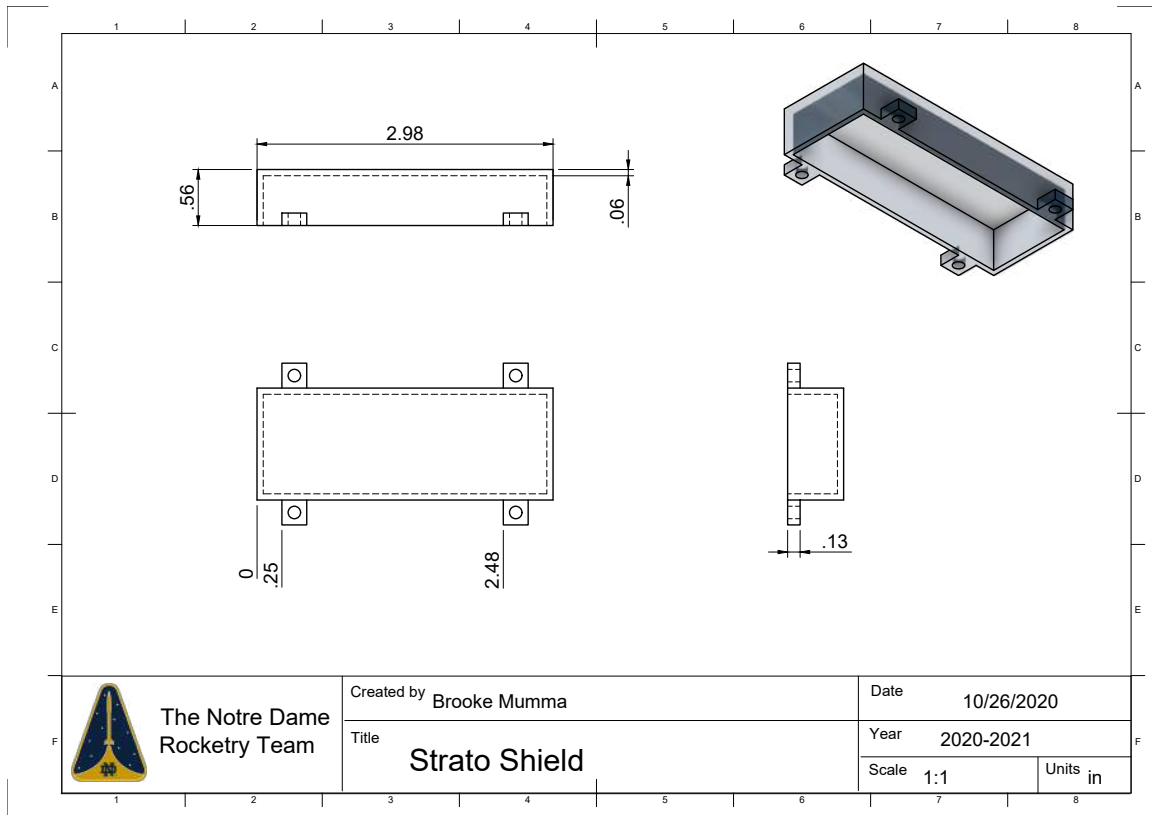


Figure 15: CAD drawing of the electronics shielding

3.4.5.2.5 Integration

IAP electronics will be attached to a 1/8 in. HDPE board which will be secured vertically between two mounts to the the top and bottom bulkheads of the CRAS-M and CRAS-S. Recessed slots of the dimensions of the HDPE boards will constrain the boards in all directions when the top and bottom bulkheads are screwed into the vertical standoffs. Tthe IAP boards will be secured in mounts horizontally and secured by the bottom and top bulkheads which will be screwed into standoffs. Figure 16 shows a drawing of the IAP integration into the CRAS-M.

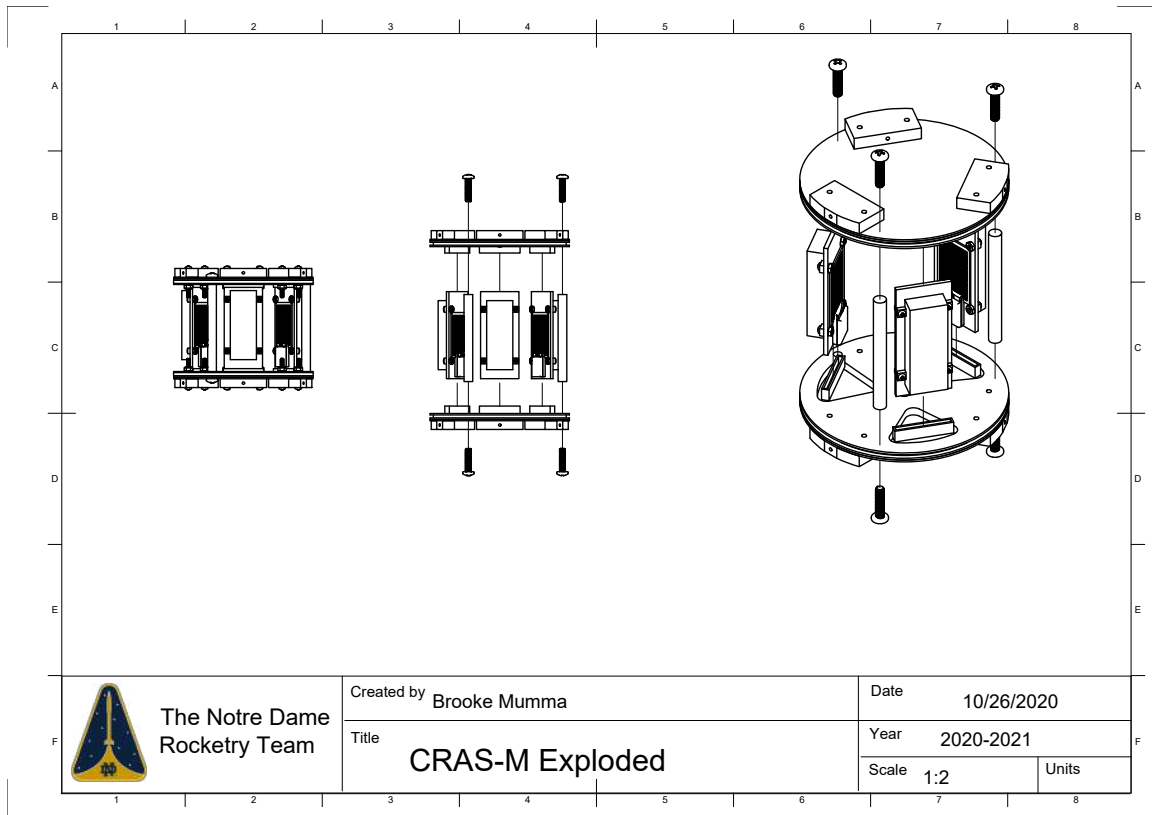


Figure 16: CAD drawing of IAP integration into the CRAS-M

3.4.6 Redundancy and Safety

Reliability of the recovery system is paramount for both successful completion of the mission and safe operation of the launch vehicle. Both the CRAS-M and CRAS-S contain redundant commercially available altimeters [(NASA Req 3.4)]. The CRAS-M, responsible for deployment of both main and drogue parachutes, contains three IAPs, which means the system can successfully deploy the parachutes even with a double altimeter failure. The CRAS-S contains two IAPs, ensuring successful nosecone deployment with an altimeter failure. The redundancy of these systems ensures a safe recovery of the launch vehicle.

3.5 Apogee Control System

3.5.1 System Overview and Mission Success Criteria

The Apogee Control System (ACS) is designed to precisely and dynamically control the drag profile of the launch vehicle in the event that the projected flight path exceeds the target apogee of 5300 feet and reduce the apogee to exactly 5300 feet. It achieves this by

applying a variable drag force to the launch vehicle, which is accomplished by extending and retracting a set of drag tabs. This is done in a closed loop control system, with a microcontroller reading in data from sensors, filtering that data, calculating an ideal tab extension, and actuating the tabs the desired amount in response to the current altitude and velocity of the vehicle. The ideal tab extension will be calculated using some subset of a PID control law. The ACS will be evaluated according to the following criteria:

- The system will ensure that the launch vehicle apogee is within 30 feet of the target apogee of 5300.
- The system will extend aft of the burnout center of gravity.
- The system will not negatively impact the stability of the launch vehicle.
- Drag tabs will not deploy until after burnout has occurred.
- Drag tabs will fully retract once apogee has occurred and remain dormant for the remainder of the flight.
- The drag tabs will retract if a jam is detected.

3.5.2 Aerodynamic Considerations

In order to ensure the stability of the launch vehicle during the early stages of flight, ACS drag surfaces will only be actuated after burnout. The only forces acting will be the drag acting on the main body of the rocket, the drag induced by the ACS, and gravity. The force of drag is given by the following equation:

$$F_{drag} = \frac{1}{2}\rho C_d A v^2 \quad (4)$$

where ρ is the density of air, C_d is the coefficient of drag, A is the effective area, and v is airspeed. Because the target apogee is approximately a mile above ground level, it is assumed that the density of air can be approximated as constant. The drag coefficient C_d will be determined for the rocket body and tabs separately using CFD.

In order to reduce any disturbances to the fins caused by the drag tabs, each tab will be offset 45° from the fins, which are offset by 90° from each other. Figure 17 below depicts a contour plot of the induced drag for the range of airspeed and effective area, utilizing a drag coefficient calculated from last year's system. The plot is generated from Eq. 4, assuming a constant drag coefficient and air density.

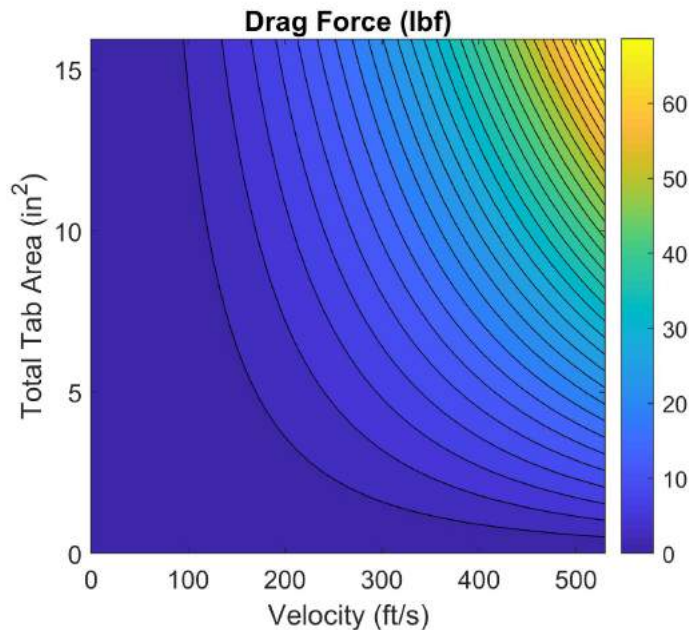


Figure 17: Induced drag force for range of total tab extension area and airspeed.

As can be seen in the figure, the magnitude of available drag drops drastically with airspeed, such that speed below approximately 250 ft/s, even at full extension the ACS will not be able to impact the flight path significantly.

3.5.3 Legacy Data and Considerations

A version of the apogee control system was demonstrated to be partially successful in last year's launch vehicle, with the control sequence identifying each control stage (armed, launched, burnout, apogee, overshoot, and landed) and the drag mechanism deploying in between burnout and apogee. However, as indicated by in flight altimeter data and verified by the on board camera, drag tabs rapidly and repeatedly deployed and retracted in response to pressure spikes and drops which seemed to indicate vast over- or under- shooting of the target apogee. A plot of the flight data is shown in Figure 18.

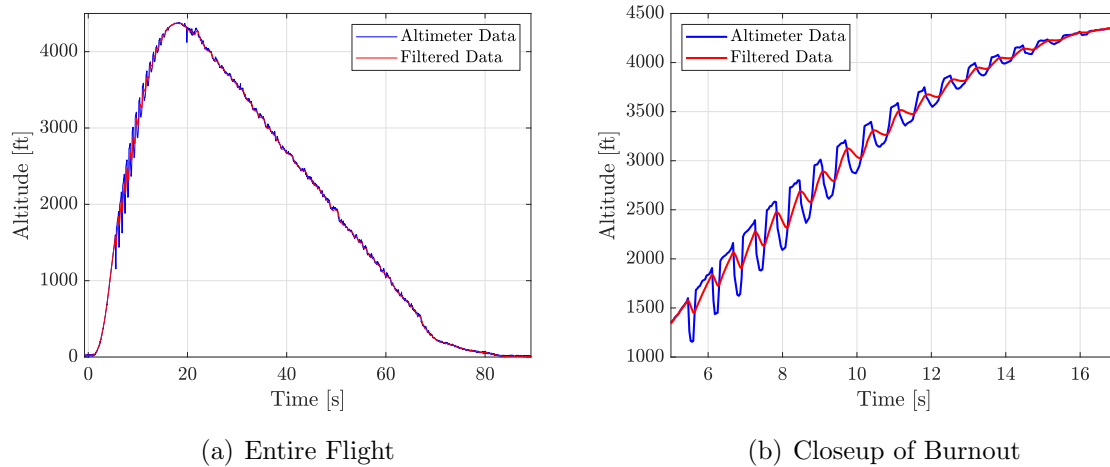


Figure 18: Raw and Filtered Altitude Data

Because the servo motor and tabs reacted as expected given the pressure data they received, it was concluded that the pressure problem was caused by transient turbulent effects aft of the drag tabs. As such, pressure data will now be collected from a hole fore of the drag tabs and fed through a pipe to the pressure sensors. Another option under consideration was to use a pitot-static probe to obtain pressure measurements, though this was deemed too complex to integrate with very marginal added utility.

3.5.4 Mechanical Design

The tab actuation mechanism (TAM) is responsible for deploying a set of tabs that increase the rocket's drag such that it reaches the target apogee of 5300 feet. The team will also work to minimize the impact on the ACS tabs on the stability of the launch vehicle. In order to facilitate this, the drag induced by the tabs will only act parallel to the velocity vector of the rocket. As Requirements [AD.1](#), [AD.2](#), and [AD.3](#) state, the TAM shall fit in a body tube with a diameter of 6 inches and a length of 10 inches, and cannot weigh more than 80 ounces. Additionally, the TAM must accurately control the amount of tab surface that is deployed. The tabs should be large to minimize the effect that any systematic errors in the code, sensor readings, or mechanical design have on the rocket's overall trajectory.

3.5.4.1 Mechanical Design Considerations

The goal of the ACS mechanical design is to give accurate control over the position of the drag tabs during flight. Three alternatives were researched and compared for the ACS mechanical designs, a summary of which is provided in the trade study found in Table 29.

The first design option is the Folding Displacement Method (FDT), which deploys by using a motor to turn a central drive screw that runs down the length of the rocket. As the motor turns the screw, a central hub is forced upwards. Linkages connected to both the tabs and the central hub then convert the upward movement of the hub outwards to deploy the tabs. The design can be seen below in Figure 19.

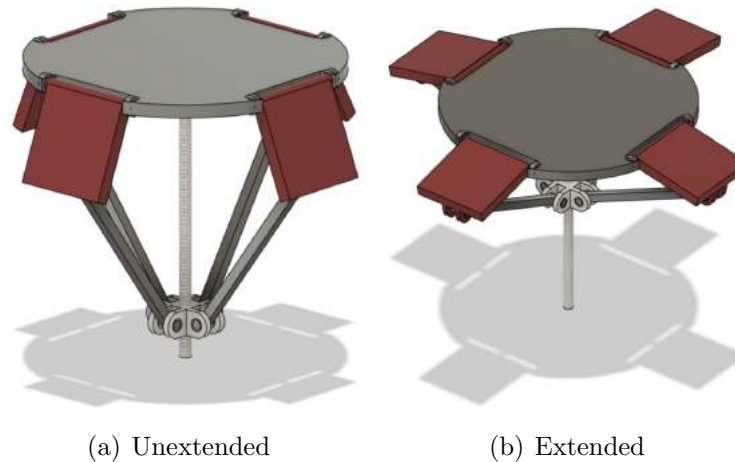


Figure 19: Folding Displacement Tabs

The FDT design has the highest available surface area for braking because unlike the other designs, the folding tabs are stored along the length of the rocket instead of being stored inside the diameter of the rocket. The FDT design also allows for a high level of precision when actuating the tabs, since one full revolution of the servo motor translates to a small adjustment to the exposed profile of the tabs. This high level of precision makes it easier to make minute adjustments in flight. However, because the tabs only move slightly every revolution of the motor, the FDT is the slowest deploying design. This comes with the disadvantages of being harder for the system to make quick adjustments to the trajectory of the launch vehicle. Further complicating the software system, when the FDT deploys, more surface area is exposed to the air in addition to the angle of attack changing which leads to an inconsistent drag profile. FDT also would be the most expensive design, since a more powerful servo motor would be needed because the motor would have to directly bear and overcome the drag force from the tabs. Finally, the FDT tabs would have to be cut from the body tube, which would add complication to the fabrication of the rocket.

The second design considered is the Radial Displacement Method (RDT). The RDT deploys by firstly translating linearly, then rotating outwards from the center of the rocket. A motor is used to rotate a central hub, that then causes the tabs to move forwards then outwards. The design can be seen below in Figure 20.

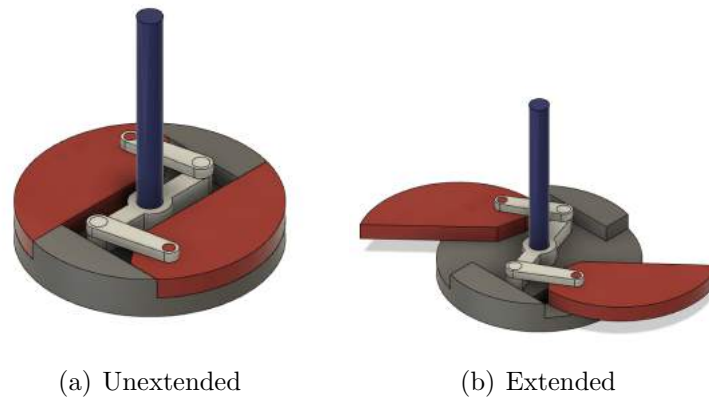


Figure 20: Radial Displacement Tabs

As shown in Table 29, the RDT offers the most drag area. However, since the RDT tabs take up a large portion of the circumference of the rocket, the structural stability of the rocket body is weakened more than the other designs being considered. Additional reinforcements would have to be added to ensure the rocket remains rigid. The RDT also has a more complex deployment method that would result in higher friction that the motor would have to overcome during deployment compared to the other designs.

The third option under consideration is the Linear Displacement Mechanism (LDM). This mechanism uses a servo motor connected to a central hub which rotates with the servo motor. The central hub is connected to the tabs by rigid linkage arms. The tabs are placed within grooves forcing the tabs to only move linearly. When the central hub is rotated by the servo motor the tabs will linearly move outward or inward depending on the direction of rotation. The design and movement can be seen below in Figure 21.

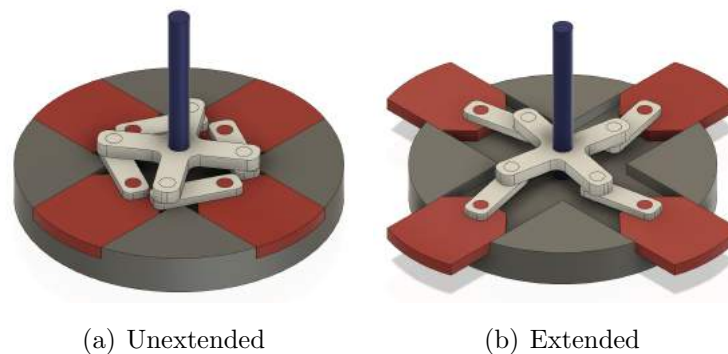


Figure 21: Linear Displacement Tabs

3.5.4.2 Mechanical Design Trade Study

The three mechanical designs were compared in a trade study. They were judged based

on their expected performance, construction requirements, and impact on the rest of the rocket. The FDT has high precision due to the fact that many revolutions of the motor are required to deploy the tabs, has the option of allowing for a large surface, and is reliable thanks to its simplicity. Its main disadvantage is that its impact on the rocket is greater than that of the other mechanisms because it requires removing material from the body tubes.

The RDT's main advantage is its manufacturability. Because it has so few parts it would be cheap and easy to build. However, because the mechanism itself is more complicated than the other two, there are more failure modes, and therefore it cannot be considered as reliable. Another disadvantage is its effect on the overall structure of the rocket. Because of the way the tabs deploy, most of the body tube's contour would need to be removed, weakening the structure of the rocket.

The LDT offers a more compact and predictable ACS mechanical system. A benefit of the mechanism is that the tabs will extend linearly outward, making the drag coefficient easier to model, which will simplify the calculations of the drag force and the coding required to make the mechanism function. A limit to the design is the amount of surface area, and thus drag that can be produced, since the tabs must fit within the body tube when retracted. The LDT can easily be inserted and removed from the body because there are no components that directly interface with the body tube.

Table 29: Mechanism Design Trade Study

Mechanism Design		Folding		Linear		Radial	
Criteria	Weight	Value	WNV	Value	WNV	Value	WNV
Manufacturability	10.34%	3	0.0310	5	0.0517	2	0.0207
Cost	10.34%	1	0.0115	4	0.0460	4	0.0460
Testability	10.34%	2	0.0207	4	0.0414	4	0.0414
Precision	10.34%	4	0.0517	2	0.0259	2	0.0259
Responsiveness	10.34%	2	0.0207	4	0.0414	4	0.0414
Effective Surface Area	10.34%	4	0.0460	2	0.0230	3	0.0345
Complexity	10.34%	3	0.0388	3	0.0388	2	0.0259
Structural Integrity	10.34%	1	0.0172	4	0.0689	1	0.0172
Effect on shape of body tubes	10.34%	2	0.0230	4	0.0460	3	0.0345
Weight	3.44%	3	0.0094	4	0.0125	4	0.0125
Power consumption	3.44%	2	0.0069	4	0.0138	4	0.0138
Total WNV		0.28		0.41		0.31	

Based on the trade study results, the LDT design scored highest and was selected as the mechanism to deploy the tabs from the rocket. Compared to the LDT, the FDT was more expensive, more complex, and would be much more difficult to fabricate. Compared to the LDT, the RDT greatly compromised the structural integrity of the rocket body, and utilized a more complex and error prone deployment system. Overall, the LDT provides a suitable amount of drag while relying on a simple and fast deployment mechanism that has been proven to be reliable in previous NDRT rockets. Therefore, the LDT mechanism will be used to deploy the tabs.

3.5.4.3 Material Selection

Several materials were compared on the basis of cost, factor of safety as calculated by the predicted maximum stress, density, and coefficient of friction. Table 30 shows the results of the trade study evaluating these materials according to the stated criteria. The weights for each category can be seen in Table ??, and the weighted results can be seen in Table ??. In accordance with FMEA Table 88, row ACS.5, the chosen materials must have a factor of

safety of at least 1.5. The ideal material would contain a high yield stress, low coefficient of friction, and be relatively inexpensive to fit the slim budget. According to Table ??, the best material for drag tabs is HDPE. It scores well in the criteria and is very affordable.

Table 30: Drag Tab Material Trade Study

Drag Tab Material		Delrin 150		HDPE		ABS		Nylon 6/6	
Criteria	Weight	Value	WNV	Value	WNV	Value	WNV	Value	WNV
Cost, \$ (6"x6")	45%	74.45	0.0517	7.57	0.162	9.67	0.158	14.97	0.150
Yield Strength (psi)	9%	11100	0.0158	4600	0.0065	5100	0.0072	10400	0.0148
Density (g/cm ³)	18%	1.42	0.0276	0.96	0.0355	1.12	0.0328	1.14	0.0324
Coefficient of Friction	28%	0.2	0.0529	0.2	0.0529	0.35	0.0348	0.23	0.0493
Total WNV		0.148		0.257		0.233		0.247	
Drag Tab Material		Acrylic		Polycarbonate		TECAFORMAH		PFTE	
Criteria	Weight	Value	WNV	Value	WNV	Value	WNV	Value	WNV
Cost, \$ (6"x6")	45%	8.97	0.159	10.56	0.157	58.35	0.0823	103.42	0.0118
Yield Strength (psi)	9%	10700	0.0152	9180	0.0130	9280	0.0132	2970	0.0042
Density (g/cm ³)	18%	1.18	.0317	1.20	0.0314	1.40	0.0280	2.07	0.0165
Coefficient of Friction	28%	0.58	0.0072	0.50	0.0168	0.21	0.0517	0.06	0.0697
Total WNV		0.213		0.218		0.175		0.102	

3.5.5 Electrical Design

The Apogee Control System depends on sensors, motors, and a microcontroller in order to dynamically alter the drag tabs in response to the current state of the launch vehicle. The microcontroller relies on fast, accurate data from its sensors in order to determine how much to extend the tabs. Likewise, it depends on its motor having a sufficient torque for the actuation of the drag tabs. In order to effectively respond to changing flight conditions, the microcontroller must be able to read data from multiple sources, quickly process it, and control a servo motor through the use of a PWM signal. In order to determine which electrical components to use in the system, the team conducted several trade studies, which are detailed below.

In addition to choosing these components, the team is considering the creation of a printed

circuit board (PCB). The team has had success with this approach in the past, finding that it allowed for more secure connections between the sensors and the microcontroller and reduced the reliance on loose wires.

3.5.5.1 Sensor Selection

The ACS requires continuous monitoring of altitude, velocity, and acceleration data to determine if and when to deploy the drag tabs to slow down the rocket and meet the target apogee. The controls section of the rocket will contain three sensors to measure this data: an altimeter, an inertial measurement unit (IMU), and an accelerometer. The altimeter will provide pressure and temperature measurements, which can be used to estimate the current altitude of the launch vehicle. The IMU uses an accelerometer, gyroscope, and magnetometer to provide 9-axis orientation data. The accelerometer will provide redundant 3-axis acceleration data.

The team has conducted trade studies on each of the sensor fields in order to determine which sensors work best to fill each role. Sensors were graded along many dimensions, with the most common being ease of implementation, sampling rate, sensitivity, and cost.

3.5.5.1.1 Altimeter

The Apogee Control System will utilize a barometer for real-time air pressure measurements. From these air pressure measurements, the altitude of the rocket can be computed. The team performed trade studies on three altimeters, grading them on ease of implementation, sampling rate, accuracy, and cost. Accuracy had the highest weight because it is critical in determining how far to extend the drag tabs to hit a target apogee. The sampling rate had the next highest weight in order quickly actuate tabs in response to changing flight conditions. Table 31 shows the results of a comparison between several altimeters.

Table 31: Altimeter Trade Study

Altimeter		MPL3115A2		BMP388		BMP280	
Criteria	Weight	Value	WNV	Value	WNV	Value	WNV
Ease of implementation	20%	10	0.0667	10	0.0667	10	0.0667
Sampling Rate (Hz)	30%	100	0.0656	200	0.131	157	0.103
Accuracy (m)	40%	0.3	0.222	0.5	0.178	1	0.0667
Cost(\$)	10%	9.95	0.0333	9.95	0.0333	9.95	0.0333
Total WNV		0.388		0.409		0.270	

The BMP388 was chosen as it has the highest sampling rate of the considered sensors, while also having a comparable ease of use and cost and reasonable accuracy.

3.5.5.1.2 Inertial Measurement Unit

The ACS will use an Inertial Measurement Unit (IMU) to provide acceleration, rotation, and magnetic field measurements to determine the motion and orientation of the rocket at any given time. The team considered three different IMU sensors: the HiLetgo MPU9250/6500, the SparkFun ICM-20948, and the Adafruit BNO055. The team graded the IMUs based on the range, sensitivity, and maximum sampling rate of their accelerometer, gyroscope, and magnetometer. Additionally, the cost and ease of use of each IMU was considered. The accelerometer specifications were weighed more heavily than the other sensors because it is critical to the software team that its range exceeds the maximum acceleration of the rocket and that the data is accurate. Additionally, the team gave the maximum sampling rate of each sensor a low weight because if the IMU is in nine-axis mode, the sampling rate will need to be adjusted to be compatible with the Raspberry Pi. Table 32 shows the results of a comparison between these IMU's.

Table 32: IMU Trade Study

Sensor		MPU9250/6500		ICM-20948		BNO055	
Criteria	Weight	Value	WNV	Value	WNV	Value	WNV
Range of Accelerometer (g)	15%	16	.0500	16	0.0500	16	0.0500
Sensitivity of Accelerometer (LSB/g)	15%	16,384	0.0728	16,384	0.0728	1000	0.0044
Max Sampling Rate of Accelerometer (Hz)	3%	32,000	0.0259	4,500	0.0036	500	0.000405
Range of Gyroscope (deg/s)	5%	2000	0.0167	2000	0.0167	2000	0.0167
Sensitivity of Gyroscope ($LSB/deg/sec$)	10%	131	0.0471	131	0.0471	16	0.0058
Max Sampling Rate of Gyroscope (Hz)	3%	8000	0.0137	9000	0.0154	523	0.000894
Range of Magnetometer (μT)	5%	4800	0.0197	4900	0.0201	2500	0.0102
Sensitivity of Magnetometer ($\mu T/LSB$)	10%	0.6	0.0738	0.15	0.0185	0.0625	0.0077
Max Sampling Rate of Magnetometer (Hz)	3%	1,000	0.0250	100	0.0025	100.00	0.0025
Cost	10%	\$8.99	0.0435	\$16.95	0.0261	\$19.95	0.0196
Ease of Implementation	20%	8	0.0615	8	0.0615	10	0.0769
Total WNV		0.450		0.334		0.195	

As Table 32 shows, the team decided to work with the HiLetgo MPU9250/6500. This IMU had ranges, sensitivities, and sampling rates comparable to the others, while also being cheaper. Additionally, several online tutorials exist to aid in interfacing with the sensor.

3.5.5.1.3 Accelerometer

In addition to an IMU, the ACS will utilize a stand-alone accelerometer to record a redundant estimate of the acceleration of the launch vehicle. The considered sensors measure three axes of acceleration. The two sensors the team considered were the ADXL345, and the BNO055. Here, the BNO055 is considered solely on its merits as an accelerometer, with the assumption that the gyroscope and magnetometer are disabled. The sensors were graded based on their ease of implementation (how easily they can be used with the raspberry pi control board), sensitivity, sampling rate, and cost. Table 33 below shows the results of this trade study.

Table 33: Accelerometer Trade Study

Accelerometer Sensor		ADXL345		BNO055	
Criteria	Weight	Value	Score	Value	Score
Ease of Implementation	20%	9	0.1	9	0.1
Sensitivity (LSB/g)	35%	32	0.0109	1000	0.3391
Sampling Rate	35%	3.2kHz	0.339	100Hz	0.0106
Cost (\$)	10%	14.95	0.0572	19.95	0.0428
Total WNV		0.507		0.493	

As Table 33 shows, both accelerometers rated high on their ease of implementation as they can communicate with the microcontroller through the I²C interface. However, the sensors had significantly different sensitivities and sampling rates. The team chose to weight these categories equally, because an effective sensor will give fast, accurate readings. The ADXL345 has a significantly higher sampling rate while the BNO055 has a significantly higher sensitivity. The team chose to go with the ADXL345 because it is more cost-effective. Additionally, the team has had issues working with the BNO055 in the past, which influenced this decision.

3.5.5.2 Motor Selection

The servo motor will be used to actuate the motion of the tabs in the LDT. The two primary design constraints on the servo motor are providing enough torque to overcome resistance during tab extension as well as providing a high level of precision in order to ensure that tabs are extended or withdrawn to the correct position. Additionally, the motor must fit within the required 80 oz. weight (NDRT Req AD.1). Lastly, the motor must have a low operating current draw in order to minimize the need of additional battery power within the system.

Table 34: Servo Motor Trade Study

Servo Motor		SB2290SG		D845WP		SV0236MG		D980TW	
Criteria	Weight	Value	WNV	Value	WNV	Value	WNV	Value	WNV
Weight (oz)	25%	2.85	0.0957	8.00	0.0334	7.05	0.0449	2.76	0.0968
Speed at 7.4 V	8.33%	0.13	0.0169	0.17	0.0221	0.17	0.0221	0.17	0.0221
Torque at 7.4 V	16.67%	694.4	0.0453	694.0	0.0453	555.0	0.0362	611.0	0.0399
Cost	16.67%	\$140	0.0418	\$105	0.0532	\$99	0.0551	\$170	0.0321
Max Travel (degrees)	8.33%	160.0	0.0229	202.5	0.0290	100.0	0.0143	120.0	0.0172
Operating Current Draw	25%	9.2	0.0036	2.6	0.1358	0.18	0.1843	0.5	0.1779
Total WNV		0.226		0.319		0.357		0.385	

The four servo motors being considered were the SB2290SG, the D845WP, the SV0236MG, and the D980TW. As Table 34 shows, weight and current draw were considered the most important factors in the trade study. Too big a motor or current draw could result in a weight that is over the budget for the system. Torque was taken into consideration next as it is integral to the actuation of the tab motion, but was weighted lower due to the large number of commercial servo motors available with more than sufficient torque. Finally, accuracy was considered for a category until it was made clear through research that each motor had their own feedback loop that offered negligible advantage in this area. From Table 34, we can see that the D980TW servo motor is the best choice for our system due to a combination of low weight and current draw, as well as a relatively high torque.

3.5.5.3 Battery Selection

The D980TW servo chosen requires an operating voltage of 7.4V, so the team considered several 2 cell lithium polymer batteries which have a nominal cell voltage of 3.7V. The three batteries considered to power the servo are shown in Table 35 below. Each battery was graded on its capacity, voltage, discharge rate, cost, size (dimensions), and mass. Both the Turnigy and Zippy batteries had a greater capacity than the Rhino battery, and the Zippy battery was rated for a higher discharge rate than the Turnigy battery. A higher discharge rate ensures that the battery will be able to continue supplying current to the servo at its nominal voltage, eliminating the possibility of a reduction of power being delivered to the

servo during the flight. Although the the cost of the Zippy battery was slightly higher than the Turnigy battery, the team decided it was beneficial to have the higher discharge rate to ensure the servo was receiving enough power to operate the ACS.

Table 35: Servo Battery Trade Study

Battery		Zippy		Turnigy		Rhino	
Category	Weight	Value	WNV	Value	WNV	Value	WNV
Capacity (mAh)	30%	1300mAh	0.1083	1300mAh	0.1083	1000mAh	0.0833
Voltage (V)	10%	7.4	0.0333	7.4	0.0333	7.4	0.0333
Discharge (C)	20%	40	0.1000	20	0.0500	20	0.0500
Cost (\$)	10%	\$9.50	0.0239	\$7.24	0.0342	\$5.25	0.0432
Dimensions (mm)	15%	76mm x 35mm x 16mm	0.0475	73m x 35mm x 17mm	0.0465	75mm x 35mm x 14.7mm	0.0523
Mass (g)	15%	82	0.0455	81	0.0462	71	0.0526
Total WNV			0.3586		0.3184		0.3147

Based on the operating needs of the chosen microcontroller; the Raspberry Pi Zero W, a nominal one-cell 3.7v battery will be used to provide power. The team considered the three batteries shown in the table below, which were graded based on their capacity, voltage, cost, size (dimensions), and mass. Discharge was not included in the grading due to the low power consumption of the microcontroller. Table 36 below shows the results of this trade study.

Table 36: Microcontroller Battery Trade Study

Battery		Turnigy 2000		Turnigy 1200		Rhino	
Category	Weight	Value	WNV	Value	WNV	Value	WNV
Capacity (mAh)	40%	2000mAh	0.2025	1200mAh	0.1215	750mAh	0.0759
Voltage (V)	10%	3.7	0.0333	3.7	0.0333	3.7	0.0333
Cost (\$)	15%	\$4.53	0.0388	\$4.71	0.0367	\$2.99	0.0578
Dimensions (mm)	20%	49mm x 34mm x 10mm	0.0458	48mm x 33mm x 6mm	0.0803	55mm x 31mm x 9mm	0.0521
Mass (g)	15%	33	0.0356	20.5	0.0572	33	0.0355
Total WNV			0.3561		0.3290		0.2547

The team decided to choose the Turnigy 2000mAh 1 cell as the battery to supply power

to the microcontroller. This battery had the highest capacity, ensuring that the Raspberry Pi would be able to operate for sufficiently long time (including idle time). Although the 1200mAh Turnigy battery had a lower mass, the cost and dimensions of the battery were similar to the Turnigy 2000mAh, which had a significantly higher capacity. The Rhino battery was very affordable and had similar scores to the Turnigy 2000mAh battery, but the team decided to settle on the Turnigy 2000mAh model due to its extra capacity.

3.5.5.4 Microcontroller Selection

In the past, the team has examined the use of several different microcontrollers. So far, the most successful has been the Raspberry Pi Zero W. This controller is a full computer with its own operating system, so the team has the freedom to develop all necessary software. It also has a full set of GPIO pins and supports the I²C, SPI, and PWM protocols. This allows it to read data from all of the sensors the team has selected and control the servo motor. Additionally, the Raspberry Pi environment is fairly popular, so tutorials and libraries exist for most sensors and motors, which makes integration of system components significantly easier. It is also fast enough for the team's needs, with previous years managing to get 10 to 30 control system iterations per second. Lastly, the controller has wireless capabilities, which makes programming and communicating with the system significantly easier.

3.5.6 Control Structure

3.5.6.1 Overarching Control Structure

The team will utilize a Raspberry Pi Zero W to control the system, reading in data from sensors and appropriately adjusting the drag tab extension. Code to control this computer will be written in Python, and will have the following structure. First, data is collected from the sensors about the current altitude, acceleration, and orientation of the launch vehicle. This sensor data will yield the current sensor state for the rocket at any given moment in time.

The sensor data will then be transmitted to a data filtering algorithm. The filter will work to minimize noise by combining disparate sensor readings into a single estimate of the current state of the launch vehicle. This filtered information will then be sent to the control algorithm. The control algorithm will be used to determine the optimal tab extension to achieve apogee. It will utilize the filtered data to calculate the angle of the servo motor required to achieve optimal tab extension. Figure 22 below shows how the control system will function over the course of a launch.

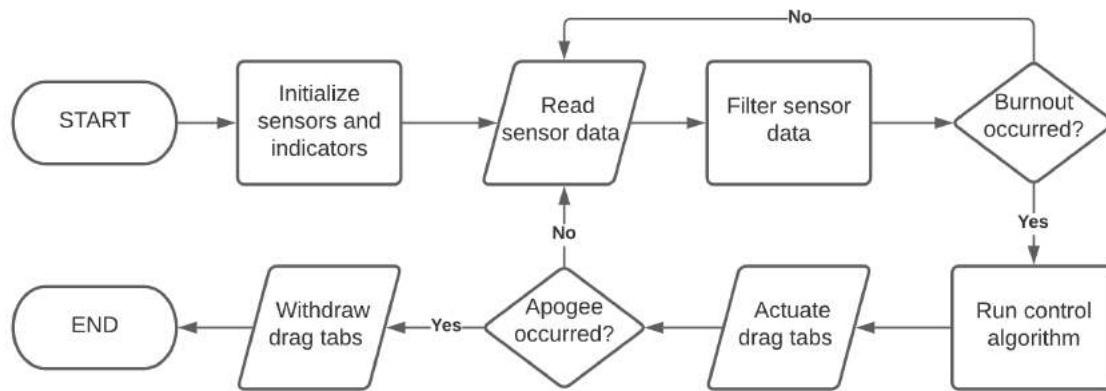


Figure 22: ACS Control Flow

The system begins by initializing sensors and any indicators present. It will then enter a closed loop, where it will read in sensor data and then act appropriately depending on the current state of the rocket. If the system detects that burnout has occurred, then the servo will be actuated appropriately. Likewise, once apogee is detected, the system will withdraw the drag tabs and shut down. In both cases, the team will build redundancy into the transitions to ensure that an incorrect transition can be reverted.

3.5.6.2 Data Filtering Algorithms

The goal of data filtering is to combine several noisy data sources into a single accurate estimate of the current state of the system. The team has considered several algorithms which accomplish this objective, including the double-exponent smoothing filter, recursive Gauss-Newton filter, Kalman filter, adaptive filter, and recursive least-squares filter.

The double-exponent smoothing filter was found to have worked 160 times faster than the kalman filter, earning the maximum grade in the speed criteria. This speed is partially due to the high memory efficiency of the filter. The filter's algorithm is fairly easy to implement and code. Despite this ease, the filter lacks in accuracy because of the nature of the double-exponential smoothing, which tends to reduce more noise than it should, which can hurt performance.

The Gauss-Newton filter, while extremely accurate regarding the actual state of the rocket, has a longer processing time than any other filter studied. It also was not as efficient as any other filter.

The Kalman filter, while not as quick nor efficient as the double exponent smoothing

filter, was one of the most accurate filters considered. Furthermore, it is relatively easy to implement and test.

The adaptive filter is by far the most median of the group. It is not as quick nor efficient as the double exponent smoothing filter, but is also not as accurate as the Kalman or the Gauss Newton filter.

The recursive least-squares filter compares the outputs of a sensor to its previous outputs, thus narrowing the scope of the data. While the filter is fundamentally similar to the Gauss-Newton Filter, the recursive least-squares filter introduces the coefficient lambda to control the sensitivity of the algorithm to noise. The ability to adjust its sensitivity makes it very accurate and allows it to run relatively quickly. However, it is more difficult to implement and test, and it has a high memory requirement because its outputs heavily rely on previous data points.

Table 37 below shows the results of a trade study conducted to decide between the considered filters. Several factors were considered when evaluating each filter. Speed is defined as the number of samples the algorithm can filter, given identical hardware. Memory efficiency is the amount of data each algorithm must hold in memory to run. Accuracy is defined as how effectively a filter can translate from noisy sensor data to an accurate picture of the current state of the launch vehicle. Ease of implementation takes into account the complexity of implementing the algorithm, as well as the existence of Python library support. Lastly, ease of testing examines the difficulty of proving the correctness of the algorithm and verifying the system's accuracy.

Table 37: Data Filter Trade Study

Algorithm		Double-Exponent Smoothing Filter		Recursive Gauss-Newton Filter		Kalman Filter	
Criteria	Weight	Value	WNV	Value	WNV	Value	WNV
Speed	30.00%	5	0.0833	2	0.0333	3	0.0500
Memory Efficiency	5.00%	5	0.0139	2	0.0056	4	0.0111
Accuracy	30.00%	3	0.0429	5	0.0714	5	0.0714
Ease of Implementation	25.00%	3	0.0417	5	0.0694	4	0.0556
Ease of Testing	10.00%	4	0.0222	3	0.0167	5	0.0278
Total WNV			0.2040		0.1964		0.2159

Algorithm		Adaptive Filter		Recursive Least Squares Filter			
Criteria	Weight	Value	WNV	Value	WNV	Value	WNV
Speed	30.00%	4	0.0667	4	0.0667		
Memory Efficiency	5.00%	4	0.0111	3	0.0083		
Accuracy	30.00%	3	0.0429	5	0.0714		
Ease of Implementation	25.00%	3	0.0417	3	0.0417		
Ease of Testing	10.00%	3	0.0167	3	0.0167		
Total WNV			0.1790		0.2048		

As Table 37 shows, the Kalman filter is the most promising algorithm of the algorithms examined. It is fairly fast and memory-efficient, while also being accurate and relatively easy to implement and test. The team will lean towards this algorithm, but will still consider different possibilities, and will test alternatives as the design progresses. A modular software design with a well-defined interface will allow for data filtering algorithms to be swapped as necessary, which will ensure that the team can explore several design possibilities.

3.5.6.3 Control Algorithms

The controller will utilize predictive modelling as a basis for actuation. When constructing a differential equation to model the system, the team will assume that the only forces acting on the rocket are the force of gravity and the drag force. This leads to the following equation:

$$F_r = F_g + F_d \quad (5)$$

where F_r is the total force exerted on the launch vehicle, F_g is the gravitational force, and F_d is the drag force. We will split F_d into two components: F_{dr} , the drag force acting on the launch vehicle, and F_{dt} , the drag force acting on the ACS mechanism. Using Eq. 4 and assuming that drag acts in the negative y direction, we can write a new equation for F_d :

$$F_d = F_{dr} + F_{dt} = -\frac{1}{2}\rho C_{dr} A_r \dot{y}^2 - \frac{1}{2}\rho C_{dt} A_t \dot{y}^2 \quad (6)$$

where C_{dr} is the coefficient of drag of the rocket, C_{dt} is the coefficient of drag of the tabs, A_r is the cross-sectional area of the rocket, and A_t is the cross-sectional area of the tabs. This can then be combined with Newton's second law and the equation for gravity at the surface of the Earth to define the following differential equation:

$$m_r \ddot{y} = -mg - \frac{1}{2}\rho C_{dr} A_r \dot{y}^2 - \frac{1}{2}\rho C_{dt} A_t \dot{y}^2 \quad (7)$$

This equation will be solved at a predetermined time interval using a Fourth Order Runge Kutta algorithm, utilizing current filtered sensor data as initial conditions, to predict what apogee will be under current conditions. This value will be compared to the target apogee, and the error will be used to determine the required actuation.

After calculating an estimated apogee, the control algorithm must determine how best to respond. The team will begin by utilizing proportional gain to determine tab extension, but will also consider using integral and derivative terms as necessary. Additionally, the controller may utilize gain scheduling if needed. If this is the case, multiple sets of gains will be determined for different velocity regimes.

3.5.6.4 Software Test Plan

The team plans to rigorously test each component of the software to ensure system

accuracy, reliability, and fault tolerance. When possible, unit tests will be written to ensure the correctness of software modules. When this is not possible, simulation, ground testing, and test flights will be utilized to further prove system correctness.

Sensors will be tested in order to ensure proper calibration and reasonable output. To carry out these tests, a physical manipulation of the system can be used, depending on the type of sensor. The altimeter will first be tested by placing it in a suction-based vacuum in order to test the barometric data. It will then be tested by carrying the system up and down stairs and observing variations of reported altitude. Likewise, the accelerometer will be tested by jostling the system and observing changes in recorded acceleration. Lastly, the IMU will be tested by flipping the system to different orientations and ensuring that the stated orientation of the system reflects this.

In order to test the effectiveness of the filtering program, sensor data from previous flight logs, as well as data derived from simulated flights, will be inputted into the data filter. After the raw data is filtered, it will be visually compared to the raw data to determine the effectiveness of the filtering. Additionally, the subscale test flight will be used as an opportunity to demonstrate the effectiveness of the data filtering algorithm.

To test the controls algorithm, filtered data from previous flights, as well as data derived from simulated flights, will be fed into the control algorithm. In the first stages of testing, this will just be observed visually. As testing progresses, this data could be fed back into the simulator to determine how different PID gains impact the performance of the controller.

Once each component has proven its effectiveness independently, the entire system will be tested in an ensemble. Simulated sensor data will be fed to the data filter as input, and the outputted tab extension will be fed back into the simulator. As the simulation progresses, each component of the system will need to function properly together to reach target apogee, and any deviations from this can be isolated and corrected.

3.5.7 Integration of System Components

When working on the design of the ACS, the team is working to minimize system weight and size in order to assist in the integration of all other system components. In order to facilitate this, several space saving decisions have been made in the system integration. A preliminary model of the system is shown in Figure 23.



Figure 23: ACS System Component Integration

Among the changes in system integration from previous iterations are the orientation of the printed circuit board (highlighted in blue) and location of the motor (yellow).

As shown Figure 23, the motor will be integrated on top of the tab deployment mechanism and the printed circuit board will be housed under the mechanism so that the majority of the electronics are shielded from any magnetic effects of the large current draws from the motor. Additionally, the tab deployment mechanism will be covered in a thin layer of copper foil in order to further isolate the motor from the electronics and ensure that there is no electromagnetic interference impacting the sensors.

3.6 Mission Performance Predictions

To ensure that the predicted performance of the Launch Vehicle aligns with the requirements for a successful mission, the flight paths, stability, and structural integrity of the design were analyzed in the following sections.

3.6.1 Simulated Flight Profiles

In order to predict a range of flight profiles within the possible launch rail cant angles of 5 - 10° and wind speeds of 0 - 20 mph, a series of flight simulations were run using OpenRocket. The outcomes of those simulations are provided in Table 38, Table 39, and Table 40, which include the velocity off the rod (ft/s), apogee altitude (ft), max velocity (ft/s), and max acceleration (ft/s²) of the launch vehicle for varying wind speeds.

Table 38: OpenRocket Simulation Critical Values for Launch Angle of 5°

Average Wind Speed (mph)	Velocity off Rod (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s ²)
0	58.4	5714	616	225
5	58.4	5674	615	225
10	58.4	5621	615	225
15	58.4	5592	614	225
20	58.4	5589	613	225

Table 39: OpenRocket Simulation Critical Values for Launch Angle of 7°

Average Wind Speed (mph)	Velocity off Rod (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s ²)
0	58.5	5659	616	226
5	58.5	5594	616	226
10	58.5	5549	615	226
15	58.5	5534	615	226
20	58.5	5475	614	226

Table 40: OpenRocket Simulation Critical Values for Launch Angle of 10°

Average Wind Speed (mph)	Velocity off Rod (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s ²)
0	58.6	5540	617	226
5	58.5	5465	617	226
10	58.5	5400	616	226
15	58.5	5346	615	226
20	58.5	5340	615	226

The accompanying flight profiles for the three tables above are provided in Figure 24, Figure 25, and Figure 26.

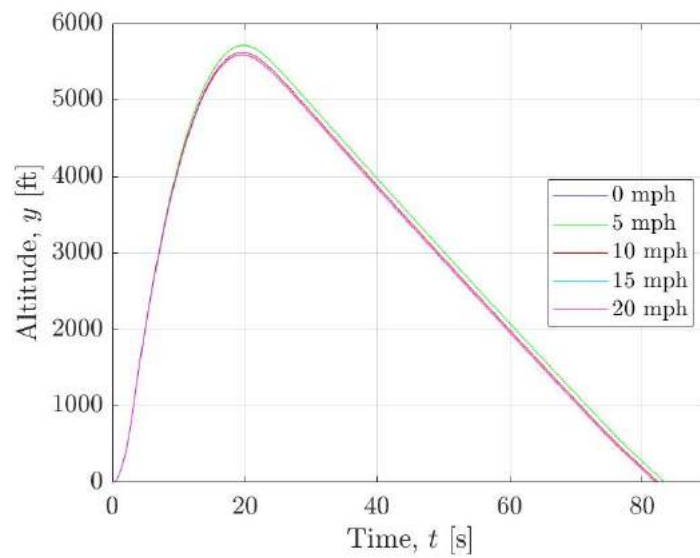


Figure 24: Flight profiles from OpenRocket simulations for Launch Angle of 5°

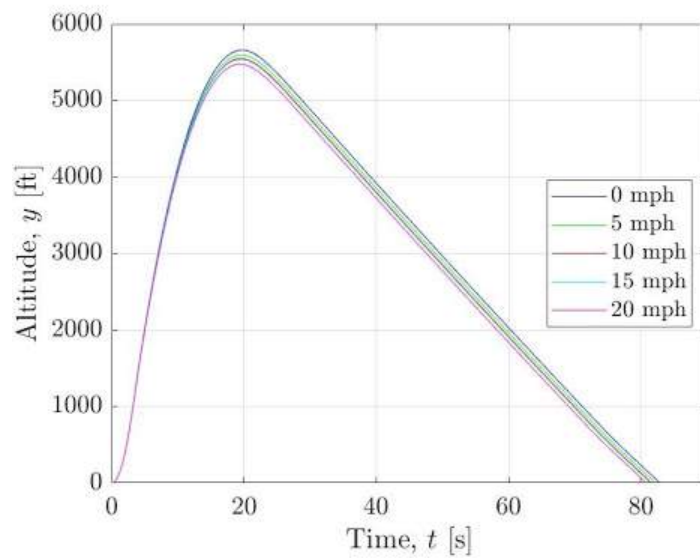


Figure 25: Flight profiles from OpenRocket simulations for Launch Angle of 7°

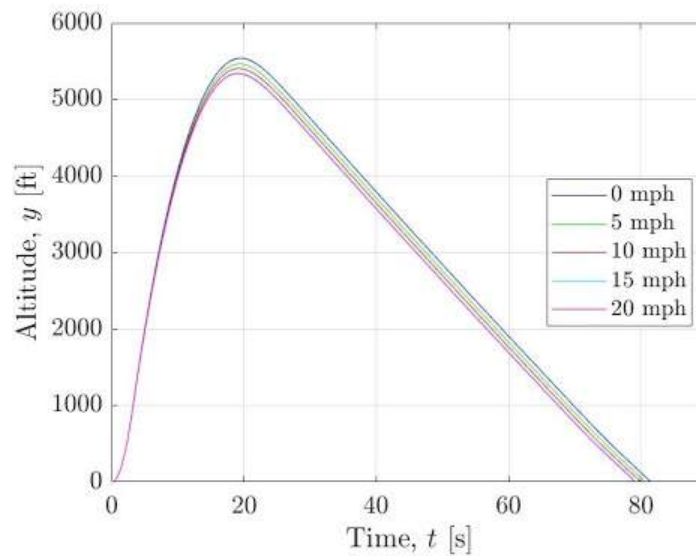


Figure 26: Flight profiles from OpenRocket simulations for Launch Angle of 10°

In order to cross-verify the validity of the OpenRocket simulations, a model of the launch vehicle was generated in RockSim, and the same setup conditions were applied. The results of the RockSim simulations are provided in Table 41, Table 42, and 43.

Table 41: RockSim Simulation Critical Values for Launch Angle of 5°

Average Wind Speed (mph)	Velocity off Rod (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s ²)
0	68.1	5714	617.0	227.6
5	68.1	5733	617.0	227.6
10	68.1	5702	616.8	227.6
15	68.1	5665	616.5	227.6
20	68.1	5624	616.1	227.6

Table 42: RockSim Simulation Critical Values for Launch Angle of 7°

Average Wind Speed (mph)	Velocity off Rod (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s ²)
0	68.1	5704	617.4	227.6
5	68.1	5663	617.5	227.6
10	68.1	5624	617.4	227.6
15	68.1	5580	617.1	227.6
20	68.1	5533	617.0	227.6

Table 43: RockSim Simulation Critical Values for Launch Angle of 10°

Average Wind Speed (mph)	Velocity off Rod (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s ²)
0	68.3	5578	618.4	227.6
5	68.3	5523	618.5	227.6
10	68.3	5474	618.5	227.6
15	68.3	5421	618.3	227.6
20	68.3	5366	617.9	227.6

The similarity of the results between the OpenRocket and RockSim simulations provides high confidence that the flight performance predictions for this launch vehicle design are accurate. In all simulations, the off-rail velocity exceeded the required 52 ft/s (NASA Req. 2.16).

The range of predicted apogee altitudes across both methods includes a maximum of 5714 ft and a minimum of 5340 ft. For this reason, the target apogee altitude of 5300 ft was selected to ensure that the launch vehicle is predicted to overshoot the target in every weather condition, so that the ACS will intervene and ensure a smaller margin of error.

3.6.2 Stability

In order to satisfy NASA Req. 2.14, the OpenRocket and RockSim models were used to check the static stability margin of the launch vehicle at the launch rail exit. In each

case, the CP was calculated using the Barrowman equations, and the stability in calibers was calculated using Equation 8.

$$\text{Stability} = \frac{CP - CG}{d} \quad (8)$$

Where CP is the location of the CP measured from the nose cone tip, CG is the location of the CG measured from the nose cone tip, and d is the launch vehicle outer diameter. With the full motor mass loaded, the static stability measured by the OpenRocket model is 2.12 calibers, and the static stability measured by the RockSim model is 2.13 calibers (NASA Req. 2.14).

In order to obtain a better estimate of the CP location at the off-rail velocity when cross-winds are present, CFD analysis will be used to generate a pressure profile around the launch vehicle airframe, which will be integrated to produce a more accurate CP location. The results of the CFD analysis will be used to provide a more accurate static stability margin at the rail exit for CDR.

3.6.3 Structural Verification

The method for verifying the structural integrity of the launch vehicle throughout flight involved first identifying the critical loading scenarios in a standard flight, identifying the forces present in each scenario through free body diagrams, then analyzing the stress incurred by critical components as a result of this loading. From this information, a factor of safety was calculated for each component to ensure that the required value of at least 2.0 is met. For extra assurance, the load scenarios used are conservative, worst-case scenarios.

3.6.3.1 Load Scenarios

Two loading scenarios were examined for the preliminary full-scale launch vehicle structural design, occurring at the two most critical events in a given flight: maximum motor thrust and main parachute deployment. These flight events were selected because they represent the moments of maximum acceleration during ascent and descent, respectively.

First, the maximum motor thrust event was evaluated because it is the point at which the largest force is exerted on the motor retention components. The motor mount tube is epoxied to three centering rings, which are epoxied into the body tube. The components

that were evaluated at this point were the motor mount tube in compression, the epoxy between the motor mount and centering ring in shear, and a centering ring in shear. The free body diagram shown in Figure 27 shows the forces on the motor retention components, where R is the resultant force from each centering ring, T is the thrust on the tube, W is the weight of the motor mount tube, and τ is the shear force on the inside of the centering ring.

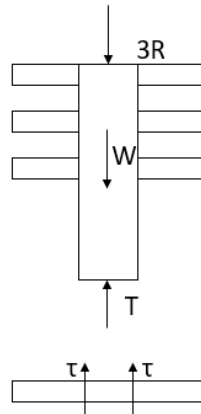


Figure 27: Free body diagram of motor retention components during maximum thrust

The motor mount is loaded in compression during this flight event, between the upwards motor thrust and the reactionary forces from the centering rings. The force on the motor mount tube from each centering ring was computed by setting the net forces from the free body diagram equal to the net acceleration of the vehicle at this point, and was found to be 161.2 lbf from each centering ring.

The other loading scenario that was analyzed was the deployment of the main parachute because it is the point at which the highest force is exerted on the bulkheads in the vehicle. The payload bulkhead was analyzed at this point, while the recovery retention and ACS retention bulkheads were analyzed separately in their respective design sections. The vehicle upper section and the force acting on the payload bulkhead can be seen in the free body diagram, where W is the weight of the vehicle and F is the force from the deployment of the parachute, with a conservatively estimated upwards acceleration of 23.28 g's. The corresponding free body diagram is shown in Figure 28.

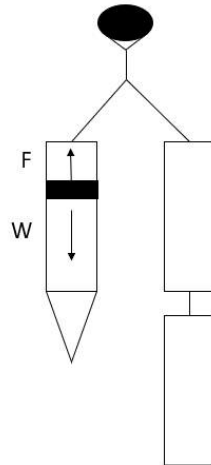


Figure 28: Free body diagram of the payload bay during main parachute deployment

3.6.3.2 Safety Margins

From the results of the analysis described below, factors of safety were calculated for the components under evaluation, where the factor of safety is defined as

$$\text{F.O.S.} = \frac{\sigma_{yield}}{\sigma} \quad (9)$$

A summary of the calculated factors of safety for the evaluated components based on the following analysis is provided in Table 44.

Table 44: Summary of safety factors calculated for structural components

Component	Flight Event	Factor of Safety
Motor mount tube	Maximum thrust	44.0
JB Weld Epoxy	Maximum thrust	131
Centering ring	Maximum thrust	6.95
Payload bulkhead	Main parachute deployment	2.82

The reactionary force from each centering ring, along with the thrust from the motor, were used to analyze the motor mount tube compressive stress during maximum thrust. The epoxy between the motor mount and each centering ring is in shear at this point. The shear force on the epoxy was calculated by dividing the force from one centering ring by the inner surface area of the centering ring. This force was compared to the shear strength of the JB

Weld epoxy that will be used. The centering ring was also connected to the body tube using epoxy; however, since the epoxy was strong enough to withstand the shear force at the inner diameter of the centering ring, it was recognized that the epoxy would therefore be strong enough when the same force was applied over a larger area.

Finally, because the loading of the Payload Bulkhead during main parachute deployment is 3-dimensional, the stress could not be analyzed using hand calculations, so an FEA model was generated using ANSYS Structural. To model the loading scenario, the bulkhead was given a fixed support on its sides where it will be epoxied to the inner wall of the body tube, and a force of 1278 N, based on the free body diagram in Figure 28 was applied at the center support where the recovery eyebolt will be attached. This setup can be seen in Figure 29.

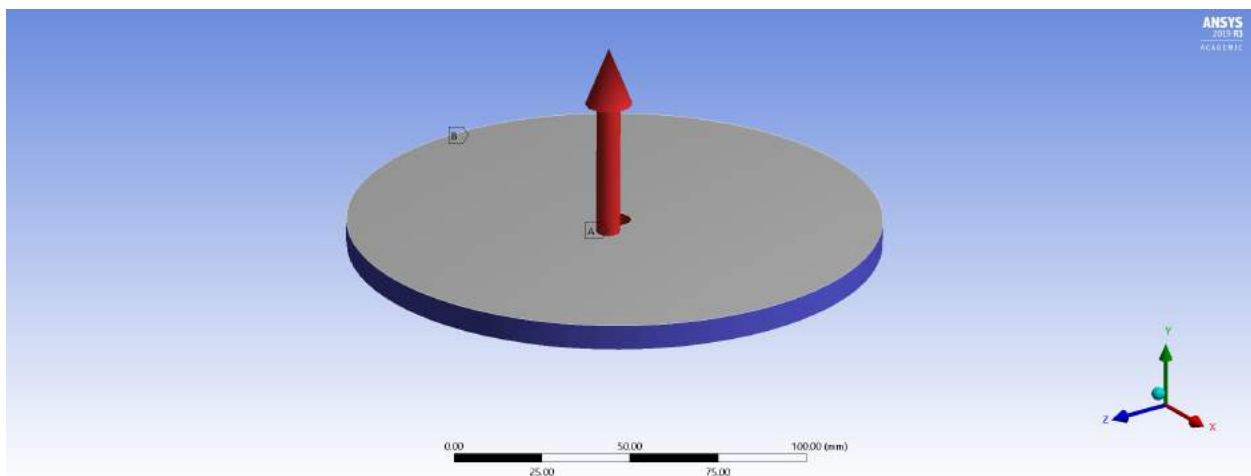


Figure 29: Setup for FEA of the Payload Bulkhead during main parachute deployment

The analysis was run at several mesh refinement levels to ensure that the results converged, ending with an element size of 2.0 mm. The analysis was set to solve for the von-Mises stress, and yielded a maximum stress of 73.24 MPa. The solution results can be seen in Figure 30.

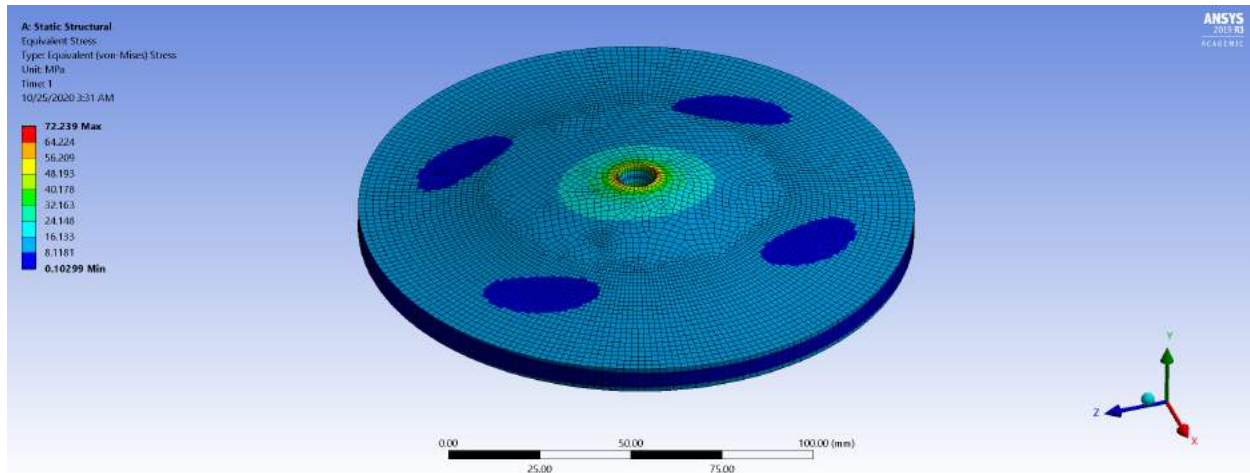


Figure 30: FEA von-Mises stress for the Payload Bulkhead during main parachute deployment

A similar procedure was used to analyze the structural integrity of each Fiberglass centering ring supporting the motor mount tube during peak thrust. The centering ring model was given a fixed support at its outer surface where it will be epoxied to the inner wall of the motor tube, and a force of 717 N was applied at the inner ring where it will be epoxied to the motor mount tube, from which the thrust is carried. This setup is shown in Figure 31.

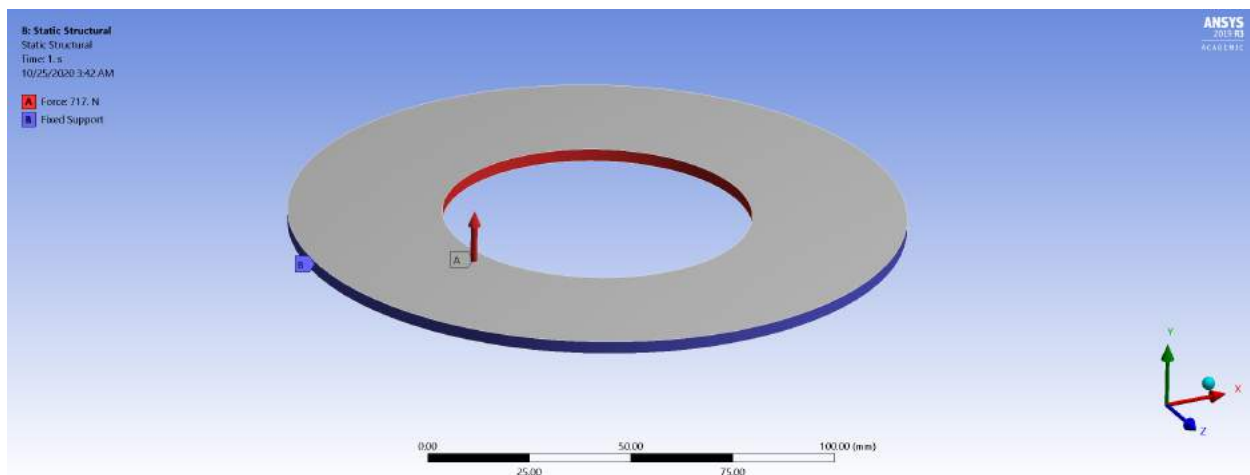


Figure 31: Setup for FEA of a Centering Ring at peak thrust

The analysis was run at several mesh refinement levels to ensure that the results converged, ending with an element size of 2.0 mm. The analysis was set to solve for the von-Mises stress, and yielded a maximum stress of 29.74 MPa. The solution results can be seen in Figure 32.

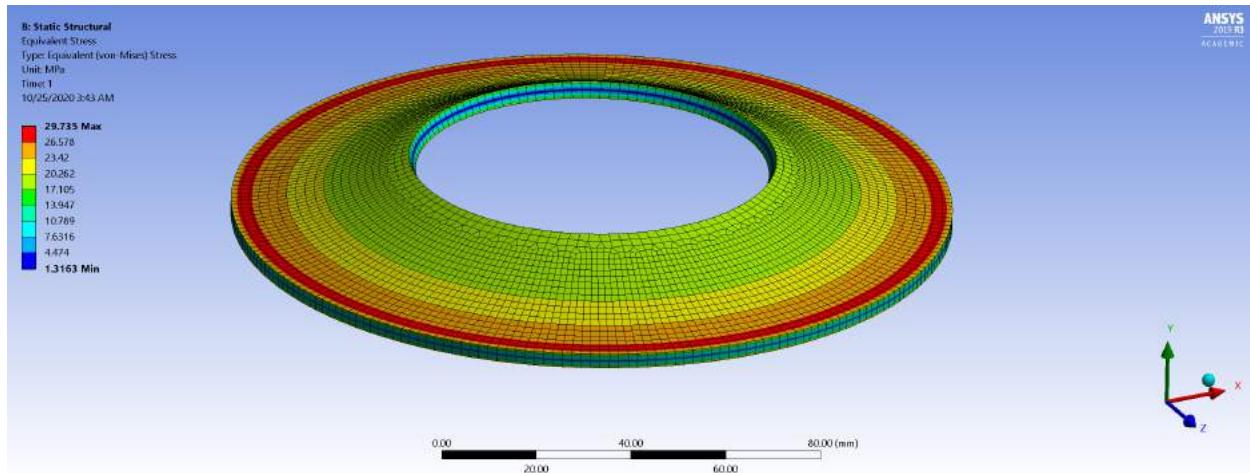


Figure 32: FEA von-Mises stress for a Centering Ring at peak thrust

3.6.4 Terminal Kinetic Energy

The vehicle will descend in 4 sections, three of which (the payload bay, recovery tube, and fin can) will descend under the main parachute, while the nosecone will descend separately under its own parachute. All of the sections will descend under the drogue parachute for the first portion of descent. The properties of these parachutes can be found in Table 45. Further discussion of the parachute selection can be found in Section 3.4.4.1.

Table 45: Selected Parachute Parameters

Parameter	Drogue	Main	Nose
C_d	1.5	0.97	1.5
Diameter (ft)	2	12	2
Descent Speed (ft/s)	89.45	18.04	20.60
Shape	elliptical	parabolic	elliptical
Brand	Fruity Chutes	Rocketman	Fruity Chutes

The descent velocities of the vehicle sections were calculated using a simple MATLAB script, and verified with OpenRocket simulation. The MATLAB code uses the weight of each vehicle section W , the drag coefficient and area of each parachute C_d and A , and density of air ρ to calculate terminal velocity, where the weight and drag forces balance. The resulting equation for terminal velocity is given in Equation 3.6.4.

$$V_{terminal} = \sqrt{\frac{2W}{C_d A \rho}} \quad (10)$$

The kinetic energies of each section are summarized in Figure 46.

Table 46: Terminal Kinetic Energy of Vehicle Sections

Section	MATLAB K.E. (ft-lb)	OpenRocket K.E. (ft-lb)
Fin Can	64.5	63.3
Recovery Tube	70.1	68.8
Payload Bay	21.5	21.1
Jettisoned Nose Cone	25.0	25.1

Each of these terminal kinetic energies is under 75 ft-lb, satisfying NASA Req 3.3 .

3.6.5 Descent Time

The descent velocities of each section were also calculated using the MATLAB code from Section 3.6.4. Using the apogee calculated in the code, which were verified using an OpenRocket simulation, the descent time for each section was calculated in three stages:

1. Descent under drogue
2. Descent under Main (Before nosecone deployment)
3. Descent under Main (After nosecone deployment)

For the first stage, the terminal velocity of the launch vehicle under drogue and the distance between apogee and drogue deployment are used to find descent time. For the second stage, the terminal velocity of the entire weight of the launch vehicle under the main parachute and the distance between main chute deployment and nosecone jettison are used to find descent time. For the third stage, two separate calculations were performed. The first was for the main launch vehicle without the weight of the PLS, CRAS-S, or the nosecone. The terminal velocity for the main launch vehicle under the main chute was calculated, and used along with the distance from nosecone deployment to the ground to find descent time. The second calculation was for the nosecone. The terminal velocity was calculated for the weight of the nosecone and CRAS-S under the nosecone parachute, and used along with the distance from nosecone deployment to the ground to find descent time. To find the total descent time, the individual descent times from stages 1, 2, and the respective times for stage 3 were added together. These values were verified by descent time calculations in OpenRocket. Descent time values are represented in Table 47.

Table 47: Descent Times of Vehicle Sections

Section	MATLAB Descent Time (s)	OpenRocket Descent Time (s)
Main Launch Vehicle	84.8	89.3
Jettisoned Nose Cone	78.2	89.1

Each of these descent times is under 90 s, satisfying NASA Req 3.11.

3.6.6 Drift Radius

The drift radius was calculated assuming the launch vehicle reached apogee directly above the launchpad. Two independent simulation tools were used to determine this measurement: an in-house MATLAB script and OpenRocket. Table 48 shows the drift calculations for the two simulations at varying wind speeds.

Table 48: Drift Radius of Vehicle Sections

Drift Radius Simulation Horizontal Wind Speed (mph)	MATLAB (ft)		OpenRocket (ft)	
	Main Body	Nose Cone	Main Body	Nose Cone
0	0	0	228.2	169.7
5	622.14	573.45	383.8	346.5
10	1244.27	1146.91	986	917
15	1866.40	1720.36	1582	1464.5
20	2488.54	2293.82	2201	2074

In the MATLAB simulation, this was modeled by multiplying the descent time for both the main vehicle and the jettisoned nose by the wind speed. The OpenRocket simulation was performed by assuming an initial rail cant of between 5 and 10 degrees, as will be accurate on launch day. Because of this assumption, the launch vehicle already had a horizontal velocity in addition to the wind velocity, which accounts for the difference in the drift radii as calculated by both the MATLAB and OpenRocket simulations. For both simulations, the vehicle maintained the 2500 ft drift radius as required by NASA Requirement 3.10

3.7 Subscale Vehicle

3.7.1 Sizing

The team is constructing a subscale vehicle in order to analyze how the full scale vehicle will fly and operate at a fraction of the cost and materials. The subscale vehicle is a 42.3%

scale model of the full scale vehicle. Each major part of the final design is built on the subscale level. These parts include the nose cone, boattail, payload bay, couplers, recovery tube, fin can, and the fins. Each of these components will be analyzed during the subscale launch to validate the design. A comparison of the dimensions of the full scale components with their sub-scale counterparts can be seen below in Table 49.

Table 49: Comparison of Full Scale and Subscale Dimensions

Part	Full Scale Material	Full Scale Dimensions	Subscale Material	Subscale Dimensions
Nose Cone	Fiberglass	L=28.5" d=6.17"	PLA (Polylactic Acid)	L=12.08" d=2.62"
Payload Bay	Kevlar and Fiberglass	L=30.5"	Phenolic	L=29.0"
Recovery Tube	Kevlar and Fiberglass	L=36"		
Coupler	Fiberglass	L=12" $d_{in}=5.9$ " $d_{out}=6$ "	Phenolic	L=5.09" $d_{in}=2.5$ " $d_{out}=2.54$ "
Fins	Fiberglass	$c_{root}=6.0$ " h=5.959"	Birch Plywood	$c_{root}=2.538$ " h=2.521"
Fin Can	Kevlar and Fiberglass	L=28"	Phenolic	L=10.21"
Boat Tail	Fiberglass	L=14.75" d=6.17"	Plastic	L=5.75" d=2.5"

While the overall dimensions of the subscale components are to scale with the dimensions of the full scale components, some parameters had to be approximated because certain vehicle components were not commercially available to the exact, ideal sizes. Certain parameters had priority over others for being kept exact. The airframe diameter, for one, was prioritized to be constant in order for accurate testing for drag. Similarly, finding a nose cone with the exact shape and dimensions was important so that the subscale vehicle could accurately model the full scale vehicle's aerodynamic performance. Since no nose cone of the desired size and shape was found, it will be 3D printed. For similar reasons, the elliptical fins will be laser cut in order to reach the exact desired dimensions. Other parameters were not as crucial in being kept exactly 42.3% the size of the full scale vehicle components. The boat tail length is shorter than ideal, but the length will not drastically affect the aerodynamic

capability of the vehicle. The full dimensioned drawing can be seen in Figure 33 below. Overall, the subscale vehicle will act as an accurate model to the performance capability of the full scale vehicle.

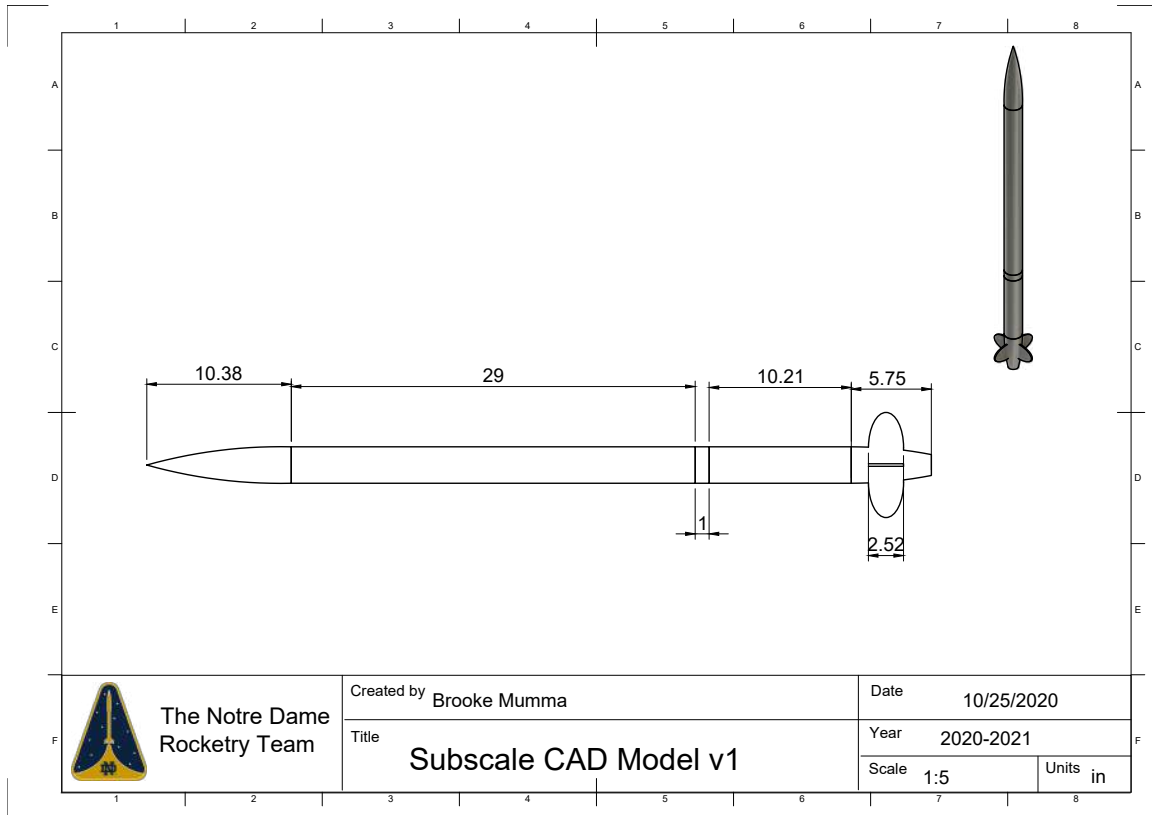


Figure 33: CAD drawing of the subscale vehicle

3.7.1.1 Motor Selection

The motor selected for our subscale rocket is the G80T-7. The team first looked into the prices of four motors that would fit in the subscale vehicle. The four motors and their specifications can be referenced in Table 50 below.

Table 50: Subscale Motor Specifications

Name	Cost (USD)	Weight (oz.)	Diameter (in.)	Length (in.)
G79-4W	27.89	4.4	1.13	-
G80T-13	35.3	4.561	1.13	5.04
G77R-4	33.16	4.339	1.13	4.88
G80T-7	26.99	4.5	1.13	-

Based on the results of previously discussed trade studies, the decision was made to focus on the G79-4W and the G80T-7 motor. In order to choose between these two motors, the apogees, velocities, accelerations, and time to reach apogee were compared. The values were found by running simulations with each motor in OpenRocket. These comparisons can be seen in Table 51 below.

Table 51: Subscale Motor Comparison

Name	Velocity (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Time to Apogee (s)
G79-4W	65.4	999	261	7.31
G80T-7	81.4	1014	293	8.18

Ultimately, the team chose the G80T-7 because the burnout time for this motor was closer to the time at which the vehicle reaches apogee. It is crucial that the parachute deployment occurs near apogee so that the velocity of the vehicle is small, to prevent excessive deceleration and loading.

3.7.2 Flight Simulations

Table 52, Table 53, and Table 54, below describe the velocity off the rail (ft/s), the apogee altitude (ft), the max velocity (ft/s), and max acceleration (ft/s²) of the sub-scale launch vehicle for varying wind speeds (0 to 20 mph in increments of 5 mph) using OpenRocket simulations. Table 52 has a launch angle of 5°, Table 53 has a launch angle of 7°, and Table 54 has a launch angle of 10°.

Table 52: OpenRocket Simulation Critical Values for Launch Angle of 5°

Average Wind Speed (mph)	Velocity off Rod (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s ²)
0	68.2	1011	256	293
5	68.2	1005	255	293
10	68.1	998	255	293
15	68.1	994	254	293
20	68.1	993*	254	293

Table 53: OpenRocket Simulation Critical Values for Launch Angle of 7°

Average Wind Speed (mph)	Velocity off Rod (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s ²)
0	68.2	1004	256	293
5	68.2	997	256	293
10	68.2	989	255	293
15	68.2	981	254	293
20	68.2	979*	253	293

Table 54: OpenRocket Simulation Critical Values for Launch Angle of 10°

Average Wind Speed (mph)	Velocity off Rod (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s ²)
0	68.3	989	256	294
5	68.3	977	256	294
10	68.2	970	255	294
15	68.2	962	254	294
20	68.2	960*	254	294

Values with an * began to tumble under thrust and may be unsafe to launch. Figures 34, 35, and 36 below show the altitude vs time for each flight simulation performed in OpenRocket.

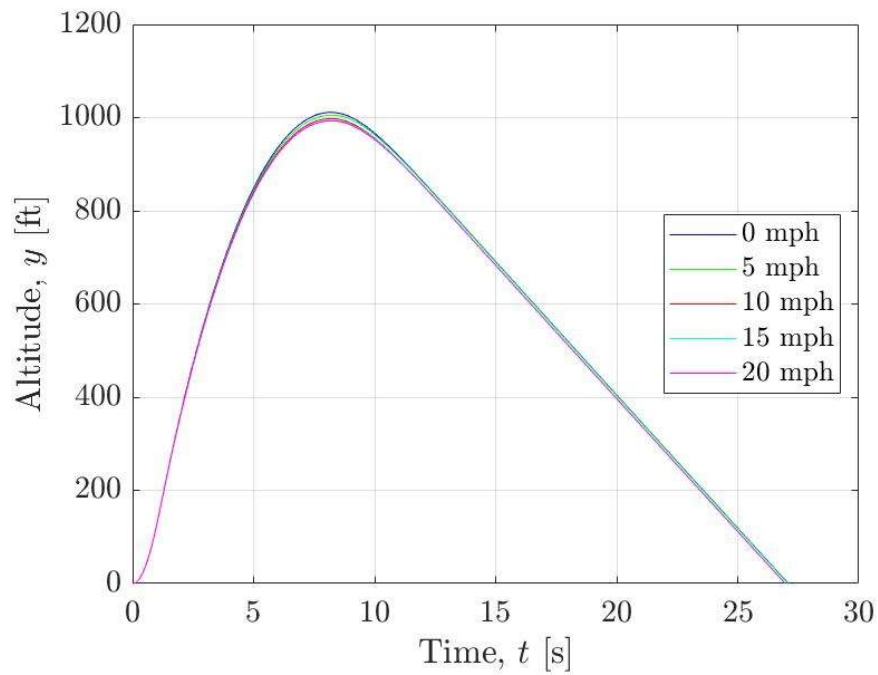


Figure 34: Plot of Altitude vs Time for launch angle of 5° for wind speeds 0, 5, 10, 15, and 20 mph.

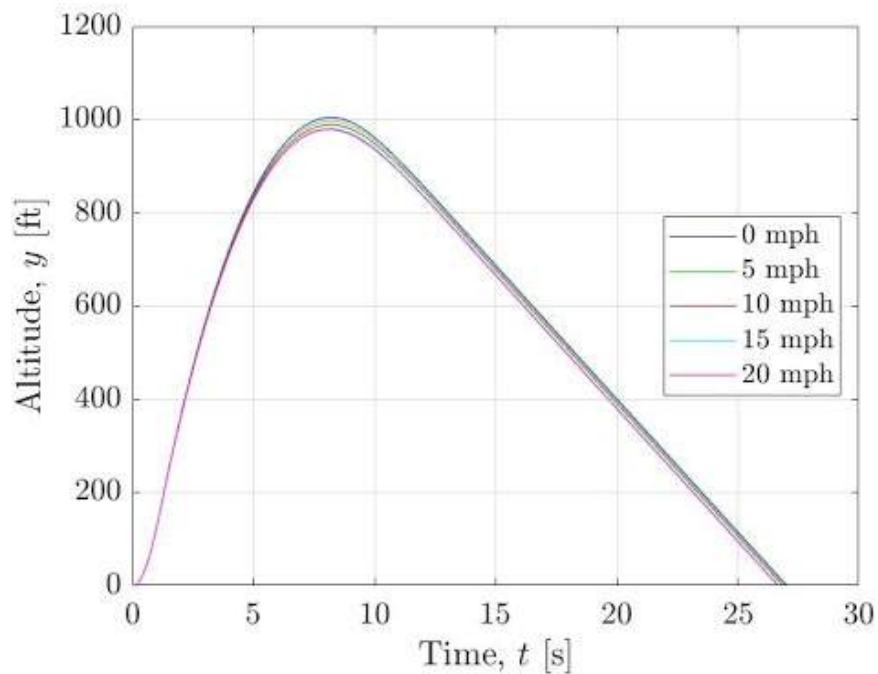


Figure 35: Plot of Altitude vs Time for launch angle of 7° for wind speeds 0, 5, 10, 15, and 20 mph.

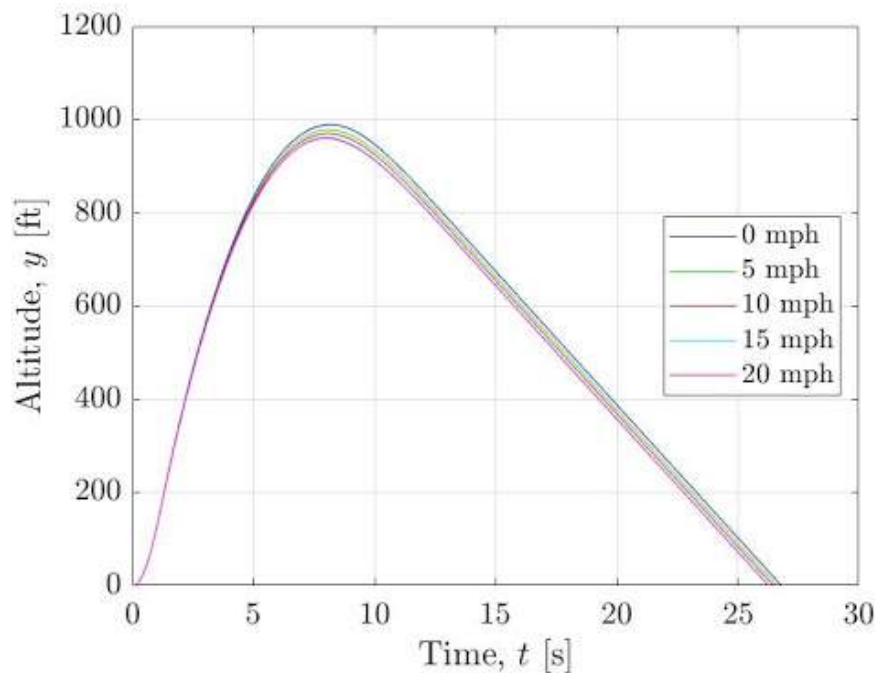


Figure 36: Plot of Altitude vs Time for launch angle of 10° for wind speeds 0, 5, 10, 15, and 20 mph.

3.7.3 Subscale Test Plan

All subscale data necessary to correctly predict and model full scale launch vehicle behavior will be collected in a series of three subscale launch scheduled for November 13th at the Three Oaks launch site in collaboration with Michiana Rocketry. Three launches are being performed: one with a 3D printed scale model of the ACS drag tabs at full, half, and no deployment in order to verify the effectiveness of ACS in lowering the apogee of the launch vehicle. The primary goals for this launch day include

- Safely and successfully launch and recover a 42.3% scale model of the launch vehicle
- Verify simulated apogee predictions
- Obtain a revised launch vehicle incompressible coefficient of drag C_d by comparing flight data to simulated data
- Predict ACS mechanism coefficient of drag C_d at different extensions
- Assess optimal location for various sensors, particularly the pressure probes (fore/aft of drag tabs)

A table of the various sensors and related subsystems is shown in Table 55

Table 55: Subscale Vehicle Sensors

System	Sensors	Purpose
ACS	Raspberry Pi Accelerometer IMU Barometer\Altimeter	computer acceleration orientation altitude
Recovery	Raven Stratalogger	altitude and parachute deployment

4 Technical Design: Planetary Landing System

The Planetary Landing System (PLS) is the Notre Dame Rocketry Team's experimental payload for the 2021 NASA Student Launch Competition. To succeed, this year's payload must be jettisoned from the launch vehicle, land safely, self level within five degrees of vertical, take a 360-degree picture of the area around the landing site, and wirelessly transmit the image to the team. The PLS layout as well as the design options currently under consideration are detailed in the following sections.

4.1 System Overview and Mission Success Criteria

In order to successfully design all aspects of the PLS, the design is broken down into three major sub-systems; Subsystem I consists of Retention, Deployment, and Descent, Subsystem II of Landing and Orientation Correction, and Subsystem III of Imaging and Data Transmission. The structure of the payload and the subsystems are found in Table 56 below.

Table 56: PLS Sub-System breakdown and mission

System		Mission
I	Retention	Securely retains payload in the launch vehicle from launch to jettison event (NASA Req. 2.18.2.1).
	Deployment	Reliably jettison payload from launch vehicle at an altitude between 500 and 1,000 ft above ground level (NASA Req. 4.3.1).
	Descent	Deploys after the payload jettisons from the launch vehicle and is responsible for slowing the payload's velocity to allow for a safe landing (NASA Req. 4.3.1).
II	Landing	Protects all internal components of the planetary landing system from impact and allows the orientation correction system to accomplish vertical orientation post landing (NASA Req. 4.3.2).
	Orientation Correction	Vertically orient imaging and data transmission system at or after landing within a tolerance of ± 5 degrees (NASA Req. 4.3.2 , NASA Req. 4.3.3). Houses an IMU to store payload orientation information at landing and after orientation correction.
III	Imaging	Responsible for taking a 360 degree image after the planetary lander system has vertically oriented. System is activated through a host computer (NASA Req. 4.3.4).
	Data Transmission	Responsible for wirelessly transmitting the captured image and GPS location to the host computer within a 2 km radius (NASA Req. 4.3.4).

Trade studies were conducted in order to evaluate design alternatives for each subsystem. The trade studies compared several options which all fulfill NASA and team derived requirements. Relevant requirements are detailed in each [System Level Design](#) section. For each study, various criteria were chosen and weighed according to their relative importance. Each strategy was then assigned a value based on its ability to fulfill each criteria. The strategy with the highest value was determined to be the optimal design for that subsystem, discussed in the [Leading Design Sections](#). Following finalization of the leading design, integration into the launch vehicle is considered in the [Vehicle Integration Section](#).

4.2 Primary Design Considerations

The main design driver of each subsection of PLS is reliability, with secondary design drivers of simplicity and ease of manufacturing. Designing with simplicity improves the reliability of the PLS by minimizing the number of components that can fail. The PLS must also be relatively easy to manufacture, in order to minimize the possibility of construction defects.

Additional team derived requirements informed each design under consideration. The system must weigh under 80 ounces (NDRT Req [PD.1](#)) and be a maximum of 21 inches (NDRT Req [PD.2](#)) in length and 6 inches in diameter (NDRT Req [VD.10](#)) to allow for integration into the launch vehicle. This weight requirement was set in order to provide a balance between design flexibility and vehicle stability, while also allowing the vehicle to reach the desired apogee. Likewise, to determine this desired deployment apogee point, the team kept in mind that the payload must jettison from the vehicle at an altitude between 500 ft and 1000 ft AGL, and land within the borders of the launch field (NASA Req [4.3.1](#)). As such, the team set the maximum terminal descent velocity of the PLS at less than 20 ft/s (NDRT Req. [PF.1](#)), so as to prevent drifting beyond a radius of 2500 ft from the launch pad (NDRT Req. [PF.2](#)). These and all team-derived specifications based on NASA requirements can be found in [Section 6.1](#).

4.3 System Level Design Alternatives

4.3.1 Retention

Retention of the PLS in the launch vehicle is a critical component of the overall lander design. The PLS must be fully retained in the axial and radial directions until deployment and all mechanisms must be remain functional and structurally sound (NASA Req [2.18.2.1](#)). Concurrently, the retention system must be able to sustain all expected flight forces without damage or unintentional deployment (NDRT Req [PF.1](#)). The team conducted a trade study to determine which of three design options was optimal. The chosen criteria for the study were security, weight, ease of manufacturing, integration, cost, and ease of release. Security of the PLS was deemed the most important criteria, as keeping the PLS stable during flight is paramount to mission success. Ease of release was the next highest rated criteria, as the retention system must not impede the deployment of the PLS. Integration was also weighted highly, as the retention system needs to easily be constructed as well as fit into the limited payload space in the vehicle. In order to successfully fulfill those requirements, three initial designs were developed and studied. A description of each design is enumerated in Table 57.

Table 57: Retention System Design Alternatives

Retention System	Description	Advantages	Disadvantages
Flanges and Pins	Utilizes the nose cone ejection to remove hairpin cotter pins attached to the nose cone	Provides good security Low weight Easy to manufacture	Difficulties during release due to the geometry of the pins and their position in relation to the nose cone
Solenoids	Maintains a set position after receiving an initial electrical current. At the appropriate moment, another current is applied in the opposite direction to release the solenoid.	Provides the best security Would allow for simple deployment once released	High weight Would require complex parts including an additional microcontroller
Shear Pins	Keeps the nose cone in place until it is ejected from the vehicle through its own mechanism, rendering the PLS free to slide out of the payload bay. Detailed more comprehensively in the deployment system section.	low weight and simple	not as secure as the other options

Table 58 shows the values of each design and the results of the trade study. Ultimately, shear pins were determined to provide the best balance of the requirements. Further design meetings conducted upon completion of this and other trade studies determined that all three retention options focused primarily on the retention of the nose cone and not that of payload as a full system. As such the team decided to use an additional retention system of dowel rods secured to the bottom bulkhead of the payload bay and extend the PLS legs to the upper bulkhead. This secondary retention system is designed to minimize radial and axial movement as well as assist with the PLS alignment (NDRT Req [PF.3](#)). Despite anticipated integration difficulty, the ease of manufacturing, additional security, low weight, and low cost make axial rods a favorable choice.

Table 58: Retention Trade Study

Retention		Flanges and pins		Solenoids		Shear Pins	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V
Security	25%	2	0.06	3	0.08	1	0.03
Weight	10%	2	0.02	1	0.01	3	0.03
Fabrication	10%	2	0.02	1	0.01	3	0.03
Integration	15%	2	0.04	1	0.02	3	0.06
Cost	5%	2	0.01	1	0.01	3	0.02
Ease of Release	20%	1	0.03	2	0.05	3	0.08
Simplicity	15%	2	0.03	1	0.02	3	0.05
Total WNV		0.21		0.20		0.29	

4.3.2 Deployment

The deployment of the PLS is critical to mission success. The PLS system must jettison from the launch vehicle during descent between 500 and 1000 ft AGL, and land separately from the launch vehicle (NASA Req 4.3.1). After separation, the nose cone bulkhead will pull out the PLS and its parachute with a shock cord. Once the PLS has successfully left the vehicle, the shock cord will be released, allowing the parachute to bring the PLS to the ground safely. In order to fulfill these specifications, the team developed three designs and performed a trade study to determine the best method of deployment. The designs were evaluated based on a set of criteria determined to be integral to deployment success. Reliability has the largest weight of all of the criteria, followed by reusability and complexity. The three designs considered are described in Table 59.

Table 59: Deployment System Design Alternatives

Deployment System	Description	Advantages	Disadvantages
Black Powder	A black powder charge engaged at 550 ft (NASA Req 4.3.1) would separate the nose cone from the main body of the vehicle. The PLS would be protected by the bulkhead that separates the nose cone from the payload bay.	Greatest reliability Simplest Team experience will inform implementation and integration.	Single use; will need to be replaced with each launch
Springs	Spring fixed to the main body of the vehicle and released using a clamp or catch.	optimal reusability	Unknown how gravitational forces will impact ejection Unknown how these components will impact recovery.
Clamp	A clamp system would attach the nose cone to the vehicle's main body. Upon its release, the nose cone would need to be ejected from the vehicle to successfully deploy the PLS.	optimal reusability	Unknown how gravitational forces will impact ejection Unknown how these components will impact

Based on the trade study, it was determined that the black powder system was the best deployment method. The various criteria, weights, and values of the deployment trade study can be seen in Table 60.

Table 60: Deployment Trade Study

Deployment		Black Powder		Pin Release		Spring	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V
Cost	5%	2	0.03	1	0.01	1	0.01
Weight	10%	2	0.03	1	0.03	1	0.05
Integration	5%	2	0.02	2	0.02	1	0.01
Fabrication	10%	3	0.05	2	0.03	1	0.02
Complexity	15%	3	0.06	2	0.04	2	0.04
Reusability	15%	2	0.04	3	0.06	3	0.06
Reliability	40%	3	0.02	1	0.08	1	0.08
Total WNV		0.49		0.27		0.27	

4.3.3 Recovery

The recovery method is a crucial part of the payload design to ensure that the entire lander system can descend without being damaged. The PLS recovery system must be able to land the payload in an upright orientation (NASA Req 4.3.2) and reliably slow the PLS to the intended safe landing speed of 20 ft/s (NDRT Req PF.1). Once landed, it should not tip over the payload or cover the cameras. This descent speed will also ensure the payload stay within the launch field (NASA Req 4.3.1) with a drift radius of less than 2500 ft (NDRT Req PF.2) To accomplish this task, the team considered 3 different design ideas and conducted a trade study to determine which method would be best suited for the payload and mission requirements. The designs under consideration are discussed in Table 61.

Table 61: Recovery System Design Alternatives

Recovery System	Description	Advantages	Disadvantages
Parachute	Light, strong, dome shaped fabric deploys above the payload and opens due to dynamic air pressure pushing outward	Safe and reliable design Easy to construct	Potential to tip the lander over if the wind catches it before it settles on the ground
Gyrocopter	Series of blades extending from the payload that passively rotate to create lift from falling through the air	More reliable static rest state Will not create any more drag or lift forces that could knock over the lander	Much more complicated design
Solid Parachute	Shaped like a parachute but with rigid attachments instead of relying on air to inflate the structure (similar to an umbrella)	Similar to the parachute in terms of reliability	Hardest to implement; would need to deploy the parachute after the payload jettisons from the launch vehicle

To select the design, each option was evaluated on a scale of 1-3, with 3 being the most desirable. The team determined that the most important criterion was reliability, given that it is necessary for the payload to return safely in order for there to be any chance of succeeding at its task. The criteria of next highest importance were weight and velocity at landing. These criteria are essential because the payload needs to be light enough for the rocket to launch, while also landing at a low enough velocity in order to prevent damage to the payload. After that, the team considered the static rest state to ensure that the lander will maintain an upright position and be able to take a picture. The next criteria that the team considered was integration, and how easy it is to embed the recovery system with the rest of the payload. Finally, the team looked at the cost and complexity of the designs. Table 62 shows the values given to each design and the results of the trade study, which determined the best option for PLS recovery to be the parachute.

Table 62: Recovery Trade Study

Recovery		Parachute		Gyrocopter		Rigid Parachute	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V
Cost	5%	3	0.02	3	0.02	1	0.01
Complexity	5%	3	0.03	1	0.01	1	0.01
Reliability	25%	3	0.09	2	0.06	3	0.09
Landing Velocity	20%	3	0.09	1	0.03	3	0.09
Integration	10%	3	0.05	1.5	0.03	1.5	0.03
Stability	15%	2	0.04	3	0.06	2	0.04
Weight	20%	2	0.06	3	0.09	2	0.06
Total WNV		.38		0.30		0.32	

4.3.4 Landing

The landing mechanism of the PLS is a critical component to ensure the success of the mission. The primary goal of the landing legs is to stabilize the PLS upon landing. Orientation of the cameras will be achieved through the passive correction as described in [Section 4.4.5](#), hence the landing legs only are required to keep the PLS in the upright position (NASA Req [4.3.2](#)). The landing legs will help retain the system within the launch vehicle, and withstand all launch and landing conditions. In order to determine what mechanism to use, three designs were evaluated in a trade study. The designs are described in [Table 63](#).

Table 63: Landing System Design Alternatives

Landing System	Description	Advantages	Disadvantages
Inflated Bag Legs	Uses a chemical reaction to inflate bags upon deployment	Occupies minimal volume within the rocket	Risk of bag tearing Difficulty in integration
Rod Legs	Legs that fold down with disks on the bottom to stabilize the landing	Simplicity ease of manufacturing High stability	May occupy significantly more space than alternatives in launch vehicle
Folded Cylinder	similar to the rod legs design, however instead of using rods for legs, the legs would be made of portions of cylinders	Low volume within launch vehicle Greater leg strength than inflated bags	Difficulty in integration

Eight criteria were employed to evaluate the designs. The landing stability was weighted highest, as a stable landing is the necessary step in the mission. The criteria of next highest importance is design complexity, as the design must be reliable and straightforward. System durability and manufacturability were both weighted highly because the landing legs must be able to withstand landing impact, and easily be manufactured by the team in an efficient fashion. The criteria and respective weights can be found in Table 64. Ultimately, the trade study determined that the folder cylinder provided the best balance of requirements and was the optimal design.

Table 64: Landing Trade Study

Landing		Inflated Bags		Rods		Cylinder	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V
Weight	15%	3	0.06	20	0.04	20	0.04
Cost	3%	60	0.01	30	0.01	20	0.00
Stability	18%	4	0.04	5	0.05	4	0.04
Volume	15%	800	0.06	200	0.02	600	0.05
Camera Height	7%	6	0.01	12	0.02	16	0.02
Complexity	17%	1	0.01	5	0.07	4	0.05
Fabrication	12%	3	0.02	5	0.04	4	0.03
Durability	13%	2	0.02	3	0.03	5	0.05
Total WNV		.24		0.26		0.28	

4.3.5 Orientation Correction

The orientation correction is an essential aspect of the design process of the payload, as the PLS must be capable of self-orienting to within 5 degrees of vertical autonomously (NASA Req 4.3.3.1). Various designs were considered and a trade study was conducted to discern the most effective orientation mechanism, as shown in Table 66. The initial angle immediately after landing will be recorded using an IMU and transmitted to the team, per NASA Req 4.3.3.2. This is discussed more fully in Section 4.3.7.

Three initial designs were developed and studied, each of which is discussed in Table 65.

Table 65: Orientation Correction System Design Alternatives

Orientation Correction System	Description	Advantages	Disadvantages
3-axis Gyroscope	Three gimbal system that allows rotation along all three axes	High reliability	More expensive than 2-axis gyroscope Large volume within launch vehicle
Retractable Legs	Legs with compressible springs inside	Increased room for camera High security	Higher complexity Increased weight & cost
2-axis Gyroscope	Two gimbal system that allows rotation along 2 axes	High reliability Simplicity	Less secure than retractable legs

The first design for orientation correction was a . The second design used that would help balance the entire payload. The last design uses a that has freedom on the x and y axes.

Seven criteria were selected as key characteristics to consider for the orientation correction system. The reliability of the system is paramount, because this system is essential to a successful mission, and therefore was weighted highest. Security was also weighted highly, as the payload vehicle must be able to withstand high forces to properly function after its landing. Furthermore, the system must also be able to fit within the bounds of the payload bay and simple enough to accurately design. Additionally, weight and time to orient were chosen as criteria as weight will affect the flight of the rocket and excessive time for orientation would reduce the system's efficiency. The cost of each design was also taken into consideration. Based on these criteria, each design was rated on a scale of 1-10.

Table 66: Orientation Trade Study

Orientation		3-Axis Gyro.		Retractable Legs		2-Axis Gyro.	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V
Reliability	0.3	8	0.1	4	0.05	7	0.09
Fits Components	0.15	7	0.04	9	0.04	8	0.04
Secure	0.25	6	0.06	8	0.07	7	0.06
Complexity	0.1	8	0.03	3	0.01	9	0.04
Cost	0.05	6	0.01	2	0.01	7	0.02
Orientation Time	0.05	7	0.02	7	0.01	8	0.02
Weight	0.1	8	0.03	3	0.01	9	0.04
Total WNV		.30		0.21		0.31	

Each design had merits and drawbacks. The 3-axis gyroscope and retractable legs, despite each having many positives, when evaluated using the trade study, have more negatives that outweigh their strengths. The 3-axis gyroscope had high scores in nearly every category, but its cost and security throughout flight weighed down the design. It is more complex than the two axis gyroscope. The retractable legs had high scores in security throughout flight, orientation time, and fitting components, but was ultimately dragged down by lower scores in reliability, cost, weight, and complexity. Ultimately, the choice came down to the 2 and 3-axis gyroscopes, which had very similar scores due to their similar designs, with the 2-axis gyroscope being chosen for its lower cost and simpler development.

4.3.6 Imaging

The PLS will contain an imaging subsystem that will allow the team to take a 360 degree panoramic photo of the landscape after landing and orientation correction, as per NASA Requirement 4.3.4. Several designs that could complete the task were developed, and a trade study, shown in Table 67, was conducted to select the optimal design. The designs considered for the imaging subsystem are: four cameras attached to a singular microcontroller, one camera rotating 360 degrees through the use of a motor, or one camera with a half-dome mirror to construct a custom 360 degree camera.

Several criteria were chosen in order to conduct this trade study. The team analyzed the weight, cost, electrical complexity, mechanical complexity, reliability, image quality, and size of the respective systems. These parameters were weighted in terms of importance, with reliability being the most critical. The electrical and mechanical complexity of the systems were also prioritized in order to choose the simplest design that can complete the necessary task. Other important, but not critical criteria include cost, image quality, and size. Each design was then given a score between 1 and 10 to indicate its desirability in each parameter, with 10 being the most desirable.

Table 67: Imaging Trade Study

Imaging		Four Cameras		Rotating Camera		Mirror	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V
Weight	10%	7	0.05	4	0.03	4	0.03
Cost	10%	5	0.02	8	0.04	9	0.04
Elec. Complexity	15%	4	0.03	7	0.06	8	0.06
Mech. Complexity	20%	8	0.09	4	0.04	6	0.07
Reliability	25%	9	0.11	7	0.09	4	0.05
Image Quality	10%	7	0.04	8	0.04	3	0.02
Size	10%	5	0.02	8	0.04	8	0.04
Total WNV		.37		0.33		0.30	

After this analysis, the strengths and weaknesses of each design became abundantly clear. The complexity of both designs with a single camera is significantly higher than the 4-camera design, and introduce more opportunity for system failure. Building and testing a custom 360 degree camera with a mirror would be very unreliable, and would significantly decrease the quality of our image. Similarly, attaching a single camera to a motor would increase the mechanical complexity of the system considerably, and would require the addition of a motor control circuit. The four camera design, on the other hand, is relatively simple and

allows the team to capture four images that will be stitched together using OpenCV on the microcontroller.

After all of the options were evaluated, the winning design is the four camera imaging subsystem. This design yields the highest chance of consistent success, and that it will fit best with the other subsystems of the PLS.

4.3.7 Wireless Transmission

The 360° image produced by the camera array must be wirelessly transmitted to the ground station (NASA Req 4.3.3). The distance between the PLS and the ground station can be up to 6000 ft (NDRT Req PF.5), so range is a significant concern. Additionally, at such long ranges even the most reliable connection may experience data loss. Thus, the ground station's ability to acknowledge and respond to the PLS's transmissions is also a requirement to ensure that the PLS is able to transmit the image consistently. Because of this determination, the PLS and the ground station must be capable of two-way communication using either a transceiver or a pair of receivers and transmitters. The team considered three designs to meet this need: a custom-designed transmitter/receiver pair, a commercially available video transceiver, and an open-source general-use transceiver. A trade study was conducted to determine the best design.

Table 68: Wireless Transmission Trade Study

Wireless Transmission		Custom		Commercial		Open Source	
Criteria	Weight	Value	W.N.V	Value	W.N.V	Value	W.N.V
Range	0.35	4	0.14	7	0.14	6	0.12
Reliability	0.25	4	0.06	8	0.11	6	0.08
Weight	0.15	4	0.04	5	0.05	5	0.05
Cost	0.15	3	0.03	4	0.04	8	0.08
Complexity	0.10	2	0.01	4	0.03	8	0.06
Total WNV		.29		0.38		0.40	

The PLS may land up to two kilometers away from the ground station, making range a necessity in any design chosen. Data transfer speed is not a significant factor due to the absence of time restrictions. In addition to the aforementioned range requirement, the transceiver's reliability, cost, weight, and complexity are relevant considerations. Reliability was deemed to be the. Each design's performance in each criterion is assigned a score of 1-10, with 10 being the most desirable performance. The three designs we considered were a

custom transmitter/receiver pair, a commercially available video transceiver, and an open-source general-use transceiver. Using the results of the trade study, the team has decided to select and implement an open-source transceiver such as the Dragino LoRa ST line. An open-source platform offers the most flexibility

4.4 Leading Design

4.4.1 Retention

The leading design for the retention system is a shear pin system as shown in Table 58. Shear pins are low weight, and low cost, with no required manufacturing. The associated ease of integration and release of this mechanism solidified them as the optimal design. While shear pins are not the most secure option out of the three designs studied, they have been extensively used by the team in the past for similar purposes and are capable of reliably retaining the nose cone and payload bay in place together with a retention bulkhead.

An additional retention system was decided upon in further design meetings to secure the payload and limit its rotation in the vehicle: a bottom bulkhead with two securing dowels that fit into the bottom of the lander. These rods are inserted into the base bulkhead of the PLS. To accommodate the rods, two holes will be manufactured in the PLS base bulkhead. The dowels will prevent the system from axial motion while the shear pins that hold the top retention bulkhead in place will prevent axial motion.

In addition to securing the PLS from rotating, retention must occur in the latitudinal and longitudinal direction. The PLS's cylindrical body concentrically fits within the payload bay. Additionally, the length of the PLS legs will be maximized to span the entire available length, restricting movement in the longitudinal direction. Additionally, the legs will transfer the force from the black powder charge into the bulkhead beneath them.

This leading design will minimize axial, radial, and vibrational movement. Further testing and study is needed to determine if friction between the rods and the PLS legs would limit its movement; in the event that the PLS is unable to slide out easily, mounted ball bearings will be utilized to reduce friction. Figure 37 shows an schematic of this retention system.

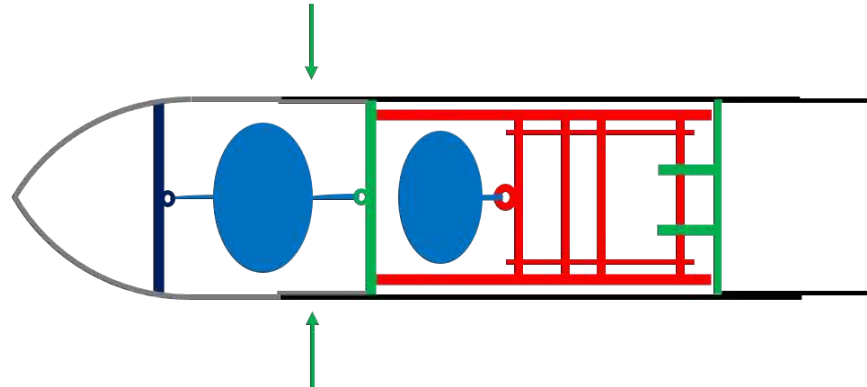


Figure 37: PLS Leading Retention Design Schematic

4.4.2 Deployment

The team has positive past experience with black powder as a deployment mechanism. The trade study, shown in Table 60, confirmed that pyrotechnic deployment is the most viable option based on the conditions and requirements of the mission. The black powder charge will be the main deployment mechanism for the nose cone. A movable bulkhead located between the nose cone and the payload bay will consequently pull the PLS out of the launch vehicle using a shock cord (as a secondary deployment mechanism). Additional effects and requirements introduced by the shock cord were taken into consideration when carrying out this trade study. Figure 38 shows a schematic of this design and how the nose cone ejection will aid in the PLS deployment.

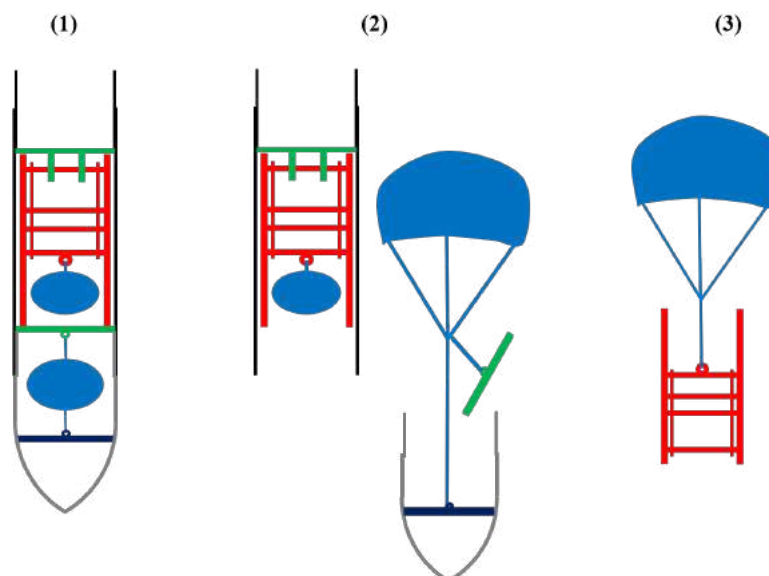


Figure 38: PLS Leading Deployment Design Schematic

The team's deployment trade study focused primarily on reliability, integration, and complexity. The black powder charge based pyrotechnic deployment was evaluated with respect to this criteria. In comparison to other deployment methods, black powder scored a higher reliability rating since it does not require moving parts, mechanical components, or complex logic statements for deployment, therefore minimizing the number of possible failure modes. To satisfy NASA Req PF.6, the black powder charge will be initiated electronically and a redundant system will also be incorporated in a subsystem known as CRAS-S. While the black powder charges must be loaded prior to each launch and cannot be reused, their use eliminates the need to calibrate mechanical components or tailor software for different conditions. In terms of manufacturing and complexity, the team has experience with black powder deployment systems which improves integration and implementation. Other factors that contribute to making the black powder charge the leading design are the cost and weight of the system, and the flexibility it provides when it comes to integration.

4.4.3 Recovery

The leading design for the recovery subsystem is a parachute system that will deploy upon ejection from the launch vehicle. The PLS will descend under the parachute and land at a maximum velocity of 20 ft/s (NDRT Req PF.4). In order to comply with this requirement, the parachute size will be calculated according to Equation 11:

$$D = \frac{1}{2}\rho C_d V^2 A \quad (11)$$

where ρ is the density of air, C_d is the drag coefficient of the parachute given by the manufacturer, V is the airspeed of the PLS, and A is the area of the parachute. The maximum airspeed will be calculated by setting weight equal to drag. Although a minimum descent velocity is desired, the PLS descent time should also be considered. In order to avoid drifting outside of the 2500 ft drift radius, in accordance with NDRT Req PF.2, the descent velocity should be set close to, but reasonably below the limit to account for uncertainty. The parameters of the selected parachute are listed in Table 69

Table 69: Selected Parachute Parameters

Parameter	Value
Brand	Fruity Chutes
Size	48 in
Shape	Elliptical
C_d	1.5
Descent Velocity	11.2 ft/s
Descent time	49 sec
Max Drift	1,400 ft

The parachute will be attached to the PLS by a shock cord, a quick-link, and an eye bolt, which will be fastened onto the top bulkhead of the payload body. The eye bolt will be steel and approximately 3/16 in. in diameter. The shock cord will be 0.125 in. kevlar. This system will allow the PLS to land safely and permit all other subsystems to accomplish their missions.

4.4.4 Landing

The primary landing legs of the selected design consists of 4 fraction-cylinder legs. This design choice was made to maximize the volumetric efficiency of the landing legs within the payload body tube. The radius of these legs will be 2.75 inches to fit snugly inside of the payload bay. Cutouts will be machined into the primary legs to reduce the weight of the legs and to allow for integration to the body. FEA will be conducted later in the design process to inform the number and size of the cutouts that is allowable to still have a sufficient safety factor in the design. Figure 39 shows the PLS primary landing legs in the stowed position within the payload bay.



Figure 39: PLS Leading Landing Design Legs in Stowed Position

The primary landing legs will be manufactured from a fiberglass airframe body tube. This design choice allows the team to utilize current vendors that already manufacture the launch vehicle airframe. Using this material for the landing legs gives the system a high strength to weight ratio compared to using traditional or 3D printed plastics.

The legs will extend past the main body of the PLS and will be flush with the bulkhead between the nose cone and the payload bay. This allows the legs to span the entire available body tube, giving them a potential maximum length of 22 inches. This increased length will serve to significantly improve the stability of the system; to determine the stability of the system basic 2D calculations were performed below as seen in Figure 40 and Equations 12-15.

$$F_w = W \cos(\theta_1) = F_p H \quad (12)$$

$$W = L \cos(\theta_2) + R_s \quad (13)$$

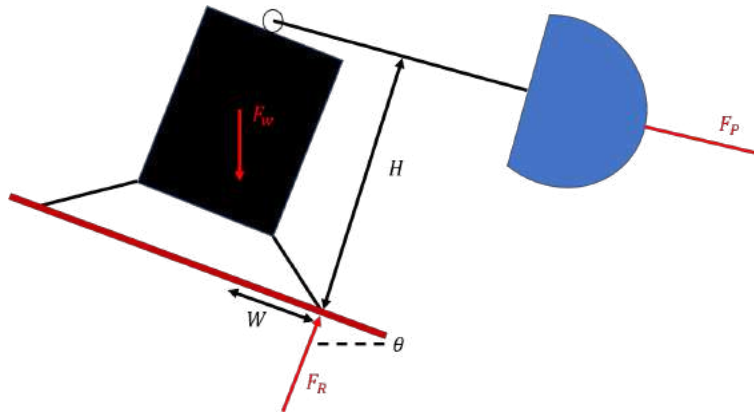


Figure 40: PLS Stability Schematic

$$H = H_s + L \sin(\theta_2) \quad (14)$$

$$F_p = \frac{1}{2} C_D A \rho V^2 \quad (15)$$

In this analysis the moment was taken about one side of the landing legs right before the tipping point (i.e. the normal force on the other legs is zero). The two major forces on the PLS will be the drag force of the parachute and the weight of the system. The parachute force is destabilizing, and the weight of the PLS is the restoring force. For this preliminary analysis, values of the drogue chute used for the launch vehicle last year were used under wind conditions of 15 mph. From this analysis it was determined that with 17.875 inch legs the system can handle an incline of 55 degrees, which is more than expected in the launch field. This analysis is also conservative, as the parachute will not be fully opened in the perpendicular direction to the PLS.

To control these primary landing legs, each leg will be hinged at the bottom of the PLS. The control of the opening of the legs will be directed by torsion springs on each leg. A passive system allows the system to have a significantly lower weight than if the legs were controlled with DC or stepper motors. The payload bay will provide the force to keep the primary landing legs in the stowed position during flight. Upon deployment of the PLS during flight, the primary landing legs will open and remain open for the duration of the descent. The passive opening of the landing legs simplifies the system without sacrificing performance.

In order to prevent the legs from closing upon the PLS landing, a locking system is required. To accomplish this, a folding support arm will be attached to the primary landing legs and the main body of the PLS. The support arms will consist of two separate linkages on each leg. One link will be attached through a hinge on the PLS main body and the other will be attached to the leg through another hinge. The two support arms will connect to

one another through another hinge. This design allows the support rod to fold and stow the primary landing legs in the payload bay. Figure 41 shows the support rod design in the open and stowed position.

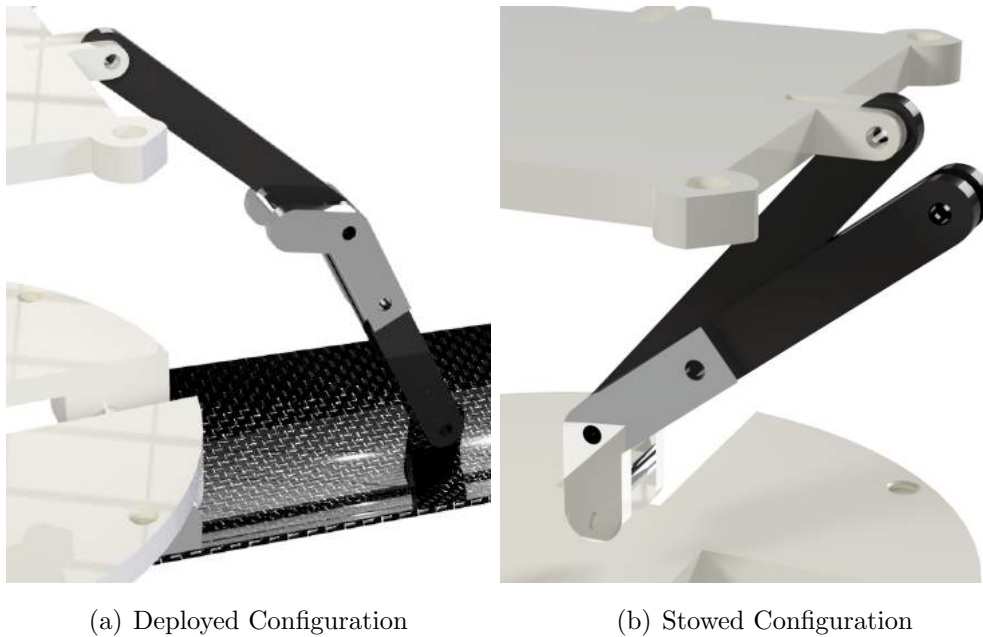


Figure 41: PLS Support Arms

To secure the support arms in place after deployment a restriction bracket will be utilized. This bracket will be located at the hinge connection between the two support rods. Upon the opening of the landing legs, the support arms will swing past a straight configuration prompted by a torsion spring. Once the system lands and force is placed upon the end of the landing legs, the arm assembly will lock in the deployed configuration. The arms will not fold again because they have swung past their neutral folding angle. Furthermore, they will also not swing due to the restriction bracket, also seen in Figure 41.

4.4.5 Orientation Correction

The results from the trade study in Table 66 determined the optimal design for orientation correction is a 2-axis gyroscope. This design is relatively simple and easy to construct, in comparison to the other designs considered. It is also reliable, since it does not have a lot of complex mechanisms, and will orient properly using only the effects of gravity. Barring any serious landing issues, the 2-axis gyroscope will always be able to orient the camera with 5 degrees of the vertical (NASA Req 4.3.3). Additionally, the 2-axis gyroscope can be constructed out of HDPE which is both lightweight and durable. The design's light weight

structure, simplicity, and passive mechanism are some of the strengths which resulted in the 2-axis gyroscope being the leading design. Shown in Figure 42 below is the leading gyroscope design which consists of two-concentric rings supported by pin rotation joints.



Figure 42: PLS Leading Orientation Design: 2-axis Gyroscope

In order to prevent damage to the gyroscope and camera setup due to shaking and vibrations during flight, the gyroscope will be rigidly secured within the launch vehicle. This will be accomplished using a servo controlled restraining bracket as shown in Figure 43 below. When the payload reaches the ground, the bracket will be released, allowing the gyroscope to rotate freely.



Figure 43: PLS Gyroscope Retention

To ensure the design is reliable, the weight forces acting to correct the orientation of the gyroscope after landing have to be large enough to overcome the frictional forces in the joints. The center of mass of the rings and electronics are assumed to be at the center of the gyroscope, along the axis of rotation; thus the team assumed there to be no moment due to their weight. Instead, the team plans on using a ballast to create a moment that will steady the gyroscope. The moment due to the frictional force, M_f , in each pin can be calculated according to Eq. 16 below,

$$M_f = \mu(m + m_b)gr \quad (16)$$

where μ is the coefficient of static friction in the joints, m is the combined weight of the gyroscope rings, base plate, pin joints, and electronics, m_b is the weight of the ballast, g is the universal gravitational constant, and r is the radius of the pin joint ($r = 1/16$ inches). The mass of the electronics on the center plate is 3 oz. HDPE, which is the leading candidate for gyrosopic ring construction has a μ value ranging between .1 and .250. The moment created by the ballast, M_b , is given as Eq. 17

$$M_b = m_b g \sin(\theta) d \quad (17)$$

where d is the distance from the center of the ring to the center of mass of the ballast, and θ is the angle between the horizontal plane and the plane of the gyroscopic ring. $M_b > M_f$ must be true to stabilize the gyroscope along each axis.

To ensure the reliability of the gyroscope, this inequality must always hold true while the gyroscope is unlevel. Thus, the calculations will be performed using the worst case scenario, or $\mu = .25$, and an assumed max ground unleveling of 10 degrees. The ballast will be located 2 inches below the center plate ($d = 2$ in). By combining the previous equations in this section, the minimum weight of the ballast, to ensure stability, is given as Eq. 18.

$$m_b = \frac{\mu m r}{\sin(\theta)d - \mu r} \quad (18)$$

Based on these calculations, the ballast needs to weigh at least .26 oz. Increasing the weight of the ballast past the stable point will allow the gyroscope to settle faster. Therefore, the team decided to use a ballast with a weight of 2 oz to ensure the stability of the gyroscope, and guarantee that the payload will meet NASA Req. 4.3.3 .

The bottom of the 2-D gyroscope center platform will house a inertial measurements unit sensor (IMU). The IMU will record the PLS's body orientation after landing and store the data in the selected microcontroller. This information will allow the team to report the vertical orientation of the system and verify that it is under $\pm 5^\circ$ from vertical.

4.4.6 Imaging

As determined via trade study (Table 67), an imaging subsystem with four individual cameras will be utilized in order to comply with NASA Req 4.3.4 . to give the highest chance of success. The four camera design involves having all of the cameras attached to a single microcontroller, hence requiring additional hardware.

The microcontroller selected for use in the PLS is a Raspberry Pi Zero, which has a singular slot for a CSI camera input. Therefore it is necessary to multiplex this singular port across four cameras. This will be done with an ArduCam multi-camera adapter module. This module takes one input and splits it into four CSI inputs, which is ideal for this system design. Furthermore, this device can be daisy-chained to incorporate up to 16 cameras on a single Raspberry Pi. This could be useful if the team decides to incorporate a level of redundancy in the system.

The camera itself will use the base Raspberry Pi camera board and connector, but the image sensor and lens itself will need to be switched out for an Arducam ultrawide lens camera. The lens will need to have a minimum field of view of 90 degrees, ideally with some

room of overlap to assist the image stitching algorithm. Arducam has several lenses that fit this profile, but more research will need to be done to determine which fits best.

By adding these two devices to the Raspberry Pi, the team will have the necessary tools to develop a 360 degree panoramic picture. Further research will need to be done to determine if redundancy is necessary, or if this system will be reliable enough to only utilize four cameras.

The entirety of the imaging subsystem will be mounted to the center plate of the 2-axis gyroscope. The tentative volume and location of these is shown in Figure 44 below.

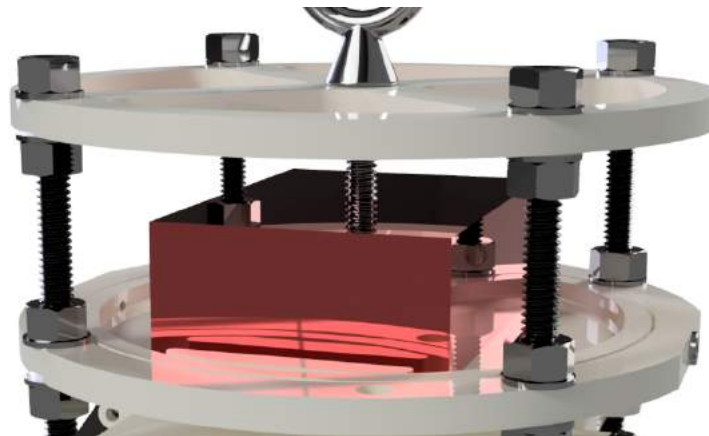


Figure 44: PLS Leading Imaging Design Volume

4.4.7 Wireless Transmission

The successful completion of the payload experiment is contingent upon the transmission of the captured 360-degree image to the team. This image must be transmitted from onboard the vehicle (NASA Req. 4.3.4.2) to the team's receiver, which will be located either within the prep or viewing area (NASA Req. 4.3.4.1). To successfully transmit the image, the team decided the chosen hardware must be able to transmit within a range of 6000 ft (NDRT Req PF.5). Furthermore, the transmitter must be able to send a GPS location and record and store orientation data from an IMU (NDRT Req PF.7).

Ultimately, the results of the trade study shown in Section 4.3.7 show that the commercial transceiver pair is best suited for the team's needs. Despite its slightly higher cost, this transceiver pair bests its custom-made counterpart in weight, reliability, and ease of use.

Choosing a commercially available transceiver pair would save the team the considerable amount of effort needed to design, build, and test a custom one. In particular, these are already optimized to function at a large range and often operate well below 250mW of RF power (NASA Req. 4.3.4.3). Furthermore, even though the custom transceiver would be designed specifically to interface with the rest of the electronics in the PLS, interfacing

between the commercial transceiver and the Pi does not imply a significant difficulty to outweigh the other aforementioned benefits of using such a component.

This system will be located and secured in the same center gyroscope panel with the imaging system shown in Figure 44.

4.5 Preliminary Mass Statement

After having evaluated all the options for each subsystem for the PLS and determining the leading design for each, it was necessary to evaluate the preliminary mass per component. Depending on the maturity and type of component, a mass growth allowance was also calculated. While the individual component weights are not a concern, the grand total weight of the PLS should not exceed that of 80 oz (NDRT Req [PD.1](#)). Table 70 shows a breakdown of all the contemplated components so far, a mass allowable, and a total predicted weight per component.

Table 70: PLS Preliminary Mass Statement with Mass Margins

Component	Basic Estimate (oz)	MGA %	Predicted Mass (oz)
Eyebolt	1.63	10	1.793
Top Aluminum Bulkhead	6.8	10	7.48
Gyroscope HDPE Platform	2	10	2.2
Gyroscope Others	0.4	10	0.44
Gyroscope Securing Mech.	2.04	15	2.346
Gyroscope Ballast	2	15	2.3
Base Nylon Bulkhead	0.3	10	0.33
Threaded Rods (4)	0.148	15	0.17
Hex Nuts and Spacers	0.19	18	0.224
Main Leg (4)	23.1	10	25.41
Support arms (8)	13.2	15	15.18
Parachute	1.6	10	1.76
Quicklink (small)	0.3	10	0.33
Raspberry Pi 0	0.3	14	0.342
BNO055 (IMU)	0.1	18	0.118
Adafruit GPS	0.3	18	0.354
LoRA Radio Bonnet	0.4	14	0.456
Antenna	0.18	23	0.22
LiPo Battery	1.2	10	1.32
Boost Converter	0.14	14	0.1596
MultiCam Adapter	0.63	14	0.718
Raspberry Pi Cam (4)	0.48	14	0.547
Total	57.44		64.20

4.6 Vehicle Integration

The PLS will sit within the payload bay of the launch vehicle, between the main parachute bulkhead and the CRAS-S bulkhead. The system will slide into the bay with its legs in the folded configuration. The bottom of the payload bay will have two dowels attached perpendicular to the main parachute bulkhead, which will slot into the lower bulkhead of the PLS body, restricting the system's roll axis while in the launch vehicle. After the system is secured in the payload bay, the CRAS-S bulkhead will be placed on top of the ends of the PLS legs, restricting the payload system on its longitudinal axis. The PLS system can be

seen fully integrated into the payload bay in Figure 45.



Figure 45: PLS Integrated into Payload Bay

5 Safety

5.1 Risk Assessment Method

All hazards will be assessed on the same scales of probability and severity to apply consistent, effective mitigations. Hazards considered include personnel hazards, failure modes and effects analysis (FMEA), and environmental hazards. Every hazard will be identified by a member of the Safety team and documented with appropriate causes, outcomes, mitigations and verifications. All hazards will be assigned a pre-assessment numerical value reflecting the combined probability and severity of the hazard before mitigation. Similarly, All hazards will be assigned a post-assessment value reflecting the combined probability and severity of the hazard after mitigation implementation. Mitigating hazards with larger pre-assessment values will be prioritized over hazards with

smaller values, although the team is confident all hazards will be successfully mitigated. Table 71 displays the values and occurrence definitions for hazard probability. Additionally, Table 71 displays the values and definitions for hazard severity in multiple contexts, specifically personnel, vehicle, and environmental hazards.

Table 71: Probability Value Criteria

Definition	Value	Probability of Occurrence
Improbable	1	Less than 1%
Rare	2	1 to 10%
Sporadic	3	10 to 25%
Likely	4	25 to 50%
Frequent	5	More than 50%

Table 72: Severity Value Criteria

Definition	Value	Personnel Injury	Vehicle and Payload Damage	Environmental Effects
Negligible	1	Minor	Insignificant	Insignificant
Minimal	2	Moderate	Slight	Completely reversible
Dangerous	3	Serious	Severe	Somewhat reversible
Catastrophic	4	Critical	Complete Loss	Irreversible

An overall assessment can be made by multiplying the values of probability and severity. Table 73 displays all potential combinations of probability and severity and their respective risks, as well as assigning color values to each combination. The key and definition for each color assignment can be seen in Table 74.

Table 73: Overall Risk Assessment

Probability	Severity			
	Negligible (1)	Minimal (2)	Dangerous (3)	Catastrophic (4)
Improbable (1)	1	2	3	4
Rare (2)	2	4	6	8
Sporadic (3)	3	6	9	12
Likely (4)	4	8	12	16
Frequent (5)	5	10	15	20

Table 74: Risk Assessment Color Code

Color	Description	Risk Value Range
Green	Low or No Risk	Less than 5
Yellow	Moderate Risk	Between 5 and 9
Red	High Risk	10 or greater

When risks are identified and prioritized, mitigations will be identified to decrease the potential risks of each hazard. To ensure these mitigations are implemented and adhered to, verifications will also be applied to each mitigation. Verifications may take the form of actions taken by specific individuals or resources provided to all team members. In this way, all mitigations will be properly carried out by informed, trained, responsible individuals, thus ensuring effective risk reduction.

All risks identified are labeled with a respective code. This allows members of the Notre Dame Rocketry Team to quickly locate and utilize safety information. The alpha-numeric format for all labels is AAA.N, where A can be any amount of letters up to 3 letters, and N is a number. For example, the fifth risk in the Vehicles Structures FMEA Table is labeled as VS.5. Table 75 outlines the naming conventions for each category.

Table 75: Risk Label Naming Convention

Safety Table	Label
Construction Personnel Hazards	C
Launch Operations Personnel Hazards	L
Vehicle Structures FMEA	VS
Vehicle Flight Mechanics FMEA	VFM
Recovery FMEA	R
Apogee Control System FMEA	ACS
Planetary Landing System FMEA	PV
Plantary Landing System Deployment and Integration FMEA	PI
Launch Equipment FMEA	LE
Environmental to Vehicle	EV
Vehicle to Environment	VE
Project Risks	PR

5.2 Overall Risk Reduction

By implementing effective mitigations and verifications, the Notre Dame Rocketry Team will decrease the overall value of each potential risk. Table ?? displays the risk assignments of each potential hazards. Table ?? displays the risk value assigned after mitigations are implemented.

To quantify the reduction resulting from effective mitigations, the team has tracked the change in distribution of risk before and after proposed mitigations. In total, 122 risks have been identified across all areas. Before mitigations, 7 risks were identified as low risk, 74 as medium risk, and 41 is high risk. Overall this means, 5.74% of risks were low risk,

60.66% were medium risk, and 33.61% were high risk. After mitigation, the expected risk values shift considerably. The Notre Dame Rocketry Team expects 118 low risks, 4 medium risks, and 0 high risks, or 96.72% low risk and 3.28% medium risks. This significant shift in risk level across all areas exemplifies the aggressive, yet realistic approach to applying mitigations and verifications. Table 76 and Table 77 display the risk value distribution pre- and post-mitigation, respectively.

Table 76: Overall Risk Assessment Distribution Pre-Mitigations

Probability	Severity			
	Negligible (1)	Minimal (2)	Dangerous (3)	Catastrophic (4)
Improbable (1)	0.00%	0.00%	0.00%	1.64%
Rare (2)	0.00%	1.64%	8.20%	9.84%
Sporadic (3)	1.64%	17.21%	22.13%	27.05%
Likely (4)	0.82%	3.28%	4.10%	1.64%
Frequent (5)	0.00%	0.82%	0.00%	0.00%

Table 77: Overall Risk Assessment Distribution Post-Mitigations

Probability	Severity			
	Negligible (1)	Minimal (2)	Dangerous (3)	Catastrophic (4)
Improbable (1)	6.56%	20.49%	16.39%	29.51%
Rare (2)	10.66%	12.30%	2.46%	0.00%
Sporadic (3)	0.82%	0.00%	0.00%	0.00%
Likely (4)	0.00%	0.00%	0.00%	0.00%
Frequent (5)	0.82%	0.00%	0.00%	0.00%

5.3 Personnel Hazard Analysis

5.3.1 Construction

Table 78: Personnel Hazards Analysis: Construction

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
C.1	Skin contact with strong adhesive materials (epoxy, etc.)	Lack of proper chemical-resistant PPE	<ol style="list-style-type: none"> Severe allergic reaction Severe skin irritation Permanent skin damage 	3	3	9	<ol style="list-style-type: none"> Team members working with adhesives will be required to wear chemical-resistant gloves and complete applicable workshop safety training A Standard Operating Procedure will be written outlining the correct procedure for epoxying 	<ol style="list-style-type: none"> All team members participating in construction will complete standard training The NDRT Safety Data Sheet Document is readily available in the workshop at all times The NDRT Standard Operating Procedures will be readily available in the workshop at all times 	2	2	4
C.2	Contact with the rotating component of a tool or machine	Improper use of a portable drill, drill press, dremel, or other rotating tools	<ol style="list-style-type: none"> Severe injury to, or loss of, extremities Severe skin abrasions or cuts 	3	4	12	<ol style="list-style-type: none"> Team members working with rotating tools or machines will be required to complete applicable workshop safety training A Standard Operating Procedure will be written outlining the correct procedure for operating workshop tools 	<ol style="list-style-type: none"> All team members participating in construction will complete standard training The NDRT Standard Operating Procedures will be readily available in the workshop at all times 	1	4	4

C.3	Materials become unsecured during construction	Parts are loose due to improper use of clamps, vice grips, or other motion-restriction tools	1. Moderate injury, including cuts and abrasions 2. Part becomes a projectile in the workshop, endangering nearby team members	3	3	9	1. Team members needing to secure materials will need to complete applicable workshop safety training 2. A Standard Operating Procedure will be written outlining the correct procedure for properly securing materials	1. All team members participating in construction will complete standard training 2. The NDRT Standard Operating Procedures will be readily available in the workshop at all times	1	3	3
C.4	Contact with the cutting blade of any type of tool or machine	Improper use of a band saw, scroll saw, hand saw, exacto knife, or any other type of cutting tool	1. Severe damage to, or loss of, extremities 2. Cuts or abrasions	3	4	12	1. Team members working with tools or machines with sharp cutting blades will be required to complete applicable workshop safety training 2. A Standard Operating Procedure will be written outlining the correct procedure for operating workshop tools	1. All team members participating in construction will complete standard training 2. The NDRT Standard Operating Procedures will be readily available in the workshop at all times	1	4	4
C.5	Contact with the abrasive surface of any type of tool or machine	Improper use of a belt sander, circular sander, portable sander, sandpaper, or other tool or machine with abrasive surfaces	1. Injury including cuts and abrasions 2. Burns on skin	3	4	12	1. Team members working with tools or machines with abrasive surfaces will be required to complete applicable workshop safety training 2. A Standard Operating Procedure will be written outlining the correct procedure for operating workshop tools	1. All team members participating in construction will complete training University standards 2. The NDRT Standard Operating Procedures will be readily available in the workshop at all times	1	4	4

C.6	Inhalation of airborne particulates resulting from part manufacturing	Failure to use a respirator when engaging in construction involving harmful airborne particulates, such as carbon fiber and fiberglass	Short and long term respiratory health issues	4	4	16	<ol style="list-style-type: none"> 1. Team members working with any airborne particulates will be required to wear a proper respirator and complete applicable workshop safety training 2. Team members will be provided the NDRT Safety Handbook containing proper usage guidelines for all PPE available in the workshop 	<ol style="list-style-type: none"> 1. All team members participating in construction will complete standard training 2. The NDRT Standard Operating Procedures will be readily available in the workshop at all times 3. The NDRT Safety Handbook will be readily available in the workshop at all times 	2	3	6
C.7	Inhalation of toxic fumes from glue, epoxy, or spray paint	Failure to use a respirator when doing work involving harmful airborne particulates, such as carbon fiber and fiberglass	Short and long term respiratory health issues	4	4	16	<ol style="list-style-type: none"> 1. Team members working with any airborne particulates will be required to wear a proper respirator and complete applicable workshop safety training 2. Team members will be provided the NDRT Safety Handbook containing proper usage guidelines for all PPE available in the workshop 	<ol style="list-style-type: none"> 1. All team members participating in construction will complete training University standards 2. The NDRT Standard Operating Procedures will be readily available in the workshop at all times 3. The NDRT Safety Handbook will be readily available in the workshop at all times 	2	3	6
C.8	Baggy clothes or hair getting caught in machinery	Failure to wear proper clothing (short sleeved shirt, long pants, closed toed shoes) while doing construction	Potential injury or death	3	4	12	<ol style="list-style-type: none"> 1. Team members will be required to wear proper clothing and complete applicable workshop safety training 2. Team members will be provided the NDRT Safety Handbook containing proper clothing guidelines in the workshop 	<ol style="list-style-type: none"> 1. All team members participating in construction will complete training University standards 2. The NDRT Standard Operating Procedures will be readily available in the workshop at all times 3. The NDRT Safety Handbook will be readily available in the workshop at all times 	1	4	4

C.9	Blunt body damage	Failure to wear proper clothing (short sleeved shirt, long pants, closed toed shoes) while doing construction	Potential injury to feet, toes, or muscles and ligaments in the lower leg	4	2	8	<p>1. Team members will be required to wear proper clothing and complete applicable workshop safety training</p> <p>2. Team members will be provided the NDRT Safety Handbook containing proper clothing guidelines in the workshop</p>	<p>1. All team members participating in construction will complete training University standards</p> <p>2. The NDRT Standard Operating Procedures will be readily available in the workshop at all times</p> <p>3. The NDRT Safety Handbook will be readily available in the workshop at all times</p>	2	2	4
C.10	Contact with a hot surface	Operating a tool or machine that expels heat during use	Burns or scarring	3	3	9	<p>1. Team members working with hot surfaces will be required to wear heat-resistant gloves and complete applicable workshop safety training</p> <p>2. A Standard Operating Procedure will be written outlining the correct procedure for operating workshop tools</p> <p>3. Team members will be provided the NDRT Safety Handbook containing proper usage guidelines for all PPE available in the workshop</p>	<p>1. All team members participating in construction will complete training University standards</p> <p>2. The NDRT Standard Operating Procedures will be readily available in the workshop at all times</p> <p>3. The NDRT Safety Handbook will be readily available in the workshop at all times</p>	1	3	3

C.11	Electric shock	Exposed wiring or a build-up or static electricity	Burns or electrocution potentially leading to long term injuries or death	3	4	12	<ol style="list-style-type: none"> 1. Team members working with electrical parts will be required to wear anti-static gloves and complete applicable workshop safety training 2. A Standard Operating Procedure will be written outlining the correct procedure for constructing electrical parts 3. Team members will be provided the NDRT Safety Handbook containing proper usage guidelines for all PPE available in the workshop 	<ol style="list-style-type: none"> 1. All team members participating in construction will complete training University standards 2. The NDRT Standard Operating Procedures will be readily available in the workshop at all times 3. The NDRT Safety Handbook will be readily available in the workshop at all times 	1	4	4
C.12	Prolonged exposure to loud machinery or construction tools	Lack of proper ear protection	Temporary or long-term hearing loss	3	3	9	<ol style="list-style-type: none"> 1. Team members working with loud tools or machines for any amount of time will be required to wear hearing protection and complete applicable workshop safety training 2. Team members will be provided the NDRT Safety Handbook containing proper usage guidelines for all PPE available in the workshop 	<ol style="list-style-type: none"> 1. All team members participating in construction will complete training University standards 2. The NDRT Safety Handbook will be readily available in the workshop at all times 	1	3	3
C.13	Tripping or falling	Obstacles on the floor such as loose cords, fluid spills, or build materials	Potential injury or disruption of other work, leading to consequent injuries	4	2	8	<ol style="list-style-type: none"> 1. Team members will be required to keep their work stations clean and orderly and complete applicable workshop safety training 2. Team members will be provided the NDRT Safety Handbook containing proper workshop organization guidelines will be available in the workshop 	<ol style="list-style-type: none"> 1. All team members participating in construction will complete standard training 2. The NDRT Safety Handbook will be readily available in the workshop at all times 	1	2	2

C.14	Fire	Overheating parts, electric components shorting, Lithium Polymer battery explosion, sparks during metal cutting, improper soldering iron placement	<ol style="list-style-type: none"> 1. Burns leading to short term health effects or death 2. Smoke inhalation leading to short and long term health effects or death 	2	4	8	<ol style="list-style-type: none"> 1. Team members will be required to keep their work stations clean and orderly and complete applicable workshop safety training 2. Team members working with hot surfaces will be required to wear heat-resistant gloves and complete applicable workshop safety training 3. A Standard Operating Procedure will be written outlining the correct procedure for operating workshop tools 4. Team members will be provided the NDRT Safety Handbook containing proper workshop organization guidelines will be available in the workshop 	<ol style="list-style-type: none"> 1. All team members participating in construction will complete training University standards 2. The NDRT Standard Operating Procedures will be readily available in the workshop at all times 3. The NDRT Safety Handbook will be readily available in the workshop at all times 	1	4	4
C.15	Contracting Sickness, specifically SARS-CoV-2	Lack of adherence to pandemic prevention protocols put in place by government, university, and team mandate to reduce the spread of sickness	Contracting of SARS-CoV-2 potentially leading to long-term health effects or death	3	4	12	<ol style="list-style-type: none"> 1. Workshop capacity will be set at 20 persons at any given time 2. All persons entering the workshop will be required to sign-in and out to aid in contact tracing efforts 3. Close contact, defined as contact less than 6 feet of distance, shall not occur for more than 15 minutes 4. All team meetings will be held on Zoom or other video chat platforms unless construction is necessary 	<ol style="list-style-type: none"> 1. The Safety Officer and team officers will verify all pandemic prevention procedures issued by NDRT the University of Notre Dame, St. Joseph's County, and the State of Indiana will be followed at all times. 2. All team members must sign and agree to all guidelines and will be held accountable with University of Notre Dame administration 	1	4	4

5.3.2 Launch Operations

Table 79: Personnel Hazards Analysis: Launch Operations

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
L.1	Catastrophic Failure	<ol style="list-style-type: none"> 1. Imperfections in motor 2. Motor improperly integrated into vehicle body 	Motor explodes causing projectile shrapnel to fly around launch area	3	4	12	<ol style="list-style-type: none"> 1. All motors will be thoroughly inspected prior to launch 2. The motor will be installed correctly and carefully 3. Motor integration construction methods will allow for a high factor of safety 4. The motor is to be purchased from a well reputed, high fidelity vendor 	<ol style="list-style-type: none"> 1. Dave Brunsting will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. All team members ordering a motor will consult the trusted vendor document and past motor data 	1	4	4
L.2	Uncontrollable launch towards individual or concentrated groups of personnel	<ol style="list-style-type: none"> 1. Launch rail leans over during launch sequence 2. Vehicle stability is unacceptable for launch conditions 	Potential high velocity impact with personnel and property	3	4	12	<ol style="list-style-type: none"> 1. The launch rail will be inspected prior to launch 2. The motor will be installed correctly and carefully 3. The recovery system will be designed to be reliable and redundant in any scenario 4. Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR). 	<ol style="list-style-type: none"> 1. Procedures for properly setting up and inspecting the launch rail will be created and made readily available for all members 2. Dave Brunsting will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 3. The Range Safety Officer will have final say as to how launch operations will proceed, including where safe viewing zones are located 4. The recovery system will be designed carefully with approval from the Vehicles Design Lead, Chief Engineer, and Safety Officer 	1	4	4

L.3	Uncontrollable descent towards individual or concentrated groups of personnel	<ol style="list-style-type: none"> The rocket lands on personnel upon descent under parachute The parachute does not deploy and the vehicle body descends vertically from apogee 	Potential high velocity impact with personnel and property	3	4	12	<ol style="list-style-type: none"> All black powder and other energetics will be carefully and properly set up before launch Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR). 	<ol style="list-style-type: none"> Dave Brunsting will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so The Range Safety Officer will have official say as to how launch operations will proceed, including where safe viewing zones are located 	2	3	6
L.4	High temperature of motor when ignited	<ol style="list-style-type: none"> Motor is hot after landing Personnel are located too close to launchpad during motor burn 	Potential skin burns and scarring	3	3	9	<ol style="list-style-type: none"> Personnel will not touch the vehicle immediately after landing Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR). 	<ol style="list-style-type: none"> All team members attending a launch will attend a pre-launch briefing prior to any launch All team members must follow all instructions given by the RSO 	1	2	2
L.5	Pinch-points	Vehicle assembly includes dangerous procedures with small clearances for extremities	Personnel are pinched/cut on their hands	4	1	4	<ol style="list-style-type: none"> Team members working with any potential pinch-points will be required to wear leather gloves and complete applicable workshop safety training Team members will be provided the NDRT Safety Handbook containing proper usage guidelines for all PPE available 	<ol style="list-style-type: none"> All team members participating in assembly will complete training University standards The NDRT Standard Operating Procedures will be readily available at launches The NDRT Safety Handbook will be readily available at launches 	2	1	2

L.6	Excessive Sunlight Exposure	Direct exposure to sun for an extended period of time without use of sunscreen or sun protection	Sunburn resulting in an increased risk of long term health effects such as skin cancer	3	1	3	1. The team leads will inform personnel attending the launch that they must wear proper clothes and sunscreen for long term exposure to sun	1. Written announcements about potential weather hazards for team personnel will be sent in the full team email 2. The Safety Officer will provide a reminder during pre-launch training sessions 3. Sunscreen will be packed with team materials for launches	1	1	1
L.7	Sharp tools used in assembling the launch vehicle of interior systems	System assemblies may require pliers, scissors, and other sharp tools	Cuts or abrasions to skin	3	3	9	1. Team members working with sharp cutting blades will be required to complete applicable workshop safety training 2. A Standard Operating Procedure will be written outlining the correct procedure for operating tools	1. All team members participating in assembly will complete training University standards 2. The NDRT Standard Operating Procedures will be readily available at launches	2	2	4
L.8	Car accident to/from the launch site	Bad traffic/road conditions to and from the launch site	Personnel injury or death	1	4	4	Only drivers who are properly licensed and certified will be allowed to drive to any team event	1. Leads will confirm possession of valid driver licenses before leaving for the launch 2. All travel of more than one hour will require University driver's training	1	2	2
L.9	Extreme cold	Inclement weather conditions	Hypothermia	2	3	6	1. The team leads will inform personnel attending the launch that they must wear proper clothes and sunscreen for long term exposure to sun 2. Blankets, hand warmers, and vehicles will be used to keep personnel dry and warm in the event of cold weather	1. Written announcements about potential weather hazards for team personnel will be sent in the full team email 2. The Safety Officer will provide a reminder during pre-launch training sessions 3. Blankets and warming materials will be packed with team materials for cold-weather launches	1	3	3

L.10	Payload uncontrolled descent	1. Payload separated from vehicle during launch 2. Payload recovery fails	Personnel injury via impact	3	3	9	1. All black powder and other energetics will be carefully and properly set up before launch 2. Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR).	1. Dave Brunsting will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. The Range Safety Officer will have official say as to how launch operations will proceed, including where safe viewing zones are located	2	2	4
L.11	Battery leakage or explosion	Battery is subject to large vibrations or high temperatures during launch	Personnel receive chemical burn from battery acid	3	3	9	1. Team members working with batteries will be required to complete applicable safety training 2. A Standard Operating Procedure will be written outlining the correct procedure for handling batteries	1. All team members participating in assembly will complete standard training 2. The NDRT Standard Operating Procedures will be readily available at launches	2	2	4
L.12	Dropping the launch vehicle	Improper handling while transporting the vehicle body and components	Bruising, cuts, or broken bones	2	2	4	1. A minimum of 5 team members will be involved in the transportation of the launch vehicle, with one team member making sure the transport path is clear during movement.	1. Pre-launch briefings will be held before each launch that inform members of their responsibility in transporting the launch vehicle, and at least one team lead will be a part of that team.	1	2	2
L.13	Missing PPE	Failure to follow launch procedure checklist	Potential bodily damage related to lack of specific PPE	3	2	6	1. Launch checklists will be created that contain all necessary launch items, including PPE	1. The Safety Officer will verify the pre-launch checklist is fully complete before all launches	1	2	2

5.4 Failure Modes and Effects Analysis

5.4.1 Vehicle Flight Mechanics

Table 80: Vehicle Flight Mechanics Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
VFM.1	Motor ignition failure	1. E-match malfunction 2. Motor imperfections	No launch results in mission failure	3	1	3	<ol style="list-style-type: none"> All motors will be thoroughly inspected prior to launch The motor will be installed correctly and carefully according to launch procedures The motor is to be purchased from a well reputable vendor that has successfully fired this motor model thousands of times 	<ol style="list-style-type: none"> Dave Brunsting will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so All team members ordering a motor will consult the trusted vendor document and past motor data Launch procedures will be written, followed step-by-step, and signed off by the Safety Officer upon completion 	1	1	1
VFM.2	Vehicle is overstable	Center of pressure is too far below the center of mass	Vehicle turns into the wind, may not reach the desired apogee of 5300 ft, resulting in potential harm to vehicle or personnel	3	2	6	<ol style="list-style-type: none"> Center of pressure will be mathematically determined using Open Rocket software Center of mass will be calculated in CAD software and by physically balancing the vehicle before launch Fin shape and placement will carefully consider stability 	<ol style="list-style-type: none"> All computer simulations will involve the Vehicles Design Lead, Chief Engineer, and Graduate Student Mentor when applicable Procedures for properly locating the center of mass on launch day will be created and made readily available for all members The stability value resulting from fin shape and placement will be approved by the Safety Officer and Chief Engineer 	1	2	2

VFM.3	Vehicle fails to clear launch rail	<ol style="list-style-type: none"> 1. Deformation of launch rail 2. Improper motor selection 3. Motor imperfections 4. Rail buttons deform or break during motor burn 5. Vehicle fails to reach sufficient exit rail velocity 	Failed launch results in mission failure and potential harm to vehicle or personnel	2	3	6	<ol style="list-style-type: none"> 1. The launch rail will be inspected prior to launch 2. The motor will be selected based on calculations and simulations to achieve a minimum velocity of 52 feet per second at rail exit 3. The motor will be installed correctly and carefully according to launch procedures 4. Rail buttons are carefully fabricated and attached to the vehicle body 	<ol style="list-style-type: none"> 1. Launch procedures will be written, followed step-by-step, and signed off by the Safety Officer upon completion 2. Procedures for properly fabricating and attaching rail buttons will be created and made readily available for all members in the team workshop 3. Dave Brunsting will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 4. The motor selection will be approved by the Vehicles Design Lead and the Chief Engineer 	1	3	3
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VFM.4	Failure of vehicle to reach sufficient velocity upon exiting launch rail	<ol style="list-style-type: none"> 1. Improper motor selection 2. Motor imperfections 3. Excessive weight in vehicle 4. External forces acting on the launch vehicle are larger than expected 	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	2	3	6	<ol style="list-style-type: none"> 1. The motor will be selected based on calculations and simulations to achieve a minimum velocity of 52 feet per second at rail exit 2. The motor will be installed correctly and carefully according to launch procedures 3. Weight budgets have been allocated to each subsystem with a 21.61% total margin, shown in Table 5 4. Camera shroud shape and location will be designed to minimize drag 5. Computational fluid dynamics (CFD) testing will be done to determine an accurate coefficient of drag 	<ol style="list-style-type: none"> 1. Dave Brunsting will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. Launch procedures will be written, followed step-by-step, and signed off by the Safety Officer upon completion 3. The motor selection will be approved by the Vehicles Design Lead and the Chief Engineer 4. Weight budgets for each subsystem will be strictly enforced by the Chief Engineer 5. Procedures for properly fabricating and attaching the camera shroud will be created and made readily available for all members in the team workshop 6. All external force calculations and simulations will be completed under the supervision of the Vehicles Design Lead and Chief Engineer 	1	3	3
VFM.5	Fin Flutter	<ol style="list-style-type: none"> 1. Fins are not manufactured to specifications 2. Fins are not properly secured to the vehicle 	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	3	3	9	<ol style="list-style-type: none"> 1. Fin design and material are chosen based on calculations, simulations and testing to reach a static stability margin of at least 2.0 2. Fin can will be constructed using proper procedures and techniques 3. Fins will be properly attached and adhered to the fin can and vehicle body 	<ol style="list-style-type: none"> 1. Fin material selection and design safety factor of at least 1.5 will be approved by the Safety Officer and Chief Engineer 2. Procedures for properly manufacturing fins will be created and made readily available for all members in the workshop 3. Procedures for properly attaching fins to the fin can and vehicle body will be created and made readily available for all members in the workshop 	2	1	2

VFM.6	Failure of launch vehicle to travel in intended direction	1. Incorrect motor alignment 2. Improper rail buttons alignment	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	3	3	9	1. Centering rings will be constructed using proper procedures and techniques 2. Rail buttons will be properly attached and adhered to the fin can and vehicle body 3. The motor will be installed correctly and carefully	1. Dave Brunsting will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. Procedures for properly fabricating and attaching rail buttons will be created and made readily available for all members in the team workshop 3. Procedures for properly fabricating and installing centering rings will be created and made readily available for all members in the team workshop	2	1	2
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5.4.2 Vehicle Structures

Table 81: Vehicle Structure Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
VS.1	Bulkhead failure	<ol style="list-style-type: none"> Improper construction Adhesive failure Bulkhead material and design cannot withstand loading 	<ol style="list-style-type: none"> Internal components damaged Unintentional vehicle separation 	3	3	9	<ol style="list-style-type: none"> The material and design of each bulkhead will be carefully selected based on mathematical calculations and structural FEA The application of adhesives will be precise and thorough, with fillets applied to reduce stress concentrations 	<ol style="list-style-type: none"> Bulkheads will be designed using verified calculations and a safety factor approved by both the Safety Officer and Chief Engineer Procedures for properly applying adhesives will be created and made readily available for all members in the team workshop Procedures for properly installing bulkheads will be created and made readily available for all members in the team workshop 	1	2	2

<p>VS.2</p>	<p>Nose cone detachment</p>	<p>1. Shear pin failure 2. Premature CRAS-S black powder charge</p>	<p>1. Unpredictable flight path leads to potential high velocity impact, which may damage internal components 2. Loss of payload components during flight</p>	<p>2</p>	<p>3</p>	<p>6</p>	<p>1. Calculations and simulations will be performed to determine proper nose cone size and shape 2. Each black powder charge and altimeter combination is entirely independent and redundant. 3. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding. 4. All components in the nose cone and payload bay will be properly secured to the vehicle body, not the nose cone</p>	<p>1. The nose cone will be designed using verified calculations and a safety factor approved by both the Safety Officer and Chief Engineer 2. Procedures for properly testing black powder will be created and made readily available for all members in the team workshop 3. Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop 4. Procedures for properly securing payload components will be created and made readily available for all members in the team workshop</p>	<p>1</p>	<p>3</p>	<p>3</p>
<p>VS.3</p>	<p>Structural failure upon landing</p>	<p>1. Vehicle body is constructed with improper materials</p>	<p>1. The vehicle may be damaged or entirely destroyed upon impact 2. Nearby property and people may be damaged or injured</p>	<p>3</p>	<p>3</p>	<p>9</p>	<p>The materials and design of structural components will be carefully selected based on mathematical calculations and structural FEA</p>	<p>1. Structural components will be designed using verified calculations and a safety factor approved by both the Safety Officer and Chief Engineer 2. Procedures for properly constructing the launch vehicle will be created and made readily available for all members in the team workshop</p>	<p>1</p>	<p>2</p>	<p>2</p>

VS.4	Motor explosion	1. Improper installation of motor casing 2. Imperfections within the motor	1. Vehicle and payload sustain considerable damages during flight 2. People nearby are potentially injured	2	4	8	1. All motors will be thoroughly inspected prior to use 2. The motor will be installed correctly and carefully 3. The motor will be purchased from a well reputed,high fidelity vendor	1. Dave Brunsting will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. All team members ordering a motor will consult the trusted vendor document and past motor data	1	4	4
VS.5	Fin failure	Fins are improperly attached to the vehicle body	Flight path becomes unpredictable and vehicle does not follow the intended trajectory	3	3	9	1. Fin can will be constructed using proper procedures and techniques 2. Fins will be constructed using proper procedures and techniques 3. Fins will be properly attached to the fin can and vehicle body	1. Procedures for properly constructing the fin can will be created and made readily available for all members in the team workshop 2. Procedures for properly fabricating the fins will be created and made readily available for all members in the team workshop 3. Procedures for properly attaching fin to the fin can and vehicle body will be created and made readily available for all members in the team workshop	1	2	2
VS.6	Dropping vehicle	Carelessness of team members when transporting the vehicle	1. Potential damages to interior payload components, 2. Potential damages to exterior vehicle body, especially components such as fins and the nose cone	2	3	6	1. Team members will use great care when transporting the vehicle	1. Procedures for transporting the vehicle will be created and made readily available for all members in the team workshop	1	1	1

VS.7	Centering Ring Failure	<ol style="list-style-type: none"> Centering rings improperly attached Centering ring imperfections 	<ol style="list-style-type: none"> Motor is not properly aligned and the vehicle does not reach the desired apogee Potential injury and harm to people nearby 	3	2	6	<ol style="list-style-type: none"> The materials and design of the centering ring will be carefully selected based on calculations and structural FEA The centering rings will be properly and carefully installed and aligned 	<ol style="list-style-type: none"> Procedures for properly constructing and installing the centering ring will be created and made readily available for all members in the team workshop 	1	3	3
VS.8	Coupler Failure	<ol style="list-style-type: none"> Couplers sized incorrectly Couplers improperly attached to vehicle body tube 	Improper vehicle separation resulting in damage to vehicle and payload	3	4	12	<ol style="list-style-type: none"> The materials and design of the couplers will be carefully selected based on calculations The couplers will be properly and carefully installed 	<ol style="list-style-type: none"> Procedures for properly constructing and installing couplers will be created and made readily available for all members in the team workshop 	1	4	4
VS.9	Electronic tracking device in nose cone fails to transmit the position of the nose cone	<ol style="list-style-type: none"> Radio frequency interference from shielding material inhibits transmission Tracking devices are disrupted by transmitters in other components of the vehicle 	NASA Req. 3.12 to track the vehicle and its components accurately during the flight is not fulfilled.	3	2	6	<ol style="list-style-type: none"> Materials surrounding the electronic tracking device will be chosen both for strength and for radio frequency transparency The transmitting frequencies of other electronic devices will be carefully chosen to avoid potential interference 	<ol style="list-style-type: none"> The electronic tracking device will be located in an unshielded segment of the nose cone Procedures for properly integrating the electronic tracking device in the nose cone will be created and made readily available to all members All transmitter frequencies will be reported prior to launch and compared to other devices at the launch site 	1	1	1

5.4.3 Apogee Control System

Table 82: Apogee Control System Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
ACS.1	Power system failure	<ol style="list-style-type: none"> Damaged circuits from poor construction Damaged circuits during launch and/or flight Insufficient battery charge 	Overshoot of target apogee greater than 30 ft, due to electrical system malfunction and loss of control of extending tabs	4	3	12	<ol style="list-style-type: none"> All electronic components will be inspected thoroughly prior to launch All batteries used during launch will be fully charged and all systems will be OFF until just prior to launch 	<ol style="list-style-type: none"> Procedures for proper construction and testing of circuits will be created and made readily available to all members in the team workshop Procedures for properly charging and checking the batteries will be created and made readily available to all members in the team workshop All electronic connections will be tested prior to launch with a multimeter 	2	2	4
ACS.2	Incorrect or unavailable sensor data	<ol style="list-style-type: none"> Sensors are improperly installed and programmed prior to launch Loss of power to the electrical system Unanticipated physical effects in flight (pressure stagnation, vibrations, etc.) 	The launch vehicle will reach an apogee outside of the acceptable range of 5300 ± 30 ft	4	3	12	<ol style="list-style-type: none"> All system code operating in the apogee control system will be tested prior to launch All electrical sensors in the apogee control system will be tested prior to launch Analysis will be performed and verified in order to ensure all physical effects are properly accounted for 	<ol style="list-style-type: none"> Procedures for properly testing and simulating apogee control system code will be created and made readily available for all members in the team workshop Procedures for properly testing apogee control system electrical sensors will be created and made readily available for all members in the team workshop CFD, FEA will be performed on all relevant systems 	2	2	4

ACS.3	Improper command signals from microcontroller	1. Electronic system is incorrectly programmed 2. Computations of live sensor data result in unexpected errors	The launch vehicle will reach an apogee outside of the acceptable range of 5300 ± 30 ft	3	3	9	1. Apogee control system code will be tested before launch in multiple data simulation environments	1. Procedures for properly testing and simulating apogee control system code will be created and made readily available for all members in the team workshop	2	2	4
ACS.4	Mechanical tab extension mechanism failure	1. Insufficient material strength 2. Improper construction techniques	Tab extensions cannot correctly deploy, resulting in the launch vehicle reaching an apogee outside of the acceptable range of 5300 ± 30 ft.	3	3	9	1. Materials are chosen based on analysis and calculations 2. Construction procedures will be written prior to construction	1. Procedures for properly constructing and testing circuits will be created and made readily available to all members in the team workshop 2. Materials will be selected using proper calculations and analysis with a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer	2	2	4
ACS.5	Loss of structural integrity of tab extensions	1. Insufficient material strength 2. Improper construction techniques 3. Unanticipated loading conditions	Tab extensions are unable to correctly deploy and are potentially damaged	3	3	9	1. Materials are chosen based on FEA and calculations 2. Construction procedures will be written prior to construction	1. Procedures for properly constructing tab extensions will be created and made readily available to all members in the team workshop 2. Materials will be selected using proper analysis and calculations with a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer	2	2	4

<p>ACS.6</p>	<p>Shearing of screws or bulkheads that anchor the Apogee Control System within the launch vehicle</p>	<p>1. Insufficient material strength 2. Improper construction techniques 3. Unanticipated loading conditions</p>	<p>Apogee Control System is unable to properly deploy and potentially shifts inside the vehicle body. This may result in internal component damage and unexpected changes in mass distribution, negatively impacting stability</p>	<p>3</p>	<p>4</p>	<p>12</p>	<p>1. Materials are chosen based on FEA and calculations 2. Construction procedures will be written prior to construction</p>	<p>1. Procedures for properly constructing and testing circuits will be created and made readily available to all members in the team workshop 2. Materials will be selected using proper analysis and calculations with a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer</p>	<p>2</p>	<p>2</p>	<p>4</p>
<p>ACS.7</p>	<p>Apogee Control System has a slow response time, preventing effective adjustments from being made in flight</p>	<p>1. Data filters leave too much data for the control system to quickly process 2. The amount of flight data collected exceeds the Apogee Control System's memory 3. Sensor sampling rate is too slow</p>	<p>Loss of effective ACS function leading to increased error in achieved vs target apogee</p>	<p>3</p>	<p>2</p>	<p>6</p>	<p>1. Data filtration system will be chosen with significant considerations of speed and memory. 2. The software program for the Apogee Control System system will be tested before launch in multiple scenarios 3. Sampling rate will factor heavily in sensor trade studies</p>	<p>1. Data filtration system will be approved by the Apogee Control System Design Lead and Chief Engineer before being implemented 2. Procedures for properly testing Apogee Control System software will be created and made readily available to all members in the team workshop</p>	<p>2</p>	<p>1</p>	<p>2</p>

ACS.8	Friction on tab extensions	<ol style="list-style-type: none"> The servo motor lacks the torque to overcome the reactionary friction force on the tab extensions during deployment and withdrawal Batteries are insufficiently charged to effectively power the servo motor 	Tab extensions completely, or partially, fail to extend, resulting in an apogee outside of the acceptable range of 5300 ± 30 ft.	3	2	6	<ol style="list-style-type: none"> Materials are chosen based on analysis and calculations Construction procedures will be written prior to construction The servo motor is selected based on analysis and calculations, and is tested prior to construction 	<ol style="list-style-type: none"> Procedures for properly constructing and testing circuits will be created and made readily available to all members in the team workshop Materials will be selected using proper analysis calculations and a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer The servo motor selection will be approved by the Apogee Control System Design Lead and the Chief Engineer All team members ordering a servo motor will consult the trusted vendor document and past servo motor data 	2	1	2
ACS.9	Incorrectly assembled battery pack leads to damage of the microcontroller	<ol style="list-style-type: none"> The battery pack fails to consistently output a voltage within the microcontroller's acceptable range Improper construction techniques 	Shutdown of the electrical system and loss of control of tab extensions resulting in error between the actual vs target apogee	3	3	9	<ol style="list-style-type: none"> All electronic components will be carefully inspected prior to launch All batteries will be fully charged prior to launch 	<ol style="list-style-type: none"> Procedures for properly constructing electrical hardware will be created and made readily available to all members in the workshop Procedures for properly charging and checking batteries will be created and made readily available to all members Procedures for properly testing electrical connections with a multimeter prior to launch will be created and made readily available to all members 	1	2	2

5.4.4 Recovery

Table 83: Recovery Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
R.1	Vehicle separation failure at apogee	1.Black powder charges are insufficient for separation 2. Black powder charges are set incorrectly. 3. Avionics malfunction or are not turned on	Drogue parachute does not deploy. Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA req. 3.3) with potential for vehicle damage and personnel injury	3	4	12	1. Black powder charges and altimeters are triply redundant and entirely independent 2. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding	1. Procedures for properly testing black powder will be created and made readily available for all members in the team workshop 2. Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop 3. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey TAR/NRA guidelines and procedures when doing so	1	4	4

R.2	Vehicle separation failure at 600 ft AGL	1.Black powder charges are insufficient for separation 2. Black powder charges are set incorrectly. 3. Avionics are not turned on or malfunction	Main parachute does not deploy. Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA req. 3.3) with potential for vehicle damage and personnel injury	3	4	12	<ol style="list-style-type: none"> 1. Black powder charges and altimeters are triply redundant and entirely independent 2. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding. 	<ol style="list-style-type: none"> 1. Procedures for properly testing black powder will be created and made readily available for all members in the team workshop 2. Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop 3. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so 	1	4	4
R.3	Vehicle separation during motor burn	1. Shear pins fail prematurely under launch loading 2. Incorrect altimeter reading cause premature black powder ignition	<ol style="list-style-type: none"> 1. Unacceptably high stress conditions, resulting in interior and exterior components being damaged 2. Potential shrapnel and debris could seriously injure personnel 	3	4	12	<ol style="list-style-type: none"> 1. Shear pins will be supplied from a a reliable and trustworthy vendor 3. Shear pins will be carefully selected based on calculations of various loading scenarios 4. Altimeters will be supplied from trusted vendors and will be surrounded by electromagnetic shielding. 5. Black powder will be properly installed prior to launch 	<ol style="list-style-type: none"> 1. Shear pins will be selected using verified calculations and a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer 2. Procedures for properly testing black powder will be created and made readily available for all members in the team workshop 3. Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop 4. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so 	1	4	4

R.4	Vehicle components fully separate after apogee	<ol style="list-style-type: none"> Shock cords connecting separating components fail due to unanticipated loading Structural component failure due to unanticipated loading Black powder detonation damages shock cords 	Vehicle components descend with unacceptably high kinetic energy (failing to comply with NASA req. 3.3) with potential for vehicle damage and personnel injury	3	4	12	<ol style="list-style-type: none"> Shock cords are to be supplied from a trusted vendor with a history of successful operations Shock cords will be carefully selected based on calculations for a variety of possible loading conditions Shock cords are securely connected to CRAS-M and CRAS-S Black powder vehicle separation will be tested on the ground prior to launch for all separation points The material, model, and design of each structural component will be carefully selected based on structural analysis All avionics will be properly sealed from any black powder residue following detonation 	<ol style="list-style-type: none"> Shock cords will be selected using verified calculations with a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer Procedures for properly testing shock cords will be created and made readily available for all members in the team workshop Procedures for properly testing structural components will be created and made readily available for all members in the team workshop Procedures for properly testing black powder separation will be created and made readily available for all members Procedures for properly constructing an avionics seal will be created and made readily available for all members in the team workshop NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so 	1	4	4
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R.5	Main parachute fails to properly reduce descent velocity after deployment	<ol style="list-style-type: none"> 1. Improperly sized main parachute. 2. Main parachute is deployed after 600 ft AGL. 3. Main parachute shroud cords tangle, preventing the chute from fully unfurling. 4. Black powder charges damage some or all of the main parachute upon deployment. 	Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA req. 3.3) with potential for vehicle damage and personnel injury	3	4	12	<ol style="list-style-type: none"> 1. Calculations and simulations will be performed to determine proper main parachute size and shape 2. Black powder charges and altimeters are triply redundant and entirely independent 3. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding. 4. Parachute folding is practiced and in accordance with manufacturer instructions 5. Nomex cloth and insulation is used to protect the parachute from damage 	<ol style="list-style-type: none"> 1. Calculations and simulations for main parachute size will be verified and approved by the Safety Officer and Chief Engineer 2. Procedures for properly testing black powder will be created and made readily available for all members in the team workshop 3. Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop 4. Procedures for properly folding the main parachute will be created and made readily available for all members in the team workshop 5. Procedures for properly protecting and insulating the main parachute will be created and made readily available for all members in the team workshop 	1	4	4
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R.6	Drogue parachute fails to properly reduce descent velocity after apogee	<ol style="list-style-type: none"> 1. Improperly sized drogue parachute. 2. Drogue parachute is not deployed at apogee: nominally 5300 ft AGL. 3. Drogue parachute shroud cords tangle, preventing drogue parachute from fully unfurling. 4. Black powder charges damage some or all of the drogue parachute upon deployment at apogee. 	Vehicle impacts descends with unacceptably high kinetic energy (failing to comply with NASA req. 3.3), potentially damaging vehicle and injuring personnel	3	4	12	<ol style="list-style-type: none"> 1. Calculations and simulations will be performed to determine proper drogue parachute size and shape 2. Each black powder charge and altimeter combination is entirely independent 3. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding. 4. Parachute folding is practiced and in accordance with manufacturer instructions 5. Nomex cloth and insulation is used to protect the parachute from damage 	<ol style="list-style-type: none"> 1. Calculations and simulations for drogue parachute size will be verified and approved by the Safety Officer and Chief Engineer 2. Procedures for properly testing black powder will be created and made readily available for all members in the team workshop 3. Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop 4. Procedures for properly folding the drogue parachute will be created and made readily available for all members in the team workshop 5. Procedures for properly protecting and insulating the drogue parachute will be created and made readily available for all members in the team workshop 6. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so 	1	4	4
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R.7	Nose cone parachute fails to properly reduce descent velocity after apogee	<ol style="list-style-type: none"> 1. Improperly sized nose cone parachute. 2. Nose cone parachute is not deployed at 550 ft AGL. 3. Nose cone parachute shroud cords tangle and the nose cone parachute chute does not deploy correctly. 4. Black powder charges damage some or all of the nose cone parachute upon deployment. 	Nose cone descends with an unacceptably high kinetic energy (failing to comply with NASA req. 3.3) potentially causing damage to the nose cone, payload, or personnel	3	3	9	<ol style="list-style-type: none"> 1. Calculations and simulations will be performed to determine proper nose cone parachute size and shape 2. Each black powder charge and altimeter combination is entirely independent 3. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding. 4. Parachute folding is practiced and in accordance with manufacturer instructions 5. Nomex cloth and insulation is used to protect the parachute from damage 	<ol style="list-style-type: none"> 1. Calculations and simulations for nose cone parachute size will be verified and approved by the Safety Officer and Chief Engineer 2. Procedures for properly testing black powder will be created and made readily available for all members in the team workshop 3. Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop 4. Procedures for properly folding the nose cone parachute will be created and made readily available for all members in the team workshop 5. Procedures for properly protecting and insulating the nose cone parachute will be created and made readily available for all members in the team workshop 6. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so 	1	3	3
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R.8	Main parachute separates from vehicle	<ol style="list-style-type: none"> Structural component failure due to unanticipated loading conditions Shock cord failure due to unanticipated loading conditions 	<ol style="list-style-type: none"> Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA req. 3.3), potentially damaging vehicle or personnel Damage to vehicle due to structural component failure 	2	4	8	<ol style="list-style-type: none"> Material, design, and model of structural components will be selected based on careful calculations Shock cords are to be supplied from a reliable and trustworthy vendor Shock cords will be carefully selected based on structural analysis Shock cords will be securely connected to CRAS-M 	<ol style="list-style-type: none"> Shock cords will be selected using verified theoretical calculations with a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer Procedures for properly testing shock cords will be created and made readily available for all members in the team workshop Procedures for properly testing structural components will be created and made readily available for all members in the team workshop 	1	4	4
R.9	Drogue parachute separates from vehicle	<ol style="list-style-type: none"> Structural component failure due to high loading Shock cord failure due to high loading 	<ol style="list-style-type: none"> Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA req. 3.3), potentially damaging vehicle or personnel Structural component failure; damage to vehicle 	2	4	8	<ol style="list-style-type: none"> Material, design, and model of structural components will be selected based on careful calculations and structural analysis Shock cords are to be supplied from a reliable and trustworthy vendor Shock cords are to be carefully selected based on calculations and stress analysis Shock cords are securely connected to CRAS-M using secure connections 	<ol style="list-style-type: none"> Shock cords will be selected using verified calculations with a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer Procedures for properly testing shock cords will be created and made readily available for all members in the team workshop Procedures for properly testing structural components will be created and made readily available for all members in the team workshop 	1	4	4

R.10	Nose cone parachute separates from nose cone	<ol style="list-style-type: none"> 1. Structural component failure due to high loading 2. Shock cord failure due to high loading 	<ol style="list-style-type: none"> 1. Nose cone impacts ground at high velocity damaging vehicle and/or personnel 2. Potential damage to payload during separation 	2	3	6	<ol style="list-style-type: none"> 1. Material, design, and model of structural components will be selected based on careful calculations 2. Shock cords will be selected from a trustworthy and reliable source 3. Shock cords are to be carefully selected based on calculations 4. Shock cords are securely connected to CRAS-S using secure connections 	<ol style="list-style-type: none"> 1. Shock cords will be selected using verified calculations with a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer 2. Procedures for properly testing shock cords will be created and made readily available for all members in the team workshop 3. Procedures for properly testing structural components will be created and made readily available for all members in the team workshop 	1	3	3
R.11	Vehicle drift exceeds allowed drift radius (per NASA req 3.10)	<ol style="list-style-type: none"> 1. Main and/or drogue parachutes deploy early (before 600 ft AGL; 5000 ft AGL respectively) 2. Main and/or drogue parachutes are too large 	<ol style="list-style-type: none"> 1. Vehicle causes personnel or property damage while drifting outside the allowable range 2. Payload mission success is compromised due to a landing zone outside the allowable range 	3	2	6	<ol style="list-style-type: none"> 1. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding 2. The black powder charges and altimeters are designed to be triply redundant 3. Main and drogue parachute sizing will be based on calculations and simulations 	<ol style="list-style-type: none"> 1. Calculations and simulations for main and drogue parachute sizing will be verified and approved by the Safety Officer and Chief Engineer 2. Procedures for properly testing black powder will be created and made readily available for all members in the team workshop 3. Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop 4. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so 	1	2	2

R.12	CRAS-M separates from vehicle body	The material and design used to construct the CRAS-M is insufficient in supporting the loads of both the main and drogue parachutes	1. Damaged internal components of vehicle 2. Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA req. 3.3), potentially damaging vehicle or personnel	3	4	12	1. CRAS-M will be designed and manufactured according to calculations and structural FEA 2. The CRAS-M will be secured to the vehicle body using components that are chosen according to calculations	1. Calculations and simulations for CRAS-M design will be verified and approved by the Safety Officer and Chief Engineer 2. Calculations for CRAS-M securing mechanism will be verified and approved by the Safety Officer and Chief Engineer	1	4	4
R.13	CRAS-S separates from vehicle body	The material and design used to construct the CRAS-S is insufficient in supporting the loads of the nose cone parachute	1. Damaged internal components of vehicle 2. Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA req. 3.3), potentially damaging vehicle or personnel	3	3	9	1. CRAS-S will be designed and manufactured according to calculations and structural FEA 2. The CRAS-S will be secured to the vehicle body using components that are chosen according to calculations	1. Calculations and simulations for CRAS-M design will be verified and approved by the Safety Officer and Chief Engineer 2. Calculations for CRAS-M securing mechanism will be verified and approved by the Safety Officer and Chief Engineer	1	3	3

5.4.5 Planetary Landing System

Table 84: Planetary Landing System (PLS) Vehicle Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
PV.1	Fire	<ol style="list-style-type: none"> Lithium ion batteries vibrate during flight or are subjected to high impact loading Electrical connections fail 	Payload and vehicle components and vehicle body are potentially damaged	3	4	12	<ol style="list-style-type: none"> Batteries will be fully charge prior to launch, and circuits will remain OFF until just prior to launch Batteries will be securely installed in the PLS All electronic components will be tested for proper functioning prior to launch 	<ol style="list-style-type: none"> Procedures for properly constructing and testing circuits will be created and made readily available to all members in the team workshop Procedures for properly charging and checking the batteries will be created and made readily available to all members in the team workshop All electronic connections will be tested prior to launch with a multimeter The lithium ion battery will be transported in a fire safe container to prevent potential fires during transportation 	1	4	4
PV.2	PLS power failure	<ol style="list-style-type: none"> Power is not turned on before flight Electronic connections fail Electrical connections in the PLS fail 	PLS is not able to properly function for a portion of the duration of the mission	3	3	9	<ol style="list-style-type: none"> Batteries will be fully charged prior to launch and circuits will remain OFF until just prior to launch All electronic components will be checked thoroughly prior to launch 	<ol style="list-style-type: none"> Procedures for properly constructing the PLS power system will be created and made readily available to all members in the team workshop All electronic connections will be tested prior to launch with a multimeter The lithium ion battery will be transported in a fire safe container to prevent potential fires during transportation 	1	3	3

PV.3	Radio transmission signal disruption	<ol style="list-style-type: none"> 1. Radio frequency interference from shielding material inhibits transmission 2. Tracking devices are disrupted by transmitters in other components of the vehicle 	PLS is unable to transmit the image from the system to a team device, failing to comply with NASA req. 4.3.4	3	2	6	<ol style="list-style-type: none"> 1. Materials surrounding the transmitter will be chosen both for strength and for radio frequency transparency 2. The transmitting frequencies of other electronic devices will be chosen so as not to interfere with transmitters. 	<ol style="list-style-type: none"> 1. All transmitters will be located in unshielded segments of the PLS 2. Procedures for properly integrating transmitters in the PLS will be created and made readily available to all members in the workshop 3. All transmitter frequencies will be reported prior to launch and compared to other devices at the launch site 	2	2	4
PV.4	Orientation mechanism failure	<ol style="list-style-type: none"> 1. Vehicle platform does not have sufficient space to properly rotate 2. The camera platform cannot move because of high material coefficient of friction 	Vehicle is not oriented within the allowable limit of 5 degrees, failing to comply with NASA req. 4.3.3	3	2	6	<ol style="list-style-type: none"> 1. The orientation mechanism will be constructed to avoid friction and incorporate appropriate clearance fits. 2. The orientation mechanism will be thoroughly tested in multiple potential landing scenarios prior to flight 	<ol style="list-style-type: none"> 1. Procedures for properly constructing the orientation mechanism will be created and made readily available to all members in the workshop 2. Procedures for properly testing the orientation mechanism will be created and made readily available to all members 	1	2	2
PV.5	Electronic tracking device on the payload fails to transmit the position of the PLS	<ol style="list-style-type: none"> 1. Radio frequency interference from shielding material inhibits transmission 2. Tracking devices are disrupted by transmitters in other components of the vehicle 	PLS fails to comply with NASA req. 3.12, which states that all independent components of the launch vehicle contain an electronic tracker.	3	2	6	<ol style="list-style-type: none"> 1. Materials surrounding the electronic tracking device will be chosen both for strength and for radio frequency transparency 2. The transmitting frequencies of other electronic devices will be carefully chosen to avoid potential interference. 	<ol style="list-style-type: none"> 1. The electronic tracking device will be located in an unshielded segment of the PLS 2. Procedures for properly integrating the electronic tracking device in the PLS will be created and made readily available to all members 3. All transmitter frequencies will be reported prior to launch and compared to other devices at the launch site 	1	2	2

<p>PV.6</p>	<p>Camera Obstruction</p>	<p>1. PLS system fails to secure the parachute such that it is out of the camera's line of sight 2. Parachute or parachute cords get caught in the camera rotation mechanism</p>	<p>Camera unable to properly capture an image of the surrounding area</p>	<p>4</p>	<p>2</p>	<p>8</p>	<p>1. Parachute and parachute cords will be packed correctly and carefully to prevent entanglement 2. Parachute detachment mechanism will be tested to prevent potential obstructions</p>	<p>1. Procedures for properly packing and integrating the PLS parachute will be created and made readily available to all members 2. Procedures for properly testing the parachute detachment mechanism will be created and made readily available to all members</p>	<p>2</p>	<p>1</p>	<p>2</p>
<p>PV.7</p>	<p>Camera Rotation Failure</p>	<p>1. Camera rotation system becomes entangled with parachute and parachute cords 2. Servo motor fails to generate sufficient torque to rotate the camera 3. Servo motor power failure</p>	<p>The captured image does not include a full 360 degrees of view, failing to comply with NASA req. 4.3.4</p>	<p>3</p>	<p>3</p>	<p>9</p>	<p>1. Parachute and parachute cords will be carefully packed according to manufacturer specifications to prevent entanglement 2. All electronic components will be checked thoroughly prior to launch 3. All batteries used during launch will be fully charged 4. The servo motor will be selected based on simulations and calculations and tested prior to construction</p>	<p>1. Procedures for properly packing and integrating the PLS parachute will be created and made readily available to all members 2. Procedures for properly constructing and testing circuits will be created and made readily available to all members in the team workshop 3. Procedures for properly charging and checking the batteries will be created and made readily available to all members in the team workshop 4. All electronic connections will be tested prior to launch with a multimeter 5. The servo motor selection will be approved by the Experimental Payload Design Lead and the Chief Engineer 6. All team members ordering a servo motor will consult the trusted vendor document and past servo motor data</p>	<p>1</p>	<p>2</p>	<p>2</p>

<p>PV.8</p>	<p>Low quality image</p>	<p>1. Image is poor due to the glare created by the reflection of the sun 2. Dust interferes with the camera lens 3. Camera is not turned on</p>	<p>Camera unable to take capture an acceptable image, failing to comply with NASA req. 4.3.4</p>	<p>3</p>	<p>2</p>	<p>6</p>	<p>1. Camera will be selected with an emphasis on image quality and anti-glare technology, such as polarized or UV filtered lenses 2. Camera housing will prevent debris from affecting the overall quality of the image 3. Only fully charged batteries will be used during flight operations 4. Electrical connections will be checked before flight</p>	<p>1. Procedures for properly constructing and testing circuits will be created and made readily available to all members in the team workshop 2. Procedures for properly charging and checking the batteries will be created and made readily available to all members in the team workshop 3. All electronic connections will be tested prior to launch with a multimeter 4. The camera selection will be approved by the Experimental Payload Design Lead and the Chief Engineer 5. All team members ordering a camera will consult the trusted vendor document and past servo motor data</p>	<p>1</p>	<p>1</p>	<p>1</p>
<p>PV.9</p>	<p>Passive Orientation Failure</p>	<p>1. Parachute restricts passive orientation system due to entanglement 2. Debris buildup restricts passive orientation system</p>	<p>Orientation will not be within the 5 degree allowance, failing to comply with NASA req. 4.3.3</p>	<p>3</p>	<p>2</p>	<p>6</p>	<p>1. Parachute and parachute cords will be packed correctly and carefully to prevent entanglement 2. Passive orientation system will be built to protect against outside debris 3. Passive orientation system will be tested in multiple environments to ensure orientation ability can overcome minor obstructions</p>	<p>1. Procedures for properly packing and inserting the PLS parachute into the vehicle body will be created and made readily available to all members 2. Procedures for properly constructing the passive orientation system will be created and made readily available to all members in the team workshop 3. Procedures for properly testing the passive orientation system will be created and made readily available to all members in the team workshop</p>	<p>2</p>	<p>1</p>	<p>2</p>

PV.10	Damaged Camera	<ol style="list-style-type: none"> 1. Large forces before or during deployment 2. Large impact force 	Camera components damaged and the camera is unable to capture an image, failing to comply with NASA req. 4.3.4	3	3	9	<ol style="list-style-type: none"> 1. Camera will be chosen for both durability and quality of image 2. PLS recovery system will be tested prior to launch for proper reduction in descent kinetic energy, in compliance with NASA req. 3.3 	<ol style="list-style-type: none"> 1. Procedures for properly testing the PLS recovery system will be created and made readily available to all members in the team workshop 2. Procedures for properly constructing the camera housing structure will be created and made readily available to all members in the team workshop 3. The camera selection will be approved by the Experimental Payload Design Lead and the Chief Engineer 4. All team members ordering a camera will consult the trusted vendor document and past camera selections 	1	3	3
PV.11	Support Leg Deployment Failure	<ol style="list-style-type: none"> 1. Launch vehicle leg retention system retains one or multiple legs in locked position 2. Torsion Spring do not successfully deploy 	The PLS becomes unbalanced and collapses	2	4	8	<ol style="list-style-type: none"> 1. Torsion springs will be chosen for strength and reliability 2. Torsion springs will be tested before launch in multiple environments 	<ol style="list-style-type: none"> 1. Procedures for properly constructing and testing circuits will be created and made readily available to all members in the team workshop 2. Torsion springs will be selected using proper calculations and a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer 	1	2	2

5.4.6 Planetary Landing System Deployment and Integration

Table 85: Planetary Land System Deployment and Integration Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
PI.1	Nose cone removal failure	Black Powder charges do not generate enough force to properly separate the nose cone from the vehicle body	PLS is unable to deploy and exit from the vehicle body payload bay	2	4	8	<ol style="list-style-type: none"> The black powder charges and altimeters are redundant each charge and altimeter combination is entirely independent Each black powder charge and altimeter combination is entirely independent Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding. 	<ol style="list-style-type: none"> Procedures for properly testing black powder will be created and made readily available for all members in the team workshop Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so 	1	4	4

PI.2	PLS failure to exit vehicle body	PLS legs produce an unacceptable amount of friction when pushing against the vehicle body	<ol style="list-style-type: none"> 1. Payload cannot deploy from vehicle body, violating NASA req. 4.3.1 2. Total mass under the main parachute is larger than intended, resulting a larger descent velocity than intended, potentially violating NASA req. 3.3 	3	4	12	<ol style="list-style-type: none"> 1. PLS legs will be designed with attention to friction minimization against inside the vehicle body during flight 2. PLS legs will not deploy until after the PLS has exited the vehicle body 3. The PLS legs will be tested in multiple environments, including inside the vehicle body, before flight 4. Main parachute will be designed to account for a total vehicle mass including the PLS 	<ol style="list-style-type: none"> 1. Procedures for properly constructing the PLS legs will be created and made readily available for all members in the team workshop 2. Procedures for properly testing the PLS legs will be created and made readily available for all members in the team workshop 3. Calculations for the PLS leg retention system will be verified and approved by the Safety Officer and Chief Engineer 4. Calculations and simulations for PLS parachute size will be verified and approved by the Safety Officer and Chief Engineer 	1	4	4
PI.3	PLS retention failure	Structural components in the retention mechanism fail during flight	PLS moves freely in the payload bay, potentially damaging internal components or the vehicle and shifting the stability margin of the vehicle, potentially violating NASA req. 2.14	3	4	12	<ol style="list-style-type: none"> 1. Structural components will be designed to adequately secure the PLS in place prior to deployment 2. Retention mechanism will be tested prior to flight 	<ol style="list-style-type: none"> 1. Procedures for properly testing PLS retention will be created and made readily available for all members in the team workshop 2. Calculations for the PLS retention mechanism will be verified and approved by the Safety Officer and Chief Engineer 	1	4	4

PI.4	PLS parachute fails to properly reduce descent velocity after apogee	<ol style="list-style-type: none"> 1. Improperly sized nose cone parachute. 2. PLS parachute is not deployed at 550 ft AGL. 3. PLS parachute shroud cords tangle and the nose cone parachute chute does not fully unfurl. 4. Black powder charges damage some or all of the nose cone parachute upon deployment. 	Nose cone descends with unacceptably high kinetic velocity, violating NASA req. 3.3	3	4	12	<ol style="list-style-type: none"> 1. Calculations and simulations will be performed to determine proper PLS parachute size and shape 2. Each black powder charge and altimeter combination is redundant and entirely independent, in compliance with NASA req. 3.4 3. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding. 4. Parachute folding is practiced and in accordance with manufacturer instructions 5. Nomex cloth and insulation is used to protect the parachute from damage 	<ol style="list-style-type: none"> 1. Calculations and simulations for PLS parachute size will be verified and approved by the Safety Officer and Chief Engineer 2. Procedures for properly testing black powder will be created and made readily available for all members in the team workshop 3. Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop 4. Procedures for properly folding the PLS parachute will be created and made readily available for all members in the team workshop 5. Procedures for properly protecting and insulating the PLS parachute will be created and made readily available for all members in the team workshop 6. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so 	1	4	3
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<p>PI.5</p>	<p>PLS parachute separates from nose cone</p>	<p>1. Structural component failure due to unanticipated loading 2. Shock cord failure due to high loading</p>	<p>1. PLS impacts ground at high velocity damaging vehicle and/or personnel, violating NASA req. 3.3 2. Potential damage to PLS or injury to nearby personnel</p>	<p>3</p>	<p>4</p>	<p>12</p>	<p>1. Material, design, and model of structural components will be selected based on careful calculations 2. Shock cords will be supplied from a reliable and trustworthy vendor 3. Shock cords are to be carefully selected based on calculations 4. Shock cords are securely connected to CRAS-S using secure connections</p>	<p>1. Shock cords will be selected using verified calculations and a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer 2. Procedures for properly testing shock cords will be created and made readily available for all members in the team workshop 3. Procedures for properly testing structural components will be created and made readily available for all members in the team workshop</p>	<p>1</p>	<p>4</p>	<p>4</p>
<p>PI.6</p>	<p>Nose cone separation during motor burn</p>	<p>1. Shear pins fail prematurely under launch loading 2. Incorrect altimeter reading cause premature black powder ignition</p>	<p>1. Unacceptably high shear stress; interior and exterior component damage 2. Potential shrapnel and debris could seriously injure personnel</p>	<p>3</p>	<p>4</p>	<p>12</p>	<p>1. Shear pins will be supplied from a reliable and trustworthy vendor 2. Shear pins are to be carefully selected based on expected shear stress calculations and structural analysis 3. Altimeters are to be supplied from trusted vendors and will be surrounded by electromagnetic shielding. 4. Black powder will be properly installed prior to launch</p>	<p>1. Shear pins will be selected using verified calculations with a safety factor of at least 1.5 approved by both the Safety Officer and Chief Engineer 2. Procedures for properly testing black powder will be created and made readily available for all members in the team workshop 3. Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop 4. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so</p>	<p>1</p>	<p>4</p>	<p>4</p>

PI.7	PLS drift exceeds allowed drift radius, violating NASA req. 3.10	<ol style="list-style-type: none"> 1. PLS deploys from vehicle body at a higher altitude than 550 ft AGL 2. PLS parachute is too large 	<ol style="list-style-type: none"> 1. Personnel or property damage while drifting outside the allowable range 2. Payload mission success is compromised due to landing outside the allowable range 	3	2	6	<ol style="list-style-type: none"> 1. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding 2. The black powder charges and altimeters are designed to be twice redundant and entirely independent, in accordance with NASA req. 3.4 3. PLS parachute sizing is based on calculations and flight simulations 	<ol style="list-style-type: none"> 1. Calculations and simulations for PLS parachute sizing will be verified and approved by the Safety Officer and Chief Engineer 2. Procedures for properly testing black powder will be created and made readily available for all members in the team workshop 3. Procedures for properly testing altimeters will be created and made readily available for all members in the team workshop 4. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so 	1	2	2
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5.4.7 Launch Support Equipment

Table 86: Launch Support Equipment Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
LE.1	Launch rail is at an improper angle, violating NASA req. 1.12	1. Launch equipment is improperly set 2. Vehicle is improperly placed on launch pad	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	3	2	6	1. Launch equipment will be set up according to NAR standards 2. The NDRT mentor and RSO recommendations will be followed when setting up the vehicle 3. The angle of the launch rail will be checked prior to launch	1. The RSO will verify that launch equipment is properly set up in accordance to Section 9 of NAR's High Powered Rocketry Safety Code 2. The vehicle set up will be verified by the NDRT mentor before launch 3. The Chief Engineer will use a level and protractor to verify the launch rail angle prior to launch	1	2	2
LE.2	Launch controller fails to ignite motor	Wire connection or controller is faulty	Motor does not ignite and flight does not occur	3	2	6	1. An official rocketry club's controllers will be used in all launch scenarios 2. All launch equipment will be thoroughly inspected prior to use	1. The RSO will verify that launch equipment is properly set up in accordance to Section 9 of NAR's High Powered Rocketry Safety Code 2. The Project Manager and Team Mentor will ensure that the only rocketry clubs with reliable and consistent records of successful launches will be used for team launches	1	2	2

LE.3	Launch ignition wires are live during set up	Launch controller unit is faulty	Premature motor ignition with potential for damage to vehicle and personnel injury	3	4	12	<p>1. An official rocketry club's controllers will be used in all launch scenarios</p> <p>2. All launch equipment will be thoroughly inspected prior to use</p>	<p>1. The RSO will verify that launch equipment is properly set up in accordance to Section 9 of NAR's High Powered Rocketry Safety Code</p> <p>2. The Project Manager and Team Mentor will ensure that the only rocketry clubs with reliable and consistent records of successful launches will be used for team launches</p>	1	4	4
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5.5 Environmental Risks

5.5.1 Environmental Hazards to Vehicle

Table 87: Environmental Hazards to Vehicle

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
EV.1	Damage to electrical circuits, batteries, and payload electronics	High humidity, rain, or snow causing electric discharge	<ol style="list-style-type: none"> 1. Potential recovery failure 2. Planetary landing system is unable to complete mission 3. Apogee control system is unable to deploy and operate 	3	4	12	<ol style="list-style-type: none"> 1. Electronic components will be stored in resealable electrostatic discharge (ESD) shielding bags before launch 2. Once placed in the launch vehicle, the altimeters for recovery, payload, and apogee control system will be electromagnetically shielded in Faraday cages 	<ol style="list-style-type: none"> 1. Procedures for properly handling electronics before launch will be created and made readily available for all members 2. Procedures for properly housing electronics in the launch vehicle will be created and made readily available for all members 	1	4	4
EV.2	Structural Damage at Launch Site during Assembly or Transport	High winds at the launch site	Potential structural damage to launch vehicle, launch equipment, or planetary landing system	3	2	6	<ol style="list-style-type: none"> 1. No vehicle or payload components will be left unattended before or during assembly 2. At least 5 team members will help transport the rocket to reduce the probability of dropping the vehicle 	<ol style="list-style-type: none"> 1. Procedures for properly assembling the launch vehicle will be created and made readily available for all members 2. Procedures for properly transporting the launch vehicle will be created and made readily available for all members 	2	2	4

EV.3	Weathercocking	High winds (greater than 20mph) at the launch site	Unexpected, and unpredictable, flight path	3	4	12	<p>1. The static stability margin will be kept under 3 calibers, per NDRT req. XX to prevent over-stability</p> <p>2. Launch will be postponed if wind speeds exceed 20 miles per hour</p>	<p>1. The launch vehicle will be designed using verified calculations and a static stability factor approved by both the Safety Officer and Chief Engineer</p> <p>2. The Range Safety Officer will have official say as to how launch operations will proceed, including when weather conditions prohibit launches</p>	1	4	4
EV.4	Excessive vehicle drift under parachute	High winds (greater than 20mph) at the launch site	Vehicle lands outside the allowable drift radius, violating NASA req. 3.10, and potentially harming personnel or property in the area	3	2	6	<p>1. The parachute will be designed primarily to properly reduce descent velocity, but also limit drift radius when possible</p> <p>2. Launch will be postponed if wind speeds exceed 20 miles per hour</p>	<p>1. The main parachute will be designed using verified calculations and expected drift calculations approved by both the Safety Officer and Chief Engineer</p> <p>2. The Range Safety Officer will have official say as to how launch operations will proceed, including when weather conditions prohibit launches</p>	1	2	2
EV.5	Unexpected loss of battery charge	Cold temperatures	Loss of power to electronics in the vehicle in flight	2	4	8	<p>1. Batteries will be stored in a temperature-controlled environment until installation during assembly</p> <p>2. The launch vehicle will be assembled to allow electronics to be installed immediately prior to launch</p> <p>3. Launch will not occur if the RSO deems the temperature to be too cold, or temperatures dip below 23°F.</p>	<p>1. Procedures for properly handling electronics before launch will be created and made readily available for all members</p> <p>2. Procedures for properly housing electronics in the launch vehicle will be created and made readily available for all members</p>	1	2	2

EV.6	Weakening of Bonding Materials	Humidity, Rain, and Heat	1. Bulkhead failure 2. Shifting interior components 3. Changes to static stability margin, potentially violating NASA req. 2.14	2	4	8	1. All adhesives will be approved for strength and reliability 2. All adhesives will be purchased from reputable vendors with past success in high-load scenarios 3. Structures with bonding materials such as epoxy will be kept in dry, cool environments until assembly when possible 4. Bonding materials will be allowed to set and cure for the maximum necessary curing time before launch day	1. Procedures for properly applying adhesives will be created and made readily available for all members 2. Procedures for properly protecting adhesives in the vehicle during assembly will be created and made readily available for all members	1	3	3
EV.7	Wetting of launch vehicle propulsion systems	High humidity, contact with swampy ground, snow, rain	Complete or partial failure to ignite motor	3	2	6	1. Motors stored by the team mentor in re-sealable, protective cases until motor integration into vehicle 2. Motors will be stored with silica gel desiccant for moisture absorption in event that water enters the bag	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so	1	3	3
EV.8	Electronics UV exposure	Long exposure to sunlight	Potentially severe damage to electronics and sensors within the launch vehicle	2	4	8	1. Electronics will be stored in ESD bags, which reflect UV rays, before assembly 2. All electronics will not be exposed to direct sunlight once integrated into vehicle	1. Procedures for properly handling electronics before launch will be created and made readily available for all members 2. Procedures for properly housing electronics in the launch vehicle will be created and made readily available for all members	1	4	4

EV.9	Blunt Force Damage to Vehicle	Hail	1. Vehicle geometry is altered resulting in altered flight dynamics 2. Structural integrity of the vehicle is compromised, points of high stress concentration are created along the length of the airframe	2	3	6	1. Launches will not occur when hail or precipitation is actively occurring	1. Weather conditions will be monitored on launch day by the Safety Officer and RSO 2. The RSO will have full authority on when launches may proceed	1	1	1
EV.10	Animal Interference	Local animal population in and around the launch site	1. Potential destruction of animal habitats 2. Potential injury or death to nearby animals	3	2	6	1. Launches will occur in an open field away from any animals	1. Team leads and the team mentor will thoroughly inspect the launch site to confirm that it is clear of wildlife and safe to launch	2	1	2
EV.11	Structural components change geometry due to swelling	Humidity or temperature changes	Components do not fit together properly, causing difficulty in assembly	2	3	6	1. Parts will be properly stored before assembly and construction 2. Launch checklists will include tools to make minor adjustments so that parts fit properly together	1. Procedures for properly handling assembly components will be created and made readily available for all members 2. Procedures for making minor alterations to vehicle parts during assembly will be created and made readily available for all members 3. The Safety Officer will verify the pre-launch checklist is fully complete before all launches	1	2	2

EV.12	Launch pad is not level	Soft or uneven ground under launch pad	1. Apogee is less than the target apogee of 5300 feet 2. Moment acting on the vehicle is greater than expected, altering flight direction	3	3	9	1. The launch pad will be set up on hard, even ground 2. A level will be used to ensure even launch pad	1. Procedures for properly leveling the launch pad will be created and made readily available for all members	1	1	1
EV.13	Poor visibility of vehicle during flight	Low cloud cover	Failure of team to track flight path, leading to potential loss of vehicle	3	4	12	1. Launch will not occur when cloud cover prohibits the team from maintaining sight of the vehicle during the entire flight	1. Weather conditions will be monitored on launch day by the Safety Officer and RSO 2. The RSO will have full authority on when launches may proceed	1	3	3
EV.14	Vehicle landing in trees	Trees in local terrain	Loss or damage of vehicle and/or payload components	3	4	12	1. Launches will occur in an open field away from any trees	1. Team leads and the team mentor will thoroughly inspect the launch site to confirm that it is clear of trees and safe to launch	1	3	3
EV.15	Wireless Signal Interference	Fog, trees, or other teams' wireless signals	Disrupted communication between systems	3	4	12	1. Launch will not occur when fog or landscape prohibits the transmitters from operating properly during the entire flight 2. All transmission frequencies will be reported prior to flight 3. Transmitters will be tested prior to launch 4. Electronics will be transported in waterproof static shielding bags	1. Weather conditions and the launch site will be monitored on launch day by the Safety Officer and RSO 2. Procedures for properly transporting and storing electronics will be created and made readily available for all members 3. Procedures for properly and thoroughly testing transmitters will be created and made readily available for all members	1	4	4

5.5.2 Vehicle Hazards to Environment

Table 88: Vehicle Hazards to Environment

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
VE.1	Airborne fiberglass particulates	Sanding of fiberglass components of launch vehicle	<ol style="list-style-type: none"> 1. Skin, eye, and respiratory tract irritation to nearby personnel 2. Particulates deplete local air quality 3. Contamination of land used for agriculture 	3	4	12	<ol style="list-style-type: none"> 1. Quantity of fiberglass particulates will be minimal so as to make effects on personnel or environment negligible 2. Team members working with fiberglass will be required to wear a respirator and complete applicable workshop safety training 3. A Standard Operating Procedure will be written outlining the correct procedure for sanding 4. All sanding of fiberglass will take place in a well ventilated indoor space 	<ol style="list-style-type: none"> 1. All team members participating in construction will complete training University standards 2. The NDRT Safety Data Sheet Document is readily available in the workshop at all times 3. The NDRT Standard Operating Procedures will be readily available in the workshop at all times 4. The University of Notre Dame workshop spaces have suitable ventilation areas 	1	3	3
VE.2	Carbon Dioxide emissions	<ol style="list-style-type: none"> 1. CO₂ will be emitted due to motor ignition 2. CO₂ will be emitted due to black powder charges 	Increased levels of carbon dioxide in the atmosphere contribute to expedited climate change	5	2	10	<ol style="list-style-type: none"> 1. CO₂ emissions from the motor will be of negligible amounts 2. CO₂ emissions from black powder charges will be of negligible amounts 	<ol style="list-style-type: none"> 1. Motors and black powder charges will be inspected by the team mentor before launch 2. All motors will be purchased from reputable vendors that limit emissions to all extent possible 	5	1	5

VE.3	Hydrogen Chloride emission	The main rocket propellant, ammonium perchlorate, produces hydrogen chloride gas	Hydrogen chloride reacts with water to create hydrochloric acid which can contaminate nearby water sources and habitats	3	2	6	1. The launch site will be located in an area with minimal importance to local wildlife; such as an unused agricultural field	1. The RSO will ensure the launch site is at a suitable location so as to leave no trace on surrounding wildlife habitats or water sources	3	1	2
VE.4	Components separate from vehicle	1. Components within vehicle are improperly secured 2. Unexpected vibration in flight	1. Wildlife could potentially ingest or be harmed by materials 2. Destruction of land used for agriculture	3	3	9	1. Components in the vehicle will be properly secured using fasteners, adhesives, or shear pins 2. Vehicle body will be designed to prevent components from separating	1. Vehicle body design to secure interior components will be verified and approved by the Safety Officer and Chief Engineer 2. Procedures for properly securing interior components will be created and made readily available for all members in the team workshop	1	2	2
VE.5	Battery rupture	Defective batteries fail to maintain acid separation	1. Soil contamination 2. Groundwater contamination 3. Contamination of land used for agriculture	3	4	12	1. Batteries will be housed in battery bag when not in use 2. All batteries will be thoroughly inspected before being placed in the vehicle 3. Batteries will be properly installed in the vehicle assembly	1. Procedures for properly transporting batteries will be created and made readily available for all members 2. Procedures for properly inspecting and installing batteries will be created and made readily available for all members in the team workshop	2	2	4

VE.6	Paint chips off of vehicle body	Launch vehicle airframe is painted for identification, tracking, and aerodynamic purposes	1. Paint chips scatter in the local area, becoming a danger to wildlife 2. Contamination of land used for agriculture	2	2	4	1. If possible, painting will be done professionally in a proper paint shop, using environmentally friendly coatings 2. If professional painting is unavailable, the spray booth at the University of Notre Dame will be used to properly paint and cure the exterior design of the vehicle	1. All professional painters must be a licensed vendor with proper certifications 2. Procedures for properly painting in the Notre Dame spray booth will be created and made readily available for all members in the team workshop	1	1	1
VE.7	Plastic Waste	Prototyping and subscale construction uses plastic due to low cost and ease of manufacturing	1. Wildlife could potentially ingest or be harmed by plastic 2. Contamination of land used for agriculture 3. Excessive contribution to overall university plastic waste, straining recycling or landfill capacity	4	3	12	1. All plastics will be disposed of properly according to local landfill and recycling guidelines 2. All designs containing plastic will be carefully inspected so as to minimize plastic waste	1. All prototypes will be overseen by Design Leads who will restrict excessive plastic usage 2. Procedures for properly disposing of plastic waste will be created and made readily available for all members in the team workshop	2	1	2
VE.8	Wire Waste	Wires used for electrical connections	1. Wildlife could potentially ingest or be harmed by wires 2. Contamination of land used for agriculture	4	3	12	1. All wires will be disposed of properly according to local landfill and recycling guidelines 2. All designs containing wires will be carefully inspected so as to minimize wire waste	1. All prototypes will be overseen by Design Leads who will restrict excessive wire usage 2. Procedures for properly disposing of wires will be created and made readily available for all members in the team workshop	2	1	2

VE.9	Solder Waste	Many electrical components use solder to secure connections	<ol style="list-style-type: none"> 1. Wildlife could potentially ingest or be harmed by solder 2. Contamination of land used for agriculture 	4	3	12	<ol style="list-style-type: none"> 1. All excess solder will be disposed of properly according to local landfill and recycling guidelines 2. All designs containing solder will be carefully checked so as to minimize solder waste 3. All soldering will be overseen by a Design Lead with experience in minimizing solder waste so as to avoid excessive waste production 	<ol style="list-style-type: none"> 1. All prototypes will be overseen by Design Leads who will restrict excessive solder usage 2. Procedures for properly soldering and disposing of solder will be created and made readily available for all members in the team workshop 	2	1	4
VE.10	Fire	<ol style="list-style-type: none"> 1. Motor burnout 2. Electrical components short circuit 	<ol style="list-style-type: none"> 1. Damage to surrounding grass 2. Damage to natural habitats of local wildlife 3. Greenhouse emissions as a result of combustion 4. Destruction of land used for agriculture 	2	4	8	<ol style="list-style-type: none"> 1. Appropriate fire extinguishers will be included on the launch checklists to be packed for launch 2. All electronics will be carefully inspected prior to launch 3. The launch pad will be positioned in a location free of debris or flammable objects 	<ol style="list-style-type: none"> 1. The Safety Officer will verify the pre-launch checklist is fully complete before all launches 2. Procedures for properly installing and inspecting electronics will be created and made readily available for all members 	1	4	4

<p>VE.11</p>	<p>High velocity impact, in violation of NASA req. 3.3</p>	<p>1. High wind speeds cause vehicle to enter an unexpected flight path 2. Recovery fails to properly reduce vehicle descent velocity</p>	<p>1. Damage to nearby personnel or property 2. Damage to power lines leading to potential fires 3. Destruction of habitats or injury to wildlife in the area 4. Destruction of land used for agriculture</p>	<p>3</p>	<p>4</p>	<p>12</p>	<p>1. The launch rail will be inspected prior to launch 2. The motor will be installed correctly and carefully 3. The recovery system will be designed to be reliable and redundant in any scenario, in accordance with NASA req. 3.4 4. Personnel will stand at least 300 ft. from the launch rail as required by the NAR</p>	<p>1. Procedures for properly setting up and inspecting the launch rail will be created and made readily available for all members 2. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the sole person to handle and install energetics and will obey NAR/TRA guidelines and procedures when doing so 3. The Range Safety Officer will have official say as to how launch operations will proceed, including where safe viewing zones are located 4. The recovery system will be designed carefully with approval from the Vehicles Design Lead, Chief Engineer, and Safety Officer</p>	<p>1</p>	<p>4</p>	<p>4</p>
<p>VE.12</p>	<p>Noise Impacts</p>	<p>Excessive noise generation from the launch vehicle's motor on launch</p>	<p>Noise could harm wildlife, bystanders, and nearby structures</p>	<p>1</p>	<p>4</p>	<p>4</p>	<p>Motor selection will limit noise to within EPA regulations, as stipulated by the noise control act of 1972 (42 U.S.C §4901 et. seq.)</p>	<p>1. The motor selection will be approved by the Vehicles Design Lead and Chief Engineer. 2. Motor selection will be approved by the Safety Officer after referencing specifications of the motor in regard to noise, from data sheets or by contacting the supplier</p>	<p>1</p>	<p>2</p>	<p>2</p>

5.6 Project Risk Analysis

Table 89: Project Risk Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
PR.1	Complete destruction or loss of full scale or subscale vehicle	<ol style="list-style-type: none"> 1. Uncontrolled descent 2. Energetics improperly installed or used 	Team must build an entirely new vehicle causing project delays and doubling the costs of the project	2	4	8	<ol style="list-style-type: none"> 1. All components will be tested individually prior to full-scale assembly 2. Construction procedures will be written prior to construction 3. A factor of safety will be used for all structural components such that some unanticipated loading may be withstood without component failure 	<ol style="list-style-type: none"> 1. Tests will be logged and documented. Multiple sources trials of calculations and simulations will be used to verify results 2. Procedures for construction and integration of all components will be created and made readily available to all team members prior to the beginning of construction 	1	4	4
PR.2	Failure to conduct subscale flight by January 4th and/or vehicle demonstration flight by March 8th	<ol style="list-style-type: none"> 1. Poor weather conditions 2. Project delays resulting in incomplete construction 3. Failure to schedule a launch date that is suitable for both the team and mentor 	Inability to participate in competition	2	3	6	<ol style="list-style-type: none"> 1. Several dates and locations were chosen for possible launches to provide the team with multiple options. 2. Implementation of a Technology Readiness Level schedule to ensure that all subsystems are meeting each deadline comfortably. 3. The team intends to launch on the first available date. 	<ol style="list-style-type: none"> 1. The team has chosen a subscale launch on November 13th in order to meet the subscale flight deadline. 2. The team has chosen February 13th and 20th in order to meet the vehicle demonstration flight deadline. 3. The team has a Gantt chart to track TRLs of individual subsystems in order to identify potential obstacles prior to deadlines. 4. The team will begin full scale construction two weeks prior to the first available launch date. 	1	3	3

PR.3	Lack of funds/exceeding budget	<ol style="list-style-type: none"> 1. Allocation of funds to a subsystem is insufficient 2. Parts are not properly sourced 	Team takes on debt or funds from travel or other subsystems diminish	3	3	9	<ol style="list-style-type: none"> 1. The allocation of funds will be based off of previous years' spending and designs 2. Parts will be sourced to find the best quality at the lowest cost 3. Each part will be considered from at least three vendors when possible 	<ol style="list-style-type: none"> 1. The budget this year has been set according to past needs and consultation with each design lead 2. Team members must submit their receipts and report all purchases to ensure all spending is properly tracked 	2	2	4
PR.4	Shipping/ Manufacturing Delays from Vendors	<ol style="list-style-type: none"> 1. Long lead times on mission critical components 2. The shipped part is incorrect or does not meet the needs of the team 	Project delays and/or mission failure	3	3	9	<ol style="list-style-type: none"> 1. Items with long lead times will be identified and ordered for arrival in advance of construction windows 2. Additional components will be ordered in the event a custom part is needed or a component fails 3. NDRT has compiled a trusted vendor list to ensure quality of parts and prompt and reliable delivery 	<ol style="list-style-type: none"> 1. Any custom parts will be ordered at least three weeks in advance of construction or earlier depending on length of lead time 2. Design leads will determine whether or not additional stock should be ordered 3. All team members ordering parts will consult the trusted vendor document 4. All purchases from new vendors will be approved by the Project Manager and Chief Engineer 	2	2	4
PR.5	Team member becomes unavailable for some or all remaining project deadlines	<ol style="list-style-type: none"> 1. Injury or illness 2. COVID-19 quarantine or self-isolation 3. Member prioritizes other commitments 	Project delays and/or incomplete work	4	2	8	<ol style="list-style-type: none"> 1. Multiple team members will be assigned to the same task to ensure completion 2. Multiple members will be made aware of the details and expectations of each task 3. Design Leads will be responsible for taking on extra work in the event that a team member becomes unable to complete a task 	<ol style="list-style-type: none"> 1. All designs and tests will be well documented in advance of deadlines in the event a reallocation of tasks occurs 	2	1	2

PR.6	Safety violations	1. Insufficient PPE 2. Improper training 3. Safety noncompliance	Injury to personnel and the potential revocation of workshop space	3	3	9	1. PPE will always be stocked and made readily available in the workshop and a part of the Safety budget 2. All personnel that will be participating in construction must be certified in the Student Fabrication Lab according to university regulations. 3. All personnel must initial and sign the Workshop Safety Agreement, acknowledging all team safety rules 4. Design Leads are responsible for enforcing safety protocol in all NDRT spaces	1. The Safety Officer will take inventory of PPE in the workshop on a bi-weekly schedule, and additional times prior to construction 2. Students must confirm their completion of Student Fabrication Lab training before entering the workshop to participate in construction	1	3	3
PR.7	Insufficient materials and parts to fully complete construction	Parts to complete the project are not ordered	Project delays or inability to complete the competition	2	4	8	1. Personnel will make an itemized list of parts in their designs at least two weeks before beginning construction.	1. Construction procedures will provide a good check to make sure all the parts need for fabrication are ordered 2. CAD models will include full assemblies with all required parts	1	4	4
PR.8	Violation of FAA by exceeding approved altitude	Launch site does not have proper waiver for the team's altitude requirement	Potential legal action	2	3	6	1. The team will not use any launch sites without the proper waiver	1. The NDRT leadership will confirm with prospective launch sites that they have the proper waiver for NDRT's selected apogee	1	3	3

PR.9	Improper testing equipment	<ol style="list-style-type: none">1. Test equipment does not perform to expected standards2. Inability to use University resources for more complex testing3. Restriction on undergraduate lab access due to COVID-19 regulations	Incorrect or missing data, resulting in faulty analyses and/or uninformed design decisions	3	2	6	<ol style="list-style-type: none">1. The team will confirm all tests with calculated results and simulations.2. The team will reach out to test facilities early to ensure lab time and comply with regulations at each facility.3. The team will work with campus resources to perform tests in spaces that are restricted to full-time researchers	<ol style="list-style-type: none">1. All test results will be documented and shared with the team.2. The team will reach out to test facilities at least three weeks in advance of the anticipated testing date	1	2	2
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5.7 Workshop Safety

The Notre Dame Rocketry Team has taken proactive steps to establish effective workshop guidelines for the 2020-2021 season. All team members, regardless of experience or contributions to construction, must complete a Workshop Safety Agreement, outlining expectations and responsibilities in the team workshop. All conventional risks associated with construction are equally valued as in past years. This year, public health risks are emphasized at all team meetings. The workshop has been outfitted with hand sanitizer stations, and an attendance sheet for contact tracing purposes. Face coverings, such as masks or face shields, are required at all times. The Workshop Safety Agreement can be viewed in [Appendix A](#). To date, 76 members of the Notre Dame Rocketry have completed and signed the NDRT Workshop Safety Agreement.

For construction tasks, the University of Notre Dame provides training on hand tools, power tools, and select machines in the Aerospace and Mechanical Engineering Student Fabrication Laboratory. The Notre Dame Rocketry Team requires members to complete the Hand and Power Tools training to be eligible to participate in any construction. All machine usage will be restricted to those who have completed the proper training and demonstrated proficiency. To date, 25 members of the Notre Dame Rocketry Team have completed the Hand and Power Tools training. Of these 25 individuals, 19 have completed training on all other machines, including the techno router, band saw, drill press, scroll saw, and belt and disk sander. The Aerospace and Mechanical Engineering Student Fabrication Lab training materials and quizzes can be accessed here: <https://sfl.nd.edu/tools-equipment>.

Additionally, the Notre Dame Rocketry Team Safety Handbook and SDS Document remain readily available electronically and in print in the workshop. The NDRT Safety Handbook contains guidelines for proper PPE usage, an overview of team tools and machines, launch safety, and other applicable safety information. The SDS is a compilation of all chemicals used by NDRT at any time within the last two years, with an easy-to-read synopses on PPE, handling, and first aid for all materials.

This year, NDRT will release Standard Operating Procedures (SOPs) for construction, testing, and launch operations. SOPs will better allow NDRT members to accessibly locate step-by-step instructions on operating tools or machines, assembling the launch vehicle, or completing a test properly. SOPs will be compiled into one, organized document. SOPs will be added to the compilation when required, and reused in future years. Preliminary construction SOPs relevant to subscale construction have been written and published, and NDRT intends to update the SOP document with each milestone.

The NDRT Safety Handbook, SDS Document, and Standard Operating Procedures can

be accessed at <https://ndrocketry.weebly.com/reports.html>.

6 Project Plan

6.1 Requirements Verification

6.1.1 NASA Requirements

Table 90: NASA General Requirements

ID	Description
1.1	Students on the team will do 100% of the project, including design, construction, written reports, presentations, and flight preparation with the exception of assembling the motors and handling black powder or any variant of ejection charges, or preparing and installing electric matches (to be done by the team's mentor). Teams will submit new work. Excessive use of past work will merit penalties.
1.2	The team will provide and maintain a project plan to include, but not limited to the following items: project milestones, budget and community support, checklists, personnel assignments, STEM engagement events, and risks and mitigations.
1.3	Foreign National (FN) team members must be identified by the Preliminary Design Review (PDR) and may or may not have access to certain activities during launch week due to security restrictions. In addition, FN's may be separated from their team during certain activities on site at Marshall Space Flight Center.
1.4	"The team must identify all team members attending launch week activities by the Critical Design Review (CDR). Team members will include: Students actively engaged in the project throughout the entire year, one mentor, and no more than two adult educators."
1.5	The team will engage a minimum of 200 participants in educational, hands-on science, technology, engineering, and mathematics (STEM) activities, as defined in the STEM Engagement Activity Report, by FRR. To satisfy this requirement, all events must occur between project acceptance and the FRR due date and the STEM Engagement Activity Report must be submitted via email within two weeks of the completion of the event. A sample of the STEM Engagement Activity Report is on page 35.
1.6	The team will establish a social media presence to inform the public about team activities.

Table 90: NASA General Requirements

ID	Description
1.7	Teams will email all deliverables to the NASA project management team by the deadline specified in the handbook for each milestone. In the event that a deliverable is too large to attach to an email, inclusion of a link to download the file will be sufficient.
1.8	All deliverables must be in PDF format.
1.9	In every report, teams will provide a table of contents including major sections and their respective sub-sections.
1.10	In every report, the team will include the page number at the bottom of the page.
1.11	The team will provide any computer equipment necessary to perform a video teleconference with the review panel. This includes, but is not limited to, a computer system, video camera, speaker telephone, and a sufficient Internet connection. Cellular phones should be used for speakerphone capability only as a last resort.
1.12	All teams will be required to use the launch pads provided by Student Launch's launch services provider. No custom pads will be permitted on the launch field. At launch, 8-foot 1010 rails and 12-foot 1515 rails will be provided. The launch rails will be canted 5 to 10 degrees away from the crowd on launch day. The exact cant will depend on launch day wind conditions.
1.13	Each team must identify a "mentor." A mentor is defined as an adult who is included as a team member, who will be supporting the team (or multiple teams) throughout the project year, and may or may not be affiliated with the school, institution, or organization. The mentor must maintain a current certification, and be in good standing, through the National Association of Rocketry (NAR) or Tripoli Rocketry Association (TRA) for the motor impulse of the launch vehicle and must have flown and successfully recovered (using electronic, staged recovery) a minimum of 2 flights in this or a higher impulse class, prior to PDR. The mentor is designated as the individual owner of the rocket for liability purposes and must travel with the team to launch week. One travel stipend will be provided per mentor regardless of the number of teams he or she supports. The stipend will only be provided if the team passes FRR and the team and mentor attend launch week in April.
1.14	Teams will track and report the number of hours spent working on each milestone.

Table 91: NASA Launch Vehicle Requirements

ID	Description
2.1	The vehicle will deliver the payload to an apogee altitude between 3,500 and 5,500 ft AGL.
2.2	Teams shall identify their target altitude goal at the PDR milestone. The declared target altitude will be used to determine the team's altitude score.
2.3	The vehicle will carry one commercially available, barometric altimeter for recording the official altitude used in determining the Altitude Award winner.
2.4	The launch vehicle will be designed to be recoverable and reusable.
2.5	The launch vehicle will have a maximum of 4 independent sections.
2.5.1	Coupler/airframe shoulders which are located at in-flight separation points will be at least 1 body diameter in length.
2.5.2	Nosecone shoulders which are located at in-flight separation points will be at least 1/2 body diameter in length.
2.6	The launch vehicle will be capable of being prepared for flight at the launch site within 2 hours of the time the FAA flight waiver opens.
2.7	The launch vehicle and payload will be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hours without losing the functionality of any critical on-board components.
2.8	The launch vehicle will be capable of being launched by a standard 12 V DC firing system, provided by the NASA-designated launch services provider.
2.9	The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other than what is provided by the launch services provider).
2.10	The launch vehicle will use a commercially available solid motor propulsion system using APCP, which is approved and certified by the NAR, TRA, and/or the CAR.
2.10.1	Final motor choices will be declared by the CDR milestone.
2.10.2	Any motor change after CDR must be approved by the NASA RSO and will only be approved if the change is for the sole purpose of increasing the safety margin.
2.11	The launch vehicle will be limited to a single stage.
2.12	The total impulse provided by a University launch vehicle will not exceed 5,120 Ns (L-class).
2.13	Pressure vessels on the vehicle will be approved by the RSO and will meet the criteria outlined in Req. 2.13.1-2.13.3.
2.13.1	The minimum pressure vessel FOS will be 4:1 with supporting design documentation included in all milestone reviews.

Table 91: NASA Launch Vehicle Requirements

ID	Description
2.13.2	Each pressure vessel will include a pressure relief valve that sees the full pressure of the tank and is capable of withstanding the maximum pressure and flow rate of the tank.
2.13.3	The full pedigree of the tank will be described, including the application for which the tank was designed and the history of the tank as defined in the NASA SL Handbook.
2.14	The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit.
2.15	Any structural protuberance on the rocket will 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.
2.16	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.
2.17	All teams will successfully launch and recover a subscale model of their rocket prior to CDR.
2.17.1	The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale will not be used as the subscale model.
2.17.2	The subscale model will carry an altimeter capable of recording the model's apogee altitude.
2.17.3	The subscale rocket must be a newly constructed rocket, designed and built specifically for this year's project.
2.17.4	Proof of a successful flight shall be supplied in the CDR report.
2.18	All teams will complete demonstration flights as outlined in Req. 2.18.1-1.18.2.4.
2.18.1	Vehicle Demonstration Flight - All teams will successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration. The rocket flown must be the same rocket to be flown on launch day. The criteria outlined in Req. 2.18.1.1-2.18.1.9 must be met.
2.18.1.1	The vehicle and recovery system will have functioned as designed.
2.18.1.2	The full-scale rocket must be a newly constructed rocket, designed and built specifically for this year's project.
2.18.1.3	The payload does not have to be flown during the full-scale Vehicle Demonstration Flight. Req. 2.18.1.3.1 and 2.18.1.3.2 still apply.
2.18.1.3.1	If the payload is not flown, mass simulators will be used to simulate the payload mass.

Table 91: NASA Launch Vehicle Requirements

ID	Description
2.18.1.3.2	The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.
2.18.1.4	If the payload changes the external surfaces of the rocket or manages the total energy of the vehicle, those systems will be active during the full-scale Vehicle Demonstration Flight.
2.18.1.5	Teams shall fly the launch day motor for the Vehicle Demonstration Flight. The team may request a waiver for the use of an alternative motor in advance if the home launch field cannot support the full impulse of the launch day motor or in other extenuating circumstances.
2.18.1.6	The vehicle must be flown in its fully ballasted configuration during the full-scale test flight. Additional ballast may not be added without a re-flight of the full-scale launch vehicle.
2.18.1.7	After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components will not be modified without the concurrence of the NASA RSO.
2.18.1.8	Proof of a successful flight shall be supplied in the FRR report. Altimeter data output is required to meet this requirement.
2.18.1.9	Vehicle Demonstration flights must be completed by the FRR submission deadline. No exceptions will be made. If the Student Launch office determines that a Vehicle Demonstration Re-flight is necessary, then an extension may be granted (for re-flight only). Teams completing a required re-flight must submit an FRR Addendum by the FRR Addendum deadline.
2.18.2	Payload Demonstration Flight - All teams will successfully launch and recover their full-scale rocket containing the completed payload prior to the Payload Demonstration Flight deadline, further described in the NASA SL Handbook. Requirements 2.18.2.1-2.18.2.4 shall be met.
2.18.2.1	The payload must be fully retained until the intended point of deployment (if applicable), all retention mechanisms must function as designed, and the retention mechanism must not sustain damage requiring repair.
2.18.2.2	The payload flown must be the final, active version.
2.18.2.3	If the above criteria are met during the original Vehicle Demonstration Flight, occurring prior to the FRR deadline and the information is included in the FRR package, the additional flight and FRR Addendum are not required.

Table 91: NASA Launch Vehicle Requirements

ID	Description
2.18.2.4	Payload Demonstration Flights must be completed by the FRR Addendum deadline.
2.19	An FRR Addendum will be required for any team completing a Payload Demonstration Flight or NASA required Vehicle Demonstration Re-flight after the submission of the FRR Report.
2.19.1	Teams required to complete a Vehicle Demonstration Re-Flight and failing to submit the FRR Addendum by the deadline will not be permitted to fly the vehicle at launch week.
2.19.2	Teams who successfully complete a Vehicle Demonstration Flight but fail to qualify the payload by satisfactorily completing the Payload Demonstration Flight requirement will not be permitted to fly the payload at launch week.
2.19.3	Teams who complete a Payload Demonstration Flight which is not fully successful may petition the NASA RSO for permission to fly the payload at launch week.
2.20	The team's name and launch day contact information shall be in or on the rocket airframe as well as in or on any section of the vehicle that separates during flight and is not tethered to the main airframe. This information shall be included in a manner that allows the information to be retrieved without the need to open or separate the vehicle.
2.21	All LiPo batteries will 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.
2.22	Vehicle Prohibitions
2.22.1	The launch vehicle will not utilize forward firing motors.
2.22.2	The launch vehicle will not utilize motors that expel titanium sponges.
2.22.3	The launch vehicle will not utilize hybrid motors.
2.22.4	The launch vehicle will not utilize a cluster of motors.
2.22.5	The launch vehicle will not utilize friction fitting for motors.
2.22.6	The launch vehicle will not exceed Mach 1 at any point during flight.
2.22.7	Vehicle ballast will not exceed 10% of the total unballasted weight of the rocket as it would sit on the pad.
2.22.8	Transmissions from onboard transmitters will not exceed 250 mW of power (per transmitter).

Table 91: NASA Launch Vehicle Requirements

ID	Description
2.22.9	Transmitters will not create excessive interference. Teams will utilize unique frequencies, handshake/passcode systems, or other means to mitigate interference caused to or received from other teams.
2.22.10	Excessive and/or dense metal will 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.

Table 92: NASA Recovery Requirements

ID	Description
3.1	The full scale launch vehicle will stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee, and a main parachute is deployed at a lower altitude.
3.1.1	The main parachute shall be deployed no lower than 500 feet.
3.1.2	The apogee event may contain a delay of no more than 2 seconds.
3.1.3	Motor ejection is not a permissible form of primary or secondary deployment.
3.2	Each team will perform a successful ground ejection test for all electronically initiated recovery events prior to the initial flights of the subscale and full scale vehicles.
3.3	Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing.
3.4	The recovery system will contain redundant, commercially available altimeters.
3.5	Each altimeter will have a dedicated power supply, and all recovery electronics will be powered by commercially available batteries.
3.6	Each altimeter will 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.
3.7	Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces).
3.8	The recovery system electrical circuits will be completely independent of any payload electrical circuits.
3.9	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.
3.10	The recovery area will be limited to a 2,500 ft. radius from the launch pads.

Table 92: NASA Recovery Requirements

ID	Description
3.11	Descent time of the launch vehicle will be limited to 90 seconds (apogee to touch down). The jettisoned payload (planetary lander) is not subject to this constraint.
3.12	An electronic tracking device will be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent section to a ground receiver.
3.12.1	Any rocket section or payload component, which lands untethered to the launch vehicle, will contain an active electronic tracking device.
3.12.2	The electronic tracking device(s) will be fully functional during the official flight on Launch Day.
3.13	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).
3.13.1	The recovery system altimeters will be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device.
3.13.2	The recovery system electronics will be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery system electronics.
3.13.3	The recovery system electronics will be shielded from all onboard devices which may generate magnetic waves (such as generators, solenoid valves, and Tesla coils) to avoid inadvertent excitation of the recovery system.
3.13.4	The recovery system electronics will be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics.

Table 93: NASA Payload Requirements

ID	Description
4.2	Teams will design a planetary landing system to be launched in a high-power rocket. The lander system will be capable of being jettisoned from the rocket during descent, landing in an upright configuration or autonomously uprighting after landing. The system will self-level within a five-degree tolerance from vertical. After autonomously uprighting and self-leveling, it will take a 360-degree panoramic photo of the landing site and transmit the photo to the team.
4.3.1	The landing system will be completely jettisoned from the rocket at an altitude between 500 and 1,000 ft. AGL. The landing system will not be subject to the maximum descent time requirement (Requirement 3.11) but must land within the external borders of the launch field. The landing system will not be tethered to the launch vehicle upon landing.

Table 93: NASA Payload Requirements

ID	Description
4.3.2	The landing system will land in an upright orientation or will be capable of reorienting itself to an upright configuration after landing. Any system designed to reorient the lander must be completely autonomous.
4.3.3	The landing system will self-level to within a five-degree tolerance from vertical.
4.3.3.1	Any system designed to level the lander must be completely autonomous.
4.3.3.2	The landing system must record the initial angle after landing, relative to vertical, as well as the final angle, after reorientation and self-levelling. This data should be reported in the Post Launch Assessment Report (PLAR).
4.3.4	Upon completion of reorientation and self-levelling, the lander will produce a 360-degree panoramic image of the landing site and transmit it to the team.
4.3.4.1	The hardware receiving the image must be located within the team's assigned prep area or the designated viewing area.
4.3.4.2	Only transmitters that were onboard the vehicle during launch will be permitted to operate outside of the viewing or prep areas.
4.3.4.3	Onboard payload transmitters are limited to 250 mW of RF power while onboard the launch vehicle but may operate at a higher RF power after landing on the planetary surface. Transmitters operating at higher power must be approved by NASA during the design process.
4.3.4.4	The image should be included in your PLAR.
4.4.1	Black Powder and/or similar energetics are only permitted for deployment of in-flight recovery systems.
4.4.2	Teams must abide by all FAA and NAR rules and regulations.
4.4.3	Any experiment element that is jettisoned, except for planetary lander experiments, during the recovery phase will receive real-time RSO permission prior to initiating the jettison event.
4.4.4	Unmanned aircraft system (UAS) payloads, if designed to be deployed during descent, will be tethered to the vehicle with a remotely controlled release mechanism until the RSO has given permission to release the UAS.
4.4.5	Teams flying a UAS will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft.
4.4.6	Any UAS weighing more than .55 lbs. will be registered with the FAA and the registration number marked on the vehicle.

Table 94: NASA Safety Requirements

ID	Description
5.1	Each team will use a launch and safety checklist. The final checklists will be included in the FRR report and used during the Launch Readiness Review (LRR) and any launch day operations.
5.2	Each team must identify a student safety officer who will be responsible for all items in section 5.3.
5.3	The role and responsibilities of the safety officer will include, but are not limited to:
5.3.1	Monitor team activities with an emphasis on safety during:
5.3.1.1	Design of vehicle and payload
5.3.1.2	Construction of vehicle and payload components
5.3.1.3	Assembly of vehicle and payload
5.3.1.4	Ground testing of vehicle and payload
5.3.1.5	Subscale launch test(s)
5.3.1.6	Full-scale launch test(s)
5.3.1.7	Launch day
5.3.1.8	Recovery activities
5.3.1.9	STEM Engagement Activities
5.3.2	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.
5.3.3	Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.
5.3.4	Assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.
5.4	During test flights, teams will abide by the rules and guidance of the local rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch does not give explicit or implicit authority for teams to fly those vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.
5.5	Teams will abide by all rules set forth by the FAA.

Table 95: NASA Final Flight Requirements

ID	Description
6.1	NASA Launch Complex
6.1.1	"Teams must complete and pass the Launch Readiness Review conducted during Launch Week."
6.1.2	The team mentor must be present and oversee rocket preparation and launch activities.
6.1.3	The scoring altimeter must be presented to the NASA scoring official upon recovery.
6.1.4	Teams may launch only once. Any launch attempt resulting in the rocket exiting the launch pad, regardless of the success of the flight, will be considered a launch. Additional flights beyond the initial launch, will not be scored and will not be considered for awards.
6.2	Commercial Spaceport Launch Site
6.2.1	The launch must occur at a NAR or TRA sanctioned and insured club launch. Exceptions may be approved for launch clubs who are not affiliated with NAR or TRA but provide their own insurance, such as the Friends of Amateur Rocketry. Approval for such exceptions must be granted by NASA prior to the launch.
6.2.2	Teams must submit their rocket and payload to the launch site Range Safety Officer (RSO) prior to flying the rocket. The RSO will inspect the rocket and payload for flightworthiness and determine if the project is approved for flight. The local RSO will have final authority on whether the team's rocket and payload may be flown.
6.2.3	The team mentor must be present and oversee rocket preparation and launch activities.
6.2.4	BOTH the team mentor and the Launch Control Officer shall observe the flight and report any off-nominal events during ascent or recovery on the Launch Certification and Observations Report.
6.2.5	The scoring altimeter must be presented to BOTH the team's mentor and the Range Safety Officer
6.2.6	The mentor, the Range Safety Officer, and the Launch Control Officer must ALL complete the applicable sections of the Launch Certification and Observations Report. The Launch Certification and Observations Report document will be provided by NASA upon completion of the FRR milestone and must be returned to NASA by the team mentor upon completion of the launch.
6.2.7	The Range Safety Officer and Launch Control Officer certifying the team's flight shall be impartial observers and must not be affiliated with the team, individual team members, or the team's academic institution.

Table 95: NASA Final Flight Requirements

ID	Description
6.2.8	Teams may launch only once. Any launch attempt resulting in the rocket exiting the launch pad, regardless of the success of the flight, will be considered a launch. Additional flights beyond the initial launch will not be scored and will not be considered for awards.

6.1.2 Team Derived Requirements

Table 96: NDRT Launch Vehicle Requirements

ID	Description	Justification
FUNCTIONAL REQUIREMENT		
VF.1	The launch vehicle shall reach and apogee at or above 5300 ft in all NASA-defined flight conditions, including winds up to 20 mph and launch rail angles of up to 10 degrees from vertical.	The launch vehicle must be capable of reaching the beyond the target apogee for the ACS to be able to modify the flight path and achieve the target apogee.
VF.2	The nose cone shall have a connection point for a shock cord, capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 2. Required load will be updated prior to CDR.	The parachute is to be recovered independently from the vehicle, and therefore needs a robust connection for parachute attachment.
VF.3	The bottom of the payload bay shall have an aft-facing shock cord connection point, capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 2. Required load will be updated prior to CDR.	The payload bay is to be tethered to the main parachute during recovery, and therefore needs a robust connection point for a shock cord.
VF.4	The fin can shall be constructed to be capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 2.. Required load will be updated prior to CDR.	The fin can, and in particular the motor mount and centering rings, need to successfully transfer the force of motor thrust to the rest of the vehicle.
DESIGN REQUIREMENT		

Table 96: NDRT Launch Vehicle Requirements

ID	Description	Justification
VD.1	The launch vehicle shall have a minimum of 3 in-flight separation points.	One separation point is required for each of the two parachutes, and a third for deployment of the payload.
VD.2	The nose cone shall contain space sufficient for the placement of a parachute capable of slowing the nosecone below 15 ft/s, along with associated shock cord and thermal protection.	The nosecone will descend independently from the rest of the vehicle, and will therefore have its own parachute.
VD.3	The recovery tube of the vehicle shall have a minimum length of 40 in, and a maximum length of 48 in.	The recovery system, as currently defined, requires at least 40 in of vehicle length to be capable of containing the main recovery avionics, main parachute, and drogue parachute, as well as associated shock cords and thermal protection. The maximum length is driven by the availability of commercial body tubes and the transportability of the disassembled vehicle.
VD.4	The vehicle fin can shall have a minimum of 10 inches of length available to house the ACS.	The ACS, as currently defined, requires a containment length of at least 10 in.
VD.5	The vehicle fin can shall have a maximum length of 48 in.	The maximum length is driven by the availability of commercial body tubes and the transportability of the disassembled vehicle.
VD.6	The payload bay of the vehicle shall have a minimum internal diameter of 6 in.	The planetary landing system, as currently defined, requires a containment diameter of at least 6 in.
VD.8	The off-rail stability of the fully loaded vehicle shall be between 2 and 3 calibers.	Excessive stability leads to increased weathercocking, reducing potential apogee and causing less predictable drift patterns.

Table 96: NDRT Launch Vehicle Requirements

ID	Description	Justification
VD.9	The payload bay shall be constructed of EM-transparent material.	The vehicle and payload must contain transmitters to relay the position of all independently recovered components. This necessitates EM-transparent body materials, to allow for signal transmission through the rocket body.
VD.10	The payload bay shall have a minimum length of 21 in, and a maximum length of 48 in.	The planetary landing system, as currently defined, requires a containment length of at least 21 in. The maximum length is driven by the availability of commercial body tubes and the ease of transport of the disassembled vehicle.
ENVIRONMENTAL REQUIREMENT		
VE.1	All airframe components shall be capable of sustaining a minimum of 46 Gs of axial acceleration.	The vehicle is expected to undergo 23 Gs of acceleration during main parachute deployment, giving a factor of safety of 2.
VE.2	The airframe shall be capable of successful launches in temperatures between 20 and 100 degrees Fahrenheit	The vehicle is expected operate in a variety of launch fields throughout the year, including winter in Michigan and spring in Alabama.

Table 97: NDRT ACS Requirements

ID	Description	Justification
FUNCTIONAL REQUIREMENT		
AF.1	The ACS shall be capable of recording vehicle altitude (via barometric pressure) and vehicle acceleration	Record of pressure and acceleration data during flight allows for tuning of the apogee control algorithm and verification of altimeter performance.
AF.2	ACS shall provide a connection for a recovery harness, capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 2. Required load will be updated prior to CDR.	The ACS is located between the recovery tube and the fin can, and therefore serves as the connection point between the main recovery harness and the fin can after separation.

Table 97: NDRT ACS Requirements

ID	Description	Justification
AF.3	The ACS shall be capable of continuously actuating its control surfaces for a minimum of one minute.	In order to maximize impact on the vehicle apogee, the ACS needs to be capable of actuating during the entire vehicle ascent. The vehicle ascent is expected to take less than 30 seconds, providing a minimum factor of safety of 2.
AF.4	The ACS shall create a pneumatic seal with the vehicle body tube at the fore end of the system.	The top of system will be exposed to black powder separation charges, and must protect its own electronics from the hot gas produced.
DESIGN REQUIREMENT		
AD.1	ACS shall have a maximum allowable weight of 80 oz	80 oz is the mass allotted to the subsystem during preliminary vehicle design.
AD.2	ACS shall have a maximum length of 10 in.	10 in is the body length allotted to the subsystem during preliminary vehicle design.
AD.3	ACS shall have a maximum diameter of 6 inches, with all external control surfaces retracted.	Maximum allowable diameter allotted to the subsystem.
AD.4	The ACS shall be capable of installation and removal from the vehicle without the use of power tools.	System must be removable in order to access the control electronics for update/modification, and to download data post-flight in the field, with limited access to tools or specialized equipment.
AD.5	All control surfaces extending from the exterior of the vehicle shall be a minimum of 2 calibers aft of the vehicle's on-pad Center of Mass.	Protrusions from the vehicle's exterior can decrease the stability of the vehicle. Ensuring that all protrusions are at least 2 calibers aft of the vehicle's CG prevents the vehicle from becoming unstable in flight.
ENVIRONMENTAL REQUIREMENT		

Table 97: NDRT ACS Requirements

ID	Description	Justification
AE.1	All ACS components shall be capable of sustaining a minimum of 46 Gs of axial acceleration.	The vehicle is expected to undergo 23 Gs of acceleration during main parachute deployment, giving a factor of safety of 2.
AE.2	The ACS shall be capable of successful launch in temperatures between 20 and 100 degrees Fahrenheit	The ACS shall be capable of successful launch in temperatures between 20 and 100 degrees Fahrenheit
AE.3	The ACS shall be capable of remaining on the launch pad for a minimum of 2 hours prior to launch.	The launch vehicle may experience launch delays, and may need to remain ready to launch on the pad for up to 2 hours.

Table 98: NDRT Recovery Requirements

ID	Description	Justification
FUNCTIONAL REQUIREMENT		
RF.1	All recovery altimeters shall store recorded data on local memory or removable storage which can readily be downloaded to a laptop computer at the launch field via a commercially available cable or adapter.	Downloadable data allows for post-flight analysis of the launch vehicle characteristics and proof of successful flight.
RF.2	All recovery parachutes and shock cords shall be thermally protected from black powder ejection charges.	Without protection, parachutes and shock cords can be burned by the ejection charges, which reduces their effectiveness and risks recovery failure.
RF.3	All recovery avionics shall be pneumatically sealed from vehicle compartments with ejection charges.	Hot gas from black powder charges can damage electronics and cause false pressure readings.
RF.4	The vehicle nosecone shall be recovered independently from the rest of the vehicle.	Independent nosecone recovery allows for more reliable payload deployment.
RF.5	The main vehicle recovery system shall have a minimum of 3 electrically isolated systems for deploying both the main and drogue parachute.	Multiple isolated systems provides a substantially increased likelihood of safe recovery.

Table 98: NDRT Recovery Requirements

ID	Description	Justification
RF.6	The nosecone recovery system shall have a minimum of 2 electrically isolated systems for deploying its parachute.	Although not critical for safety, multiple redundant systems for nosecone deployment increases the chance of success in payload deployment.
RF.7	The avionics bay shall contain 2 parachute connections, both capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 2. Required load will be updated prior to CDR.	Both the main and drogue parachute shock cords will connect to the avionics bay.
DESIGN REQUIREMENT		
RD.1	The recovery system for the main vehicle shall have a maximum allowable mass of 160 oz.	160 oz is the mass allotted to the subsystem during preliminary vehicle design.
RD.2	The main vehicle recovery system shall take a maximum of 40 in of body length.	40 in is the body length allotted to the subsystem during preliminary vehicle design.
RD.3	All recovery components shall have a maximum diameter of 6 in.	Maximum allowable diameter allotted to the subsystem.
RD.4	The recovery system for the nosecone shall have a maximum allowable mass of 20 oz.	20 oz is the mass allotted to the subsystem during preliminary vehicle design.
RD.5	All recovery avionics shall be removable from the launch vehicle without the use of power tools.	The recovery electronics need to be available for modification and data download after flight in the field, with limited axes to tools or specialized equipment.
RD.6	All arming switches used for main vehicle recovery shall be accessible from one location on the rocket body.	Allows for streamlined recovery activation on the launch pad.
RD.7	All arming switches used for nosecone recovery shall be accessible from one location on the rocket body.	Allows for streamlined recovery activation on the launch pad.

Table 98: NDRT Recovery Requirements

ID	Description	Justification
RD.8	The main vehicle shall have a minimum of 3 electrically isolated systems for deploying both the main and drogue parachute.	Multiple redundancies in the vehicle electronics allows for more reliable vehicle recovery.
ENVIRONMENTAL REQUIREMENT		
RE.1	The recovery systems shall be capable of sustaining a minimum of 46 Gs of axial acceleration.	The vehicle is expected to undergo 23 Gs of acceleration during main parachute deployment, giving a factor of safety of 2.
RE.2	All recovery systems shall be capable of successful launch in temperatures between 20 and 100 degrees Fahrenheit	The vehicle is expected operate in a variety of launch fields throughout the year, including winter in Michigan and spring in Alabama.
RE.3	The recovery system(s) shall be capable of remaining on the launch pad for a minimum of 2 hours prior to launch.	The launch vehicle may experience launch delays, and may need to remain ready to launch on the pad for up to 2 hours.

Table 99: NDRT PLS Requirements

ID	Description	Justification
FUNCTIONAL REQUIREMENT		
PF.1	The PLS shall descend with a maximum terminal velocity of 20 ft/s.	A descent velocity significantly above 20 ft/s risk damage to property and/or injury to personnel on during payload recovery.
PF.2	The PLS shall have a drift radius of less than 2500 ft from the launch pad.	The payload must remain within the launch field during all phases of flight.
PF.3	All moving elements of the PLS shall be locked in place during flight.	Vibration and movement within the vehicle during flight can cause damage to the payload or retainment failure.
PF.4	The PLS shall be capable of withstanding an impact with the ground at a minimum of 20 ft/s.	The payload is will descend with a maximum velocity of 20 ft/s, as defined in Requirement PF.1.

Table 99: NDRT PLS Requirements

ID	Description	Justification
PF.5	The PLS shall be capable of transmitting data to a minimum distance of 6000 ft.	A minimum transmission distance of 6000 ft will allow for successful connection to the PLS up to the maximum allowable vehicle apogee.
PF.6	The PLS shall contain minimum of 2 electrically isolated systems for deployment from the vehicle.	Redundancy in deployment electronics allows for more reliable payload deployment, and therefore more reliable mission success.
PF.7	The PLS shall contain a GPS module and method of transmitting GPS data to the team.	Reception of GPS data simplifies the process of locating and recovering the payload from the launch field.
PF.8	The PLS ground station electrical components shall be powered via commercially available batteries or a USB connector.	Ground station must be capable of being used in remote field conditions, without outlet power or generators.
DESIGN REQUIREMENT		
PD.1	The PLS shall have a maximum weight of 80 oz, including the lander, retention, deployment and descent hardware.	Maximum allowable weight allotted to the system.
PD.2	The PLS shall have a maximum length of 21 in.	21 in is the length allotted to the payload during preliminary vehicle design.
ENVIRONMENTAL REQUIREMENT		
PE.1	The PLS shall be capable of sustaining a minimum of 46 Gs of axial acceleration.	The vehicle is expected to undergo 23 Gs of acceleration during main parachute deployment, giving a factor of safety of 2.
PE.2	The PLS shall be capable of successful launch and mission completion in temperatures between 20 and 100 degrees Fahrenheit	The vehicle is expected operate in a variety of launch fields throughout the year, including winter in Michigan and spring in Alabama.
PE.3	PLS shall be capable of remaining on the launch pad for a minimum of 2 hours.	The launch vehicle may experience launch delays, and may need to remain ready to launch on the pad for up to 2 hours.

Table 99: NDRT PLS Requirements

ID	Description	Justification
PE.4	Ground station power supply shall be capable of powering the system for a minimum of 2 hours.	Ground station must be capable of remaining powered and operational for as long as the payload.

Table 100: NDRT Safety Requirements

ID	Description	Justification
S.1	Team shall develop standard operating procedures (SOPs) to instruct and standardize the use of tools and manufacturing processes.	SOPs allow for more consistent construction operations, as well as a basis for teaching new members how construction operations are performed.
S.2	Team shall develop SOPs to standardize test procedures and processes	SOPs allow for more consistent, documented testing, as well as a basis for teaching new members how testing operations are performed.
S.3	The team shall develop documentation containing safety information pertinent to the use of PPE, energetics, and rocket materials. This documentation will be stored in the team workshop and made readily available to all team members of visitors.	Quickly referenceable documentation regarding important safety issues, such as the use of PPE and the potential hazards of materials, can reduce the likelihood of injury or safety incidents.
S.4	All NDRT members shall sign a Workshop Safety Agreement prior to participating in any team construction activities.	All team members need to be made aware of the rules they are expected to follow in the team workshop.
S.5	All NDRT members shall complete the workshop safety and tools quiz administered by the AME SFL workshop and present proof of completion with a passing grade prior to participating in any team construction activities.	All team members need to understand the potential hazards of working in an active workshop environment before participating in vehicle construction.

Table 100: NDRT Safety Requirements

ID	Description	Justification
S.6	The team shall develop documentation outlining team safety compliance processes, as well as the team safety agreement and updated copies of the team's FMEA and hazard tables. This documentation will be stored in the team workshop and made readily available to all team members of visitors.	Quickly referencable documentation regarding safety compliance practices and potential hazards specific to the current project can reduce the likelihood of injury or safety incidents.
S.7	The team shall comply with all University rules and regulations regarding COVID-19 safety, as defined at https://here.nd.edu/policies/	Prevention of COVID-19 transmission is extremely important in maintaining the health of team members, and the community at large.

6.2 Budget

The team's funding plan can be seen in Table 101. The team is grateful to have the financial contributions of several alumni and corporate sponsors. The team will continue to pursue sponsorships in order to fund potential travel and more technology development.

Table 101: NDRT 2020/2021 Revenue

Source	Amount
Carryover (2019/2020)	\$9,297
AIAA Funds	\$3,800
Electrical Engineering Department	\$500
NDRT Alumni	\$1,000
ND Day Fundraising	\$940
Collins Aerospace	\$5,000
Total	\$20,537

An overview of the expenses for each of the subsystems of the team can be seen in Table 102. Most of the expenses thus far are for subscale construction. The materials the team needs will be acquired from trusted vendors used in the past or have positive reviews. Following the overview are the line item budgets for the three subsystems that have begun purchasing items.

Table 102: Budget Overview

Category	Amount Allocated	Funds Spent
Vehicle Design	\$4,000.00	\$358.03
Air Braking System	\$1,000.00	\$63.92
Recovery Subsystem	\$1,200.00	\$430.81
Planetary Landing System	\$1,700.00	\$0.00
<i>Vehicle Subtotal</i>	<i>\$7,900.00</i>	<i>\$852.76</i>
Safety	\$300.00	\$0.00
STEM Engagement	\$100.00	\$0.00
Competition Travel	\$9,000.00	\$0.00
Apparel (will be refunded upon payment)	\$2,307.95	\$2,307.95
Total Expenses	\$19,607.95	\$3,160.71
Total Revenue	\$20,537.00	\$20,537.00
Remaining Funds	\$929.05	\$17,376.29

Table 103: Vehicles Line Item Budget

Item	Vendor	Qty	Price Per Unit	Total Cost
Rocksim v10 Licenses	Apogee Components	3	\$21.25	\$63.75
Standard Rail Button (fits 1" Rail - 1010) - 2 Per Pack	Apogee Components	1	\$3.48	\$3.48
Motor Mount Tubing - 29mm x 12" Motor Mount Tube	LOC Precision	2	\$1.99	\$3.98
Aerotech G80 Blue Thunder 29 mm - Single Use	BuyRocketMotors.com	3	\$26.99	\$80.97
Aerotech 29mm Aluminum Motor Retainer	BuyRocketMotors.com	1	\$14.39	\$14.39
UPS HAZMAT Shipping Fee	BuyRocketMotors.com	1	\$37.00	\$37.00
BTL-2.5-1.5	Public Missiles, Ltd.	1	\$31.95	\$31.95
2.6" Tube Coupler. 5" Long for Bays	Rocketarium	2	\$2.75	\$5.50
2.6" Phenolic Tube. 36" Long	Rocketarium	3	\$19.95	\$59.85
Shipping of all subscale parts	Subscale Shipping	1	\$57.16	\$57.16
			Total	\$358.03

Table 104: ACS Line Item Budget

Apogee Control System Components	Vendor	Qty	Price Per Unit	Total Cost
Raspberry Pi Zero W	Adafruit	1	\$10.00	\$10.00
Adafruit ADXL345	Adafruit	1	\$17.50	\$17.50
Adafruit MPL3115A2	Adafruit	1	\$9.95	\$9.95
HiLetgo MPU9250/6500	Amazon	2	\$8.99	\$17.98
SanDisk 32GB Ultra microSDHC	Amazon	1	\$8.49	\$8.49
			Total	\$63.92

Table 105: Recovery Line Item Budget

Recovery System Components	Vendor	Qty	Price per Unit	Total Cost
Keylock Switch (KO117A125)	Digi-Key	5	\$8.19	\$40.95
12 Ft. Standard Parachute	Rocketman	1	\$155.00	\$155.00
24" Elliptical Parachute	FruityChutes	1	\$64.00	\$64.00
Square-Profile Oil-Resistant Buna-N O-Ring	McMaster-Carr	1	\$9.30	\$9.30
StratologgerCF Altimeter	PerfectFlite Direct	2	\$54.95	\$109.90
Multipurpose 6061 Aluminum (1/4" x8" x8")	McMaster-Carr	2	\$18.31	\$36.62
Multipurpose 6061 Aluminum (3/8" x2" x12")	McMaster-Carr	1	\$7.26	\$7.26
Clear Impact-Resistant Polycarbonate Sheet (1/16" x12" x24")	McMaster-Carr	1	\$7.78	\$7.78
			Total	\$430.81

6.3 Timeline

The overall timeline remains the same as the proposed timeline in the Proposal. The next major milestone the team is preparing for is the subscale launch on November 13th. This timeline can be seen in Figure 46. There will be significant challenges for the team in regards to the timeline due to the impact of COVID-19 on University planning. School will not be in session from November 20th until February 3rd. This will pose significant risks for construction and full scale launch deadlines. The team is evaluating options that include using school machine shops prior to class starting, considering more commercially available options, and outsourcing machining. The following Gantt charts reflect the current plan to start construction two weeks out from the first launch date.

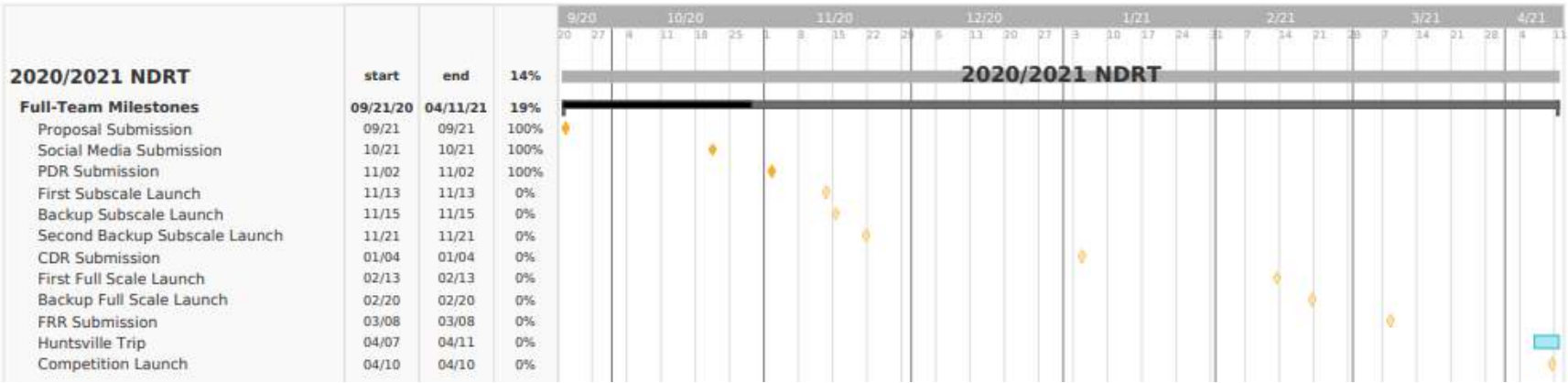


Figure 46: Overall project timeline milestones.

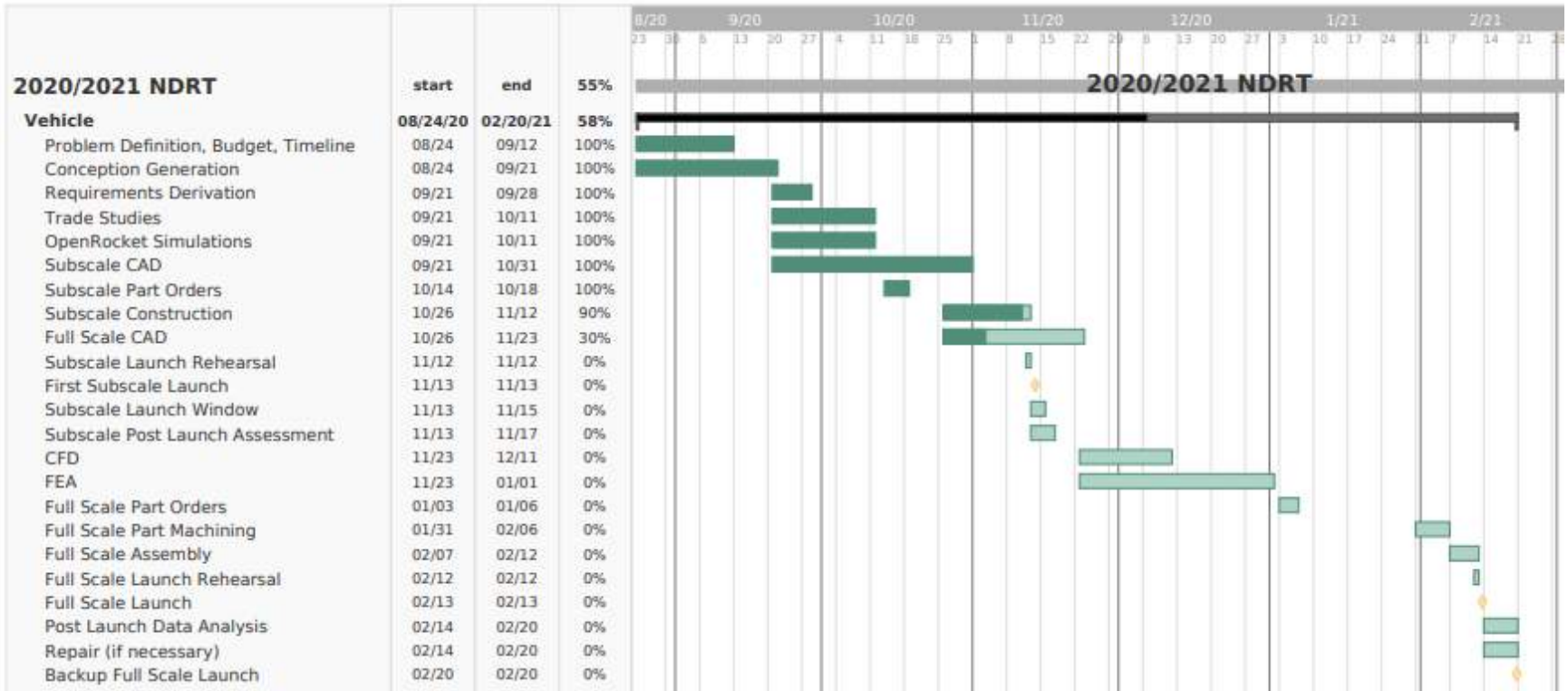


Figure 47: Project timeline for the Vehicles team.

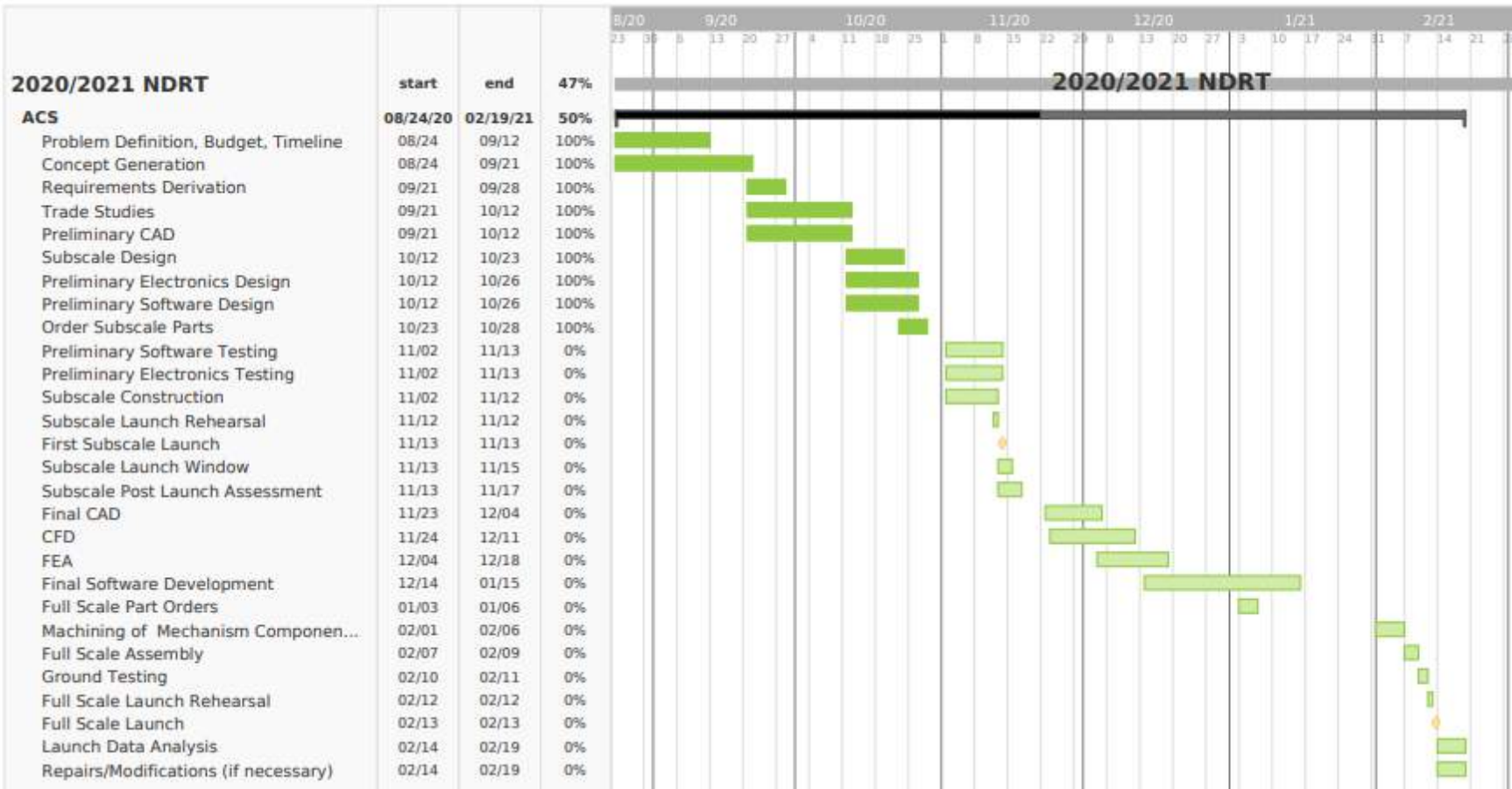


Figure 48: Project timeline for the ACS team.

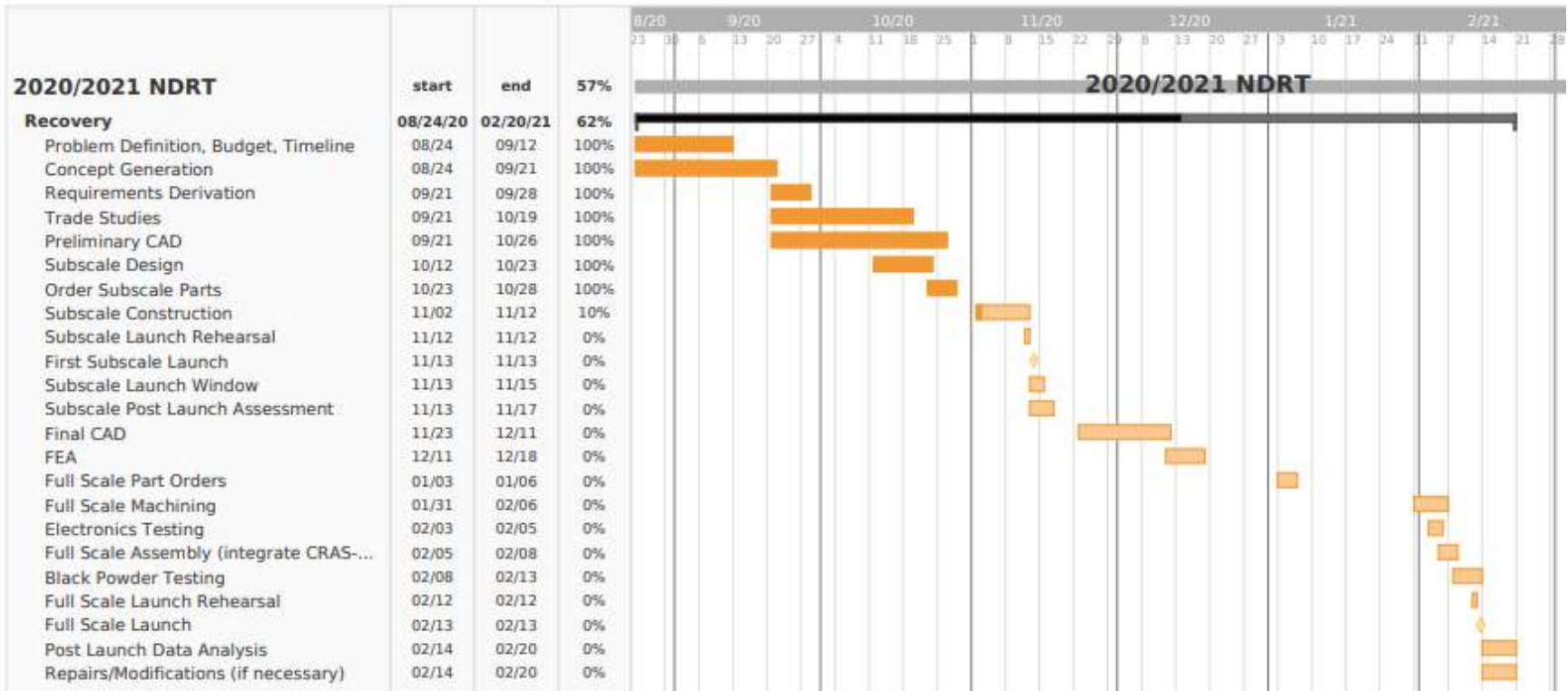


Figure 49: Project timeline for the Recovery team.

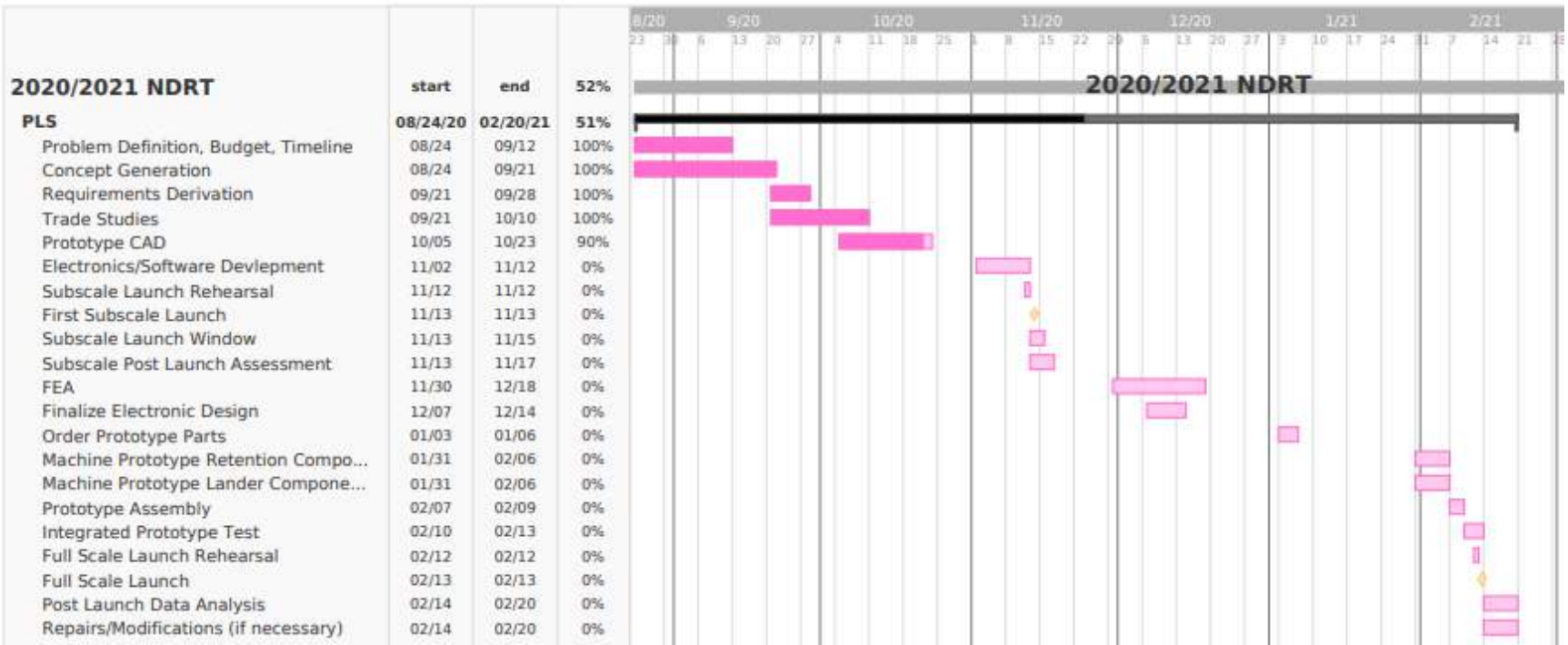


Figure 50: Project timeline for the PLS team.

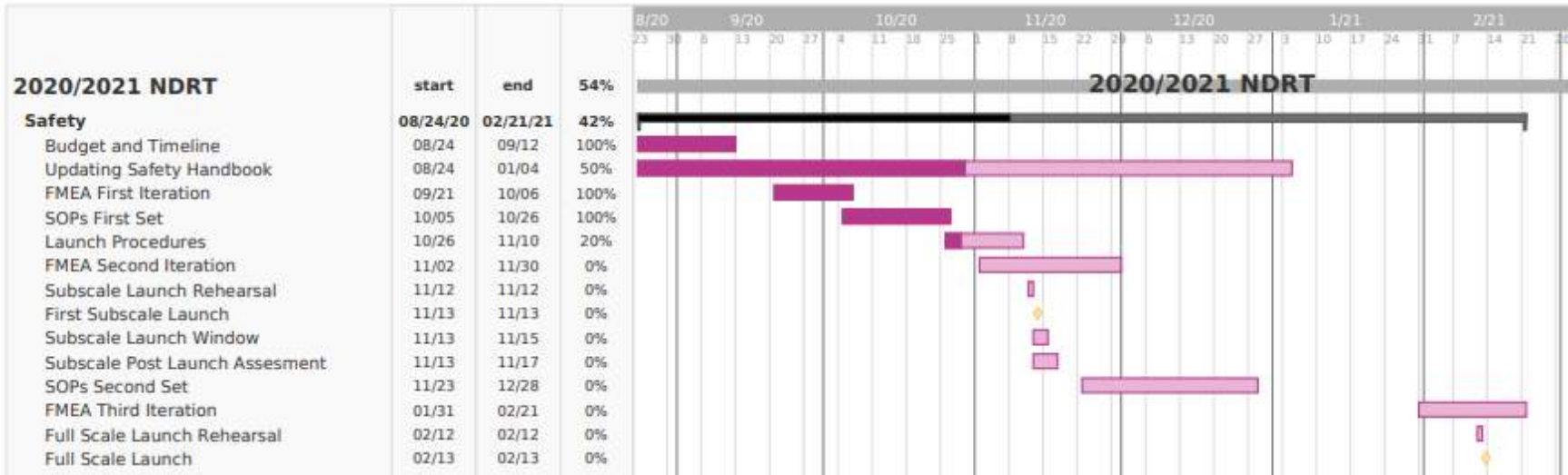


Figure 51: Project timeline for the Safety team.



Figure 52: Project timeline for the Educational Outreach events.

A Workshop Safety Agreement



AIAA Workshop Safety Agreement

The AIAA workshop, located in Stinson-Remick 217, is home to the Notre Dame Rocketry Team and Design Build Fly design competition teams. It is the responsibility of each member of these teams to uphold safe practices and develop safe habits to prevent potential injury.

Please print this document, read each statement and initial on the provided lines to indicate your acceptance and commitment to ensuring a safe work environment. When complete, please scan and upload a PDF or JPEG with the naming convention “Last_First_Agreement” to this [Google Folder](#).

- _____ I agree to wear a protective face covering at all times. Appropriate face coverings include cloth masks, paper masks, respirators, face shields, or other approved coverings.
- _____ I agree to wash my hands with soap and water for at least 20 seconds or utilize the provided hand sanitizing station immediately upon entering Stinson-Remick 217.
- _____ I agree to utilize the provided [Attendance Form](#) when entering and exiting the workshop, and acknowledge that the Attendance Form is readily available as a QR code in multiple locations in and around the workshop.
- _____ I agree to maintain a capacity limit of 20 individuals in Stinson-Remick 217 and maintain 6 feet of distance unless absolutely necessary for construction. I agree to limit all close contact (less than 6 feet) to less than 15 minutes at a time.
- _____ I agree to yield the workshop to those requiring the space for construction if I am engaging in activities unrelated to construction. I agree to respect the scheduled times and reservations for team leadership and sub-squad construction time.
- _____ I agree to comply with all other statements and mandates issued by the University of Notre Dame Student Activities Office in regard to public health safety and Covid-19.
- _____ I agree to complete required tool and machine certifications before using the respective tools and machines. I understand that new training and certifications may require recertification for a specific tool during the same school year.
- _____ I understand that a violation of appropriate tool or machine usage may result in a required recertification or restrictions on workshop tool and machine usage.

_____ I understand that I am only allowed to enter the workshop if a leader on NDRT is present in the workshop.

_____ I agree to wear safety glasses or safety goggles in the workshop at all times construction or any assembly is taking place. If I wear prescription glasses, I acknowledge that I must wear safety goggles over my glasses, or acquire appropriate safety side shields.

_____ I agree to wear a short sleeve shirt, long pants, and closed-toe shoes when in the workshop. I agree to tie my hair back while actively working if my hair is longer than shoulder-length.

_____ I understand that I am unable to handle chemicals or hazardous materials while wearing contact lenses.

_____ I understand and will comply with all guidelines noted in the Notre Dame Rocketry Team Safety Handbook, found on the [NDRT website](#).

_____ I agree to report unsafe working practices to the [Safety Reporting Form](#) when spotted in the workshop. I understand the reporting of unsafe conditions in the workplace leads directly to eliminating minor and major injuries.

_____ I agree to maintain an inclusive environment, promoting academic achievement. I will not under any circumstance harass or discriminate another individual on the basis of race, color, religion, sex, sexual orientation, gender identity or expression, national origin, age, disability, marital status, citizenship, and genetic information.

_____ I understand that any discrimination or harassment in the AIAA Workshop should be reported non-confidentially to the [SpeakUp](#) Reporting website or confidentiality to the [University Counseling Center](#). NDRT leadership are not properly equipped to act on serious instances of harassment and discrimination, but are available for support and guidance.

Additional safety agreements will be required for activities taking place outside of the workshop, such as a test launch, travel to competition, or usage of other University of Notre Dame facilities. By signing and dating this form, I agree to all information in safety documents provided by the Notre Dame Rocketry Team, Notre Dame Student Activities Office, and Stinson-Remick facilities office.

Print Name: _____

Signature: _____

Date: _____